EVS32 A world of E MOTION 2019 MAY 19-22

INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION

# Self-adaptive ageing model for Li-ion batteries using Machine Learning methods

ikerlan

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# Content

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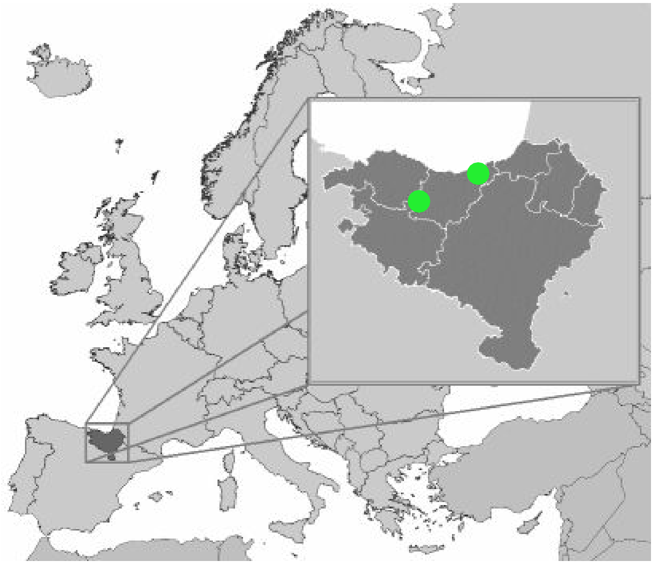
# WHERE TECHNOLOGY IS AN ATTITUDE



## "3 RESEARCH FOCUSES ALIGNED WITH OUR 3 AREAS OF EXPERTISE"

- ENERGY AND POWER ELECTRONICS
- ELECTRONICS, INFORMATION, AND COMMUNICATION TECHNOLOGIES
- ADVANCED MANUFACTURING

TEAM OF **360** PEOPLE

# Context

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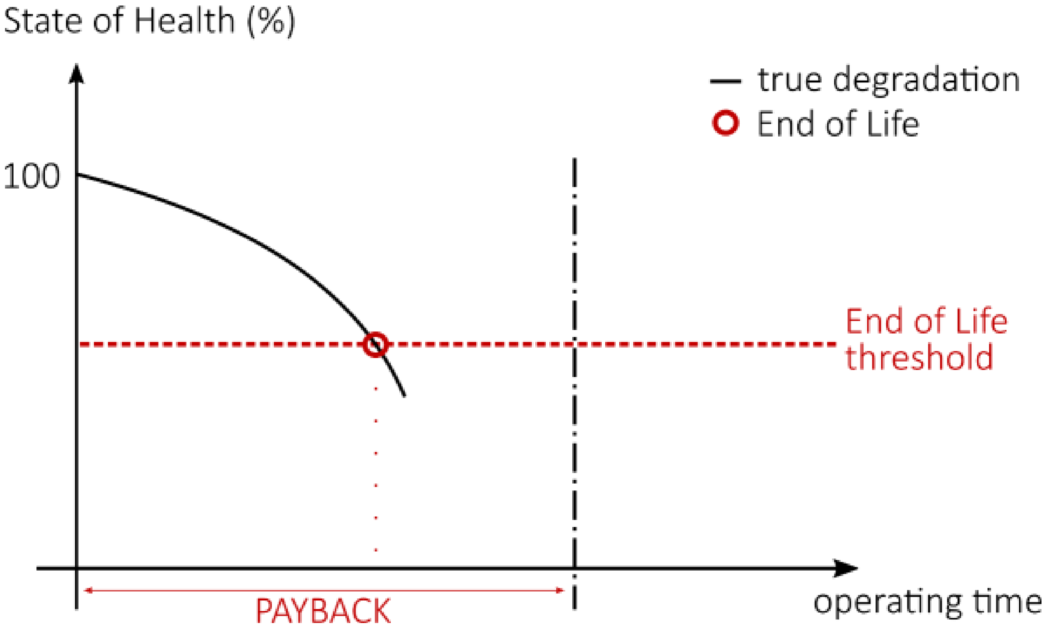
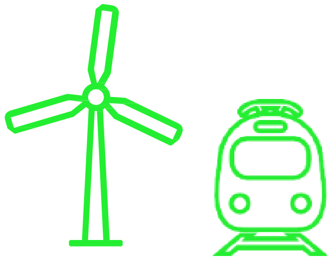
Lithium-ion batteries suffer **capacity loss** and **resistance increase**, due to different **ageing mechanisms**




