

A SIMULATED ANNEALING APPROACH TO THE BATTERY ELECTRIC BUS CHARGING PROBLEM

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Outline

Introduction

The Position Allocation Problem Approach With Linear Battery Dynamic

The Simulated Annealing Approach With Linear Battery Dynamics

TODO The Simulated Annealing Approach With Non-Linear Battery Dynamics

Introduction

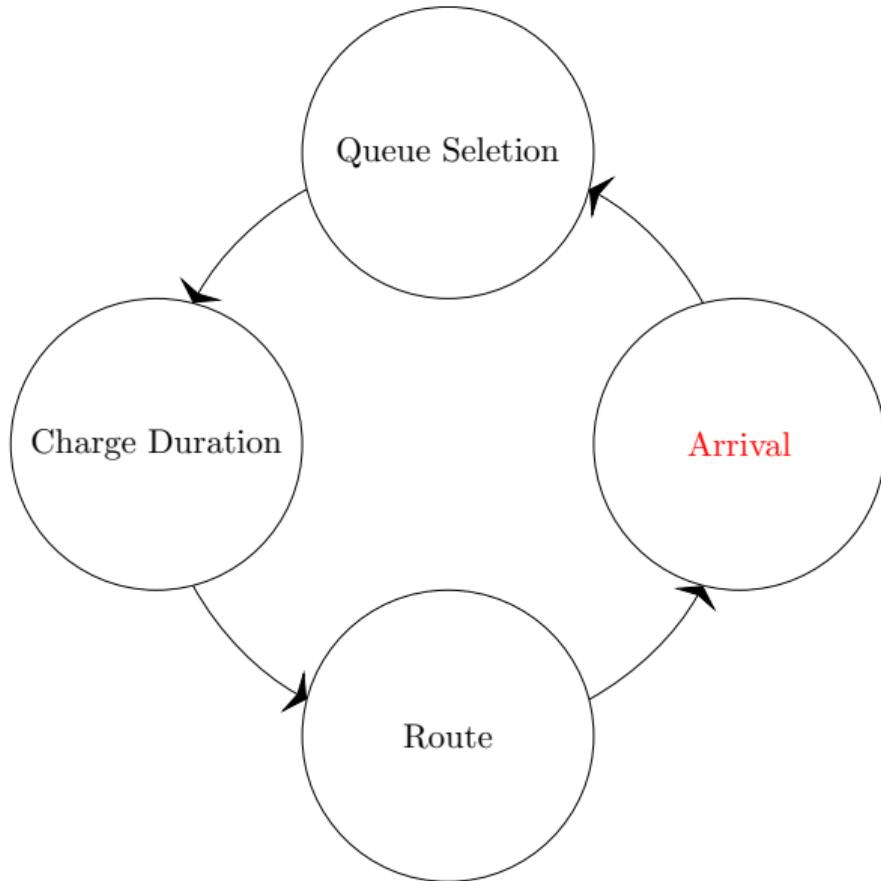
The Position Allocation Problem Approach With Linear Battery Dynamic

The Simulated Annealing Approach With Linear Battery Dynamics

TODO The Simulated Annealing Approach With Non-Linear Battery Dynamics

Ref	Demand	Consumption	Linear Battery	Non-linear Battery	Charger Minimization	Battery Health
[9]	✓					
[7]	✓			✓		
[9]	✓					
[8]	✓					
[1]	✓					
[6]	✓					
[3]	✓	✓	✓	✓	✓	
[2]	✓	✓	✓			
[5]	✓	✓	✓			

Problem Description



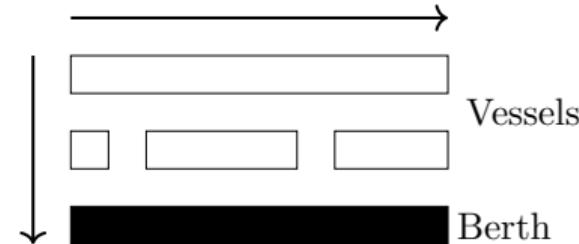
The Berth Allocation Problem¹



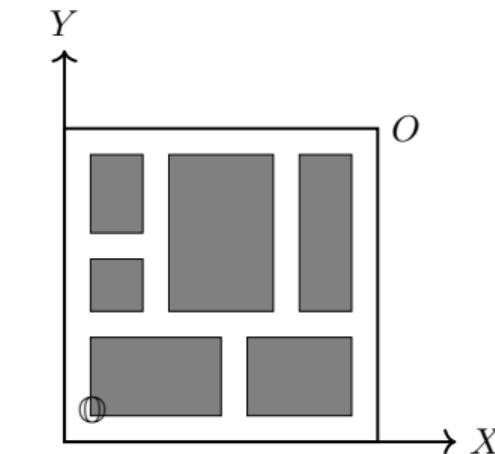
¹<https://www.mdpi.com/2077-1312/11/7/1280>

The Berth Allocation Problem

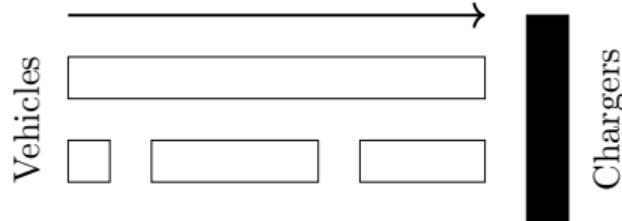
- ▶ Vessels move down toward the quay
 - ▶ Receive service
 - ▶ Exit to the right
-



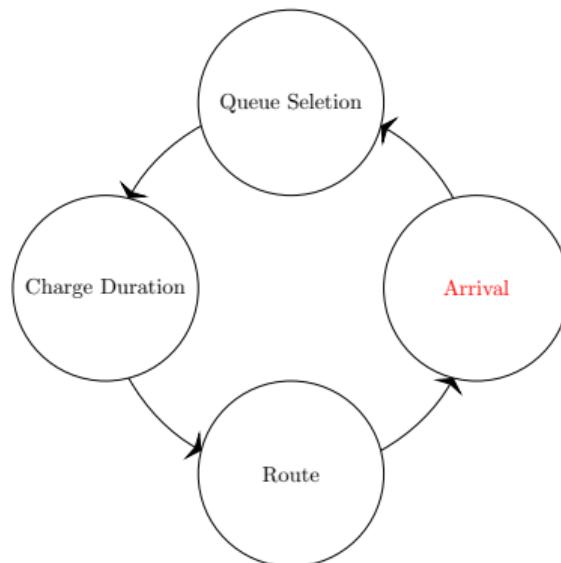
- ▶ A variant of the rectangle packing problem
- ▶ Solves the problem of optimally assigning incoming vessels to be serviced



The Position Allocation Problem



- ▶ Service flow is left to right
- ▶ Single charger type
- ▶ All arrivals are considered unique
- ▶ Service times are assumed to be known



Introduction

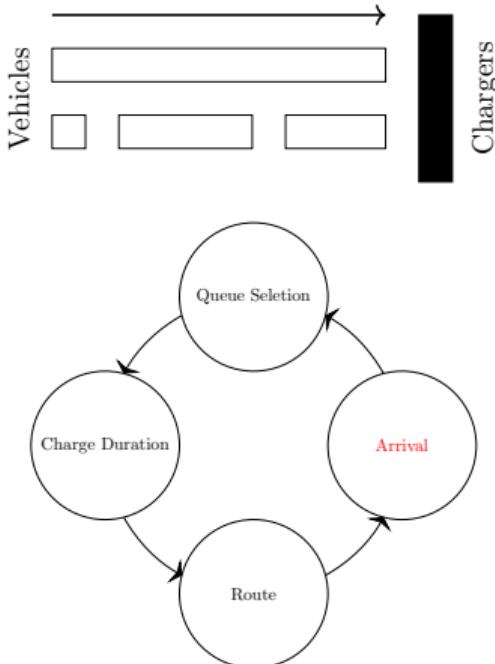
The Position Allocation Problem Approach With Linear Battery Dynamic

The Simulated Annealing Approach With Linear Battery Dynamics

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Requirements For BEB Implementation

- ▶ Charges must be able to be tracked
- ▶ Service time is unknown
- ▶ Accommodate chargers of different speeds
- ▶ Minimize charger count
- ▶ Minimize consumption cost
- ▶ Encourage slow charger use for battery health



