An Efficient Robust Approach to the Day-ahead Operation of an Aggregator of Electric Vehicles

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Joint work with:

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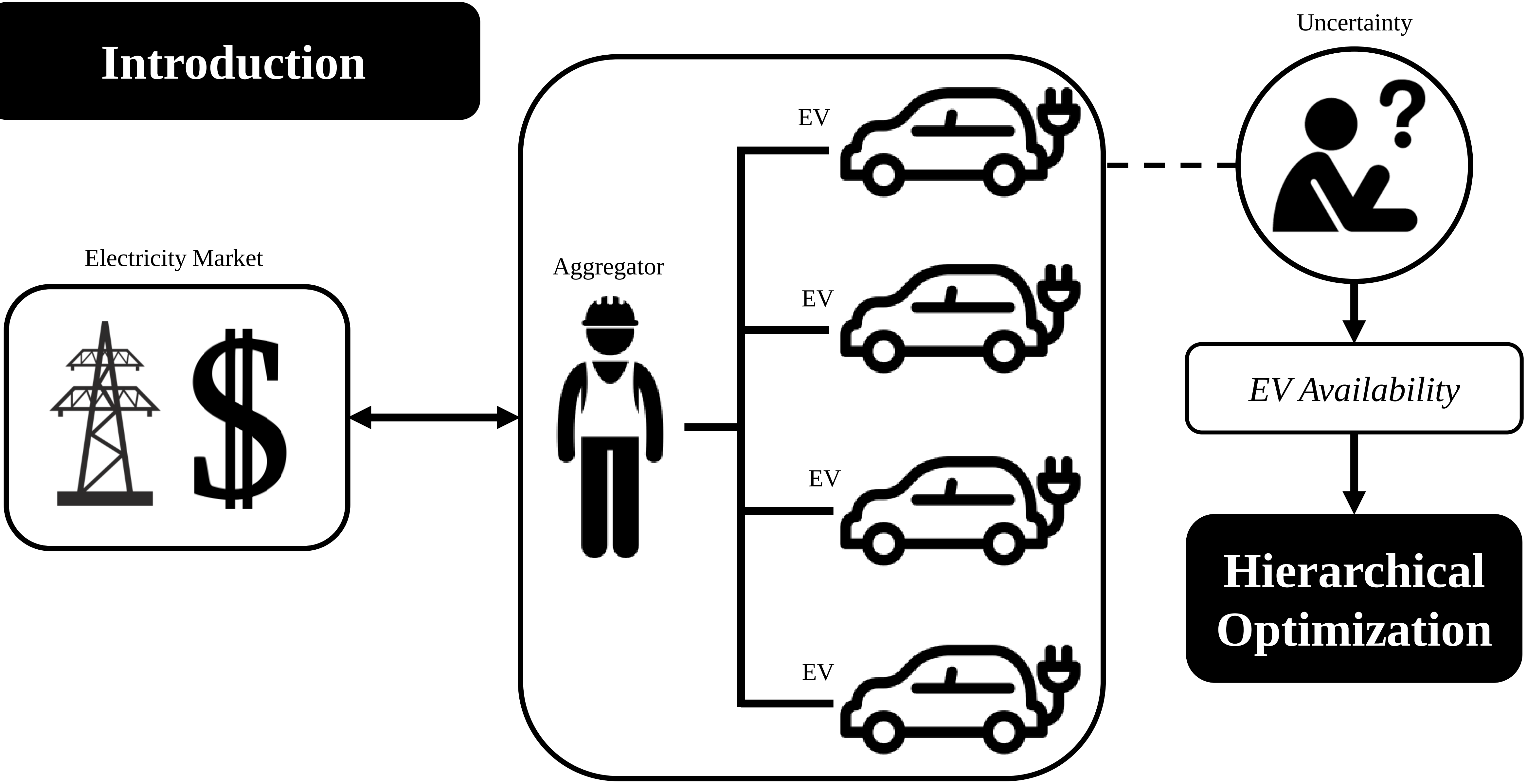
Introduction



Problem Formulation

Deterministic Formulation

- Uncertainty is disregarded.
- Optimal for expected values.
- Computationally tractable.

Stochastic Formulation

- Uncertainty using scenarios.
- Optimal on average.
- Number of scenarios.

Hierarchical Formulation

- Uncertainty using a few intuitive parameters.
- Robust against adverse situations.
- Scalability.

