Integrating Model-Based Projection with Data-Driven Correction for Prognostics of All-Solid-State Battery-Supercapacitor Hybrid Devices

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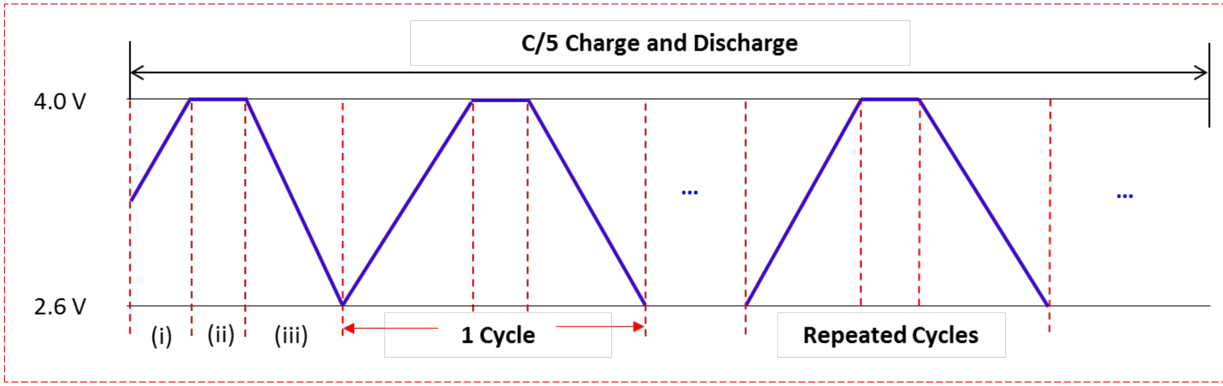
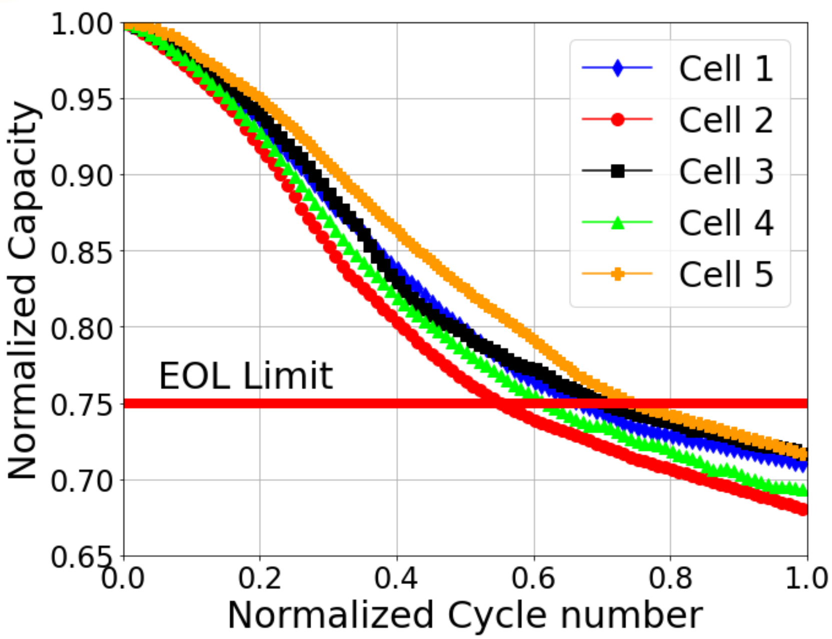
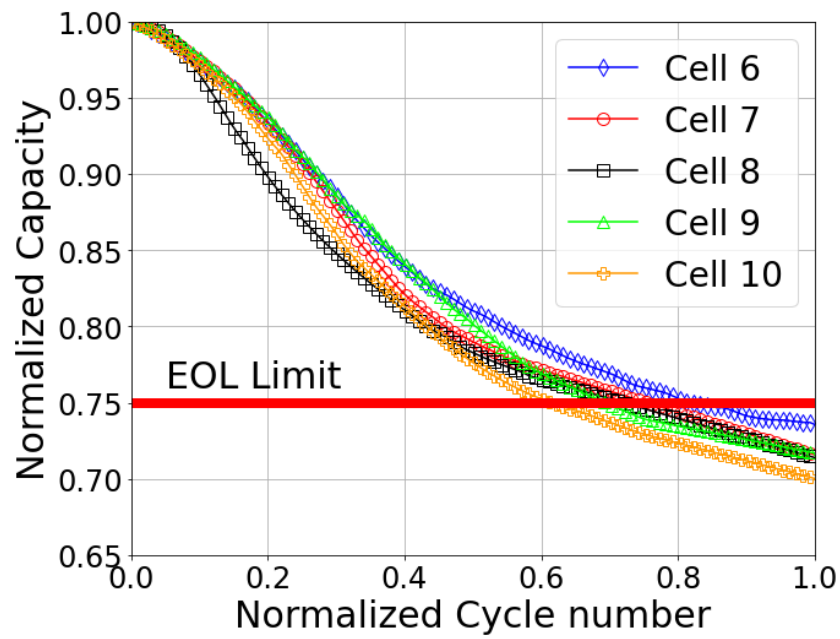
Overview

- Introduction to the battery aging tests
- What is remaining useful life (RUL)?
- Comparison of current RUL prediction methods
- RUL prediction with Gaussian Process
- Data-driven error correction
- Results and Discussion
- Conclusions and Future work

Capacity Fade of Hybrid Energy Storage Devices in Cycle Ageing Study



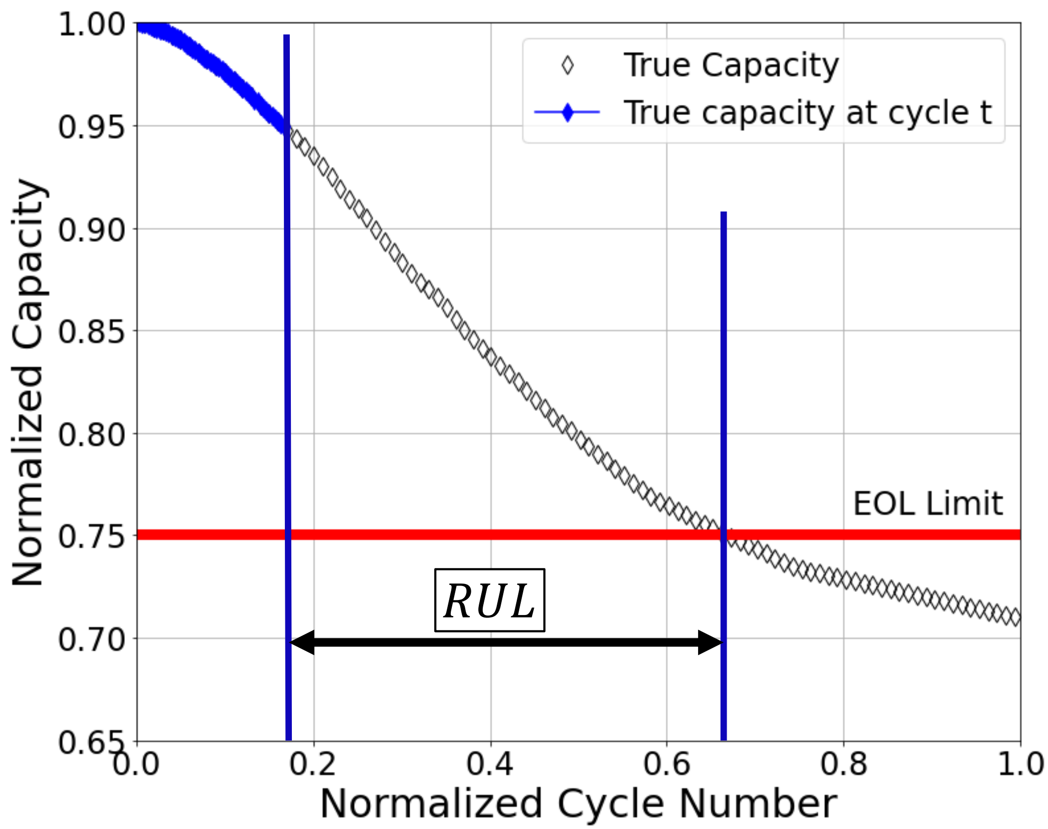




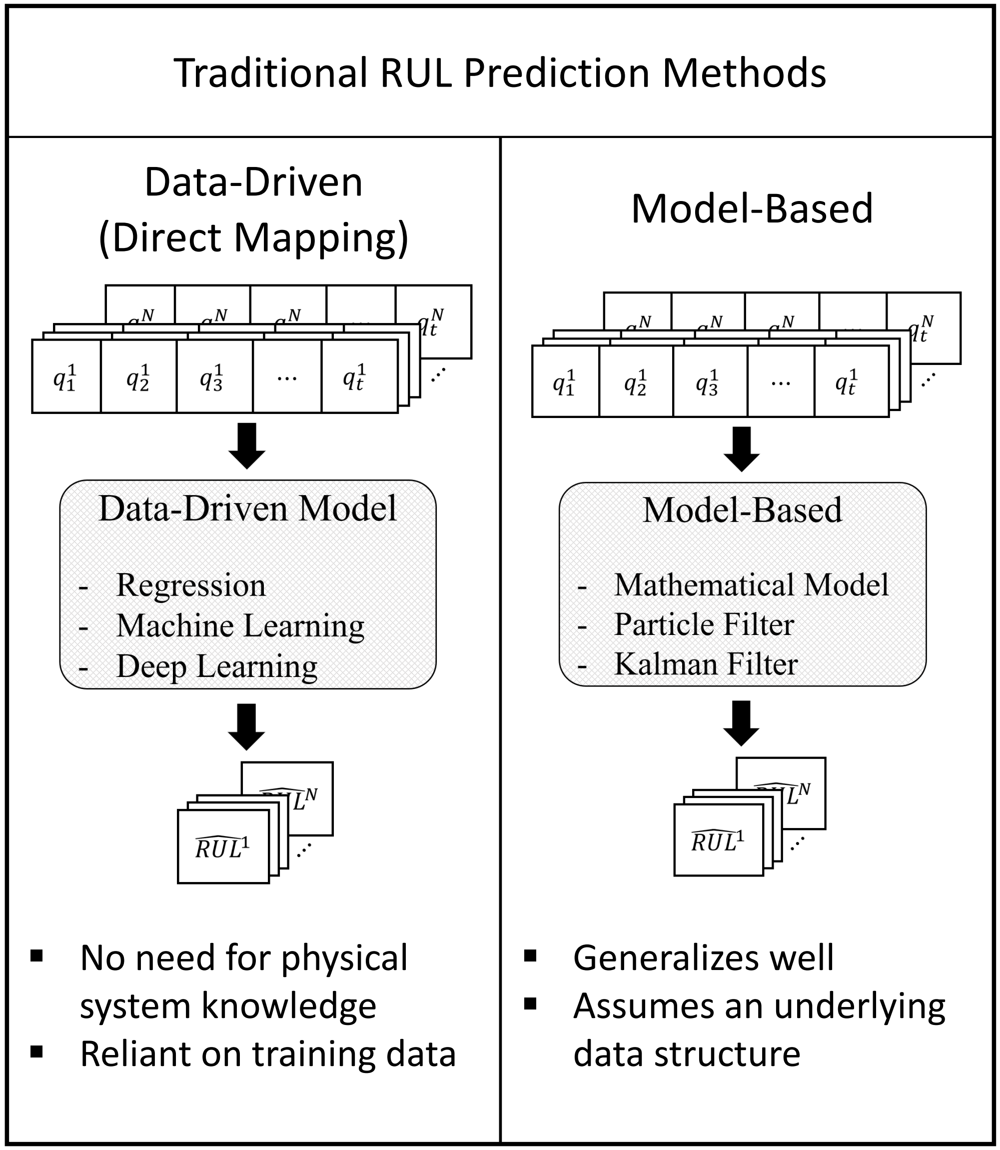
- All the ten hybrid energy storage devices (cells) were charged/discharged under C/5.
- The capacity fade trend of each cell is nonlinear and time-varying.