## Ageing rate depends on the operating conditions



- Temperature
- Depth of Discharge (DOD)
- Middle State of Charge (MidSOC)
- C-rate
  - in charge
  - in discharge

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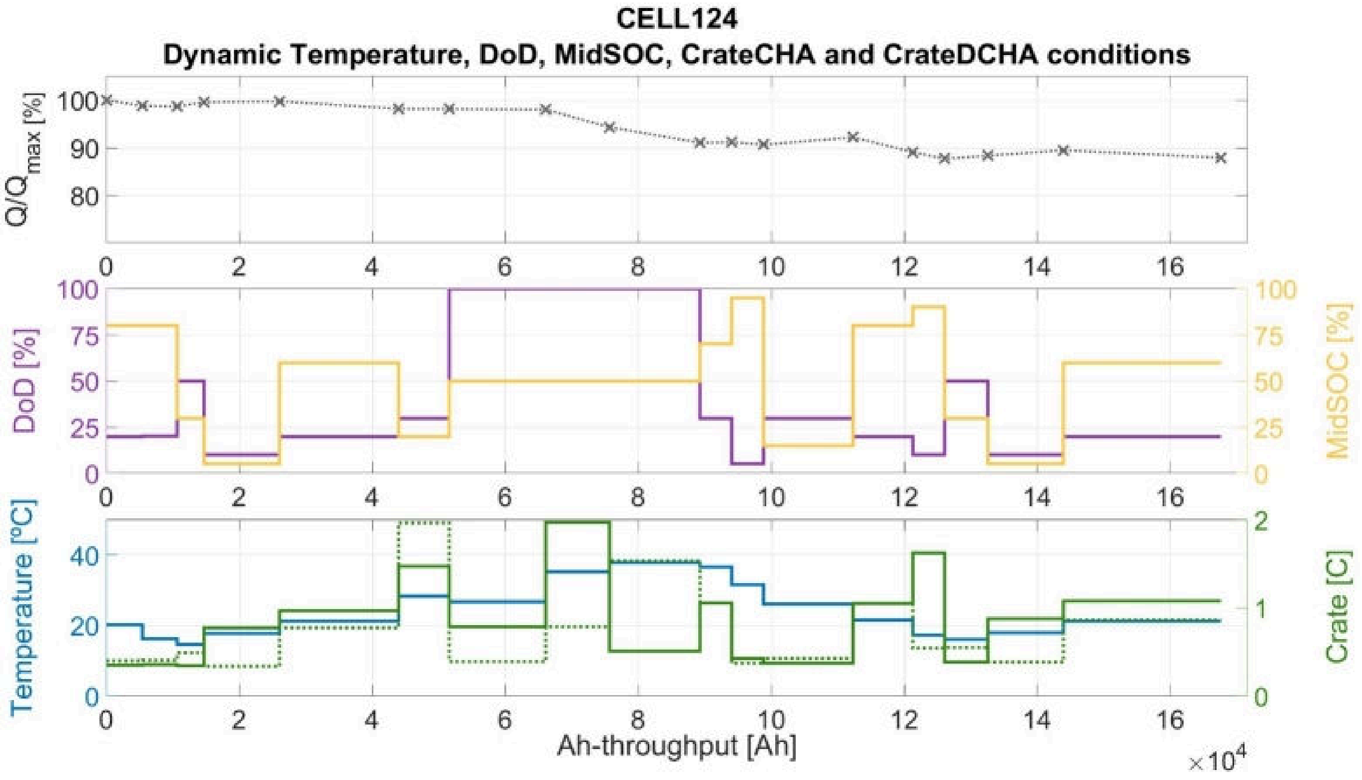
## Common research field

Models able to perform accurate ageing predictions at **dynamic operating conditions**




- Improve system sizing
- Energy management strategies

# Context

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122 cells aged at **static cycle ageing** conditions

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

Ageing data from Batteries 2020 consortium (grant agreement No. 608936)

# Context

- 122 cells aged at **static cycle ageing** conditions
- 30 cells aged at **static calendar ageing** conditions
- 6 cells aged at **dynamic calendar / cycle** ageing conditions
- 8 cells aged with **realistic driving profiles**

- **166 In total**

To develop a (semi-) empirical ageing model, covering a broad window of the operating conditions...