Constraints



$$\min \sum_{i=1}^{n_V} \sum_{q=1}^{n_Q} \left(w_{iq} m_q + g_{iq} \epsilon_q \right)$$

$$u_j - u_i - s_i - (\sigma_{ij} - 1)T \geq 0$$

$$s_i + u_i = d_i$$

$$v_j - v_i - (\psi_{ij} - 1)n_Q \geq 1$$

$$a_i \leq u_i \leq (T - s_i)$$

$$\sigma_{ij} + \sigma_{ji} \leq 1$$

$$d_i \leq \tau_i$$

$$\psi_{ij} + \psi_{ji} \leq 1$$

$$\eta_i + \sum_{q=1}^{n_Q} g_{iq} r_q - \Delta_i = \eta_{\gamma_i}$$

$$\sigma_{ij} + \sigma_{ji} + \psi_{ij} + \psi_{ji} \geq 1$$

$$\eta_i + \sum_{q=1}^{n_Q} g_{iq} r_q - \Delta_i \geq \nu_{\Gamma_i} \kappa_{\Gamma_i}$$

$$\sum_{q=1}^{n_Q} w_{iq} = 1$$

$$\eta_i + \sum_{q=1}^{n_Q} g_{iq} r_q \leq \kappa_{\Gamma_i}$$

$$v_i = \sum_{q=1}^{n_Q} q w_{iq}$$

Constraints

$$u_j - u_i - s_i - (\sigma_{ij} - 1)T \geq 0$$

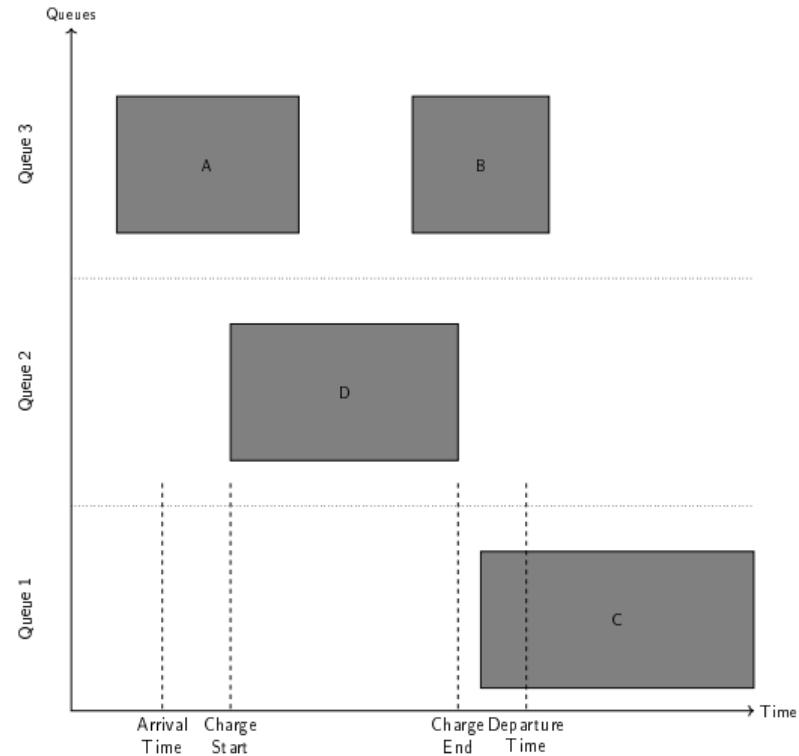
$$v_j - v_i - (\psi_{ij} - 1)n_Q \geq 1$$

$$\sigma_{ij} + \sigma_{ji} \leq 1$$

$$\psi_{ij} + \psi_{ji} \leq 1$$

$$\sigma_{ij} + \sigma_{ji} + \psi_{ij} + \psi_{ji} \geq 1$$

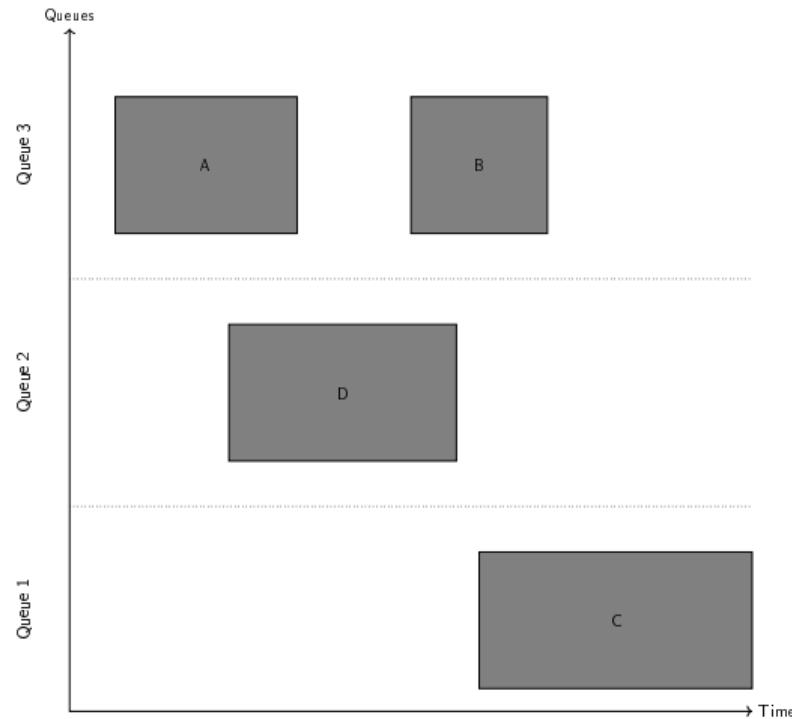
- ▶ Used to ensure that gray rectangles do not overlap
- ▶ σ_{ij} establishes temporal ordering when active
- ▶ ψ_{ij} establishes spacial ordering when active



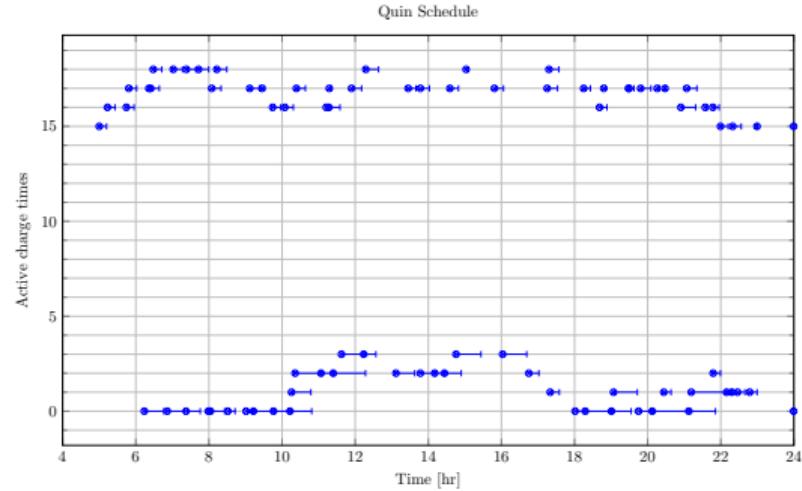
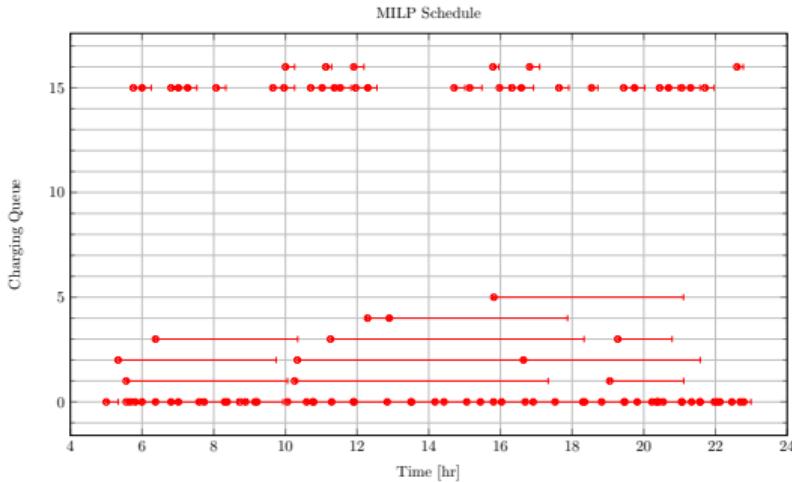
Parameters



Execution	2 hr
T	24 hr
n_V	338
n_A	35
α_i	90%
β_i	70%
ν_i	20%
β_i	70%
m_q	1000q



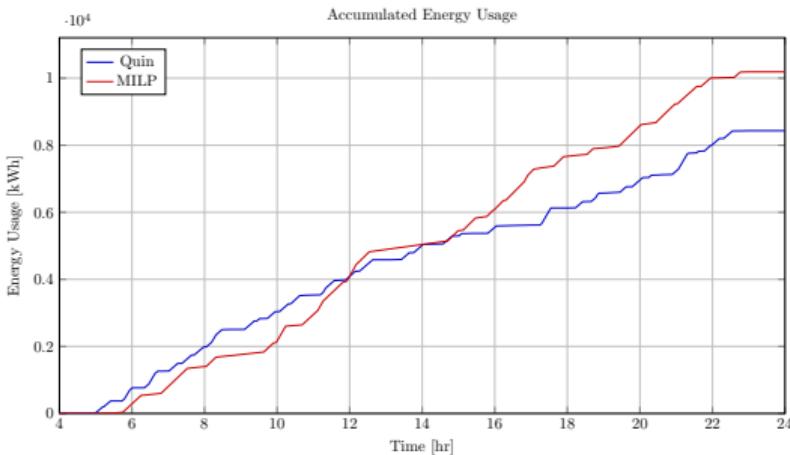
Schedules



- ▶ Utilized more slow chargers for longer durations
- ▶ Fast chargers utilized more sparingly
- ▶ Extensive use of fast chargers
- ▶ Slow chargers used for short durations