Remaining Useful Life Definition

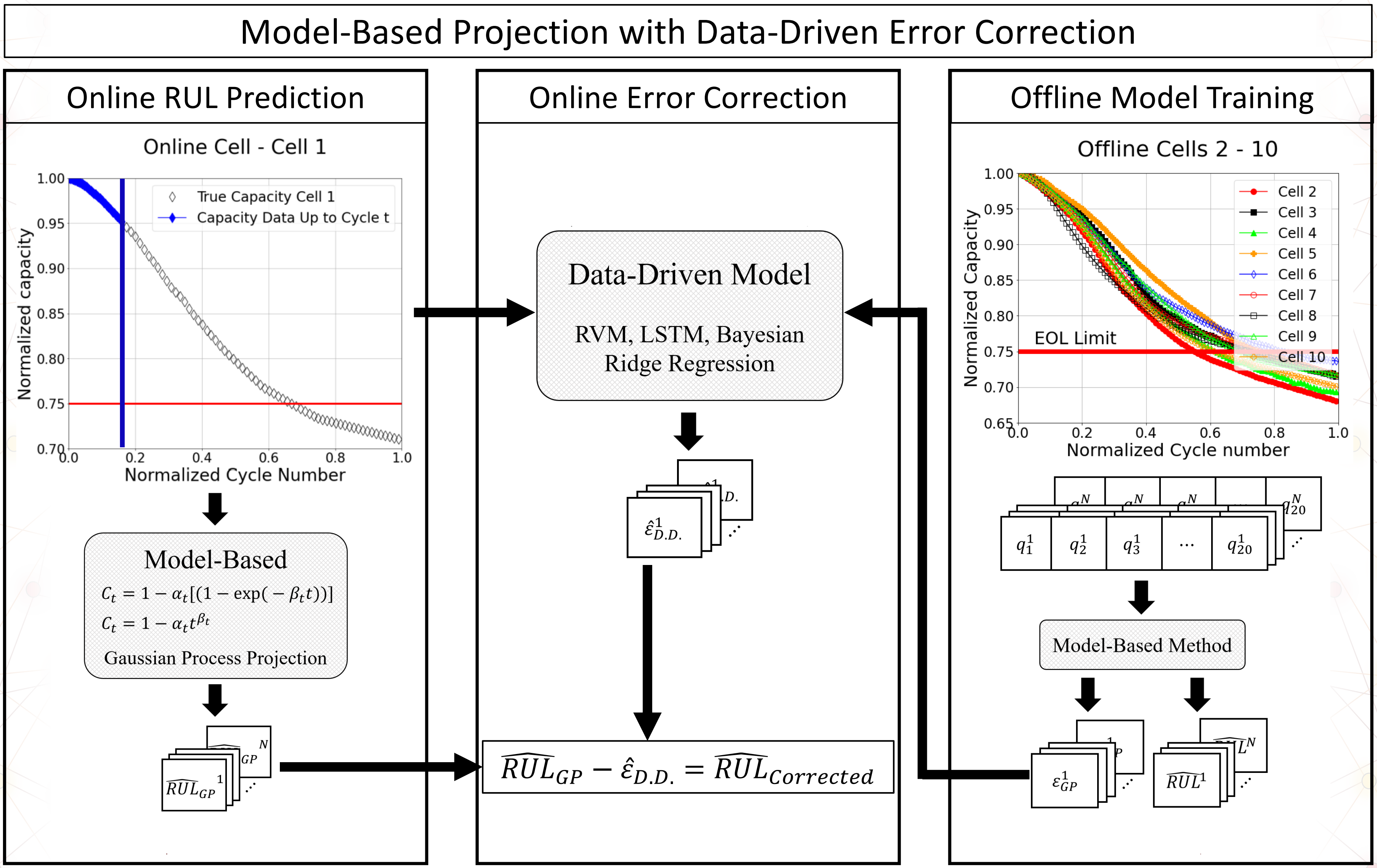
- Remaining Useful Life (RUL) is subjectively defined as the number of remaining cycles a battery cell can undergo before reaching 75% of its initial capacity (i.e., the end-of-life (EOL) limit).



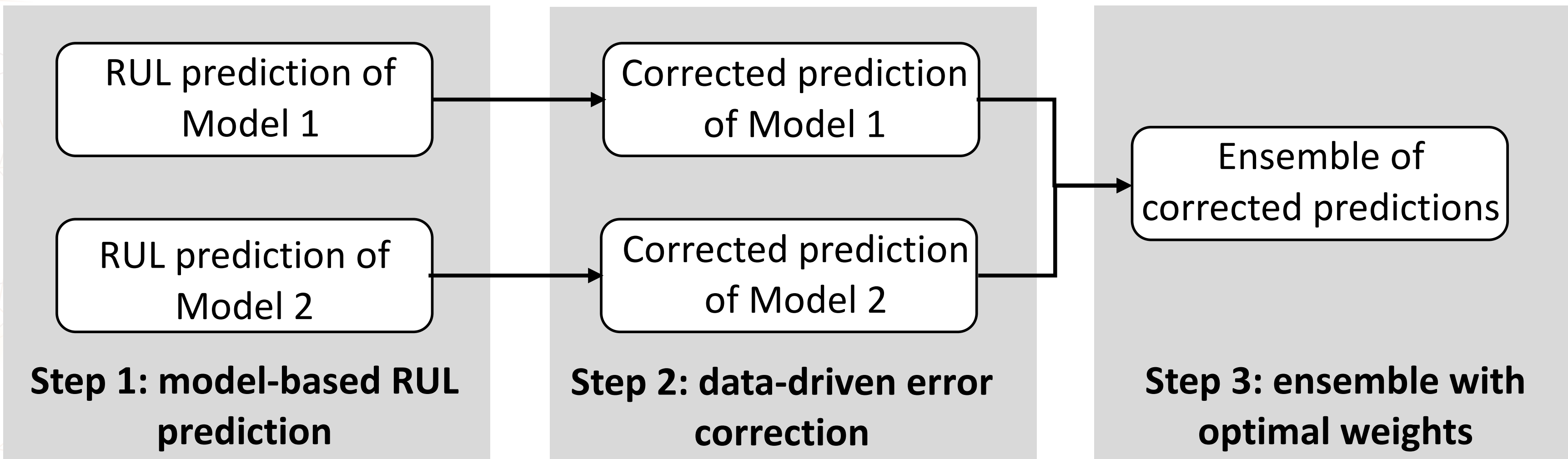
Model-Based and Data-Driven RUL Prediction Methods



Model-Based/Data-Driven RUL Prediction Method



Flowchart of Integrated Model-Based/Data-Driven RUL Prediction Framework



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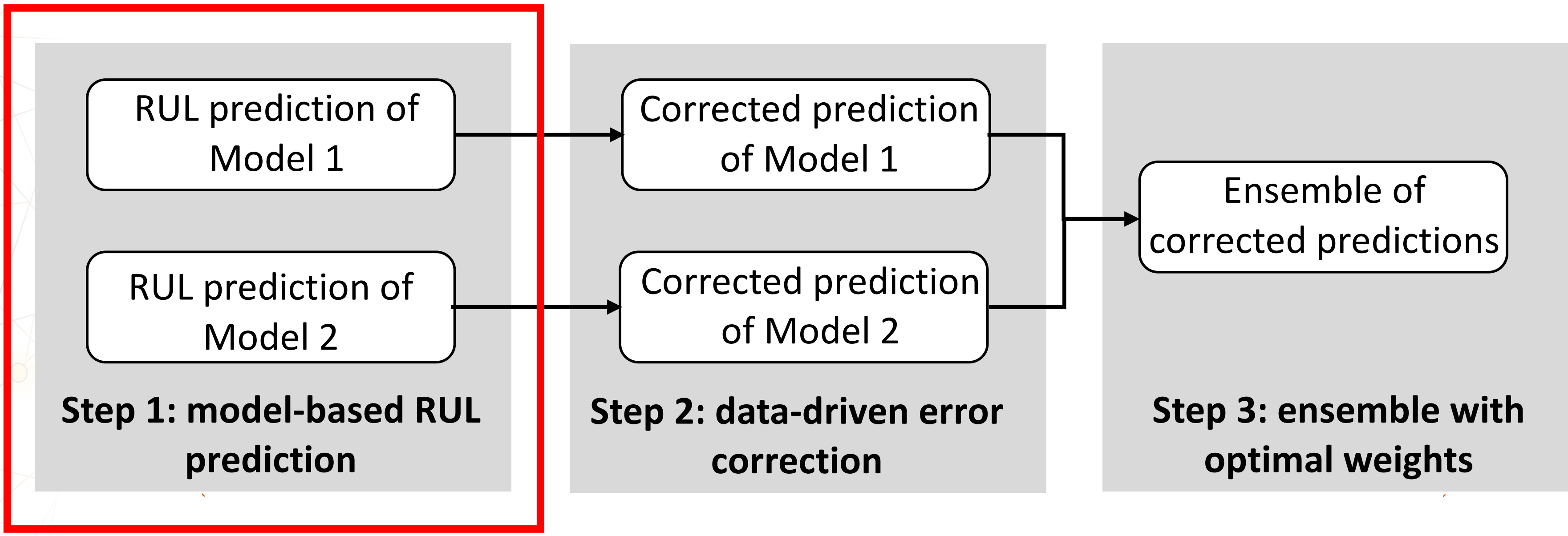


Model-Based RUL Prediction with Gaussian Process

Gaussian Process (Kriging)

$$C(t) = \underbrace{M(t)}_{\text{trend function}} + \underbrace{Z(t)}_{N(0,\sigma^2)}$$

Trend Function $M(t)$

Model 1: $C_t = 1 - \alpha_t[(1 - \exp(-\beta_t t))]$

Model 2: $C_t = 1 - \alpha_t t^{\beta_t}$

where t is the cycle number, α_t and β_t are the coefficients to be curve fit using all the online cell data up to cycle t.

- A Gaussian process (GP) defines a probability distribution over a function, in our case, the trend functions $M(t)$. It is denoted as

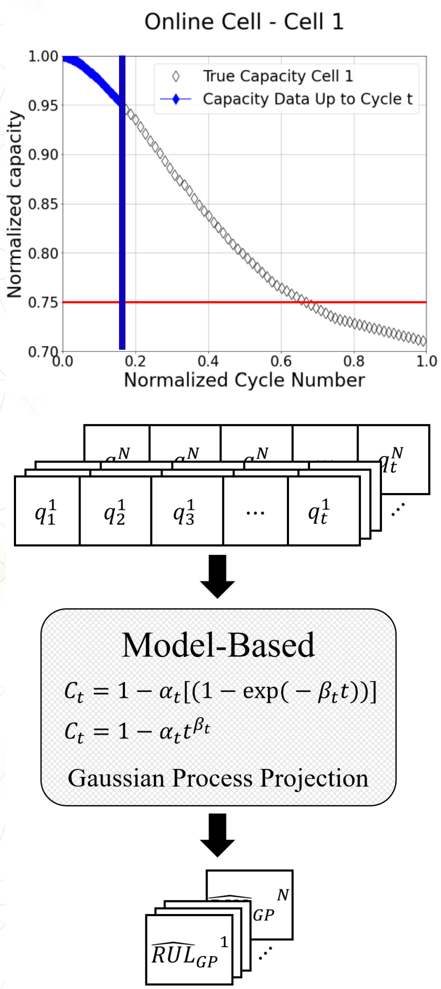
$$f(t) \sim GP(m(t), k(t,t'))$$

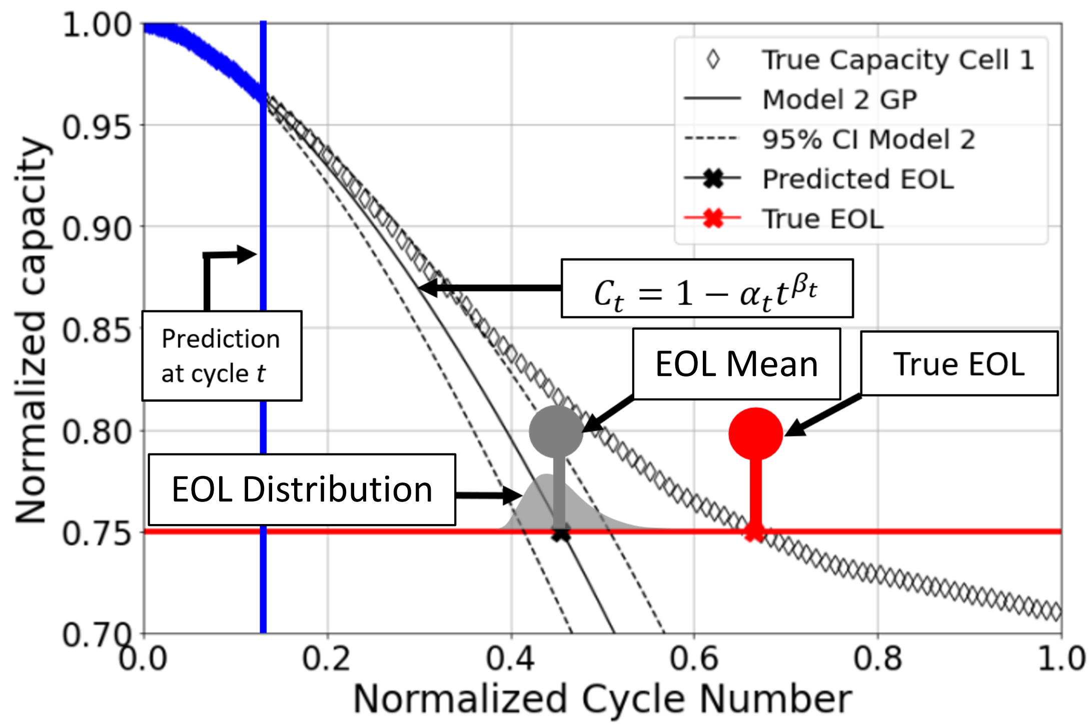
where $m(t)$ and $k(t,t')$ are the trend function and covariance function of the GP model

$$m(t) = \mathrm{E}\left[f(t)\right]$$

$$k(t,t') = \mathrm{E}\left[\left(f(t) - m(t)\right)\left(f(t') - m(t')\right)^T\right]$$