Problem Formulation

Deterministic Formulation

- λ_t are expected values $\rightarrow \hat{\lambda}_t$
- $\alpha_{v,t}$ are expected values $\rightarrow \hat{\alpha}_{v,t}$

$(c_{v,t}, d_{v,t}, s_{v,t}, c_{v,t}^D) \in \Phi(\hat{\alpha}_{v,t}, \hat{\tau}_{v,t})$

$$\min_{\Xi^D} \sum_{t\in\mathcal{T}} \widehat{\lambda}_t p_t + \sum_{t\in\mathcal{T}} \sum_{v\in\mathcal{V}} \left(c_{v,t}^D + C_1^p s_{v,t}\right)$$

subject to:

$$p_t = \sum_{v\in\mathcal{V}} (c_{v,t} - d_{v,t}), \quad \forall t \in \mathcal{T}$$

$$-P^G \leq p_t \leq P^G, \quad \forall t \in \mathcal{T}$$

$$e_{v,t} = e_{v,t-1} + \eta_v c_{v,t} \widehat{\alpha}_{v,t} - \frac{d_{v,t}}{\eta_v} - \widehat{\tau}_{v,t} + s_{v,t}, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$c_{v,t} \leq \overline{C}_v, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$d_{v,t} \leq \overline{D}_v \widehat{\alpha}_{v,t}, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$\underline{E}_v \leq e_{v,t} \leq \overline{E}_v, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$e_{v,N_T} = e_{v,0}, \quad \forall v \in \mathcal{V}$$

$$c_{v,t}^D = \left|\frac{S}{100}\right| C_v^E \left(\frac{1}{\eta_v} d_{v,t} + \widehat{\tau}_{v,t}\right), \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$c_{v,t}, d_{v,t}, e_{v,t}, c_{v,t}^D, s_{v,t} \geq 0, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

