Price-Based Demand Response Participation in Implicit Balancing Services: A Value-Oriented Inverse Optimization Framework

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Overview

1. Context
2. Demand Response
3. Mobilization of Demand Response Resources (DRRs)
4. Price-response Behavior
5. Inverse Optimization (IO)
6. Implicit Balancing
7. Price-response Model Selection
8. Results

Context

Transition to Carbon-Neutral Energy Systems

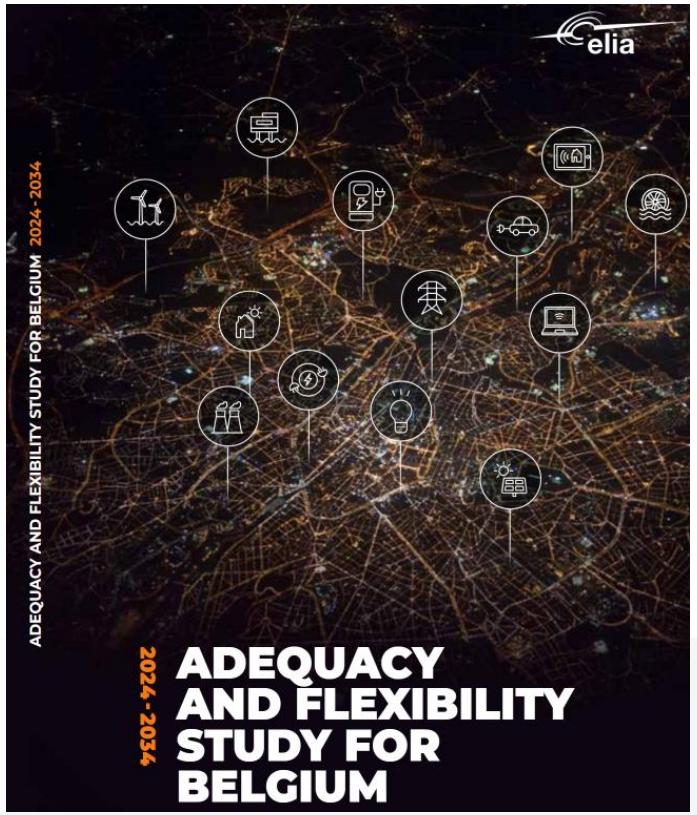
- Requires integration of **flexible resources** to manage renewable energy variability
- **Demand Response (DR)** programs enable consumers to **adjust consumption/production**

Belgium's Demand-Side Flexibility Outlook (by 2034)

- **143,000 home batteries**
- **930,000 smart-charging EVs** (up to 2.3M in high-flexibility scenario)
- **300,000 controllable heat pumps** (up to 1.2M in high-flexibility scenario)

Impact on Grid

- Effective coordination can **reduce capacity gap by 1.1 GW**
  - More than double the **0.5 GW** from flexible industrial processes
  - Estimated annual savings of **€205–438 million** by 2034



Demand Response

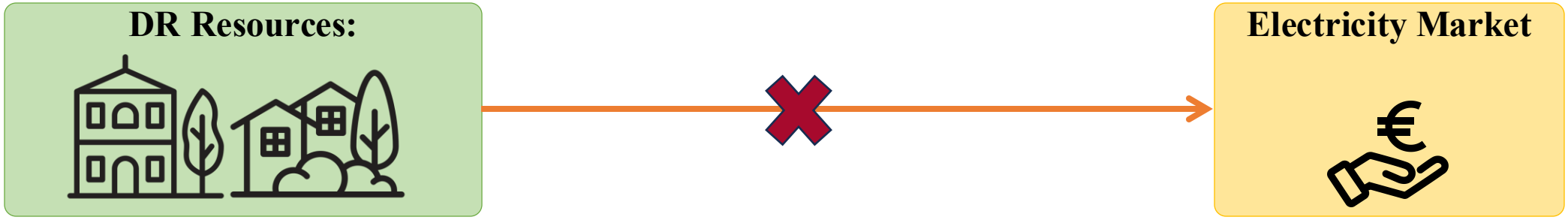
*"Demand response is the actions of **customer-sited** energy resources, **located downstream of metering points**, to **voluntarily, actively, and temporarily** adjust their electricity **production and/or consumption** in response to signals (e.g., commands, prices, measurements)[1]."*

[1] J. L. Mathieu et al., "A New Definition and Research Agenda for Demand Response in the Distributed Energy Resource Era," in IEEE Transactions on Energy Markets, Policy and Regulation, doi: 10.1109/TEMPR.2025.3554734