SOC And Energy Use

	MILP	Q_{in}
Mean	265.873	355.93
Min	97.04	0.000
Max	388	368.354



- ▶ SOC of Q_{in} allowed to drop to 0
- ▶ PAP maintained minimum SOC and final SOC

- ▶ PAP accumulated energy is larger due to minimum SOC constraints

Introduction

The Position Allocation Problem Approach With Linear Battery Dynamic

The Simulated Annealing Approach With Linear Battery Dynamics

TODO The Simulated Annealing Approach With Non-Linear Battery Dynamics

Simulated Annealing²



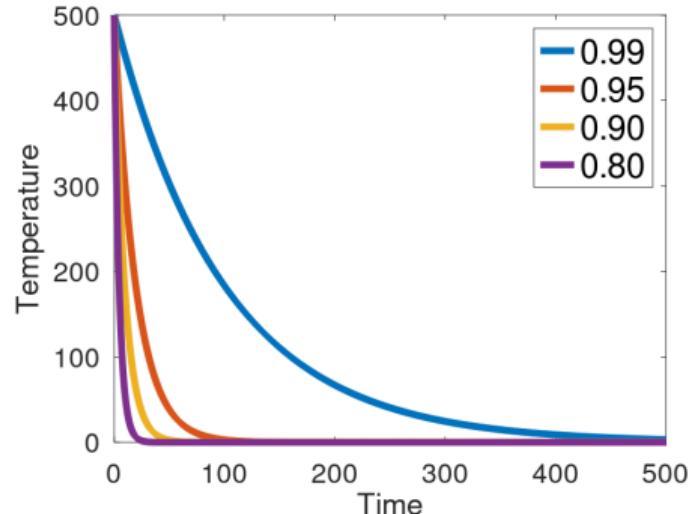
- ▶ A probabilistic technique for approximating the global optimum of a given function.
- ▶ Often applied to problems that contain many local solutions
- ▶ Three key components:
 - ▶ Cooling Schedule
 - ▶ Acceptance Criteria
 - ▶ Generation Mechanisms

²https://en.wikipedia.org/wiki/Simulated_annealing

Cooling Schedule



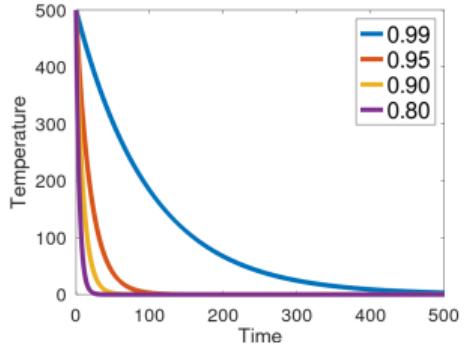
- ▶ The cooling equation models the rate at which the temperature decreases over time in the SA process.
- ▶ The temperature is high, SA encourages exploration. As the temperature decreases, exploitation is encouraged.



$$t_m = \beta t_{m-1}$$

Acceptance Criteria³

$$f(\mathbb{I}, \bar{\mathbb{I}}, t_m) = \begin{cases} 1 & \Delta E > 0 \\ e^{-\frac{\Delta E}{t_m}} & \text{otherwise} \end{cases}$$

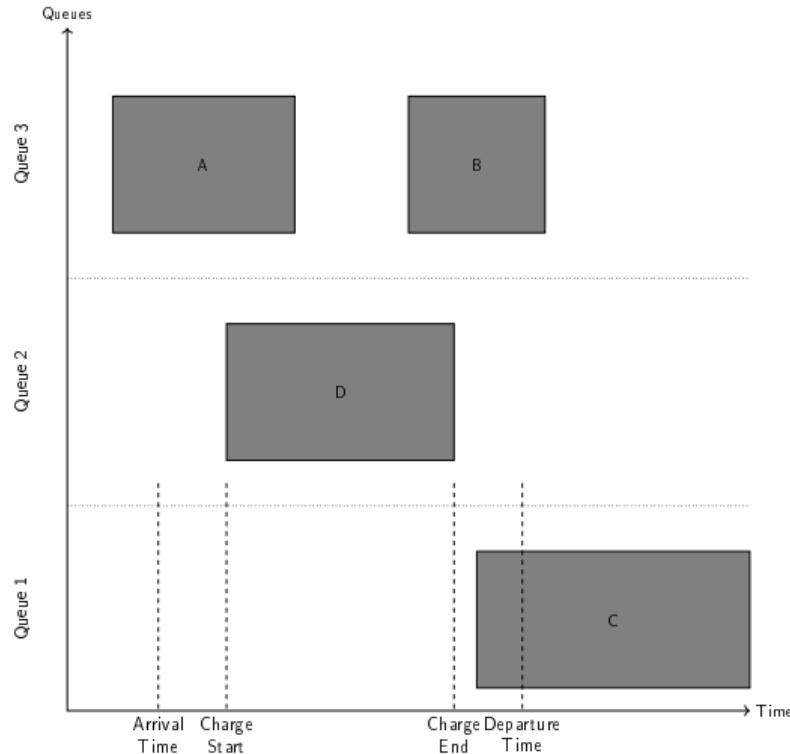


³https://en.wikipedia.org/wiki/Simulated_annealing

Generation Mechanisms - Primitive Functions



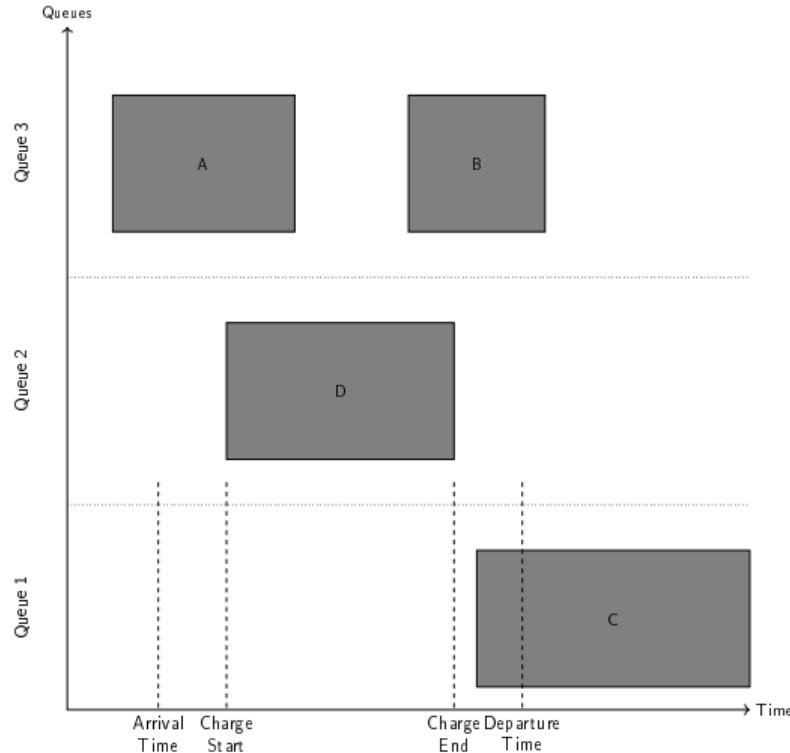
- ▶ New Visit: Move a bus from a wait queue to charge queue
- ▶ Slide Visit: Change the charge duration of a visit
- ▶ New Charger: Move a visit to a new charger
- ▶ Wait: Move a visit to its idle queue
- ▶ New Window: Execute Wait then New Visit primitives



Generation Mechanisms - Wrapper Functions



- ▶ Charge Schedule Generation:
Iterate through each visit and execute New Visit
- ▶ Perturb Schedule: Randomly execute one of the primitives with a weighted distribution



Objective Function



$$J(\mathbb{I}) = z_d p_d + \sum_{i=1}^{n_V} \left[\epsilon_{q_i} r_{q_i} + z_p \phi_i (\eta_i - \nu_{b_i} \kappa_{b_i}) + z_c r_{q_i} s_i \right]$$

► Demand cost

- $p_{T_p, h} = \frac{1}{T_p} \sum_{k=h-\frac{T_p}{dt}+1}^h p_k dt$
- $p_{max} = \max_{k \in [h-\frac{T_p}{dt}+1, h]} p_{T_p, h}$
- $p_d = \max(p_{fix}, p_{max})$