# Context

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- 122 cells aged at **static cycle ageing** conditions
- 30 cells aged at **static calendar ageing** conditions
- 6 cells aged at **dynamic calendar / cycle** ageing conditions
- 8 cells aged with **realistic driving profiles**

- **166 In total**

To develop a (semi-) empirical ageing model, covering a broad window of the operating conditions…

**… for $N_4M_4C_2$ / graphite cells**

# Context



**166 ageing tests!**

- Testing equipment cost
- Scientists' time is expensive


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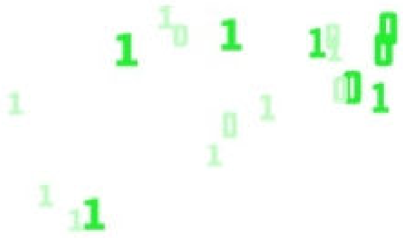
# Context

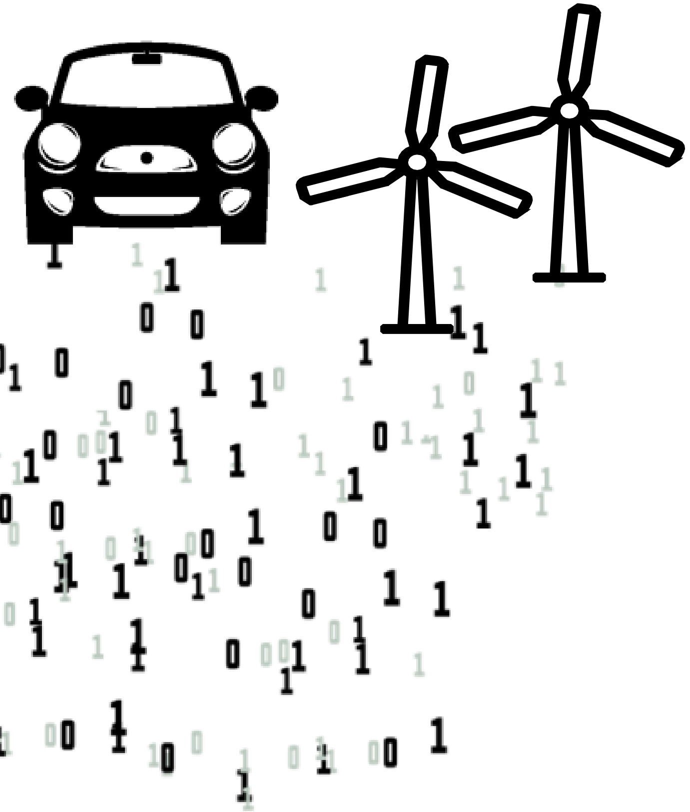
Need to imagine
models requiring
**less laboratory data…**