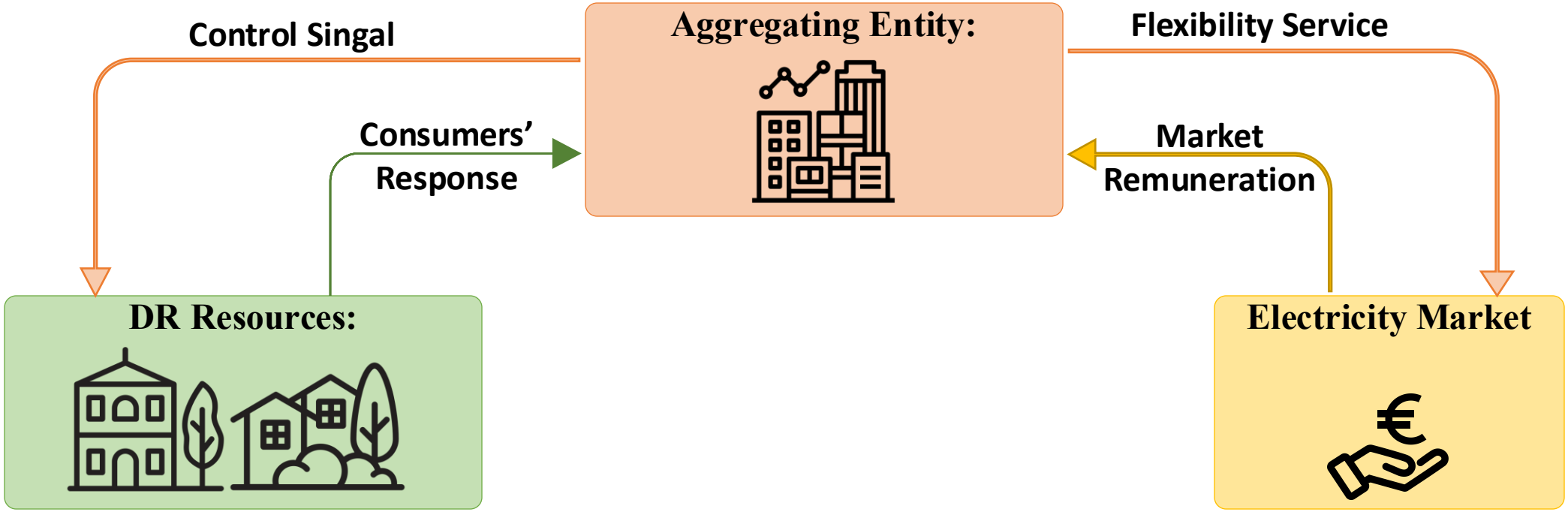
Mobilization of Demand Response Resources

Challenges with Integration of Individual Residential Loads in the Wholesale Market

- **Too small and diverse**
- **Lack of sufficient monitoring/telemetry**
- Do not meet **minimum bid sizes** or **verification standards** for market participation



Mobilization of Demand Response Resources



Direct Control Approach (Switch appliances on/off or set consumption levels)

+ Precise load management
- **Computationally intensive** for large-scale residential DR
- **High communication/infrastructure requirements**
- **Privacy and user acceptance** concerns due to appliance-level control

Indirect Control Approach (Price Based)

+ Scalability
+ Privacy preservation
+ Low communication/infrastructure requirements
- High Response Uncertainty

Price-Response Behavior

From Individual Consumer's Perspective:

DR Resources:

$$\max_{y_{i,t}^{\mathrm{DA}}} \quad \sum_{t\in\mathcal{T}} y_{i,t}^{\mathrm{DA}} \left(U_i - \lambda_t^{\mathrm{DA}}\right) \Delta t \qquad (1a)$$

$$\text{s.t.} \quad 0 \le y_{i,t}^{\mathrm{DA}} \le \overline{y}_i, \quad \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \qquad (1b)$$

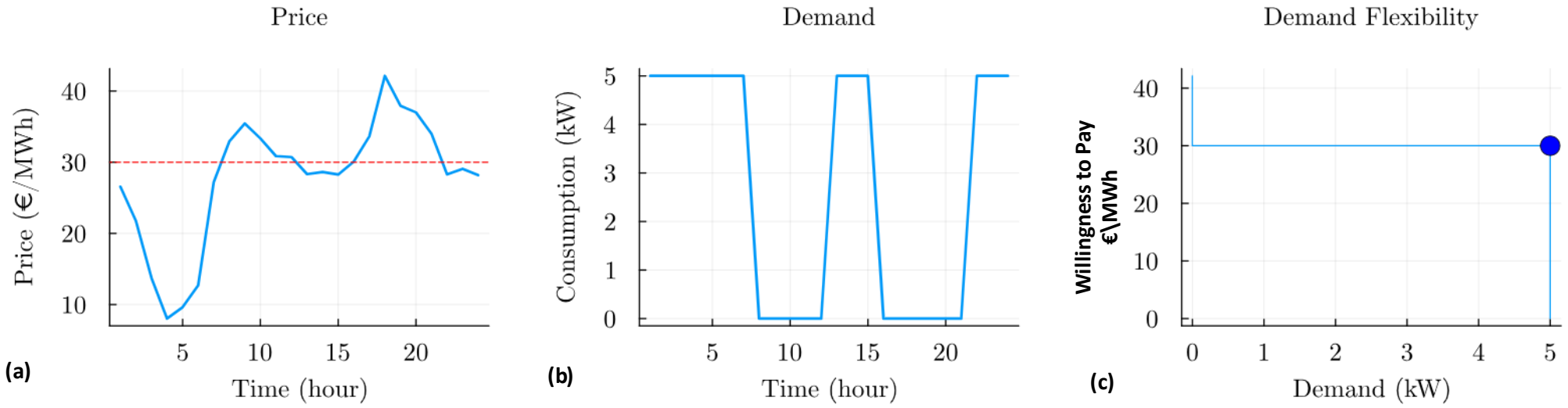


Fig. 1 – Price-Response of an Individual Consumer

Price-Response Behavior

From the Aggregator's Perspective:

Aggregating Entity:

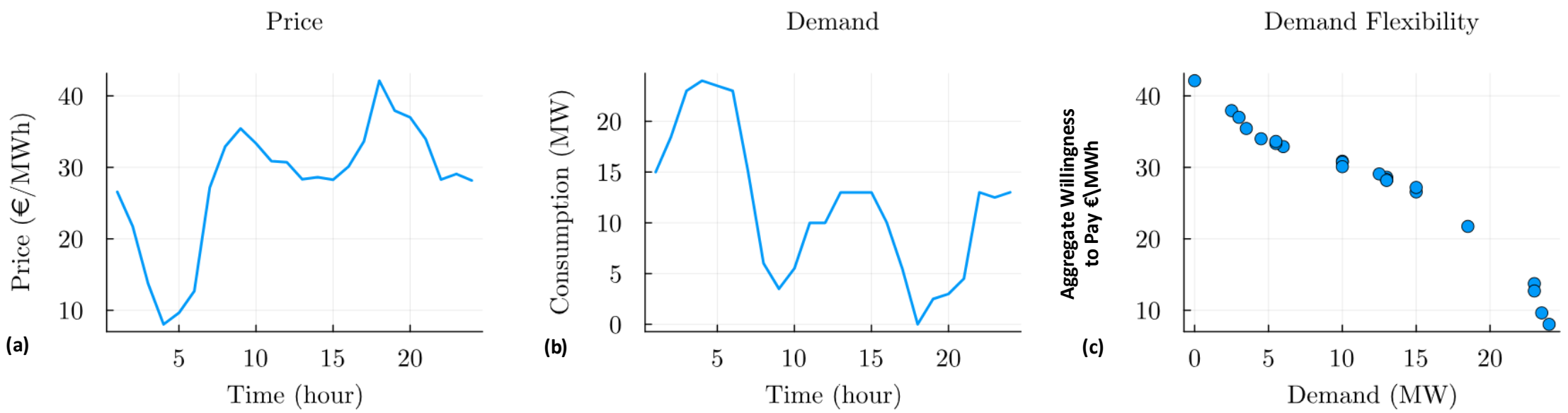


Fig. 2 – Aggregate Price-Response of all the Consumers For a Single Day

Price-Response Behavior

From the Aggregator's Perspective:

Aggregating Entity:

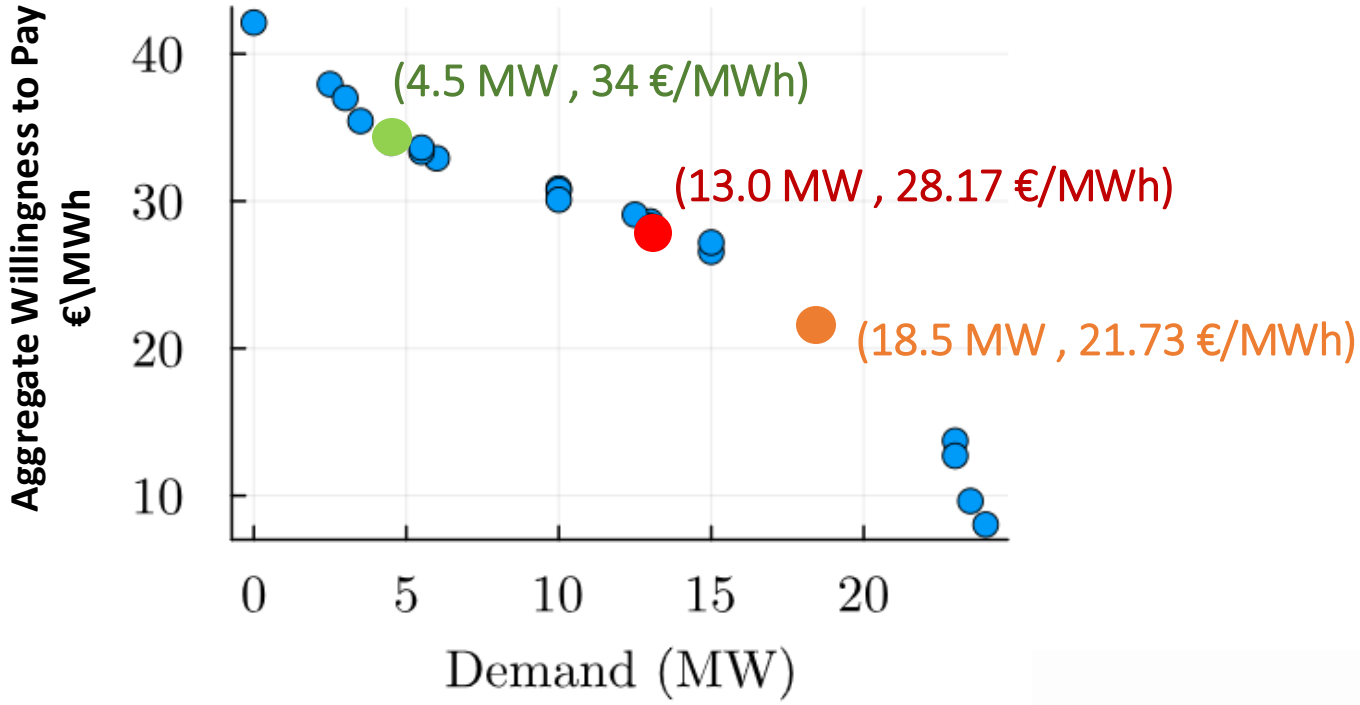


Fig. 3 – Aggregate Price-Response Flexibility of all the Consumers for a Single Day

Price-Response Behavior

From the Aggregator's Perspective:

Aggregating Entity:

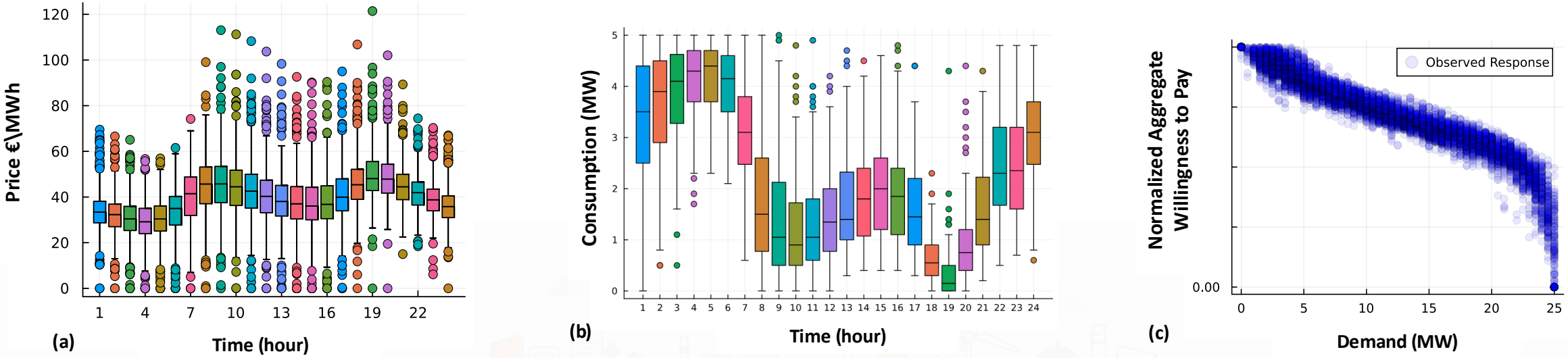
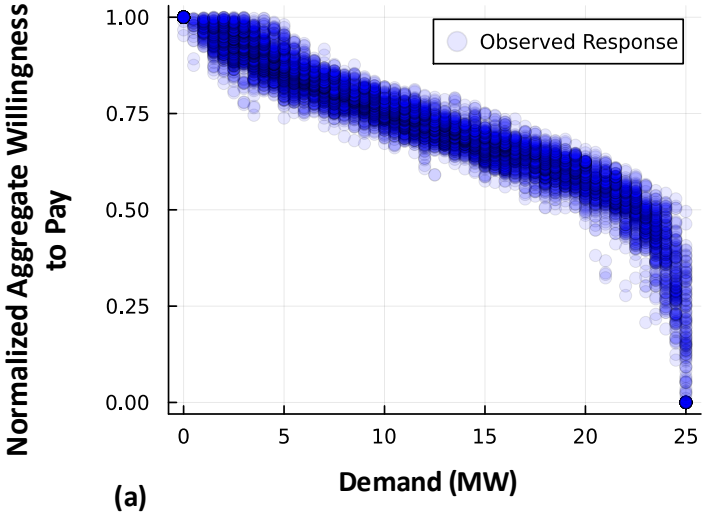


Fig. 4 – Historical Aggregate Price-Response of all the Consumers

Price-Response Behavior

From the Aggregator's Perspective:

Aggregating Entity:



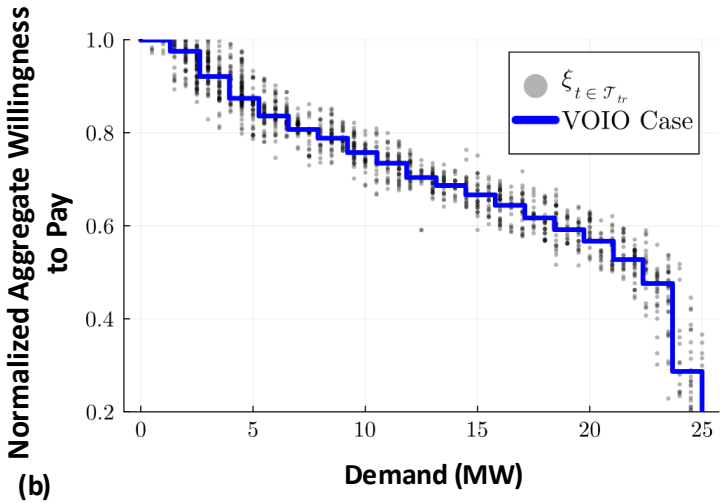
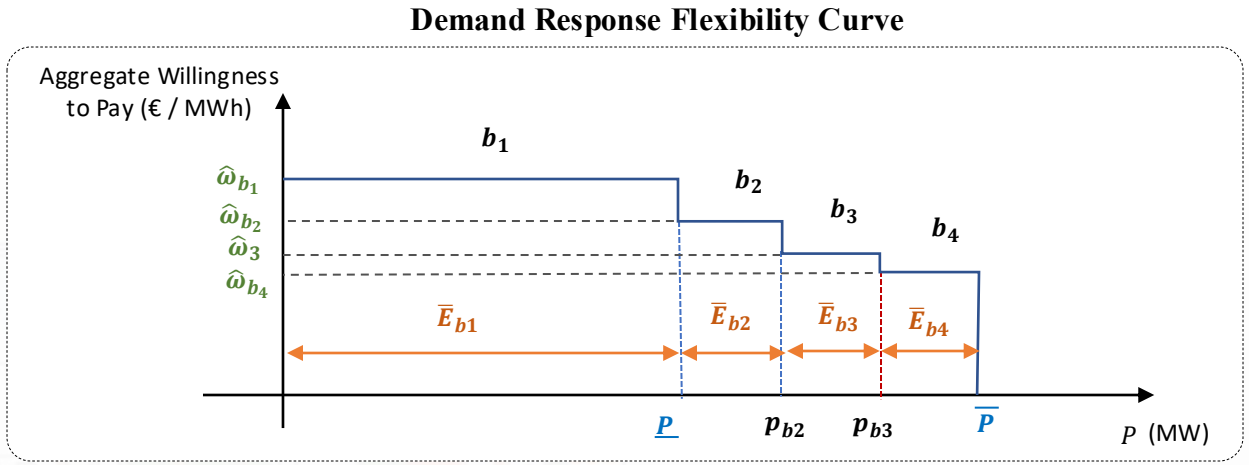


Fig. 5 – Constructing Flexibility Curve

$$\max_{p_{b,t}} \quad \sum_{t\in\mathcal{T}}\sum_{b\in\mathcal{B}} p_{b,t}\left(\hat{\omega}_b - \lambda_t\right)\Delta t \qquad (2a)$$

$$\text{s.t.} \quad \underline{P} \leq \sum_{b\in\mathcal{B}} p_{b,t} \leq \overline{P}, \qquad (2b)$$

$$0 \leq p_{b,t} \leq \overline{E}_b, \qquad (2c)$$

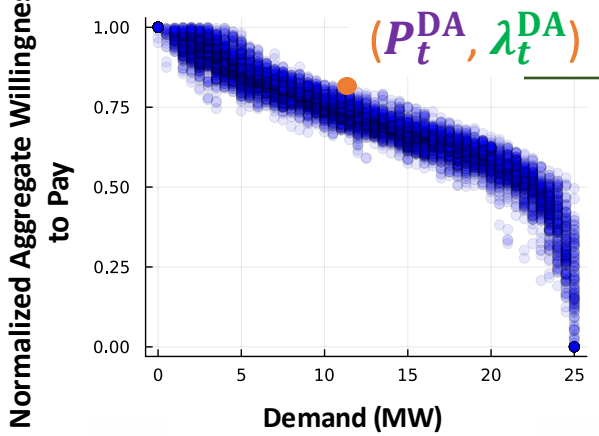


Inverse Optimization

From the Aggregator's Perspective:

Aggregating Entity:

Historical Data:



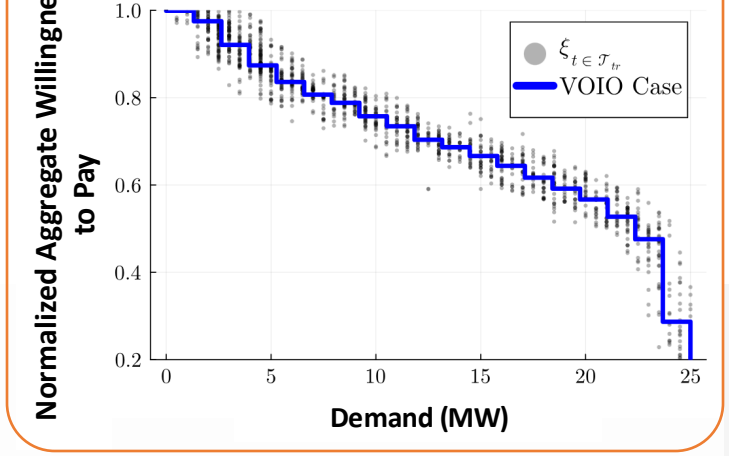
Inverse Optimization Problem:

$$\min_{\omega_b} \quad \frac{1}{|\mathcal{T}_{tr}|} \sum_{t \in \mathcal{T}_{tr}} \left| P_t^{DA} - \sum_{b \in \mathcal{B}} p_{b,t} \right| \tag{3a}$$

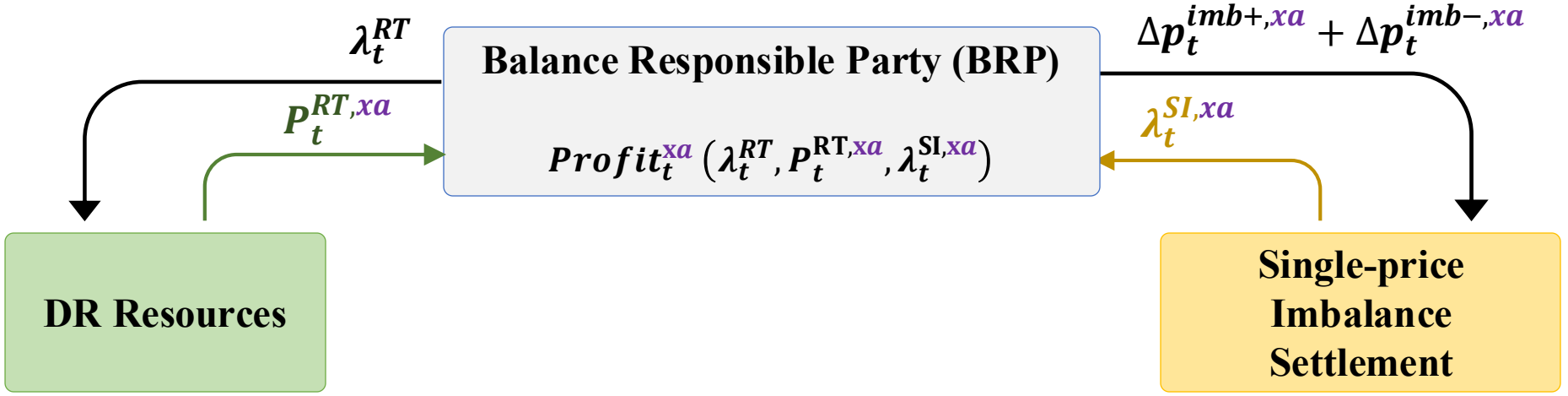
$$\text{s.t.} \quad \omega_b \leq \omega_{b-1}, \quad \forall b \in B \setminus \{b_1\}, \tag{3b}$$

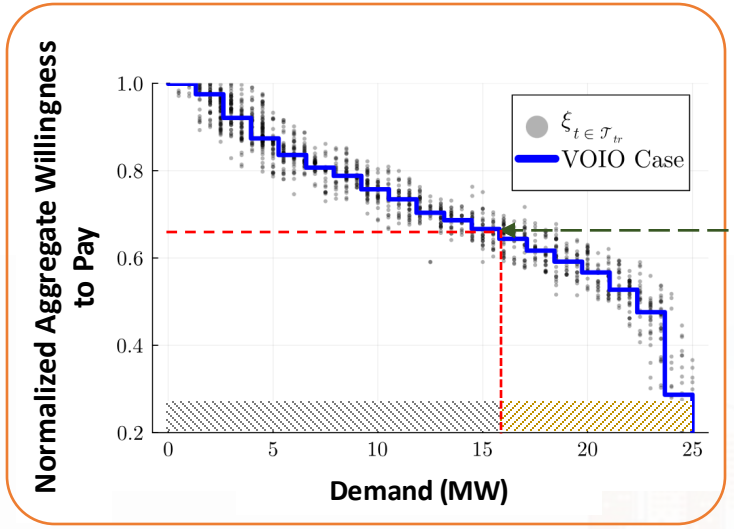
$$\omega_b \leq \bar{\omega}, \quad b = b_1, \tag{3c}$$