- $\epsilon_{q_i} r_{q_i}$: Assignment Cost
- $z_p \phi_i (\eta_i - \nu_{b_i} \kappa_{b_i})$: Penalty Function
- $z_c r_{q_i} s_i$: Consumption Cost

Constraints

$$u_j - d_i - (\sigma_{ij} - 1)T \geq 0$$

$$q_j - q_i - 1 - (\psi_{ij} - 1)Q \geq 0$$

$$\sigma_{ij} + \sigma_{ji} \leq 1$$

$$\psi_{ij} + \psi_{ji} \leq 1$$

$$\sigma_{ij} + \sigma_{ji} + \psi_{ij} + \psi_{ji} \geq 1$$

$$s_i = d_i - u_i$$

$$\eta_{\xi_i} = \eta_i + r_{q_i} s_i - \Delta_i$$

$$\kappa_{\Xi_i} \geq \eta_i + r_{q_i} s_i$$

$$a_i \leq u_i \leq d_i \leq e_i \leq T$$

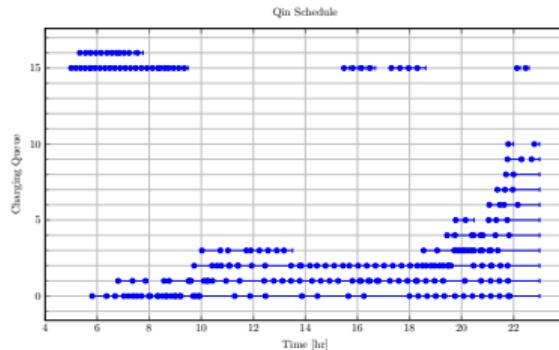
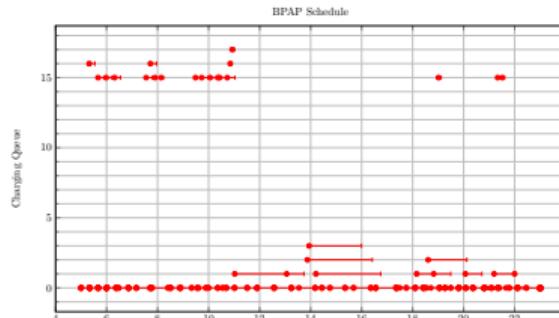
Parameters

Model	Execution Time [s]	Iteration [s]
MILP	1900	N/A
Quick	1532.8	0.4
Heuristic	1916	0.5

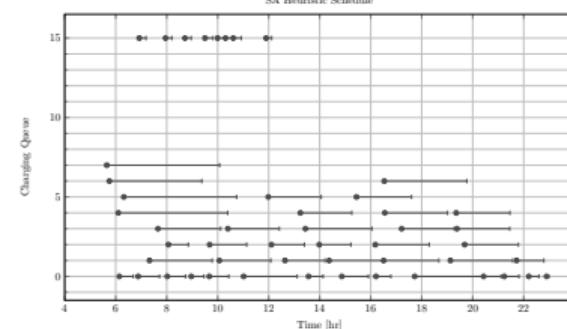
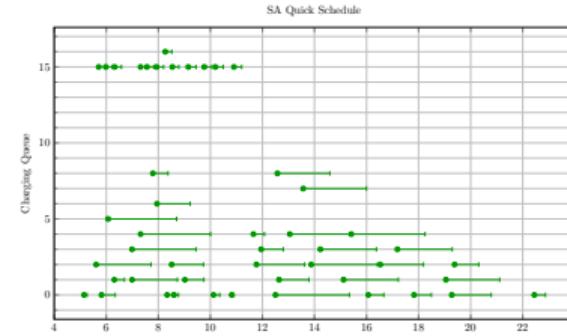
- ▶ $T_0 = 90000$
- ▶ $\beta = 0.997$
- ▶ $|t| = 3797$
- ▶ $n_K = 500$

Schedule

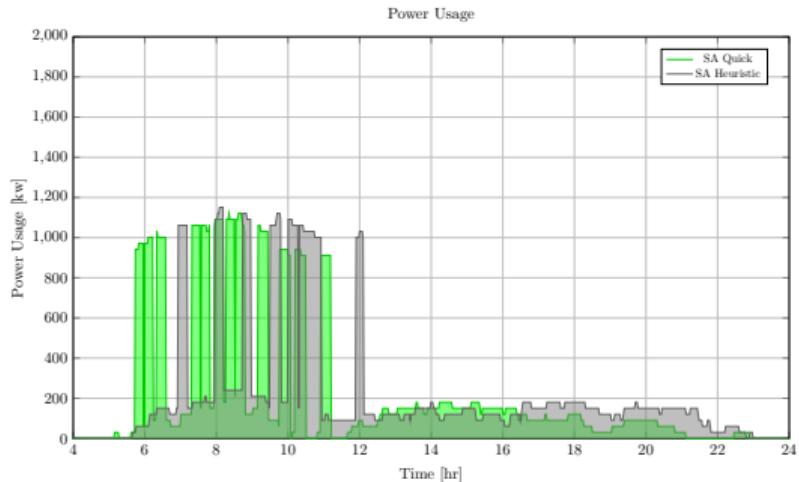
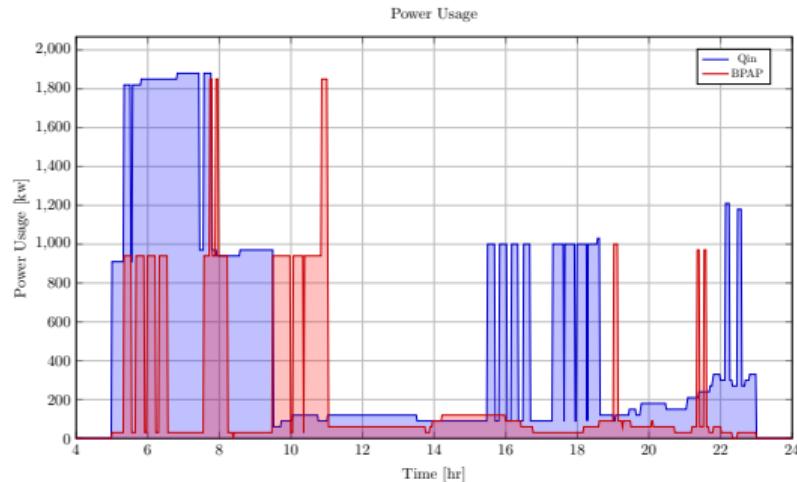
- ▶ Qin heavily utilizes fast charger
- ▶ PAP emphasizes slow queues, but utilizes fast chargers readily



- ▶ SA techniques heavily utilize slow charging
- ▶ SA techniques utilize fast chargers more sparingly