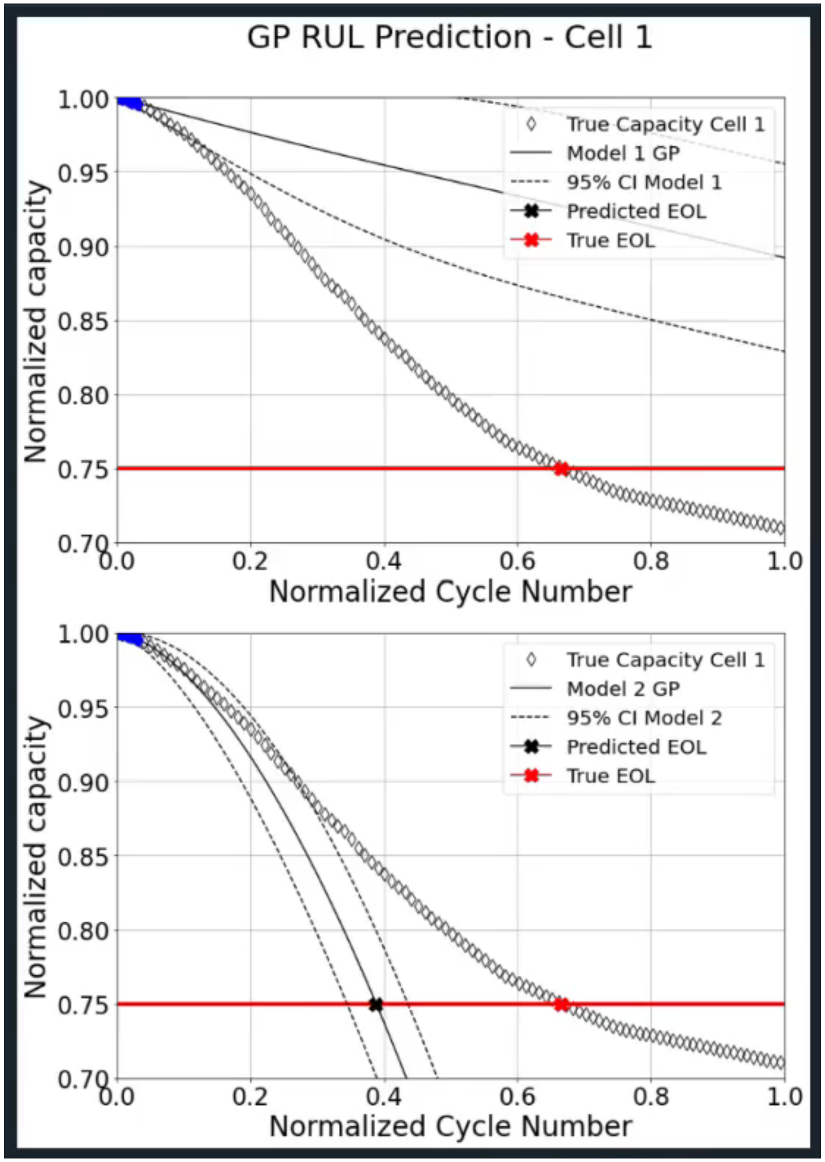
Model-Based RUL Prediction with Gaussian Process

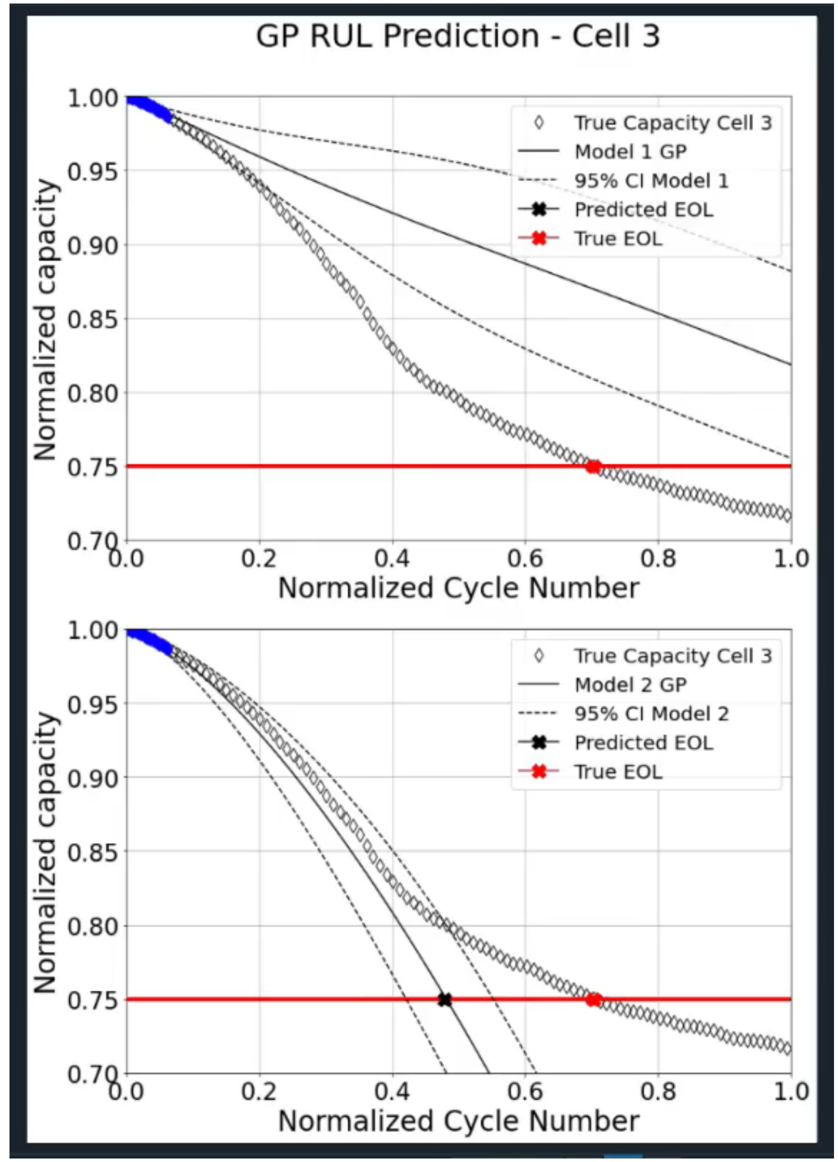




Example figure showing the probabilistic Gaussian Process projection using the underlying function $C_t = 1 - \alpha_t t^{\beta_t}$ (Model 2)

Model-Based RUL Prediction with Gaussian Process





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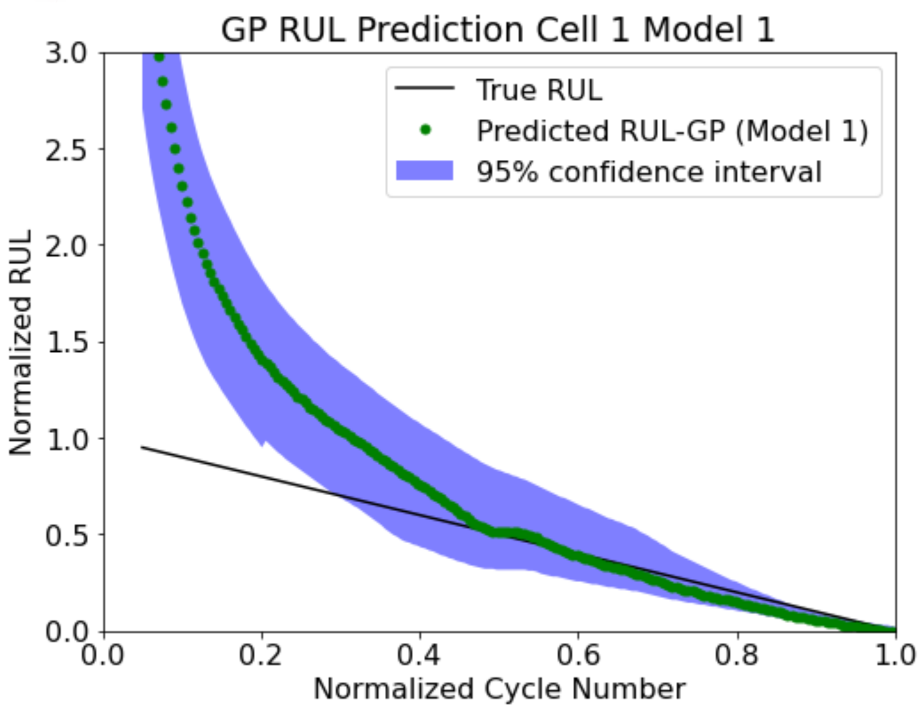
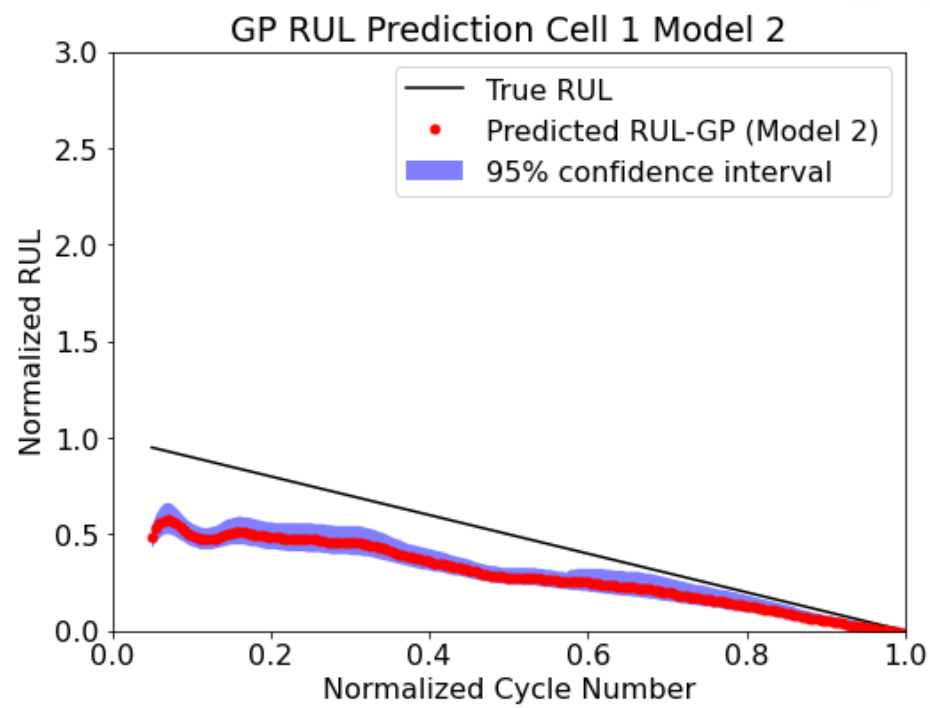
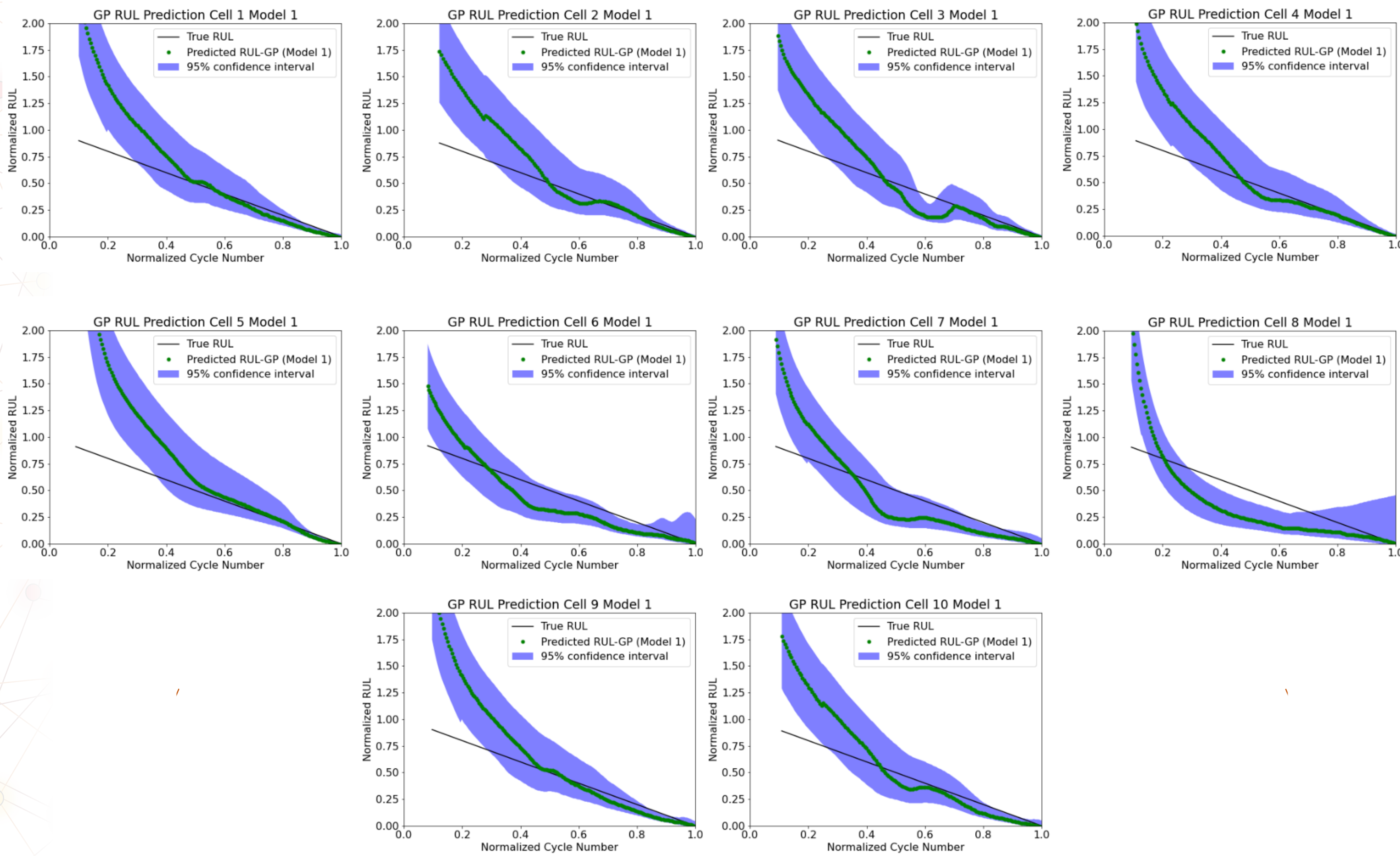
Model-Based RUL Prediction with Gaussian Process