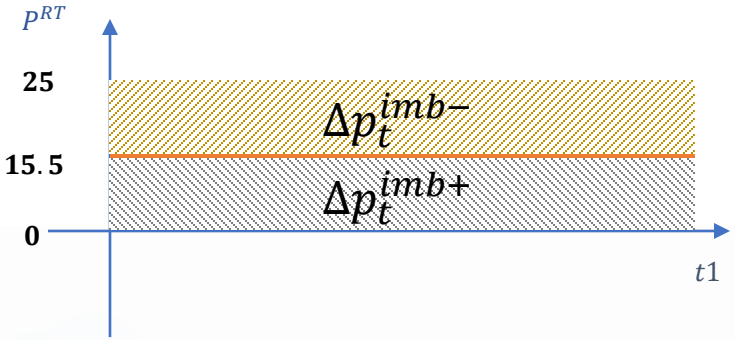
$$p_{b,t} \in \left\{ \arg\max_{p_{b,t}} \sum_{b \in \mathcal{B}} p_{b,t} \left(\omega_b - \lambda_t^{DA} \right) \;\middle|\; \text{(2b), (2c)} \right\} \tag{3d}$$



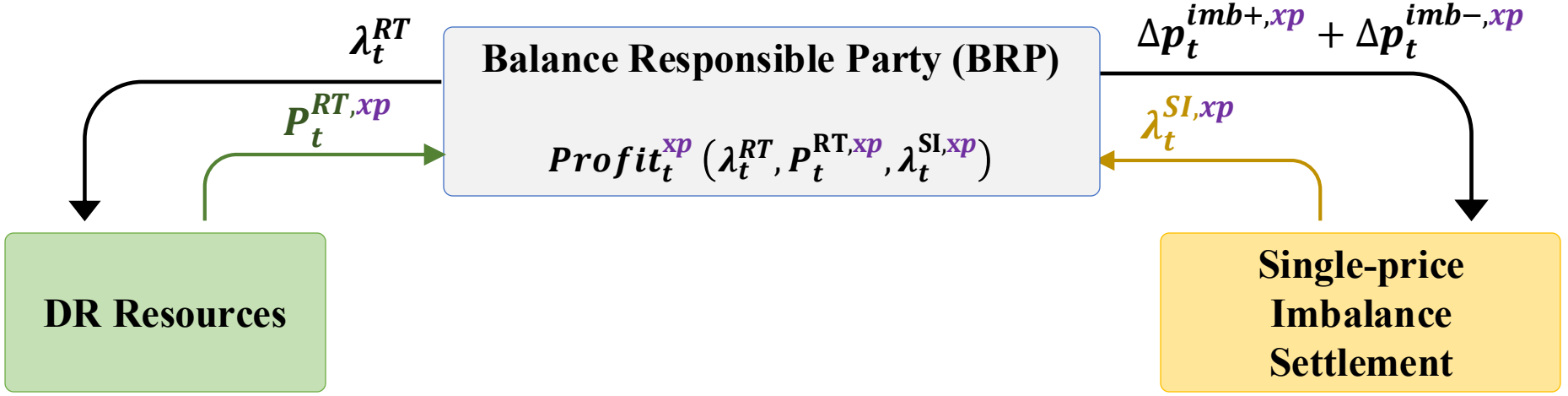
Implicit Balancing

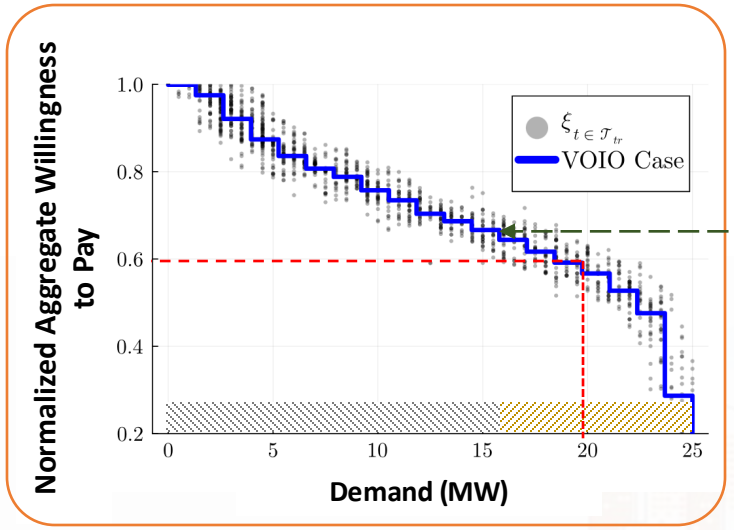


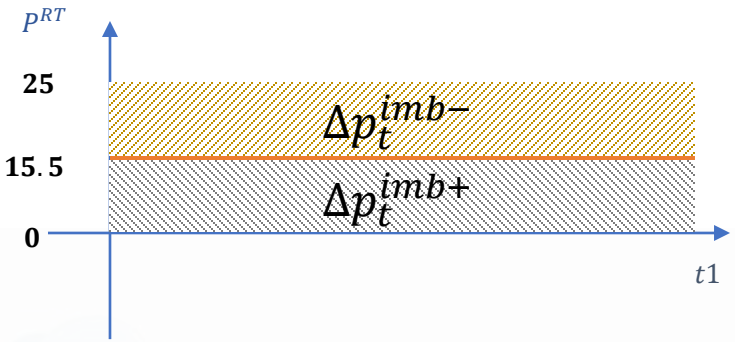




Implicit Balancing







Aggregate Price-Response Model Selection

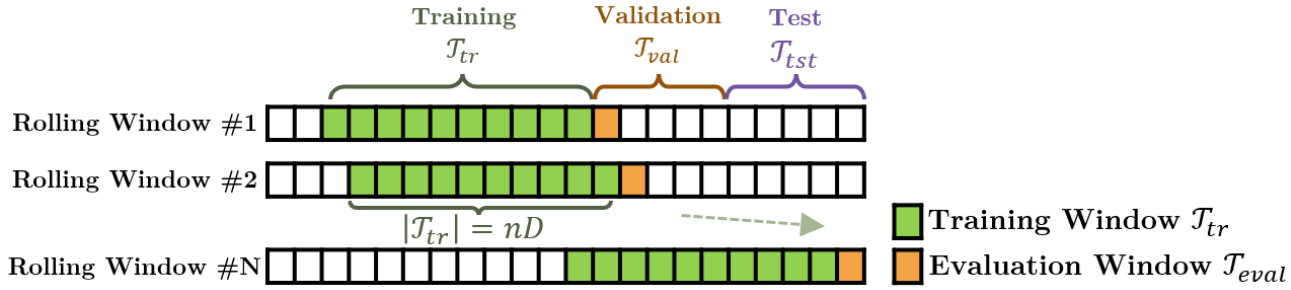


Fig. 6 – The rolling horizon method used for calculating validation and test scores. Each block represents one day (96 quarter-hourly intervals