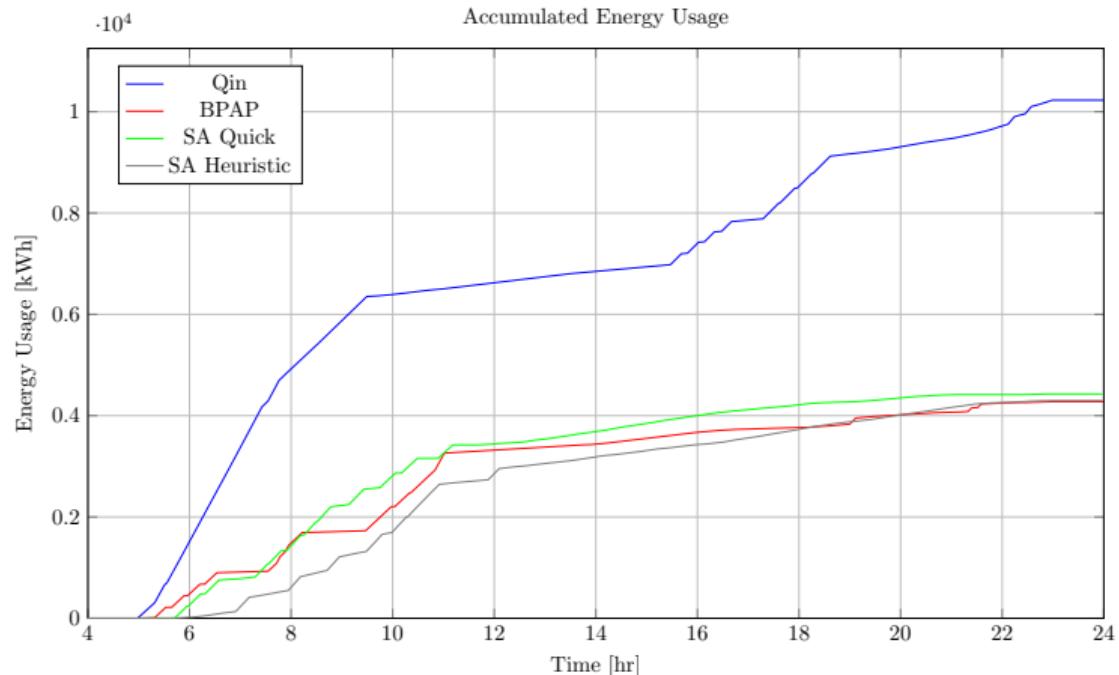
Power



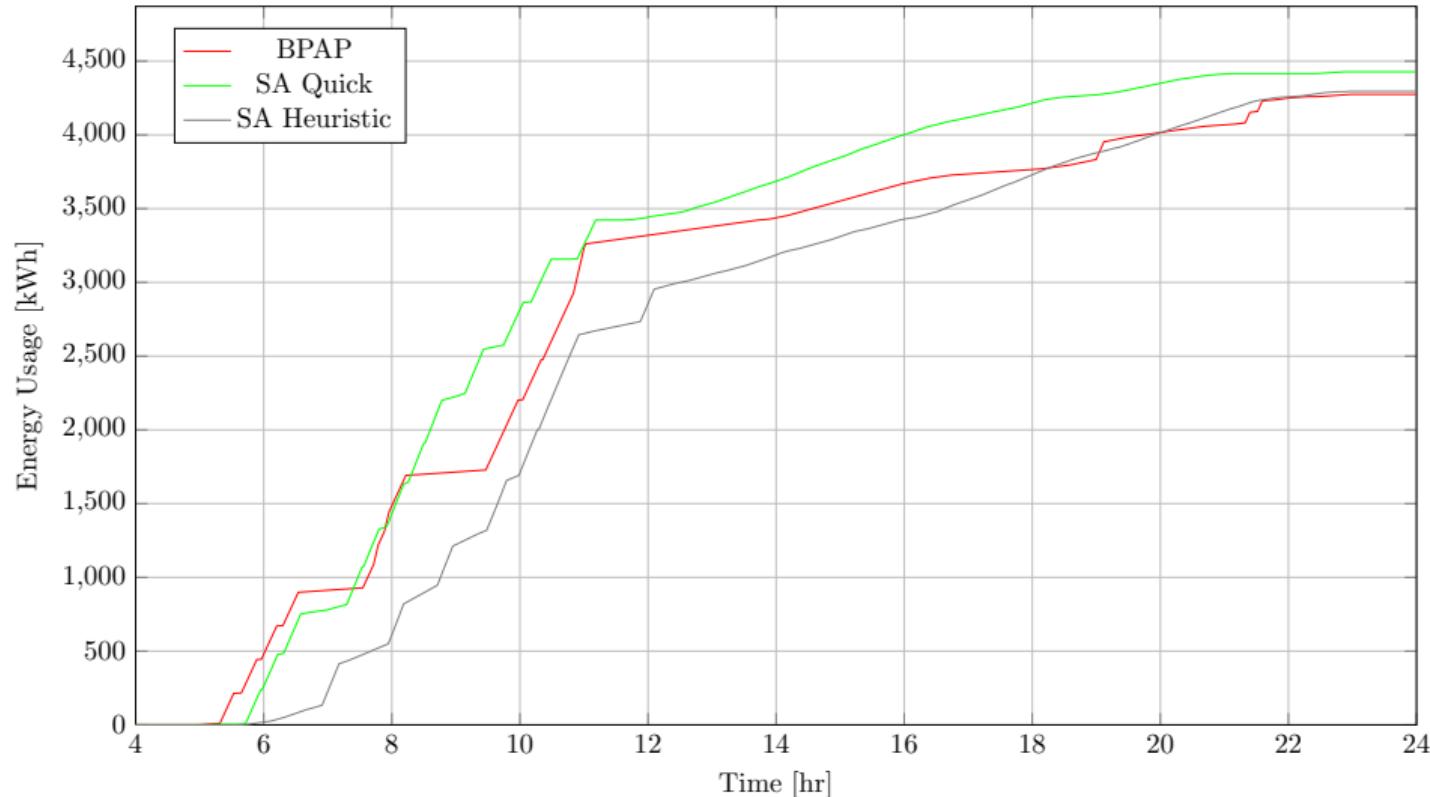
- ▶ Heuristic SA maintained the lowest demand peak
- ▶ Quick SA peak demand comparable to the PAP peak

Energy and SOC

- ▶ PAP maintained lowest energy consumption
- ▶ Second lowest consumed energy by the heuristic SA (185 kW difference)
- ▶ Trade off of the lower peak demand



Accumulated Energy Usage



Introduction

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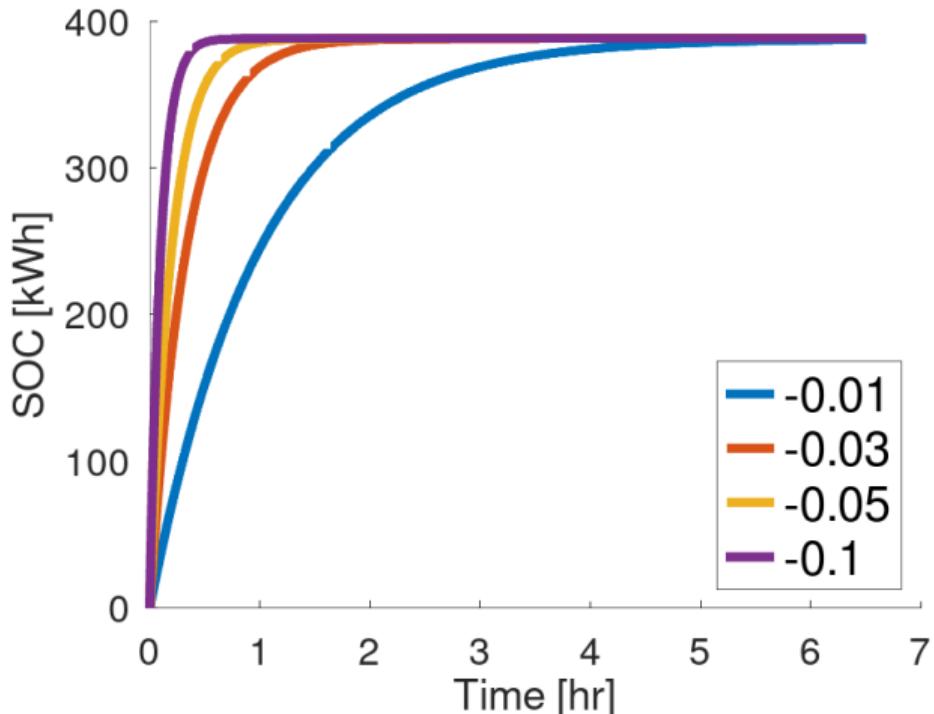
The Simulated Annealing Approach With Linear Battery Dynamics

TODO The Simulated Annealing Approach With Non-Linear Battery Dynamics

Introduction



- ▶ Higher fidelity in approximating charge at high SOC
- ▶ Implemented in SA for simplicity