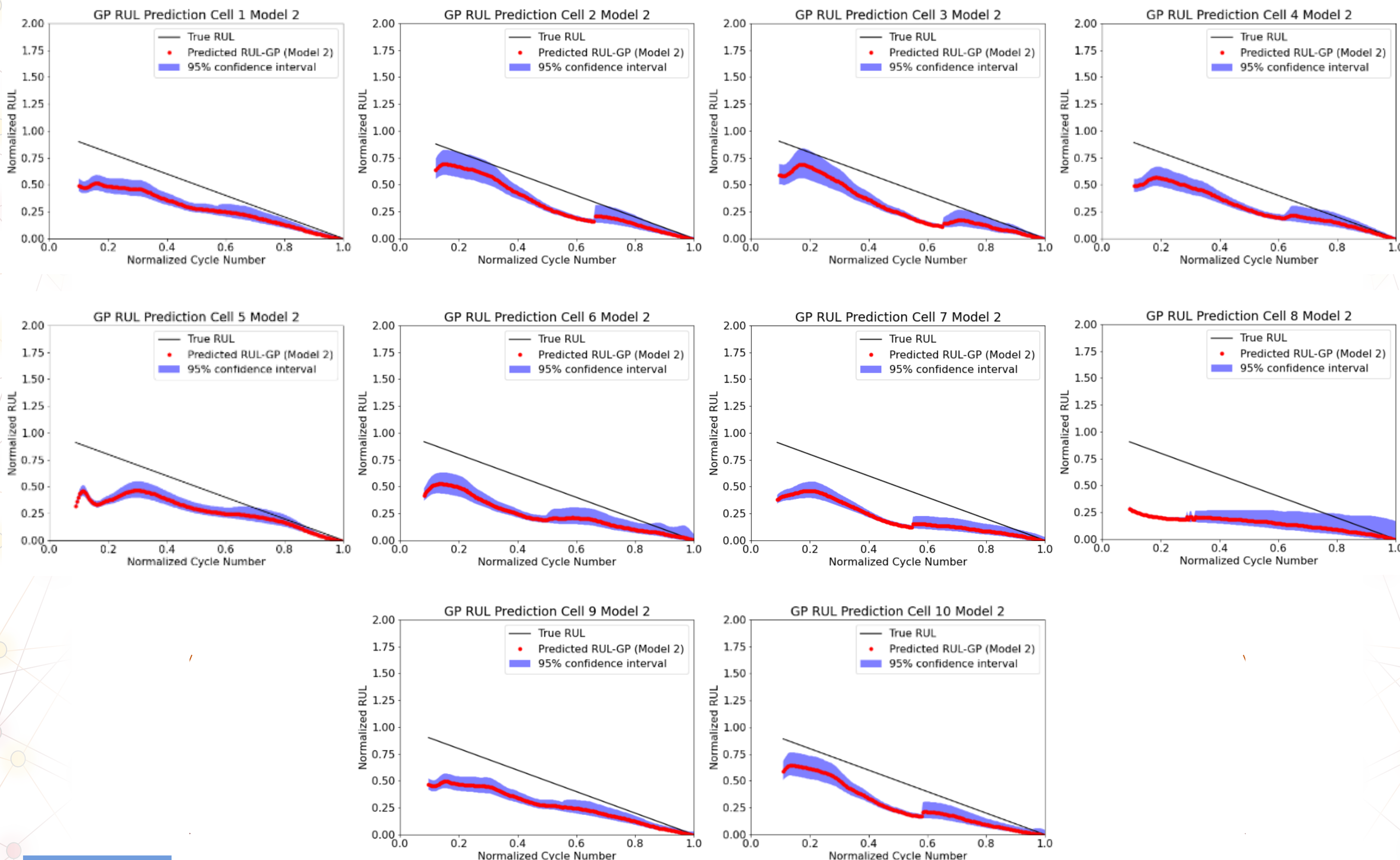


RUL prediction results with GP using Model 1 (left) and Model 2 (right) as the trend functions on Cell 1

Model-Based RUL Prediction with Gaussian Process – Model 1



Model-Based RUL Prediction with Gaussian Process – Model 2



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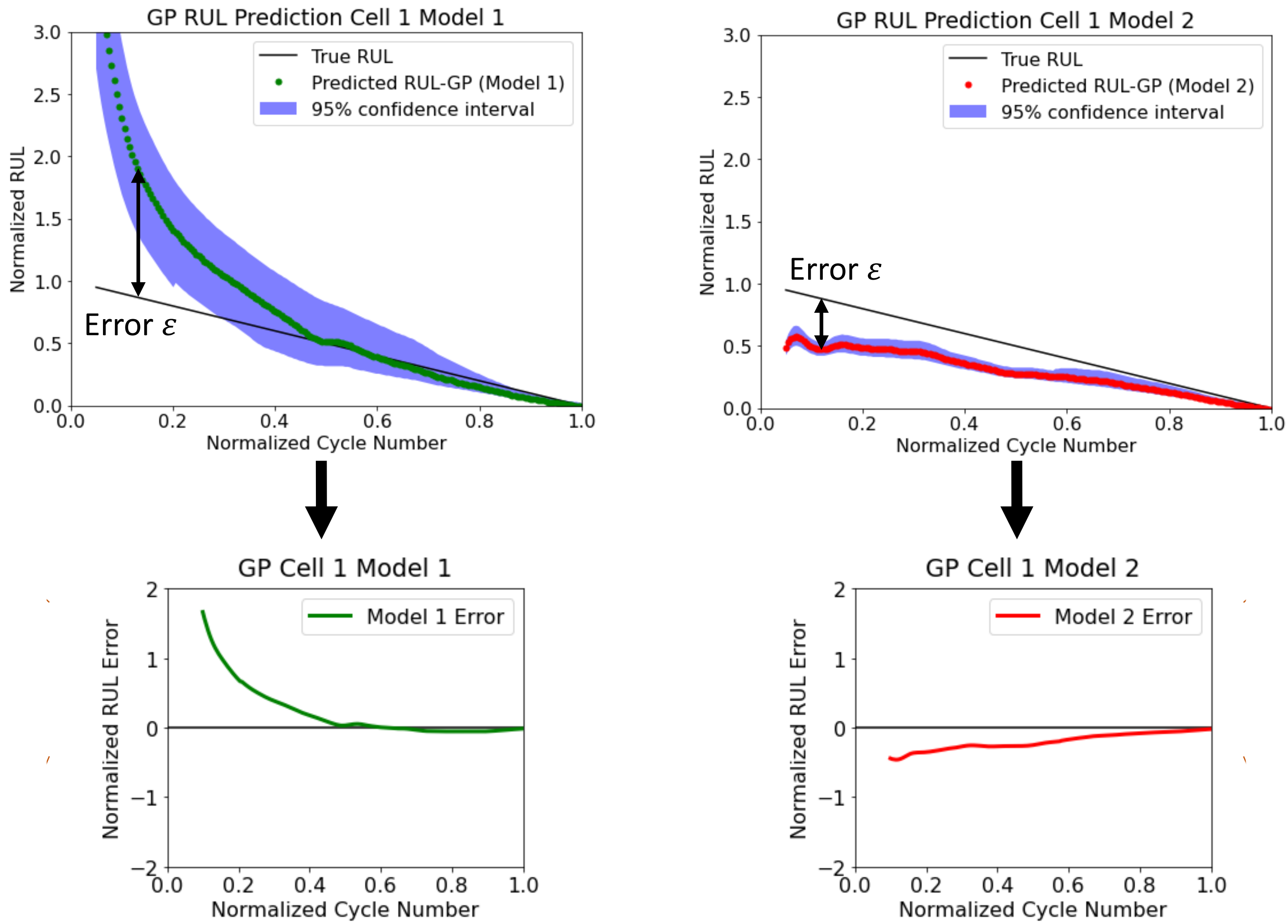
Model-Based RUL Prediction with Gaussian Process – Error



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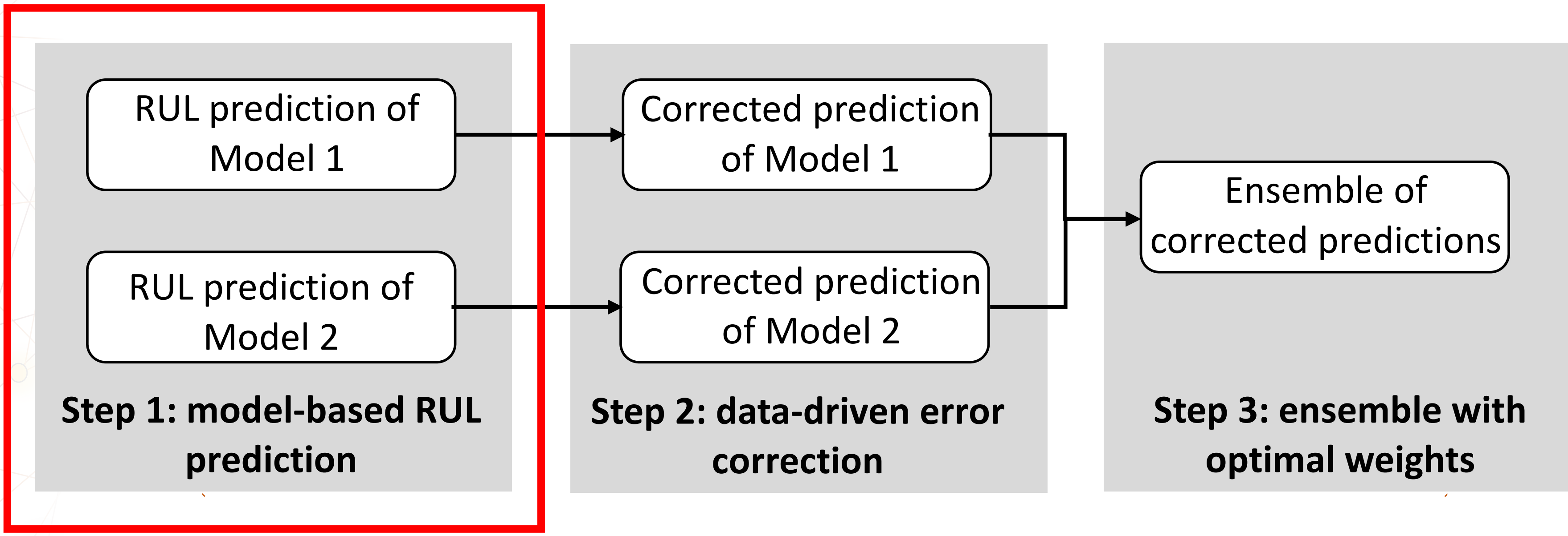
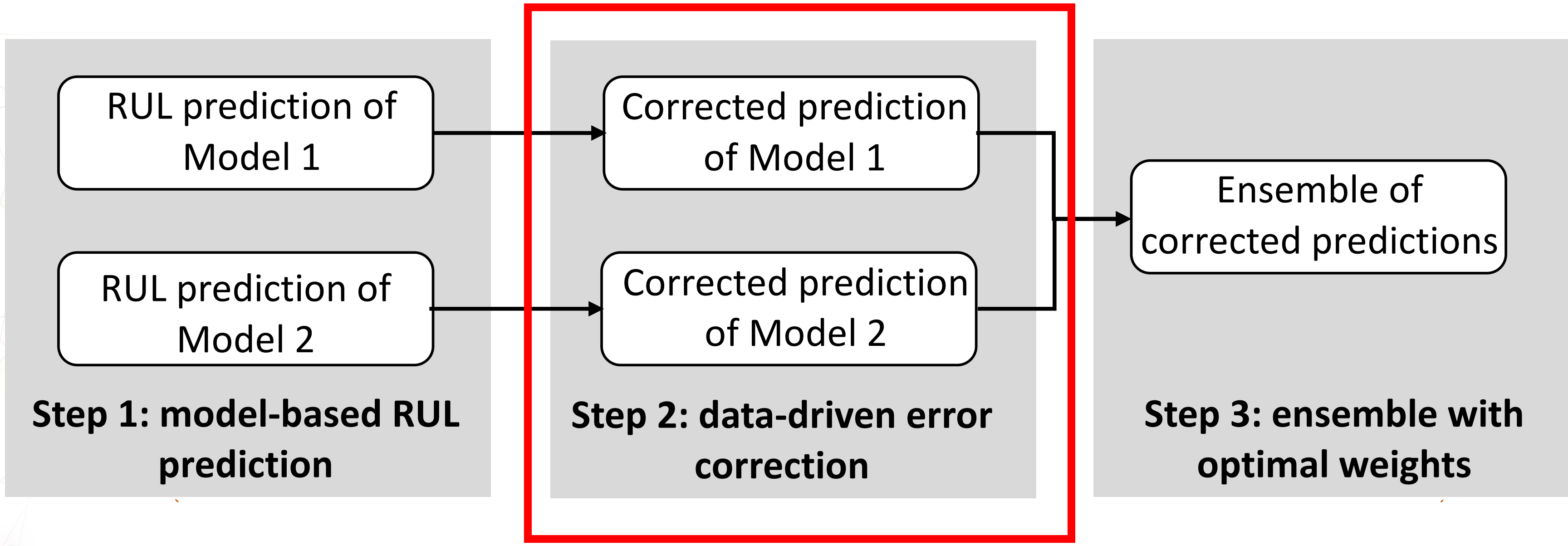
Flowchart of Integrated Model-Based/Data-Driven RUL Prediction Framework



