Toward Integrating Operation Research and Machine Learning: A Closed-Loop Predict-and-Optimize Framework and Its Application in Power Systems

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I Introduction

Real-world scheduling is **"predict-then-optimize"**:

1) Machine learning predicts uncertainties;

2) Given predictions, scheduling plans are optimized.

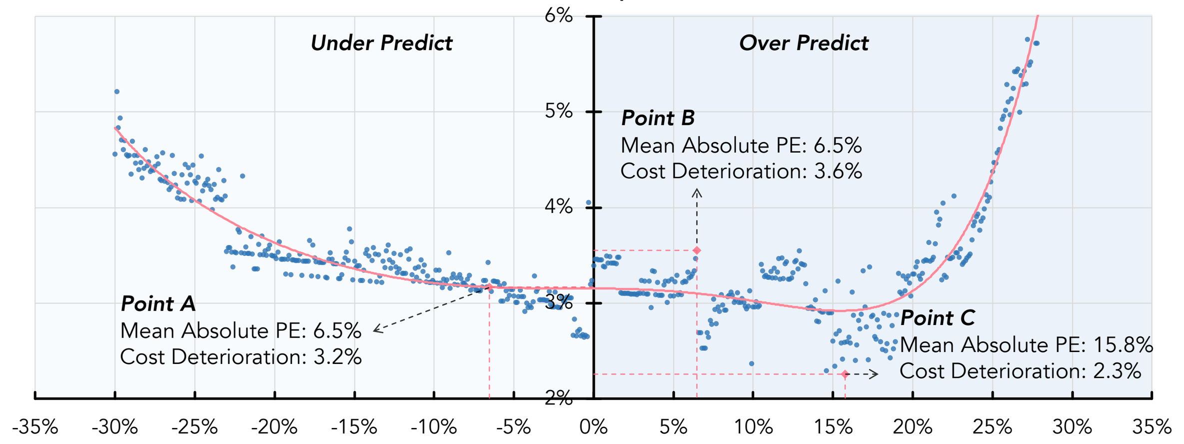
But the prediction ignores its impact on the optimization, making the process **opened-loop**. So, **will it be beneficial to feed the optimization back to the prediction?**

II Motivation from Power System

Power system operations in the open-loop predict-then-optimize process:

Machine Learning-based Predictor	$\xrightarrow{\hat{\boldsymbol{w}}}$	$z(\hat{\boldsymbol{w}}) = \min_{\boldsymbol{x}} \boldsymbol{c}^\top \boldsymbol{x}$ s.t. $\boldsymbol{A}\boldsymbol{x} \le \boldsymbol{u} + \boldsymbol{B}\hat{\boldsymbol{w}}$, $\boldsymbol{x} \in \{0,1\}^m \times \mathbb{R}^n$	$\xrightarrow{\boldsymbol{x}^*}$	$J(\boldsymbol{x}^*, \tilde{\boldsymbol{w}}) = \min_{\boldsymbol{y}} \boldsymbol{d}^\top \boldsymbol{y}$ s.t. $\boldsymbol{C}\boldsymbol{x}^* + \boldsymbol{D}\boldsymbol{y} \le \boldsymbol{v} + \boldsymbol{E}\tilde{\boldsymbol{w}}$, $\boldsymbol{y} \in \{0,1\}^p \times \mathbb{R}^q$
Predict energy availability $\hat{\boldsymbol{w}}$		Optimize operation plan $\boldsymbol{x}^*$		Optimize adjustment plan $\boldsymbol{y}^*$ according to actual availability $\tilde{\boldsymbol{w}}$

Asymmetrical relationship between operation cost and prediction error:



$$Deterioration\ of\ Operation\ Cost = \frac{Cost^{With\ Error} - Cost^{Error-Free}}{Cost^{Error-Free}} \times 100\%$$