Problem Formulation

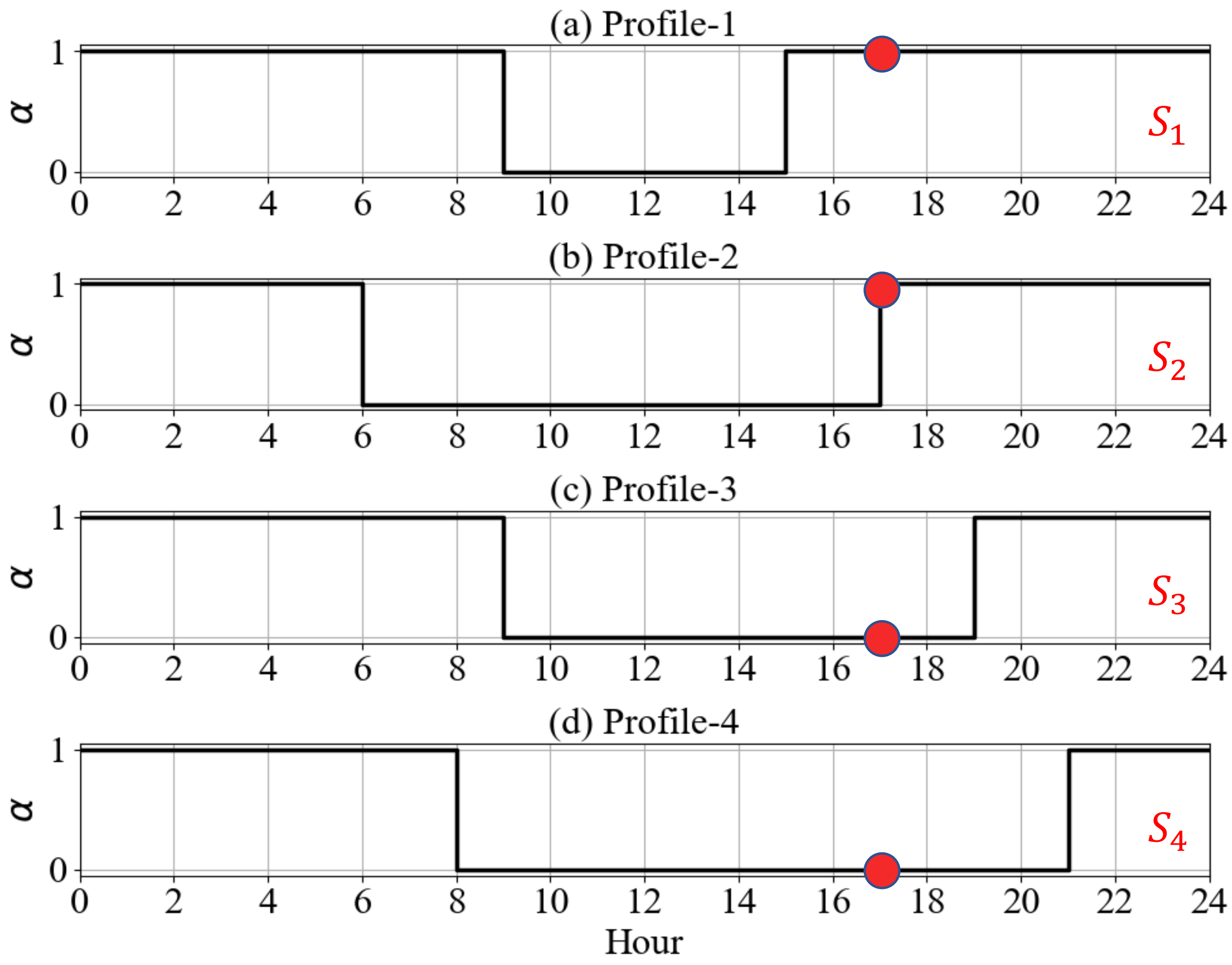
$\hat{\alpha}_{v,19} = 0,5$

Deterministic Formulation

Average of all profiles

Stochastic Formulation

Each profile is a scenario



Problem Formulation

Deterministic Formulation

- Uncertainty is disregarded.
- Optimal for expected values.

Stochastic Formulation

- Optimal on average.
- Number of scenarios.

Hierarchical Formulation

Problem Formulation

Proposed Approach

- Characterization of the uncertainty in EV availability using a parameter set:

$$\Theta_v = \left\{K_v, \underline{\alpha}_{v,t}, \overline{\alpha}_{v,t}\right\}$$

- Now, $\alpha_{v,t}$ are variables that depend on an uncertainty set:

$$\sum_{t \in \mathrm{T}} \alpha_{v,t} \geq K_v, \forall t \in \mathcal{T}, v \in \mathcal{V}$$

$$\underline{\alpha_{v,t}} \leq \alpha_{v,t} \leq \overline{\alpha_{v,t}}, \forall t \in \mathcal{T}, v \in \mathcal{V}$$