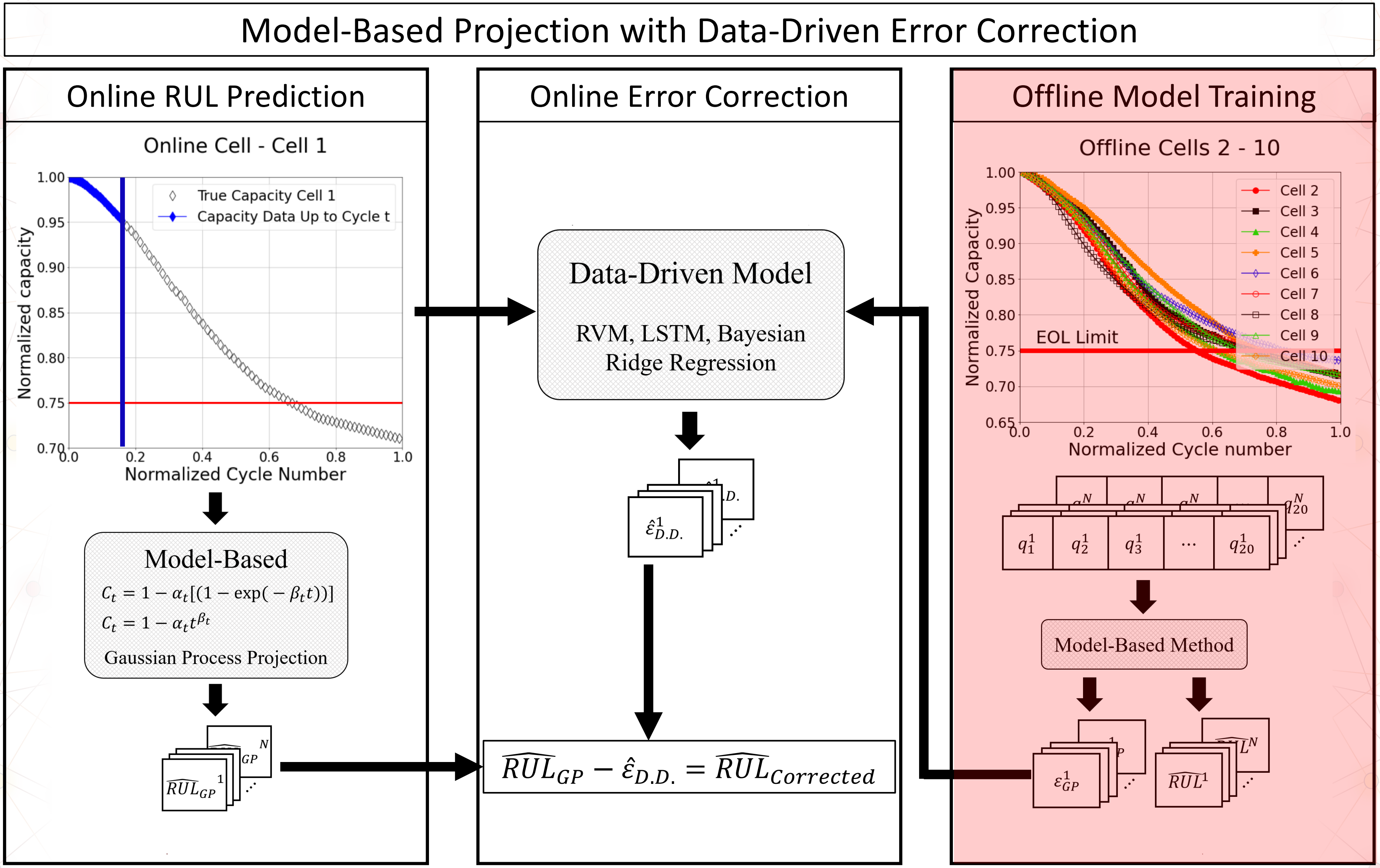
Flowchart of Integrated Model-Based/Data-Driven RUL Prediction Framework



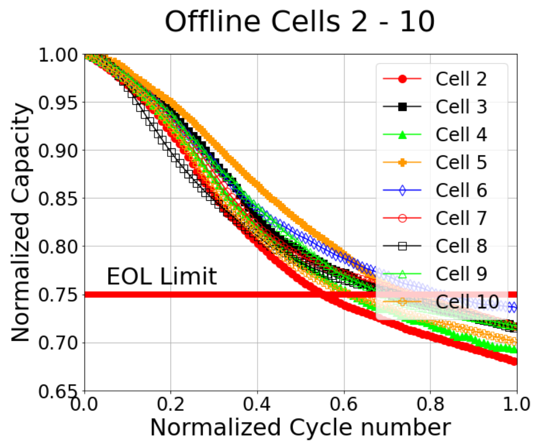
Notes

- Offline data includes the capacity measurements and the true RULs of the offline cells.
  - The data-driven method is trained using the offline data.
- Online data includes the capacity measurements of an online cell up to the current cycle.

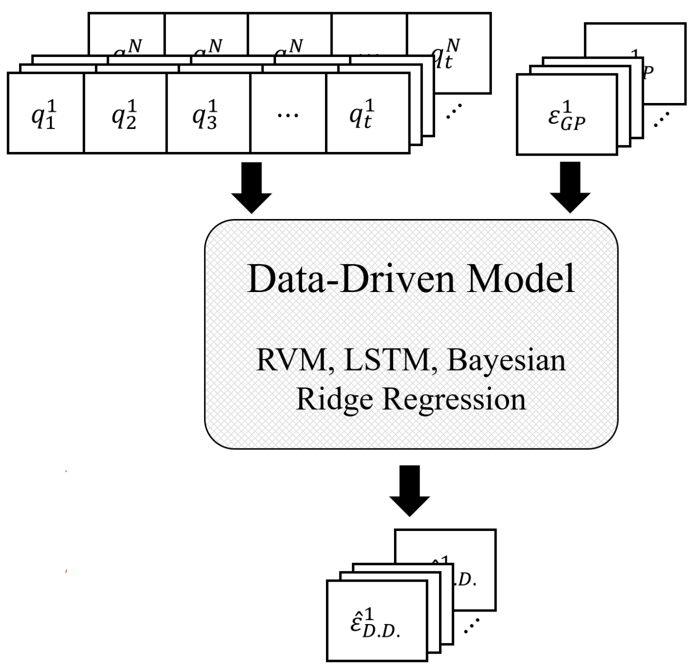
Model-Based/Data-Driven RUL Prediction Method