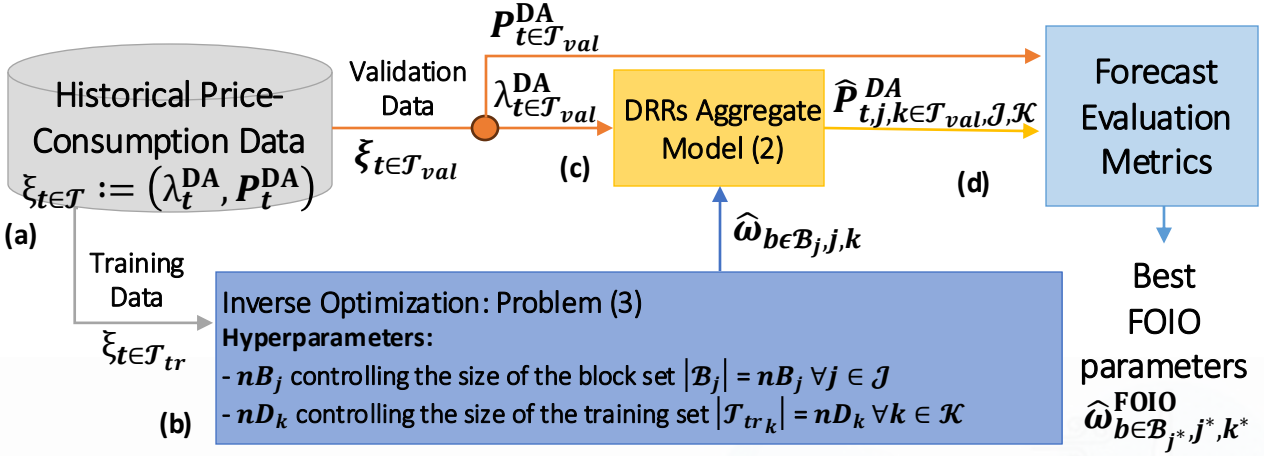


Fig. 7 – Forecast-Oriented IO (FOIO) hyperparameter selection

Aggregate Price-Response Model Selection

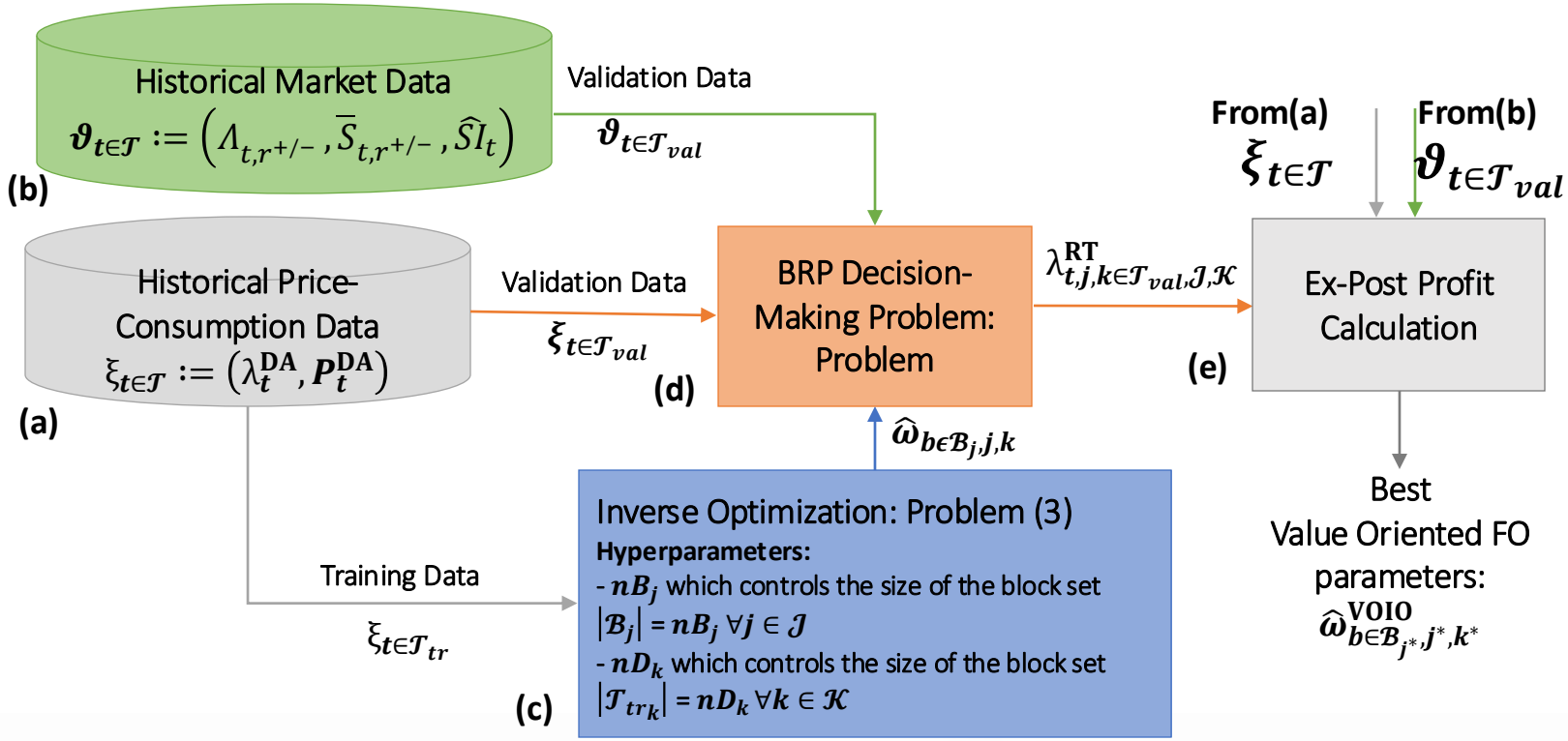


Fig. 8 – Value-Oriented IO (VOIO) hyperparameter selection

Results

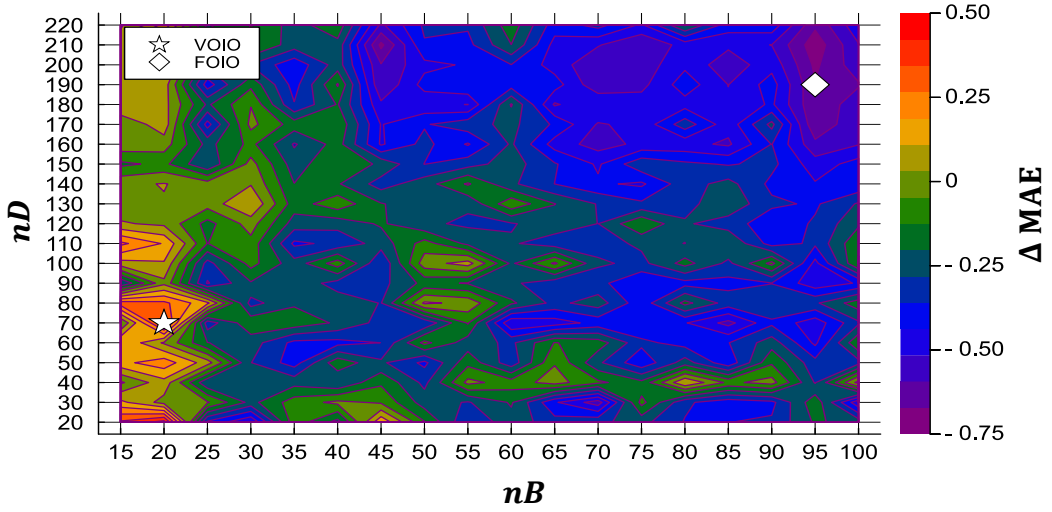


Fig. 9 – Difference between normalized prediction MAE values and ex post profit MAE scores, plotted for nD ∈ {20,30,40,…,220} and nB ∈{15,20,25,…,100}

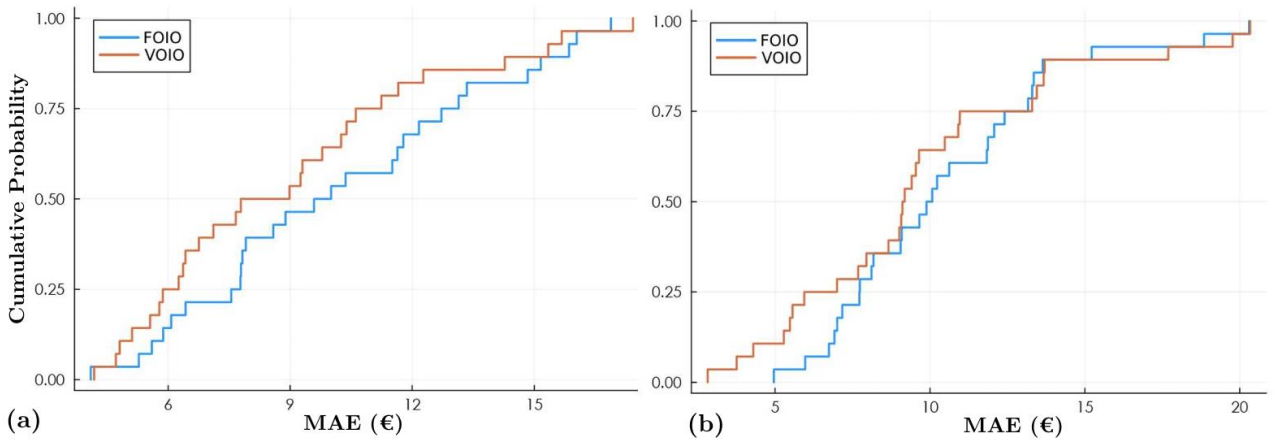


Fig. 10 – Comparison of the empirical cumulative distribution function (ECDF) of quarter-hourly ex-post profit performance scores for the FOIO and VOIO methods: (a) validation MAE (€), (b) test MAE (€)

TABLE I
COMPARISON OF FORECAST AND PROFIT KPIS BETWEEN FOIO AND VOIO $\left(\Delta\% = \frac{\text{FOIO}-\text{VOIO}}{\text{FOIO}} \times 100\right)$

Model	Forecast KPI				Profit KPI			
	MAE (MW)		RMSE		MAE (€)		RMSE	
	Val.	Test	Val.	Test	Val.	Test	Val.	Test
FOIO	0.993	1.033	1.277	1.258	10.169	10.54	20.757	24.264
VOIO	1.068	1.064	1.364	1.309	8.96	9.774	18.682	21.7
Δ%	-7.49	-3.07	-6.81	-3.99	11.88	7.269	9.998	10.565

Thank You!

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