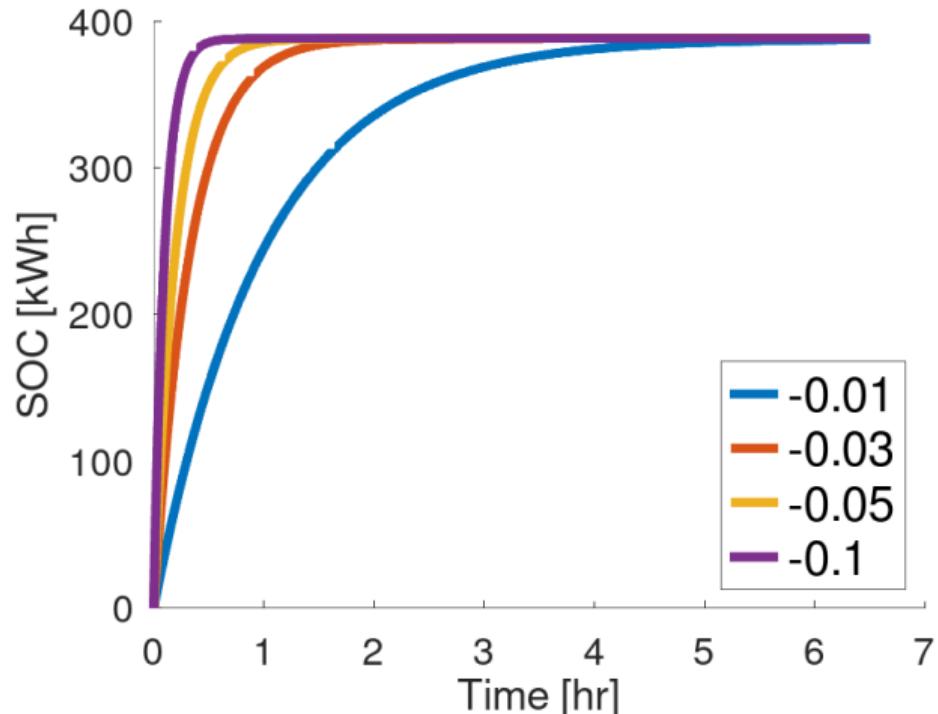


Non-Linear Battery Dynamics Model



$$\eta_{\xi_i} = \bar{a}_q \eta_i - \bar{b}_q \kappa_{\Xi_i}$$

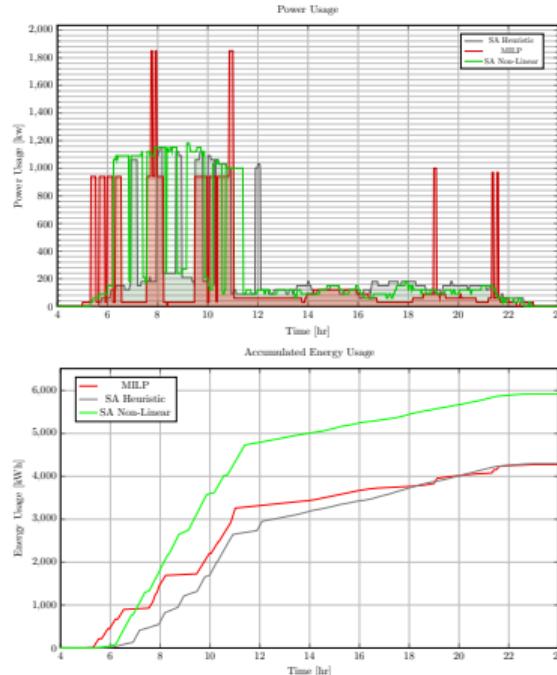
$$\bar{a}_q = e^{a_q dt} \quad \bar{b}_q = e^{a_q dt} - 1$$



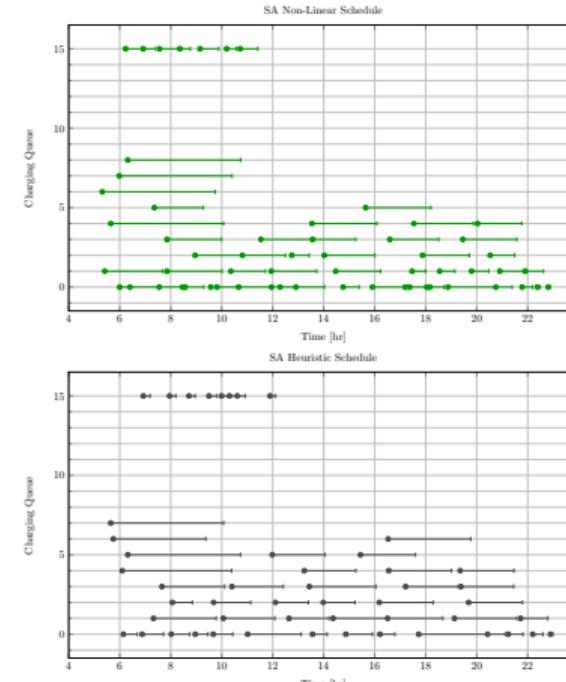
Results



- ▶ Minimized demand power
- ▶ Larger energy consumption due to fast charger duration



- ▶ Similar schedule output, longer fast charger durations due to nonlinear model
- ▶ Minimum SOC of 85 kWh



Appendix



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Mixed Integer Linear Programming

$$\begin{aligned} \max J &= \sum_j c_j x_j + \sum_k d_k y_k \\ \text{subject to } & \sum_j a_{ij} x_j + \sum_k g_{ik} y_k \leq b_i & (i = 1, 2, \dots, m) \\ & x_j \geq 0 & (j = 1, 2, \dots, n) \\ & y_k \in \mathbb{Z}^+ & (k = 1, 2, \dots, n) \end{aligned}$$

- ▶ J : Objective function
- ▶ $x_j \in \mathbb{R}$ and $y_k \in \mathbb{Z}^+$: Decision Variables
- ▶ $c_j, d_k, a_{ij}, g_{ik}, b_i \in \mathbb{R}$: Parameters

SA Primitive Generators



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Algorithm 0: New visit algorithm

Algorithm: New Visit**Input:** \mathbb{S} **Output:** $\bar{\mathbb{S}}$ **begin**

```
1       $i \leftarrow \mathbb{S}_i;$                                 /* Extract visit index */
2       $a \leftarrow \mathbb{I}_{i.a};$                             /* Extract the arrival time for visit  $i$  */
3       $e \leftarrow \mathbb{I}_{i.e};$                             /* Extract the departure time for visit  $i$  */
4       $q \leftarrow \mathbb{I}_{i.q};$                             /* Extract the current charge queue for visit  $i$  */
5       $\bar{q} \leftarrow \mathcal{U}_Q;$                          /* Select a random charging queue with a uniform distribution */
6       $C \leftarrow \mathcal{U}_{\mathbb{C}_q};$                       /* Select a random time slice from  $\mathbb{C}_q$  */
7      if  $(\bar{C}, \bar{u}, \bar{d}) \leftarrow \text{findFreeTime}(C, i, q, a, e) \notin \emptyset$  then    /* If there is time available in  $C_q^j$  */
8          |   return  $(i, (\bar{q}, \bar{u}, \bar{d}), \bar{C})$                                 /* Return visit */
9      end
10     return  $(\emptyset);$                                 /* Return nothing */
11
12 end
```

Algorithm 1: Slide Visit Algorithm

Algorithm: Slide Visit**Input:** \mathbb{S} **Output:** $\bar{\mathbb{S}}$

```
1 begin
2    $(i, \mathbb{I}, \bar{C}) \leftarrow \text{Purge}(\mathbb{S});$            /* Purge visit  $i$  from charger availability matrix */
3    $C \leftarrow \bar{C}_{i,q_i};$                          /* Get the time availability of the purged visit */
4   /* If there is time available in  $C$  */
5   if  $(\bar{C}, \bar{u}, \bar{d}) \leftarrow \text{findFreeTime}(C, \mathbb{S}_i, \mathbb{I}_q, \mathbb{I}_{i.a}, \mathbb{I}_{i.e}) \notin \emptyset$  then
6     | return  $(i, \mathbb{I}, (\mathbb{I}_{i.q_i}, \bar{u}, \bar{d}), \bar{C})$           /* Return updated visit */
7   end
8   return  $(\emptyset);$                                 /* Return nothing */
9 end
```

Algorithm 2: New Charger Algorithm

Algorithm: New Charger

Input: \mathbb{S}

Output: $\bar{\mathbb{S}}$

1 **begin**

```
2    $(i, \mathbb{I}, \bar{\mathbb{C}}) \leftarrow \text{Purge}(\mathbb{S});$            /* Purge visit  $i$  from charger availability matrix */
3    $q \leftarrow \mathcal{U}_Q;$            /* Select a random charging queue with a uniform distribution */
4   if  $(\bar{\mathbb{C}}, \bar{u}, \bar{d}) \leftarrow \text{findFreeTime}(\bar{\mathbb{C}}_{i,q}, \mathbb{S}_i, \mathbb{I}_q, \mathbb{I}_{i,u}, \mathbb{I}_{i,d}) \notin \emptyset$  then /* If there is time available in
       $C_q$  */
      | /* Return visit, note  $u$  and  $d$  are the original initial/final charge times. */
      | return  $(i, \mathbb{I}, (q, \mathbb{I}_{i,u}, \mathbb{I}_{i,d}), \bar{\mathbb{C}})$ 
6   end
7   return  $(\emptyset);$            /* Return nothing */
8 end
```

Algorithm 3: Wait algorithm

Algorithm: Wait**Input:** \mathbb{S} **Output:** $\bar{\mathbb{S}}$

```
1 begin
2    $(i, \mathbb{I}, \bar{\mathbb{C}}) \leftarrow \text{Purge}(\mathbb{S});$            /* Purge visit  $i$  from charger availability matrix */
3    $\bar{\mathbb{C}}'_{\mathbb{I}_{i,r_i}} \leftarrow \mathbb{C}' \cup \{[\mathbb{I}_{i,a}, \mathbb{I}_{i,e}]\};$  /* Update the charger availability matrix for wait queue  $\bar{\mathbb{C}}_{i,q_i}$  */
4   return  $(i, \mathbb{I}, (\mathbb{I}_{i,b}, \mathbb{I}_{i,a}, \mathbb{I}_{i,e}), \bar{\mathbb{C}})$            /* Return visit */
5 end
```