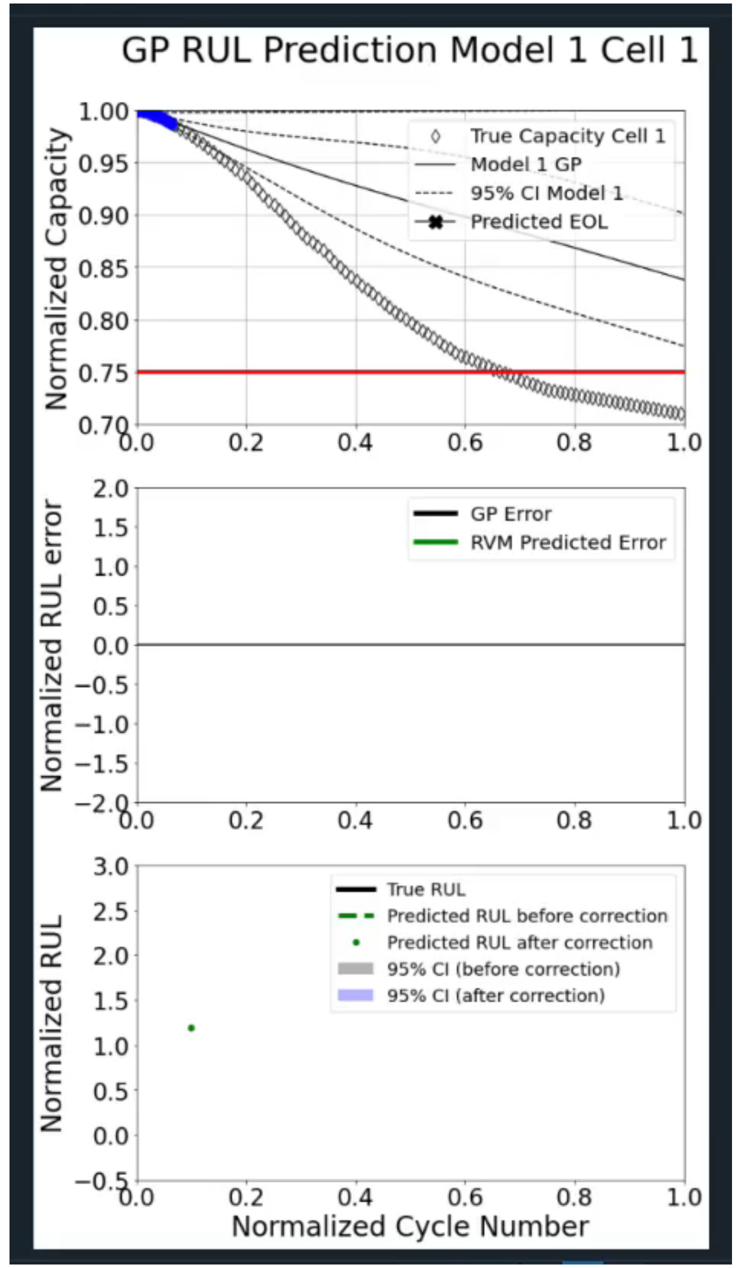


Data-Driven Model – Error Prediction Results



Offline Data-Driven Model Training





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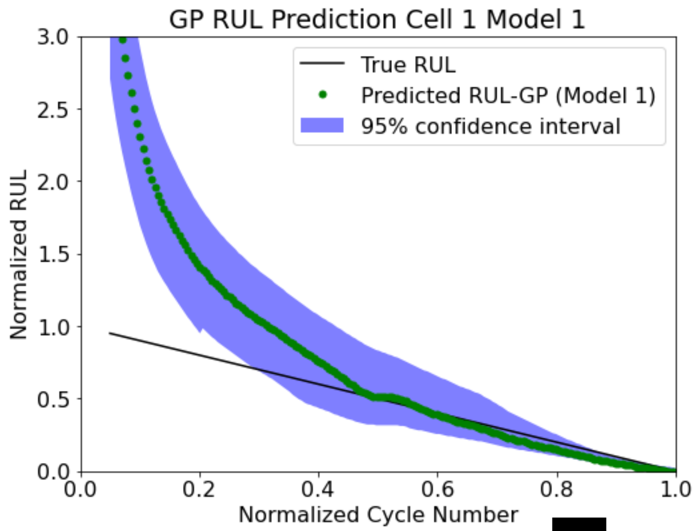
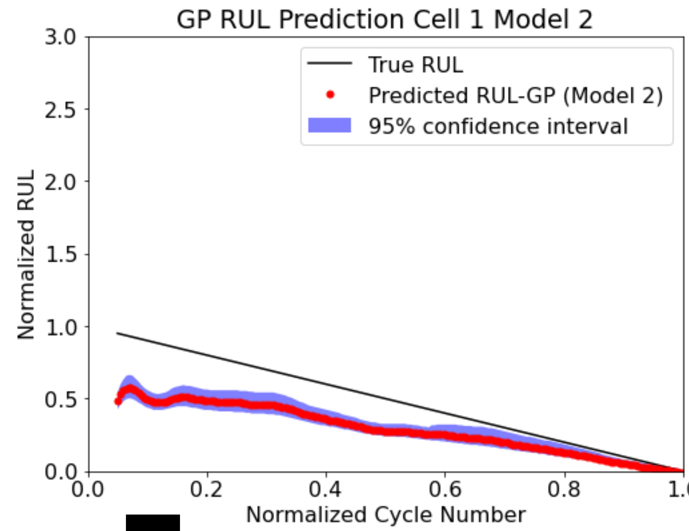
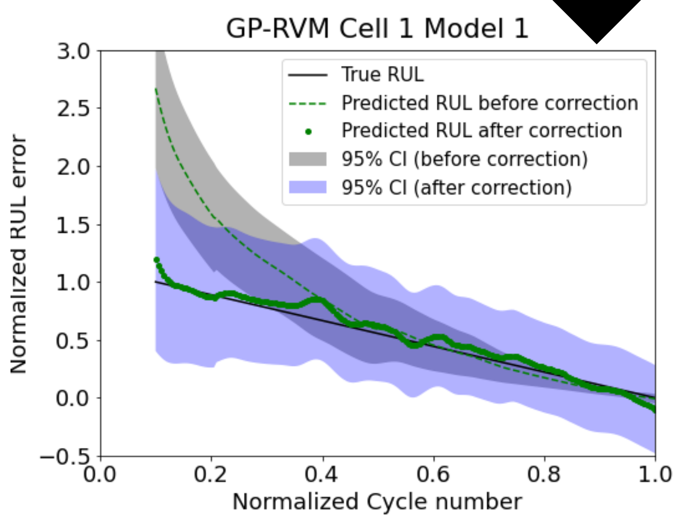
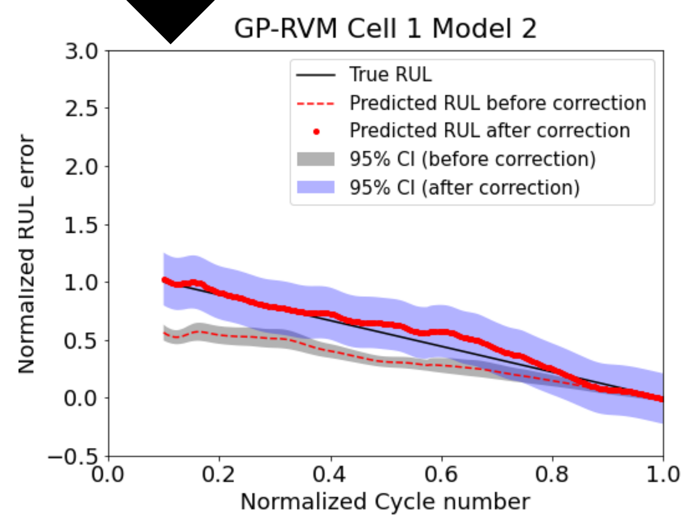
Data-Driven Error Correction Results



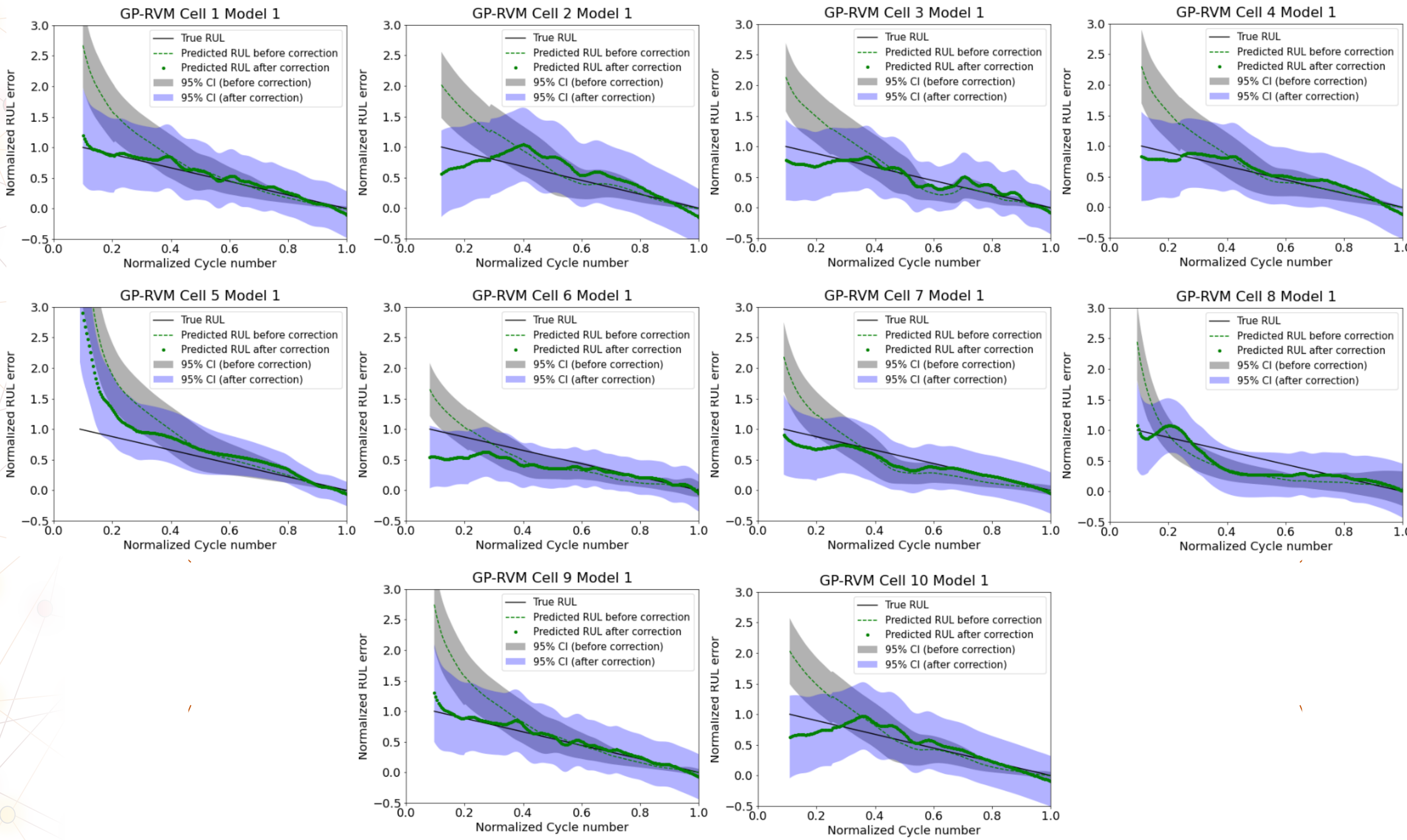


$$\widehat{RUL}_{GP} - \hat{\varepsilon}_{D.D.} = \widehat{RUL}_{Corrected}$$

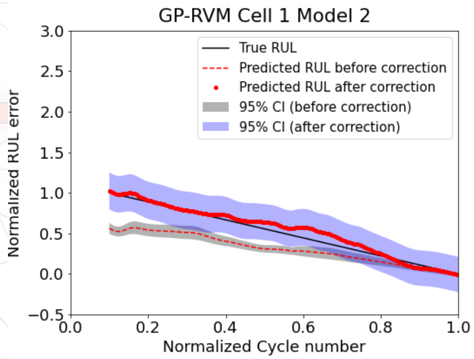


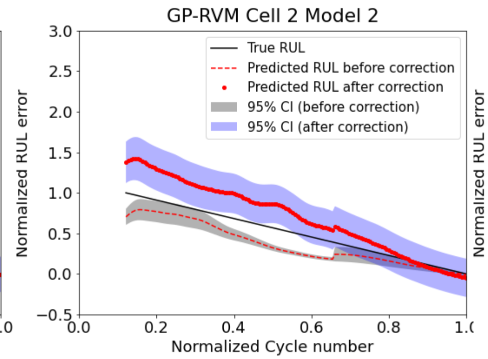


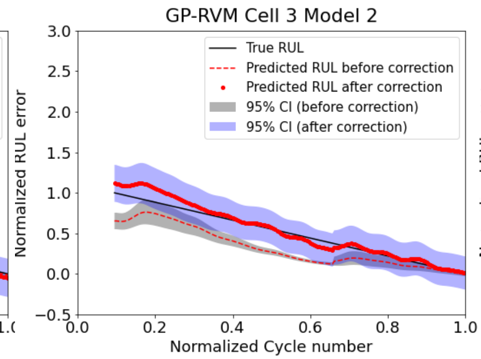
Data-Driven Error Correction Results – Model 1

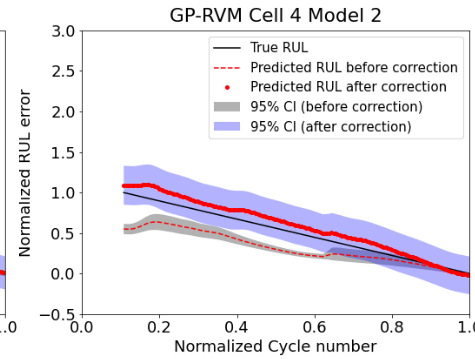


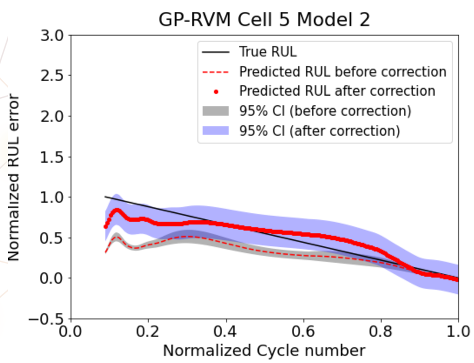
Data-Driven Error Correction Results – Model 2