$$\alpha_{v,t} \in \{0,1\}, \forall t \in \mathcal{T}, v \in \mathcal{V}$$

Problem Formulation

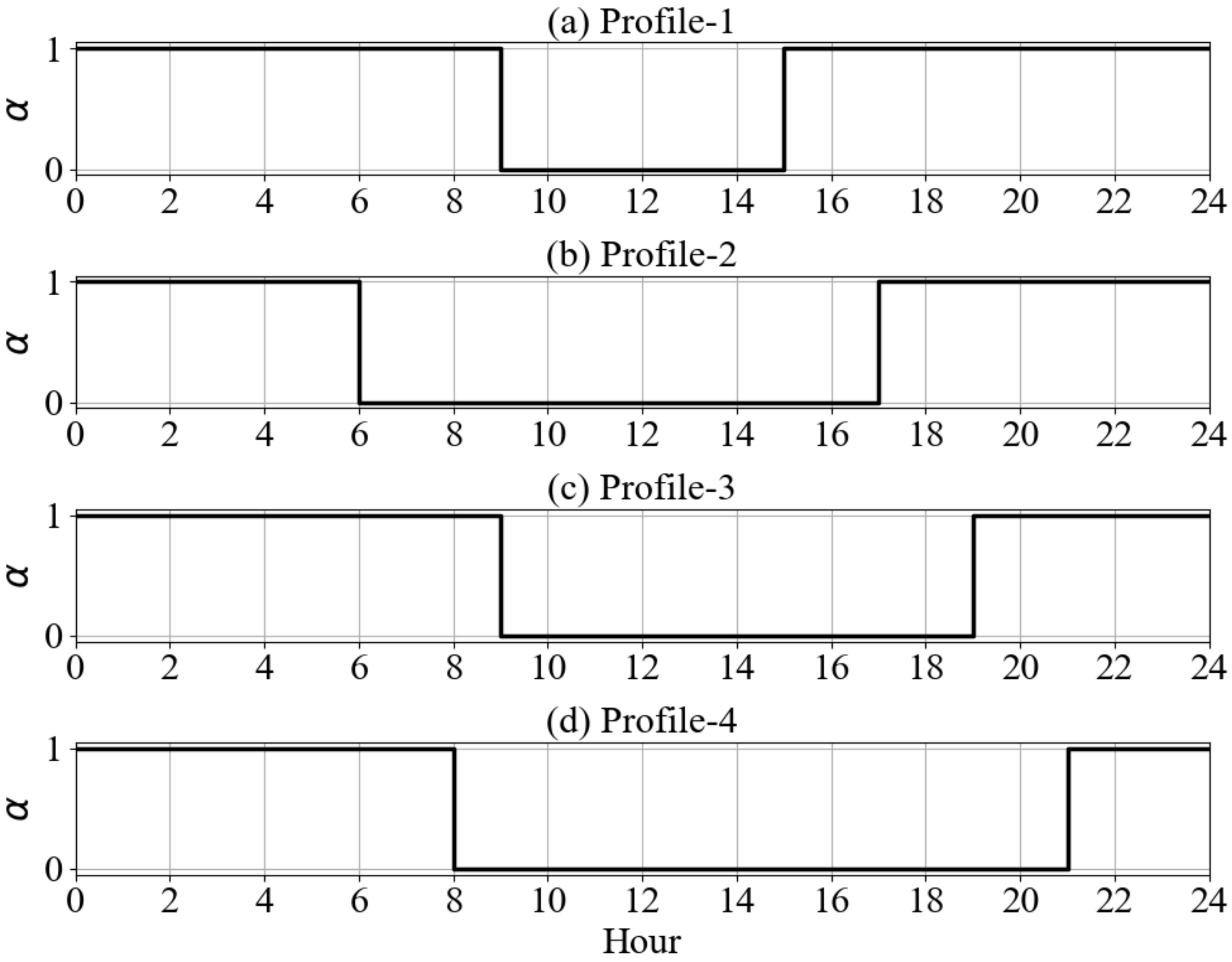
K_v

Available Periods → 18

Available Periods → 13

Available Periods → 14

Available Periods → 11



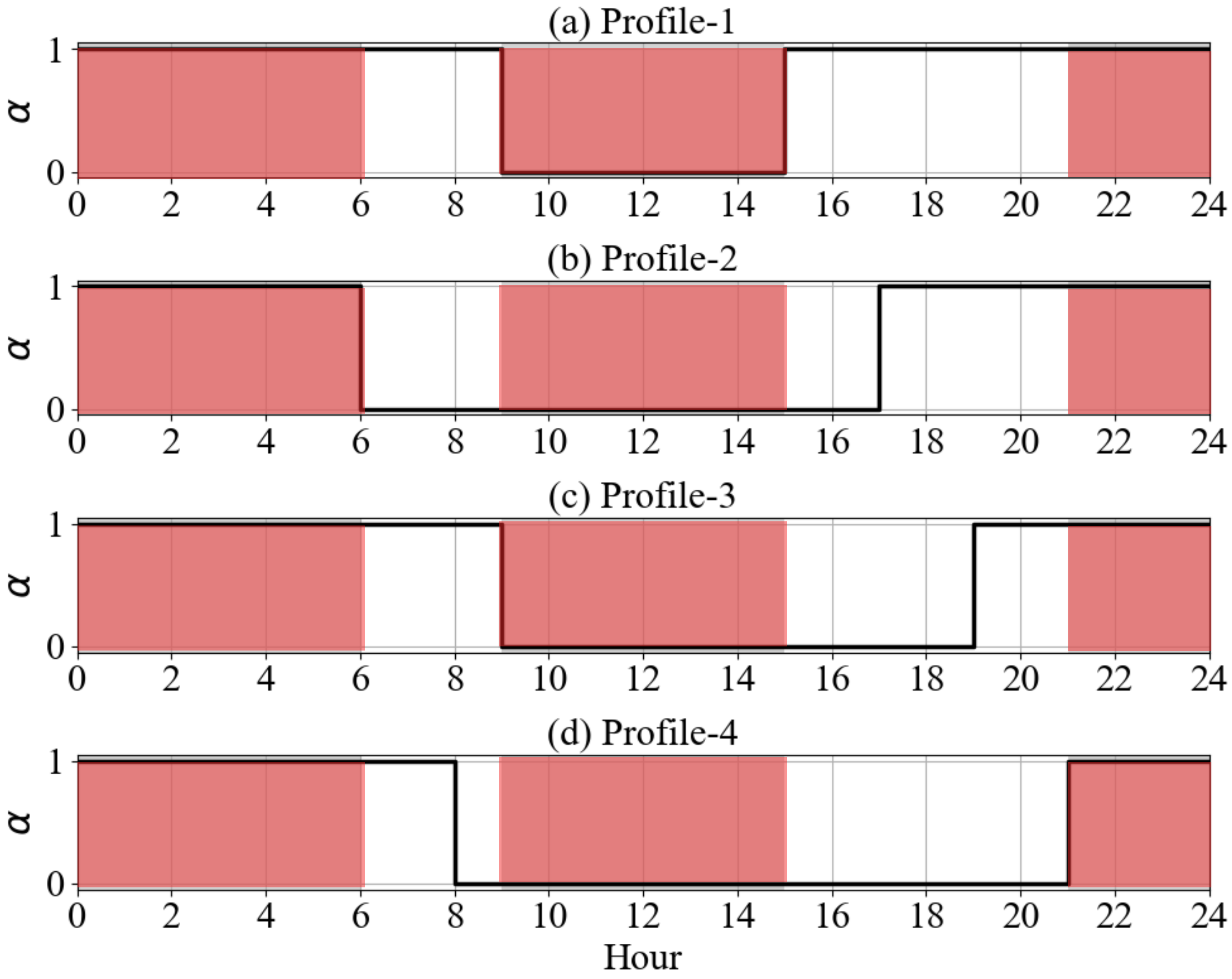
$K_v = 12$

Problem Formulation

$\underline{\alpha}_{v,t}, \overline{\alpha}_{v,t}$

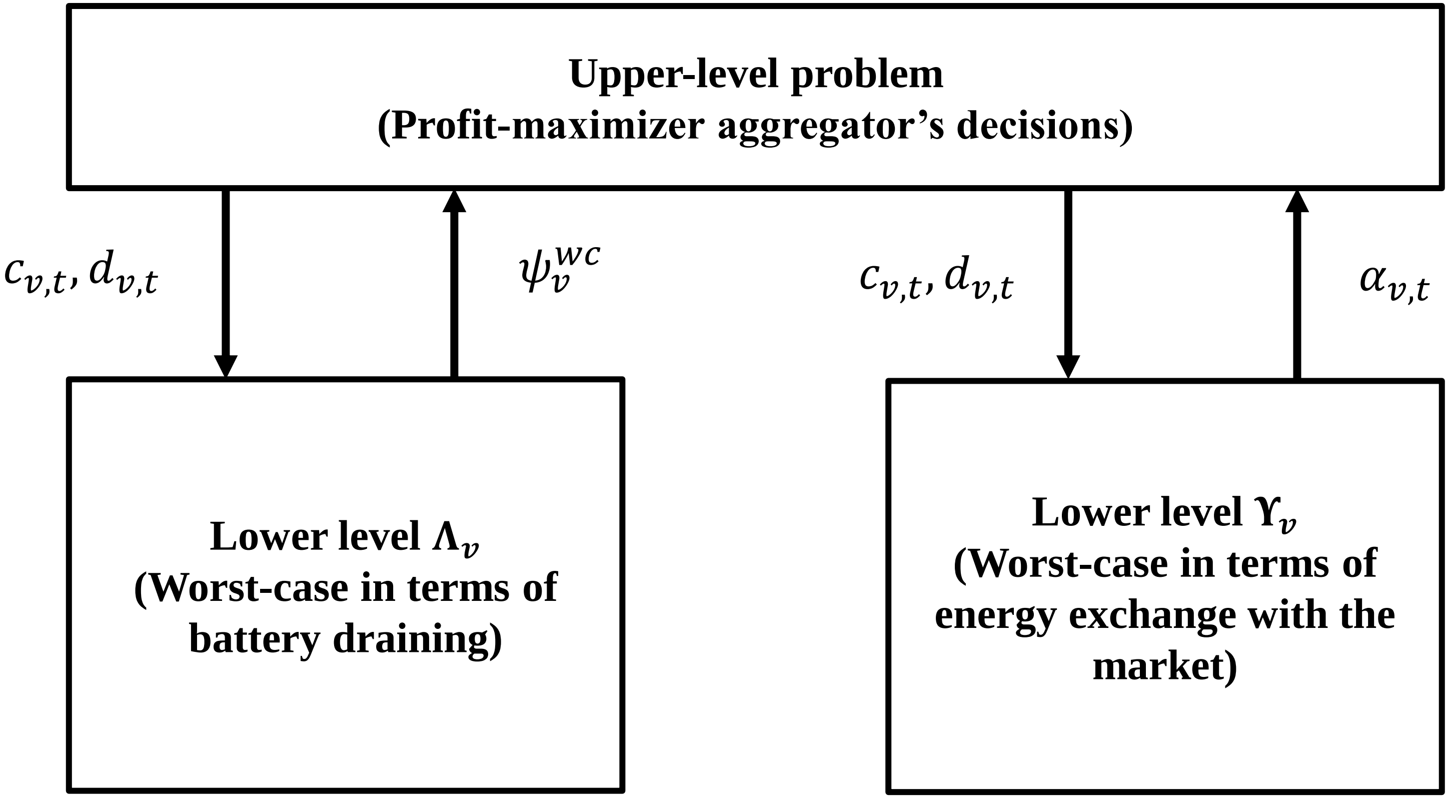
$\underline{\alpha}_{v,t} = 1$

$\overline{\alpha}_{v,t} = 0$



Problem Formulation

Hierarchical Formulation



UL

LL2

LL1

Problem Formulation

Hierarchical Formulation

Energy required for transportation

Total net energy injections into the EV-battery

Availability profiles

$$\min_{\Xi^R} \sum_{t\in\mathcal{T}} \widehat{\lambda}_t p_t + \sum_{t\in\mathcal{T}} \sum_{v\in\mathcal{V}} \left(c^D_{v,t} + C^p_1 s_{v,t}\right)$$