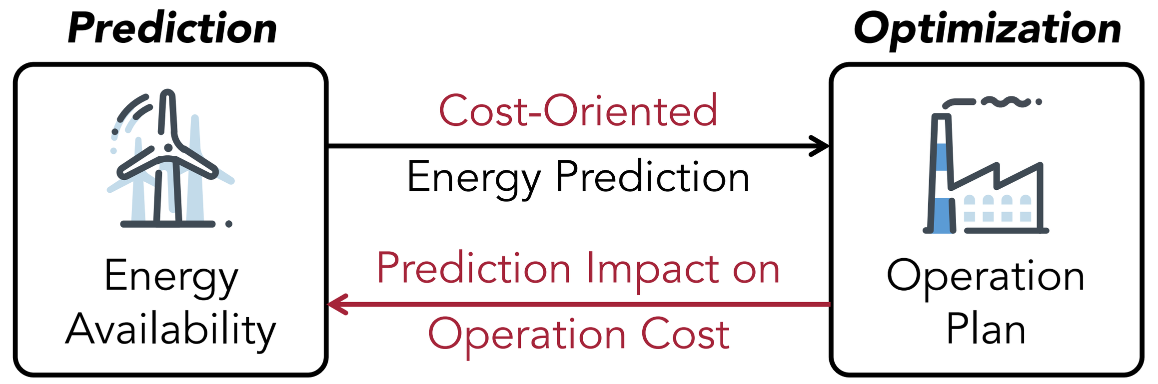
Observation

- ***Point A vs. Point B:*** Same error but different costs.
- ***Point B vs. Point C:*** Worse error but lower cost.

Real-world systems are nonlinear. We should **close the** opened-loop between prediction and optimization.

III What is Closed-Loop Predict-and-Optimize?

vs.



Open-Loop Predict-then-Optimize

- Measure prediction quality with prediction accuracy. (Open-loop and accuracy-oriented)
- Sequentially predict energy and optimize operation. (Predict-then-Optimize)

Closed-Loop Predict-and-Optimize

- Measure prediction quality with operation cost. (Closed-loop and cost-oriented)
- Simultaneously predict energy and optimize operation. (Predict-and-Optimize)

IV How to Closed-Loop Predict-and-Optimize?

Data Processing

Select the most relevant feature type to form feature vectors $\boldsymbol{f}$.

Select S representative scenarios as training scenarios.

Goal: Form the empirical risk minimization problem for training predictor.

Cost-Oriented Predictor Training

Form a bilevel empirical risk minimization (ERM) problem. Then solve it via a cutting-plane method. The solution is an optimally trained predictor $\boldsymbol{H}^*(\cdot)$.

$$\min_{\boldsymbol{H}} \frac{1}{S}\sum_{s=1}^{S} \boldsymbol{b}^\top \boldsymbol{x}_s + \boldsymbol{d}^\top \boldsymbol{y}_s \quad s.t.\ \hat{\boldsymbol{w}}_s = \boldsymbol{H}(\boldsymbol{f}_s);\ \forall s$$

Upper Level: *Given feature $\boldsymbol{f}_s$, train predictor $\boldsymbol{H}(\cdot)$ with objective of minimum operation cost $\boldsymbol{b}^\top \boldsymbol{x}_s + \boldsymbol{d}^\top \boldsymbol{y}_s$.*

$$\boldsymbol{x}_s \in \arg\min \boldsymbol{c}^\top \boldsymbol{x}_s;\ \forall s \quad s.t.\ \boldsymbol{A}\boldsymbol{x}_s \le \boldsymbol{u} + \boldsymbol{B}\hat{\boldsymbol{w}}_s,\ \boldsymbol{x}_s \in \{0,1\}^m \times \mathbb{R}^n$$

Lower Level: *Given prediction $\hat{\boldsymbol{w}}_s$, optimize operation plan $\boldsymbol{x}_s$.*

$$\boldsymbol{y}_s \in \arg\min \boldsymbol{d}^\top \boldsymbol{y}_s;\ \forall s \quad s.t.\ \boldsymbol{C}\boldsymbol{x}_s + \boldsymbol{D}\boldsymbol{y}_s \le \boldsymbol{v} + \boldsymbol{E}\tilde{\boldsymbol{w}}_s,\ \boldsymbol{y}_s \in \{0,1\}^p \times \mathbb{R}^q$$

Lower Level: *Given plan $\boldsymbol{x}_s$ and actual realization $\tilde{\boldsymbol{w}}_s$, optimize adjustment plan $\boldsymbol{y}_s$.*

Feedback the prediction impact on the operation optimization

Goal: Solving the ERM problem can provide a predictor $\boldsymbol{H}^*(\cdot)$ that can generate cost-oriented prediction $\hat{\boldsymbol{w}}$ (feature $\boldsymbol{f}$ as input) for the operations. The cost-oriented prediction $\hat{\boldsymbol{w}}$ is tailored to reduce the operation cost.