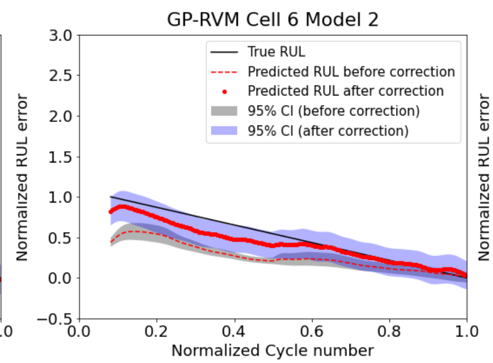


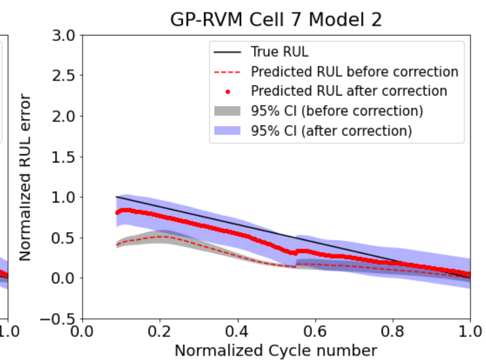


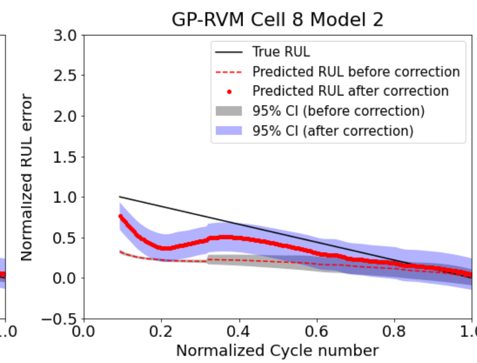


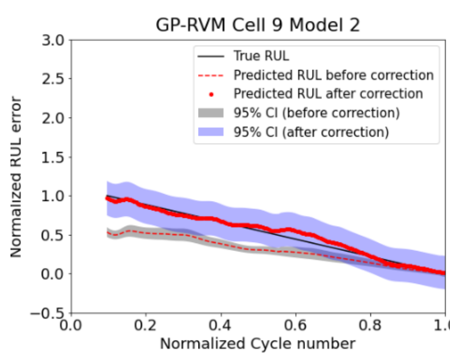


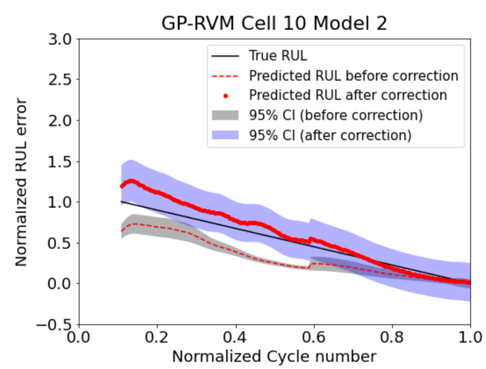












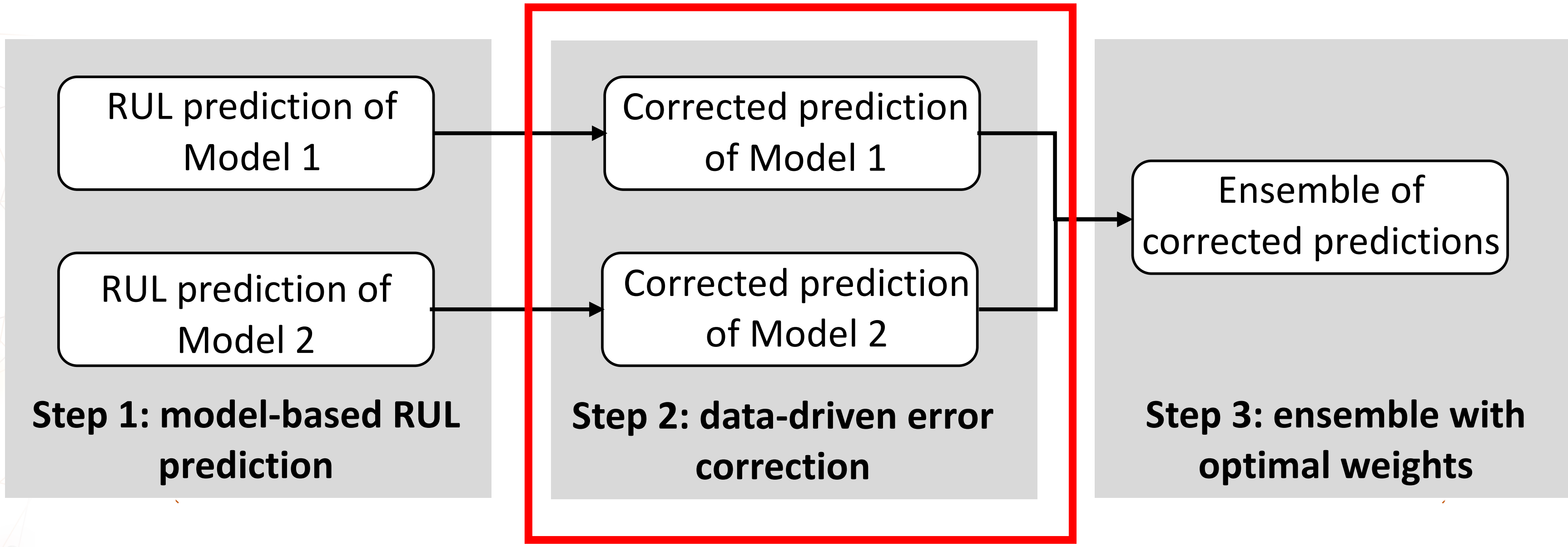
Results for Different Data-Driven Error Correction Methods

- Data-driven error correction improves the overall prediction accuracy
  - Compared to purely model-based projection (GP)

	Method	Cell 1 RMSE	Cell 2 RMSE	Cell 3 RMSE	Cell 4 RMSE	Cell 5 RMSE	Cell 6 RMSE	Cell 7 RMSE	Cell 8 RMSE	Cell 9 RMSE	Cell 10 RMSE	Average RMSE
Model 1	**GP**	77.7	49.8	65.5	59.8	161.3	39.9	59.3	59.3	81.3	52.3	70.6
	GP-LSTM-RMSE	22.9	47.5	20.9	32.4	105.9	42.5	24.8	48.4	36.6	28.1	41.0
	GP-LSTM-KL	42.8	31.3	35.1	18.8	131.0	26.6	27.9	48.4	47.7	15.9	42.6
	GP-LSTM-NLL	36.2	24.1	23.6	18.0	132.1	41.2	26.7	44.3	42.0	16.4	40.5
	GP-RVM	11.8	28.4	22.3	17.4	90.8	44.4	22.2	32.3	11.3	23.0	30.4
	GP-Ridge Regression	22.7	45.1	16.4	23.5	101.7	52.5	28.8	37.1	23.3	26.4	37.7
Model 2	**GP**	40.8	23.3	38.8	35.3	52.8	62.6	63.7	78.4	44.9	34.7	47.5
	GP-LSTM-RMSE	15.2	34.9	20.8	17.2	19.3	21.5	21.8	35.8	10.1	17.9	21.5
	GP-LSTM-KL	21.7	54.3	37.1	36.4	18.3	21.4	24.6	36.5	28.4	38.1	31.7
	GP-LSTM-NLL	15.7	33.9	20.5	18.7	24.1	19.8	22.8	37.5	9.2	17.3	21.9
	GP-RVM	11.2	35.6	14.4	16.3	22.6	23.4	21.9	45.2	8.8	19.8	21.9
	GP-Ridge Regression	11.9	33.5	18.9	17.9	20.1	23.4	23.6	40.6	8.8	19.1	21.8

Color-coded by Cell

Flowchart of Integrated Model-Based/Data-Driven RUL Prediction Framework



Notes

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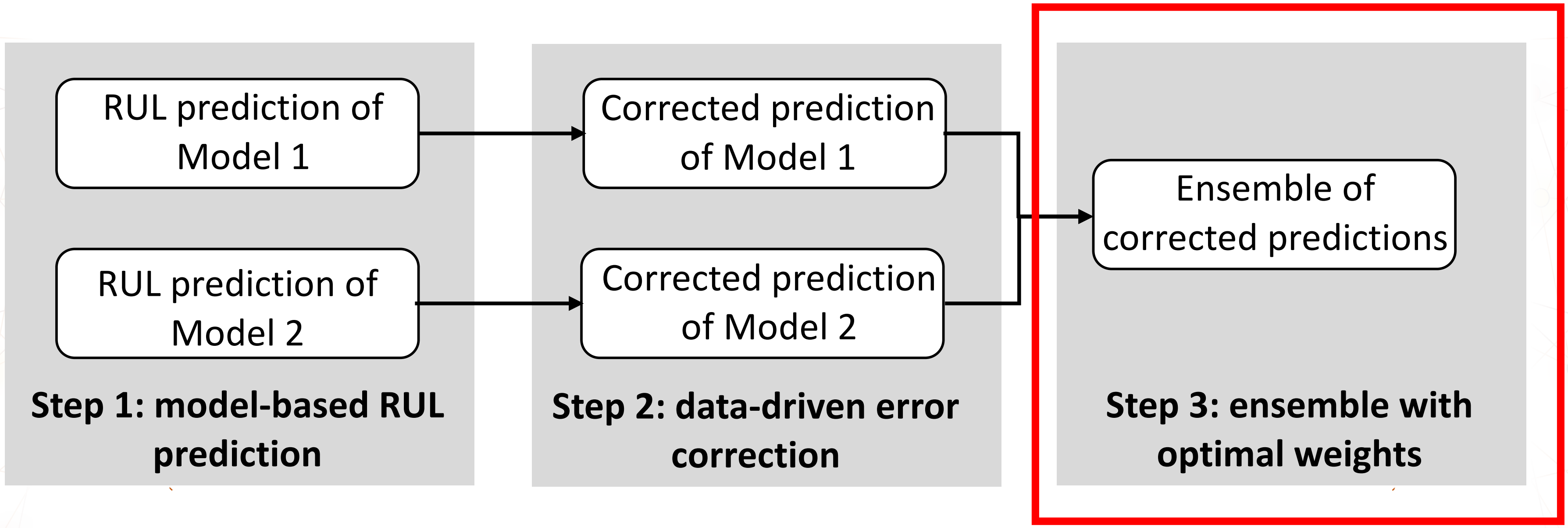

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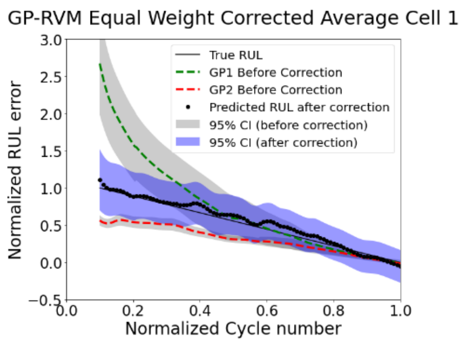
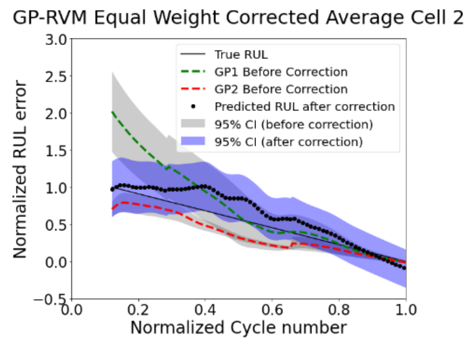
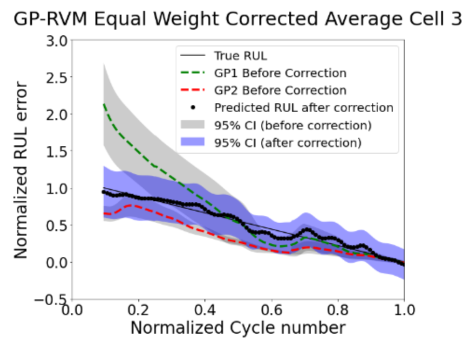
Data-Driven Error Correction Ensemble Methods

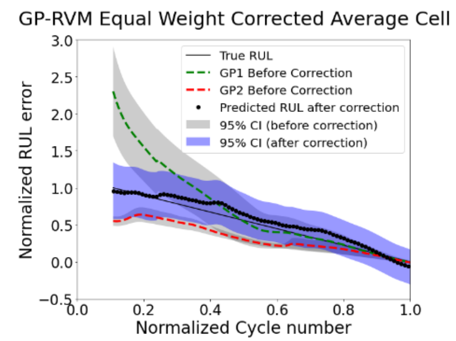
Weighted Average Method
Model 1: $x \sim N(\mu_x, \sigma_x^2)$ Model 2: $y \sim N(\mu_y, \sigma_y^2)$ $\text{Corrected Average} \triangleq \alpha x + (1-\alpha) y$ $= N\left(\alpha\mu_x + (1-\alpha)\mu_y,\ \alpha^2\sigma_x^2 + (1-\alpha)^2\sigma_y^2\right)$ Equal Weight Average: $\alpha = 0.5$ Note: Also investigating optimization-based weighting methods

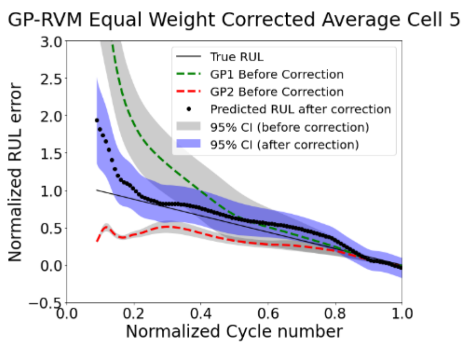
Equal Weight Average of Data-Driven Error Correction – Results