subject to:

$$p_t = \sum_{v\in\mathcal{V}} \left(c_{v,t} - d_{v,t}\right), \quad \forall t \in \mathcal{T}$$

$$-P^G \leq p_t \leq P^G, \quad \forall t \in \mathcal{T}$$

$$\left(c_{v,t}, d_{v,t}, s_{v,t}, c^D_{v,t}\right) \in \Phi(\alpha_{v,t}, \tau_{v,t}), \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$\sum_{t\in\mathcal{T}} \tau_{v,t} = \widehat{\xi}_v, \quad \forall v \in \mathcal{V}$$

$$\tau_{v,t} \leq \left(\overline{E}_v - \underline{E}_v\right)\left(1 - \alpha_{v,t}\right), \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$\tau_{v,t} \geq 0, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$\psi^{wc}_v \geq \widehat{\xi}_v, \quad \forall v \in \mathcal{V}$$

$$\psi^{wc}_v \in \Lambda_v(c_{v,t}, d_{v,t}), \quad \forall v \in \mathcal{V}$$

$$\alpha_{v,t} \in \Upsilon_v(c_{v,t}, d_{v,t}), \quad \forall v \in \mathcal{V}$$

Problem Formulation

Lower level Problems Determining the Sets Λ_v

$$
\begin{aligned}
\psi_v^{wc} = \min_{\alpha'_{v,t}} & \sum_{t\in\mathcal{T}} \alpha'_{v,t}\left(\eta_v c_{v,t} - \frac{1}{\eta_v} d_{v,t}\right) \\
\text{subject to:} & \\
& \sum_{t\in\mathcal{T}} \alpha'_{v,t} \geq K_v : (\zeta'_v) \\
& \underline{\alpha}_{v,t} \leq \alpha'_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}'_{v,t}, \overline{\beta}'_{v,t}), \quad \forall t \in \mathcal{T} \\
& \alpha'_{v,t} \in \{0,1\}, \quad \forall t \in \mathcal{T}
\end{aligned}
$$

Lower level Problems Determining the Sets Υ_v

$$
\begin{aligned}
& \min_{\alpha_{v,t}} \sum_{t\in\mathcal{T}} \alpha_{v,t}\left(\eta_v c_{v,t} + \frac{1}{\eta_v} d_{v,t}\right) \\
& \text{subject to:} \\
& \sum_{t\in\mathcal{T}} \alpha_{v,t} \geq K_v : (\zeta_v) \\
& \underline{\alpha}_{v,t} \leq \alpha_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}_{v,t}, \overline{\beta}_{v,t}), \quad \forall t \in \mathcal{T} \\
& \alpha_{v,t} \in \{0,1\}, \quad \forall t \in \mathcal{T}
\end{aligned}
$$

Methodology

- *Non-convex.*
- *KKT conditions not applicable.*

$$\psi_v^{wc} = \min_{\alpha'_{v,t}} \sum_{t\in\mathcal{T}} \alpha'_{v,t}\left(\eta_v c_{v,t} - \frac{1}{\eta_v} d_{v,t}\right)$$

subject to:

$$\sum_{t\in\mathcal{T}} \alpha'_{v,t} \geq K_v : (\zeta'_v)$$

$$\underline{\alpha}_{v,t} \leq \alpha'_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}'_{v,t}, \overline{\beta}'_{v,t}), \quad \forall t \in \mathcal{T}$$

$$\boxed{\alpha'_{v,t} \in \{0,1\}, \quad \forall t \in \mathcal{T}}$$

$$\min_{\alpha_{v,t}} \sum_{t\in\mathcal{T}} \alpha_{v,t}\left(\eta_v c_{v,t} + \frac{1}{\eta_v} d_{v,t}\right)$$

subject to:

$$\sum_{t\in\mathcal{T}} \alpha_{v,t} \geq K_v : (\zeta_v)$$

$$\underline{\alpha}_{v,t} \leq \alpha_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}_{v,t}, \overline{\beta}_{v,t}), \quad \forall t \in \mathcal{T}$$

$$\boxed{\alpha_{v,t} \in \{0,1\}, \quad \forall t \in \mathcal{T}}$$

- *Convex.*
- *KKT conditions applicable.*

$$\psi_v^{wc} = \min_{\alpha'_{v,t}} \sum_{t\in\mathcal{T}} \alpha'_{v,t}\left(\eta_v c_{v,t} - \frac{1}{\eta_v} d_{v,t}\right)$$

subject to:

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$$\underline{\alpha}_{v,t} \leq \alpha'_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}'_{v,t}, \overline{\beta}'_{v,t}), \quad \forall t \in \mathcal{T}$$

$$\boxed{0 \leq \alpha'_{v,t} \leq 1, \quad \forall t \in \mathcal{T}}$$

$$\min_{\alpha_{v,t}} \sum_{t\in\mathcal{T}} \alpha_{v,t}\left(\eta_v c_{v,t} + \frac{1}{\eta_v} d_{v,t}\right)$$

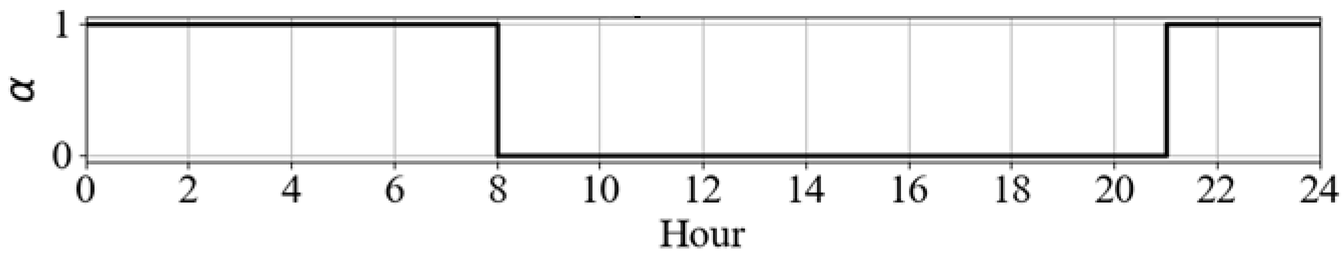
subject to:

$$\sum_{t\in\mathcal{T}} \alpha_{v,t} \geq K_v : (\zeta_v)$$

$$\underline{\alpha}_{v,t} \leq \alpha_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}_{v,t}, \overline{\beta}_{v,t}), \quad \forall t \in \mathcal{T}$$

$$\boxed{0 \leq \alpha_{v,t} \leq 1, \quad \forall t \in \mathcal{T}}$$

Methodology



Matrix Totally Unimodular

Integer

$$\psi_v^{wc} = \min_{\alpha'_{v,t}} \sum_{t \in \mathcal{T}} \alpha'_{v,t} \left(\eta_v c_{v,t} - \frac{1}{\eta_v} d_{v,t} \right)$$

subject to:

$$\sum_{t \in \mathcal{T}} \alpha'_{v,t} \geq K_v \quad (\zeta'_v)$$

$$\underline{\alpha}_{v,t} \leq \alpha'_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}'_{v,t}, \overline{\beta}'_{v,t}), \quad \forall t \in \mathcal{T}$$

$$0 \leq \alpha'_{v,t} \leq 1, \quad \forall t \in \mathcal{T}$$

$$\min_{\alpha_{v,t}} \sum_{t \in \mathcal{T}} \alpha_{v,t} \left(\eta_v c_{v,t} + \frac{1}{\eta_v} d_{v,t} \right)$$

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$$0 \leq \alpha_{v,t} \leq 1, \quad \forall t \in \mathcal{T}$$

Optimal solution takes integer values

Methodology

The original hierarchical program can be transformed into a single-level equivalent as follows:

Dual objective function

Dual feasibility constraints

- *Primal feasibility constraints.*
- *Dual feasibility constraints.*
- *The equality corresponding to the strong duality condition.*

$$\min_{\Xi^R} \sum_{t\in\mathcal{T}} \widehat{\lambda}_t p_t + \sum_{t\in\mathcal{T}} \sum_{v\in\mathcal{V}} \left(c_{v,t}^D + C_1^p s_{v,t}\right)$$

subject to:

$$p_t = \sum_{v\in\mathcal{V}} \left(c_{v,t} - d_{v,t}\right), \quad \forall t \in \mathcal{T}$$

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$$\left(c_{v,t}, d_{v,t}, s_{v,t}, c_{v,t}^D\right) \in \Phi(\alpha_{v,t}, \tau_{v,t}), \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