Algorithm 4: New window algorithm

Algorithm: New Window

Input: \mathbb{S}

Output: $\bar{\mathbb{S}}$

```
1 begin
2   |  $\bar{\mathbb{S}} \leftarrow \text{Wait}(\mathbb{S})$ ;           /* Assign visit to its respective idle queue */
3   | if  $\bar{\mathbb{S}} \leftarrow \text{NewVisit}(\bar{\mathbb{S}}) \neq \emptyset$  then
4   |   | return  $\bar{\mathbb{S}}$                          /* Add visit  $i$  back in randomly */
5   | end
6   | return ( $\emptyset$ );                          /* Return visit */
7 end
```

SA Wrapper Functions



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Algorithm 5: Charge schedule generation algorithm

Algorithm: Candidate Solution Generator

Input: \mathbb{S}

Output: $\bar{\mathbb{S}}$

```
1 begin
2   /* Select an unscheduled BEB visit from a randomly indexed set of visits */ 
3   foreach  $\mathbb{I}_i \in \mathbb{I}$  do
4     |  $(i, \bar{\mathbb{I}}, \bar{\mathbb{C}}) \leftarrow \text{NewVisit}((\mathbb{I}_i, \mathbb{I}, \mathbb{C}))$ ;           /* Assign the bus to a charger */
5   end
6   return  $(0, \bar{\mathbb{I}}, \bar{\mathbb{C}})$ 
7 end
```

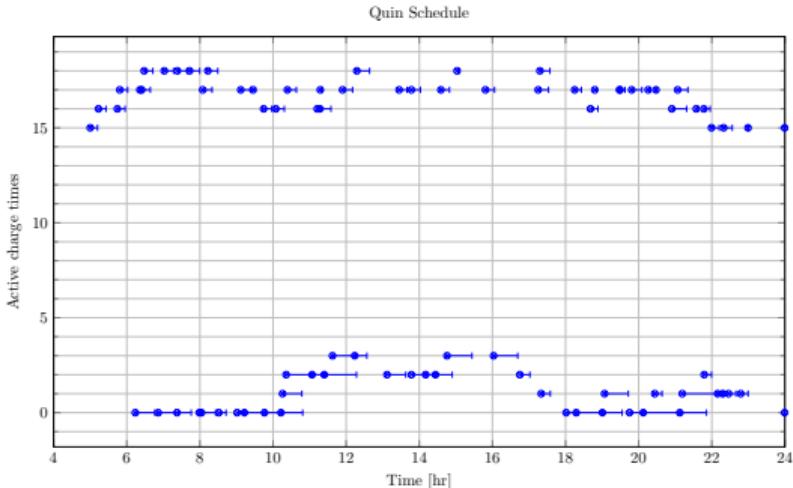
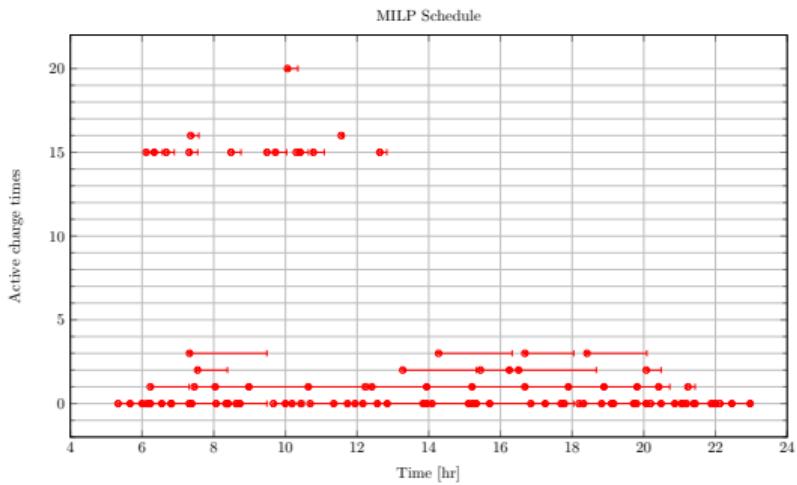
SA Thesis Results

Parameters

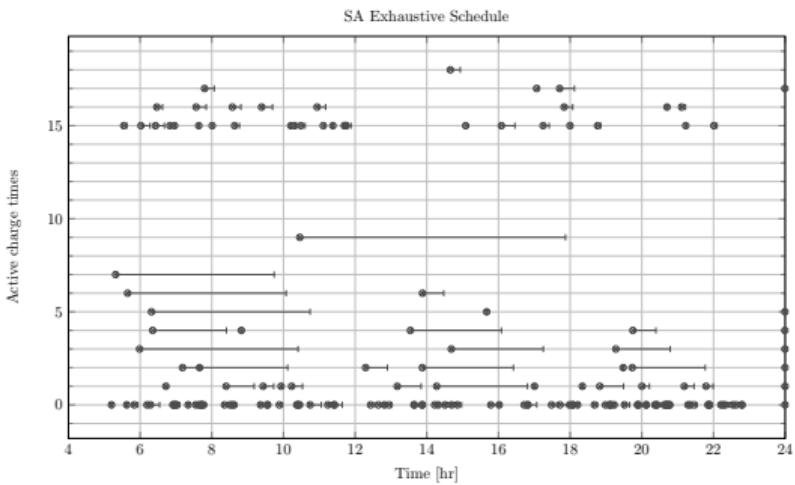
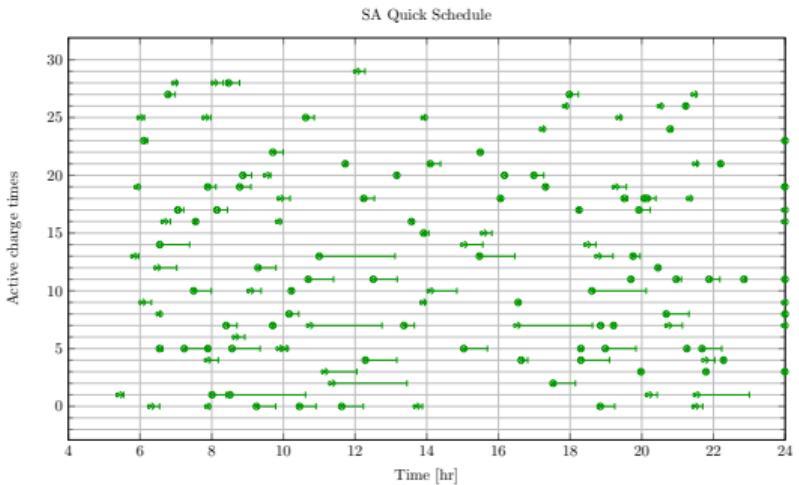
Model	Execution Time [s]	Iteration [s]
MILP	3600	N/A
Quick	2275.25	0.25
Heuristic	3640.4	0.4

- ▶ $T_0 = 99999$
- ▶ $\beta = 0.999$
- ▶ $|t| = 3797$
- ▶ $n_K = 500$

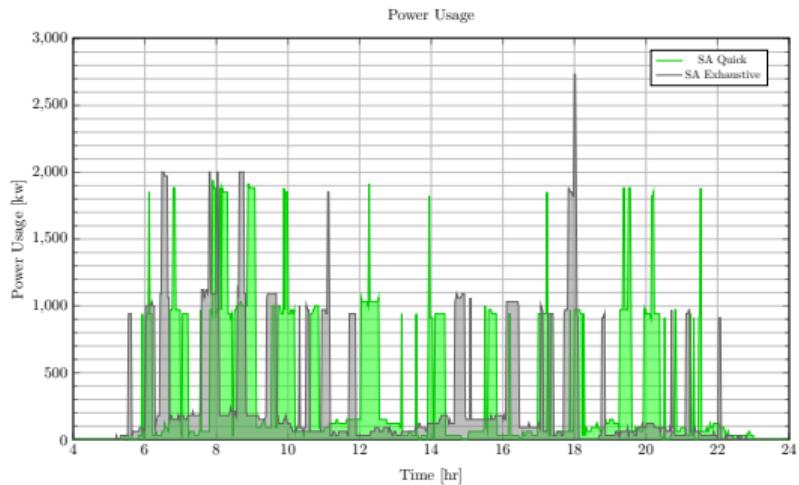
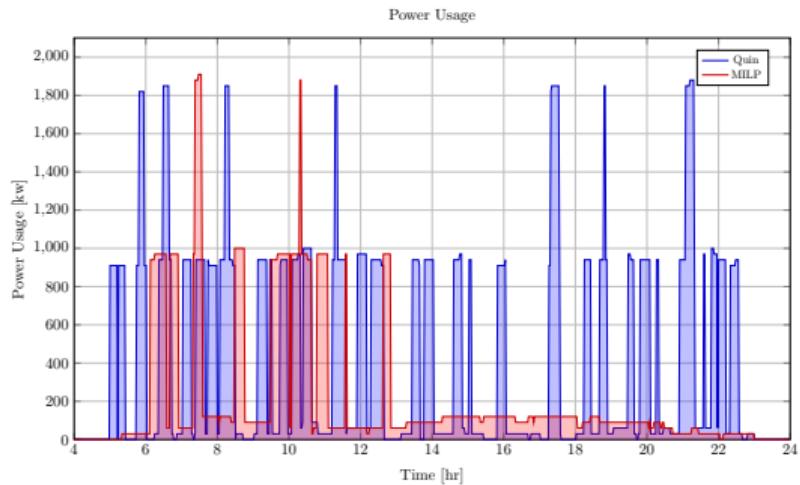
Schedule