Predict and Optimize

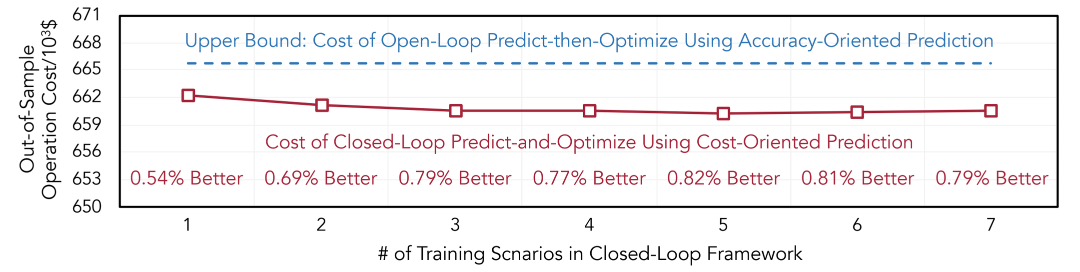
Embed the trained predictor $\boldsymbol{H}^*(\cdot)$ into the original operation model to form a prescriptive model:

$$z(\boldsymbol{f}) = \min_{\boldsymbol{x},\hat{\boldsymbol{w}}} \boldsymbol{c}^\top \boldsymbol{x} \quad s.t.\ \boldsymbol{A}\boldsymbol{x} \le \boldsymbol{u} + \boldsymbol{B}\boldsymbol{H}^*(\boldsymbol{f}),\ \boldsymbol{x} \in \{0,1\}^m \times \mathbb{R}^n.$$

Now, the operation plan $\boldsymbol{x}$ is driven by feature $\boldsymbol{f}$.

Goal: Use the prescriptive model to predict and optimize simultaneously.

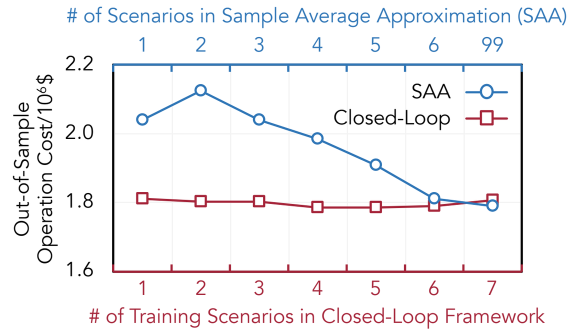
V Major Results

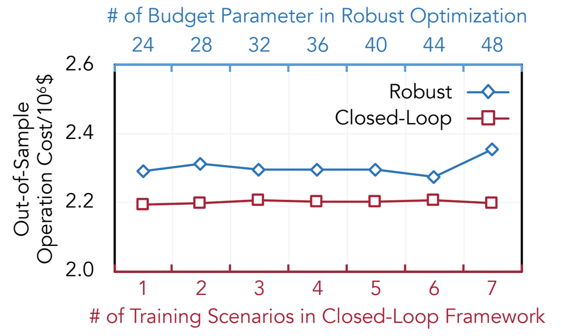


Type of Prediction $\hat{\boldsymbol{w}}$	Mean Absolute Error (MAE)	Root Mean Square Error (RMSE)
Accuracy-Oriented	**15.0MW**	**21.0MW**
Cost-Oriented	16.5MW	23.2MW

Closed-Loop vs. Open-Loop

- Closed-loop reduces operation cost by 0.54%-0.82%. **Implication:** Closed-loop is economically effective.
- Cost-oriented $\hat{\boldsymbol{w}}$ is worse in MAE and RMSE. **Implication:** A more accurate prediction may not result in a better optimization.





Closed-Loop vs. SAA

- Closed-loop outperforms SAA when scenarios are limited.

Closed-Loop vs. Robust

- Closed-loop achieves a better operation cost.

VI References

[1] X. Chen, Y. Yang, Y. Liu and L. Wu, "Feature-Driven Economic Improvement for Network-Constrained Unit Commitment: A Closed-Loop Predict-and-Optimize Framework," *IEEE Transactions on Power Systems*, 2022.

[2] X. Chen, Y. Liu and L. Wu, "Towards Improving Operation Economics: A Bilevel MIP-Based Closed-Loop Predict-and-Optimize Framework for Prescribing Unit Commitment," *arXiv:2208.13065*, 2023.