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$$\tau_{v,t} \geq 0, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$\boxed{\psi_v^{wc}} \geq \widehat{\xi}_v, \quad \forall v \in \mathcal{V}$$

$$\boxed{\psi_v^{wc} \in \Lambda_v(c_{v,t}, d_{v,t}), \quad \forall v \in \mathcal{V}}$$

$$\boxed{\alpha_{v,t} \in \Upsilon_v(c_{v,t}, d_{v,t}), \quad \forall v \in \mathcal{V}}$$

Case Study

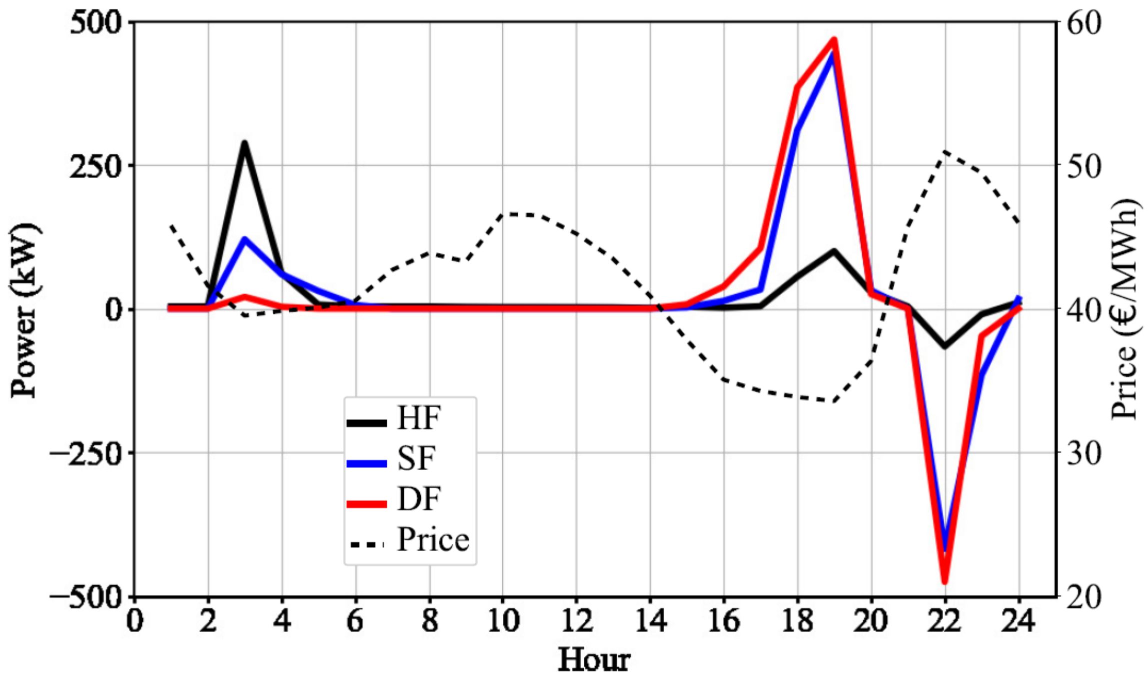
Base Case

- 120 days of simulation.
- 100 EVs.

Metric	DF	SF	HF
Total Cost (€)	2.282,4	2.708,4	2.888,4
Total energy bought (MW)	162.2	155.1	114.2
Total energy sold (MW)	96.5	83.1	47.7
Deviations from energy balance of EV's battery (MW)	10,3	4,7	4,0
Deviations from the minimum value of energy sold (MW)	13,4	1,2	0,4

DF and SF compared to HF:

- Total cost decreases by 21.0% and 6.2%.
- Energy deviations from EV-batteries increase by 157.5% and 17.5%.
- Deviations from the minimum value of the energy sold increase up to 13.4 and 1.2 MWh.



Conclusion

- EV’s aggregator market participation model:
    - *simple*, *effective* and *efficient.*

- **Reduction** of deviations from the energy balance of EV batteries.

- Reductions come at the expense of increasing the total trading costs in the day-ahead market.

- The computational speed of the proposed model is up to 25% faster than its stochastic counterpart.

Á. Porras, R. Fernández-Blanco, J. M. Morales and S. Pineda, “An Efficient Robust Approach to the Day-ahead Operation of an Aggregator of Electric Vehicles,” in IEEE Transactions on Smart Grid, DOI: 10.1109/TSG.2020.3004268, Jun. 2020

An Efficient Robust Approach to the Day-ahead Operation of an Aggregator of Electric Vehicles

Thank you for your attention

Any question?

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