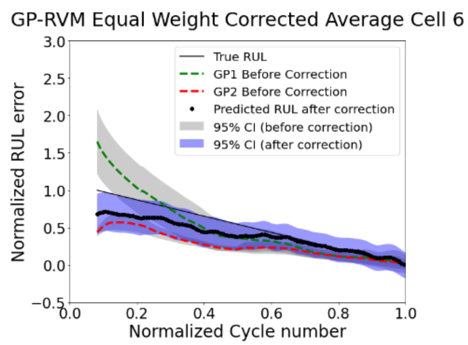


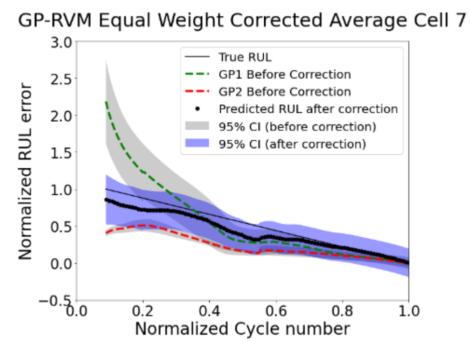


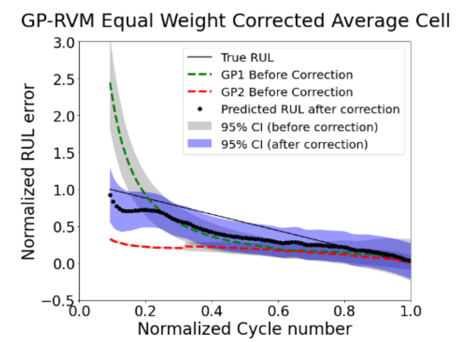


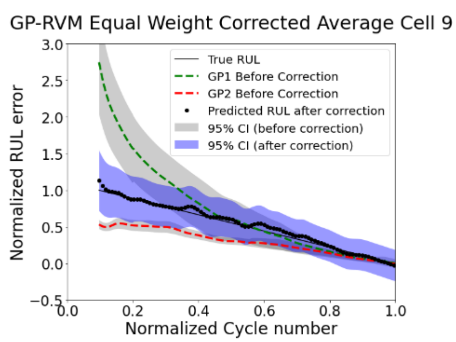


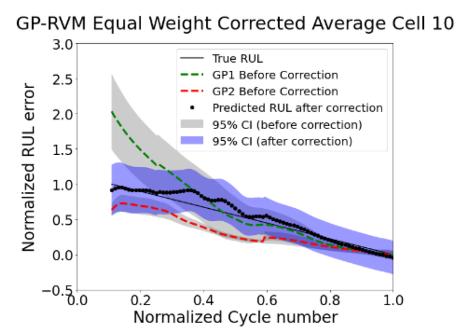












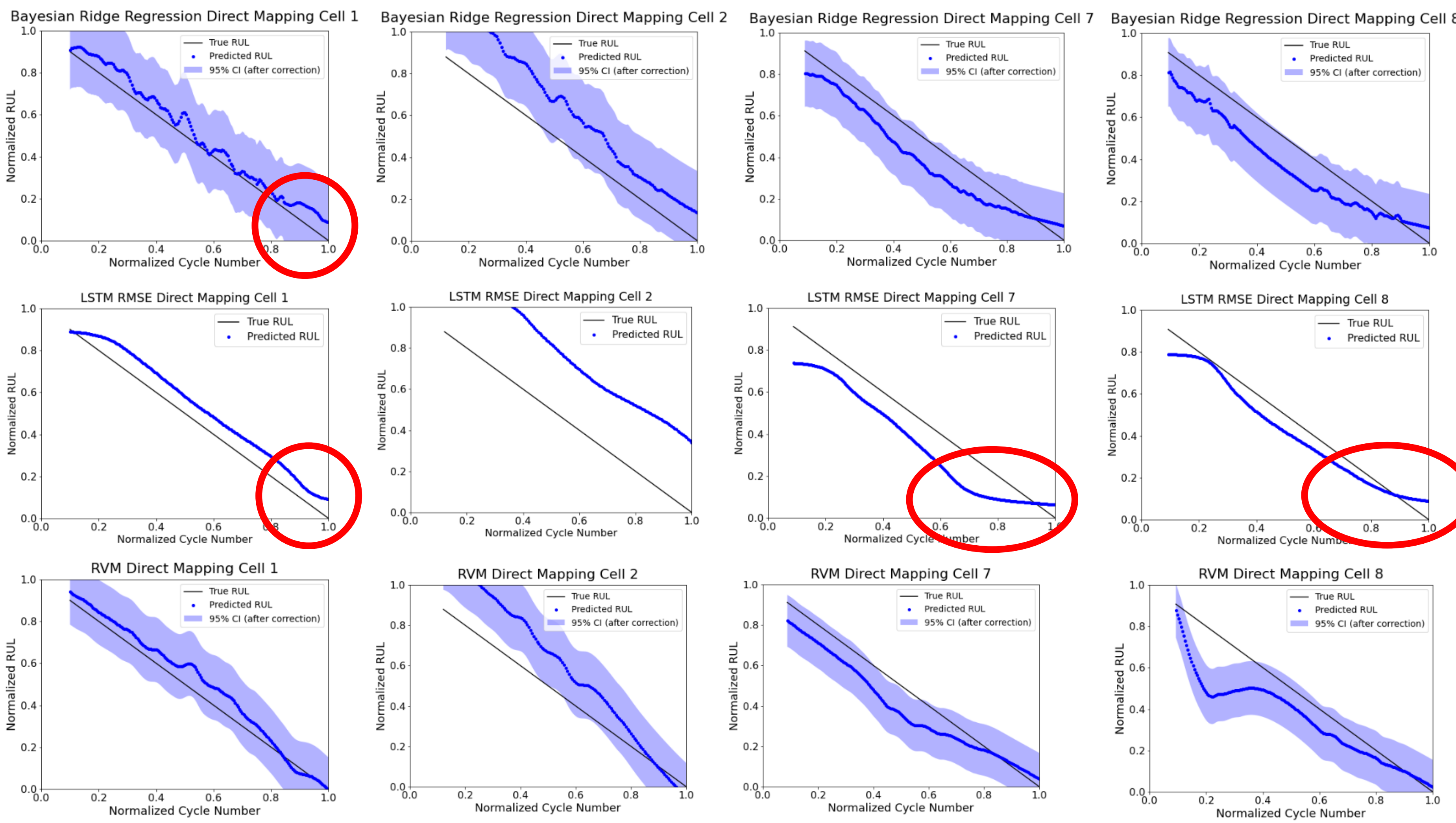
Data-Driven Direct Mapping and Corrected Average Comparison

- The ensemble further improves the accuracy of the error correction.
  - This could be further improved with more models, or weight optimization

	Method	Cell 1 RMSE	Cell 2 RMSE	Cell 3 RMSE	Cell 4 RMSE	Cell 5 RMSE	Cell 6 RMSE	Cell 7 RMSE	Cell 8 RMSE	Cell 9 RMSE	Cell 10 RMSE	Average RMSE
	Direct Map-LSTM	16.3	52.6	9.5	9.8	19.4	33.0	26.6	13.3	9.7	22.6	21.3
	Direct Map-RVM	11.8	28.6	6.8	16.6	13.3	28.1	20.7	30.4	7.9	13.8	17.8
	Direct Map-BRR	11.8	31.7	8.2	18.4	7.9	31.7	21.3	23.8	8.0	16.5	17.9
Model 1	**GP-RVM**	11.8	28.4	22.3	17.4	90.8	44.4	22.2	32.3	11.3	23.0	30.4
Model 2	**GP-RVM**	11.2	35.6	14.4	16.3	22.6	23.4	21.9	45.2	8.8	19.8	21.9
	GP-RVM Ensemble	10.5	25.4	10.7	13.9	40.7	32.8	21.2	30.3	7.8	13.8	20.7

Color-coded by Cell

Data-Driven Direct Mapping and Corrected Average Comparison



Cell 1 | Cell 2 | Cell 7 | Cell 8

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Data-Driven Direct Mapping and Corrected Average Comparison

- Cell 2 RUL prediction performance is poor across the board. . .why?

	Method	Cell 1 RMSE	Cell 2 RMSE	Cell 3 RMSE	Cell 4 RMSE	Cell 5 RMSE	Cell 6 RMSE	Cell 7 RMSE	Cell 8 RMSE	Cell 9 RMSE	Cell 10 RMSE	Average RMSE
Model 1	GP	77.7	49.8	65.5	59.8	161.3	39.9	59.3	59.3	81.3	52.3	70.6
	GP-LSTM-RMSE	22.9	47.5	20.9	32.4	105.9	42.5	24.8	48.4	36.6	28.1	41.0
	GP-LSTM-KL	42.8	31.3	35.1	18.8	131.0	26.6	27.9	48.4	47.7	15.9	42.6
	GP-LSTM-NLL	36.2	24.1	23.6	18.0	132.1	41.2	26.7	44.3	42.0	16.4	40.5
	GP-RVM	11.8	28.4	22.3	17.4	90.8	44.4	22.2	32.3	11.3	23.0	30.4
	GP-Ridge Regression	22.7	45.1	16.4	23.5	101.7	52.5	28.8	37.1	23.3	26.4	37.7
Model 2	GP	40.8	23.3	38.8	35.3	52.8	62.6	63.7	78.4	44.9	34.7	47.5
	GP-LSTM-RMSE	15.2	34.9	20.8	17.2	19.3	21.5	21.8	35.8	10.1	17.9	21.5
	GP-LSTM-KL	21.7	54.3	37.1	36.4	18.3	21.4	24.6	36.5	28.4	38.1	31.7
	GP-LSTM-NLL	15.7	33.9	20.5	18.7	24.1	19.8	22.8	37.5	9.2	17.3	21.9
	GP-RVM	11.2	35.6	14.4	16.3	22.6	23.4	21.9	45.2	8.8	19.8	21.9
	GP-Ridge Regression	11.9	33.5	18.9	17.9	20.1	23.4	23.6	40.6	8.8	19.1	21.8

Color-coded by Cell

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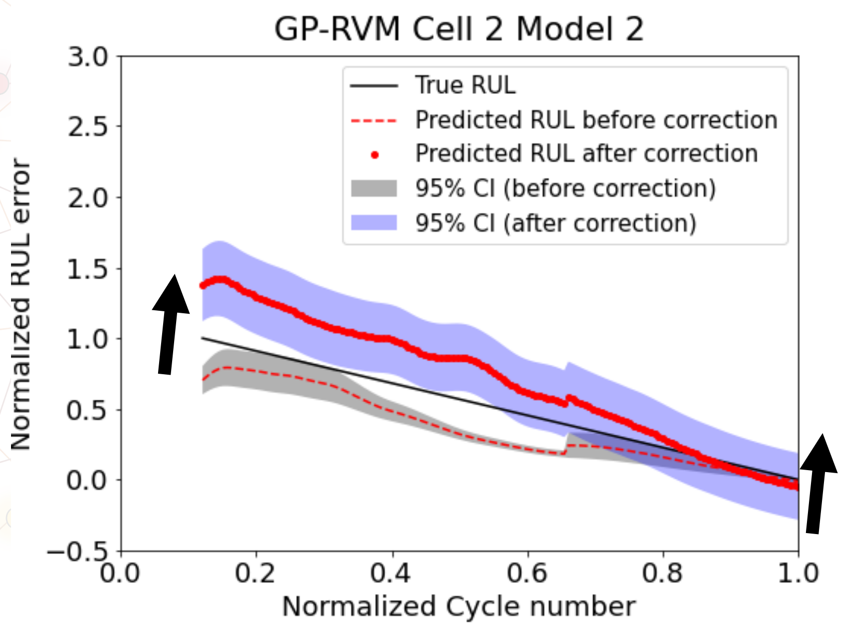
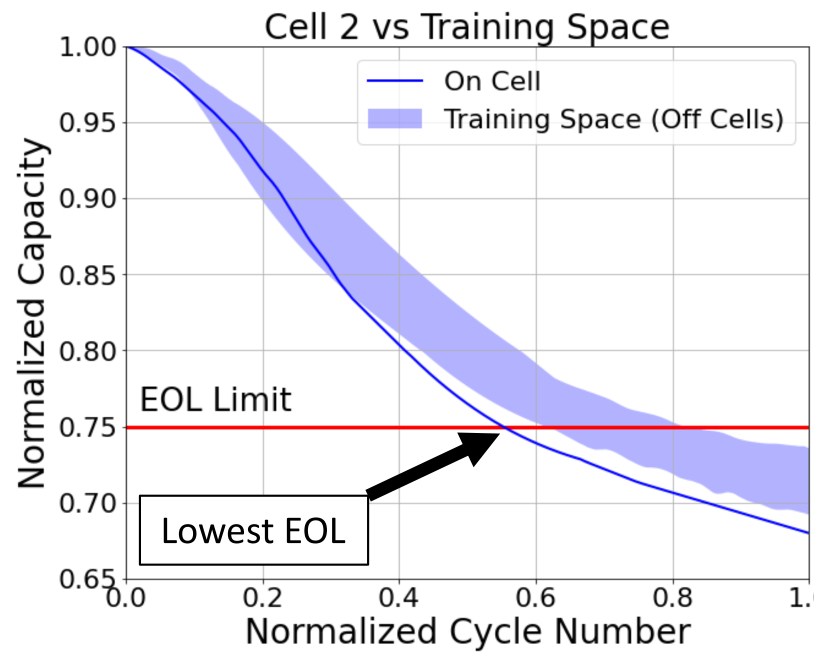
Training Data Investigation: Model 2 Cell 2





Model 2	**GP**	40.8	23.3
	GP-LSTM-RMSE	15.2	34.9
	GP-LSTM-KL	21.7	54.3
	GP-LSTM-NLL	15.7	33.9
	GP-RVM	11.2	35.6
	GP-Ridge Regression	11.9	33.5

- Model 2 Cell 2 RUL prediction is accurate because Model 2 consistently underestimates the EOL.
- The data-driven error correction models train on cells with higher EOL, which causes over-correction.

Conclusions and Future Work

Conclusions

- Using both model-based and data-driven methods allows us to dynamically adjust between the two in the final output.
    - Useful when we know one method will perform better in a certain setting. i.e. end of life convergence.
- An ensemble of models provides increased accuracy.

Future Work

- Develop an algorithm to weigh the error correction based on data-driven model confidence.
    - Examine methods to detect outliers in a dataset (e.g. Cell 2) and quantify their levels of deviation.

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Thank You!

Q/A