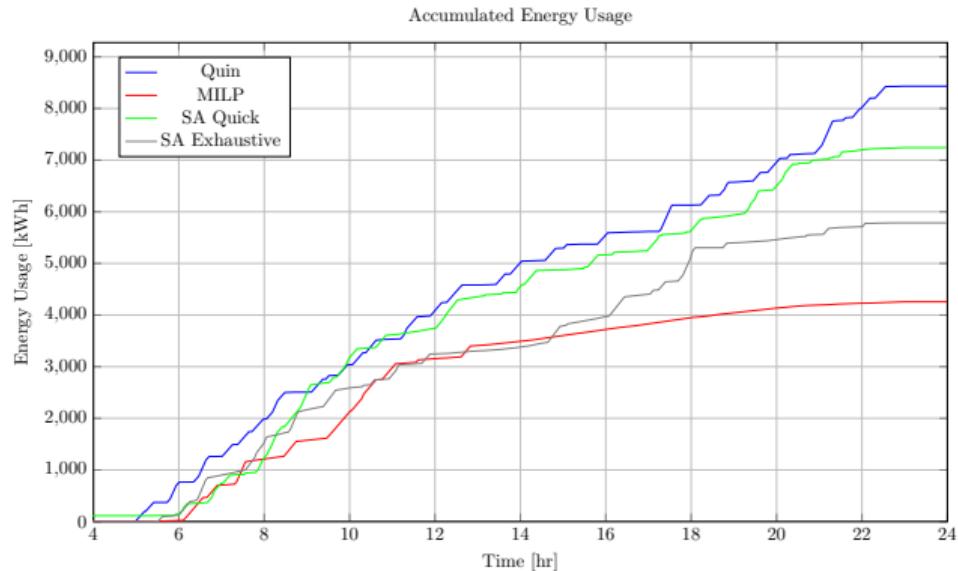


Schedule



Power



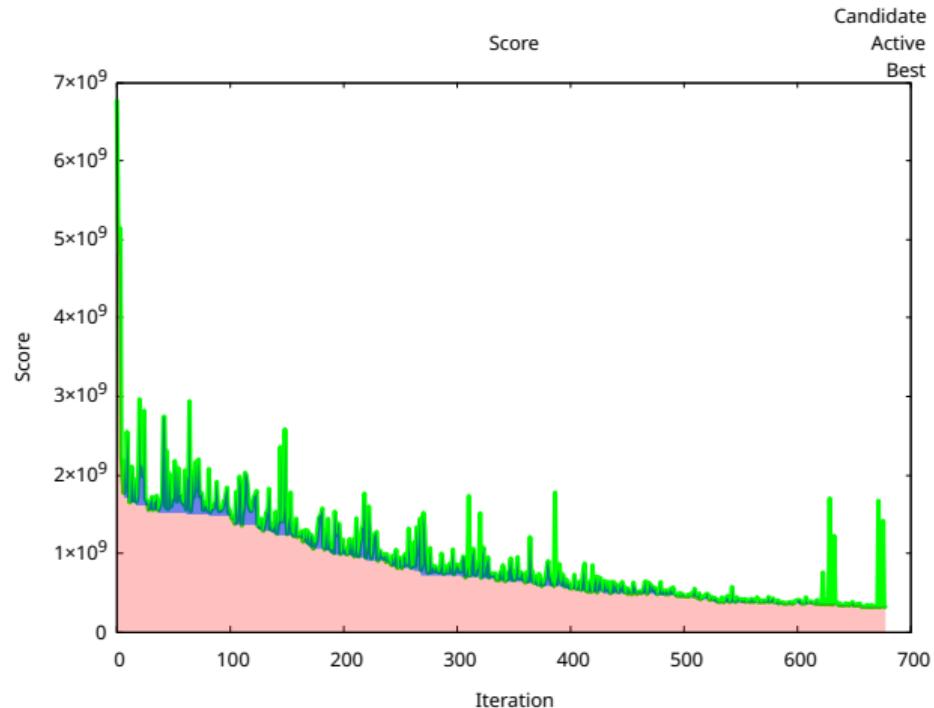


What Happened?



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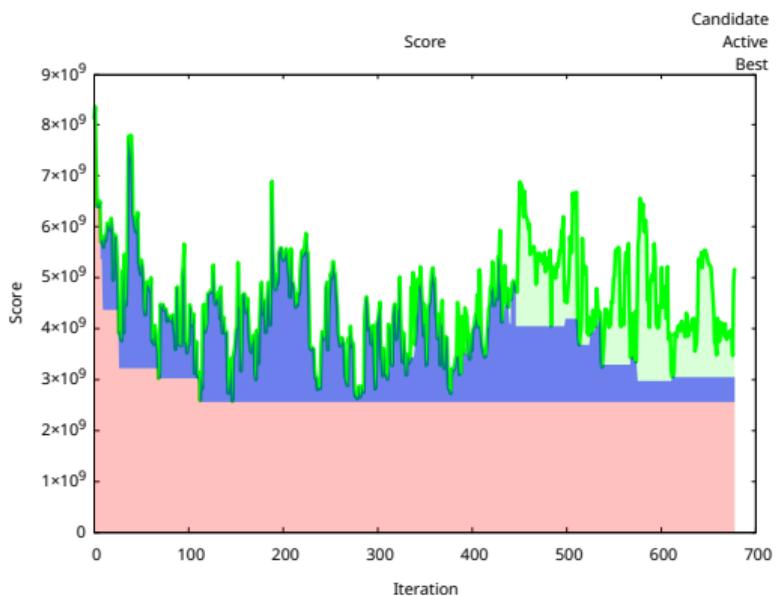
How To Resolve This Problem?



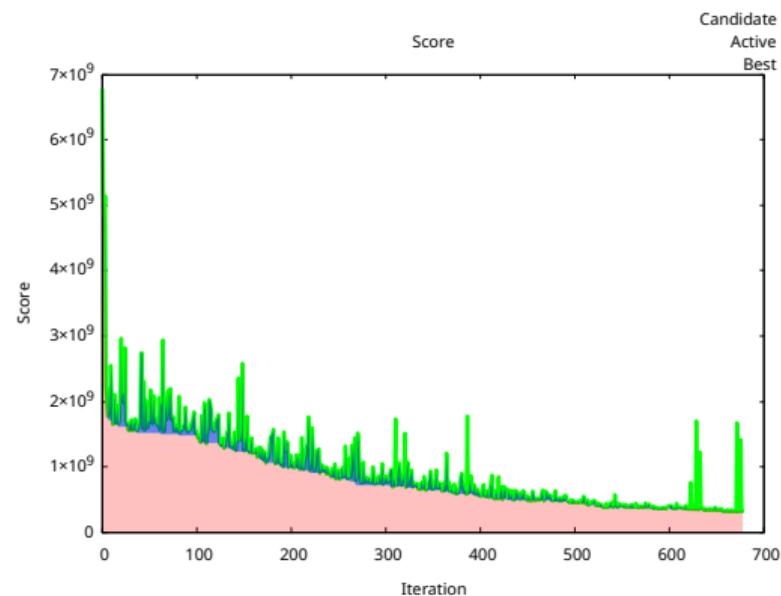
- ▶ Reverse search and weight the visit indices
- ▶ Be more aggressive in exploiting the best solution

Score Convergence Comparison

Before Fix



After Fix



References

-  Mengyuan Duan, Geqi Qi, Wei Guan, Chaoru Lu, and Congcong Gong.
Reforming mixed operation schedule for electric buses and traditional fuel buses by an optimal framework.
IET Intelligent Transport Systems, 15(10):1287–1303, Jul 2021.
-  Oliver Frendo, Nadine Gaertner, and Heiner Stuckenschmidt.
Open source algorithm for smart charging of electric vehicle fleets.
IEEE Transactions on Industrial Informatics, 17(9):6014–6022, September 2021.
-  Amra Jahic, Mina Eskander, and Detlef Schulz.
Preemptive vs. non-preemptive charging schedule for large-scale electric bus depots.
In *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*.
IEEE, September 2019.
-  Daniel Mortensen, Jacob Gunther, Greg Droke, and Justin Whitaker.
Cost minimization for charging electric bus fleets.
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