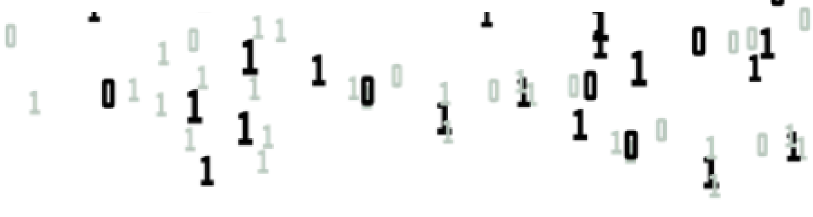
# Context

Need to imagine models requiring **less laboratory data…**

**Digitalisation**
of industry



Forthcoming availability of **huge amount** of real-world battery operation data



# Context

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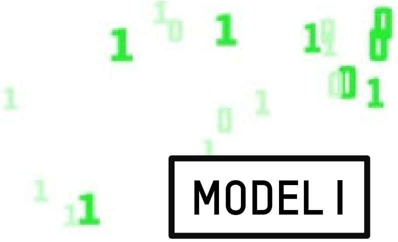
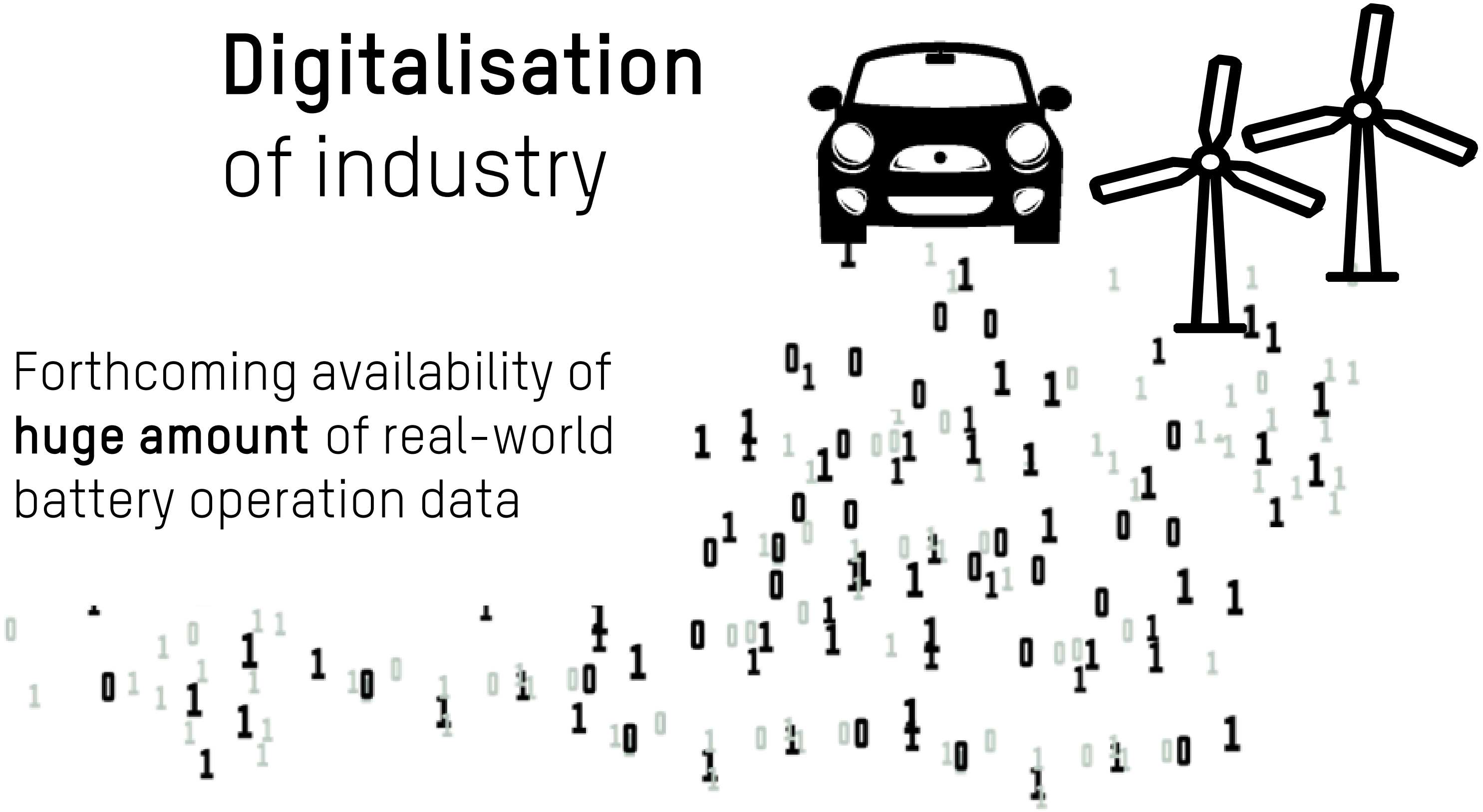
Need to imagine models requiring **less laboratory data…**



MODEL I

- **Generic** model
- **Relatively broad** operating window
- Sufficient accuracy to help in **system sizing**

**Digitalisation**
of industry



Forthcoming availability of **huge amount** of real-world battery operation data

# Context

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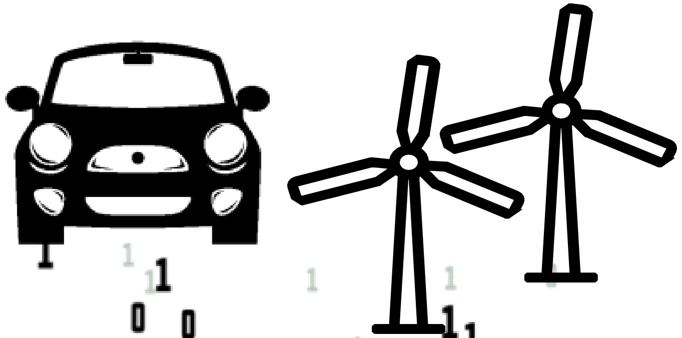
Need to imagine models requiring **less laboratory data…**

**MODEL I**

**Digitalisation** of industry



Forthcoming availability of **huge amount** of real-world battery operation data

**MODEL II**

- **Generic** model
- **Relatively broad** operating window
- Sufficient accuracy to help in **system sizing**

- Higher level of **specialisation**
- **Increasingly broader** operating window
- Improved accuracy
  - **Predictive maintenance**
  - Adaptive **energy management strategies**, etc.

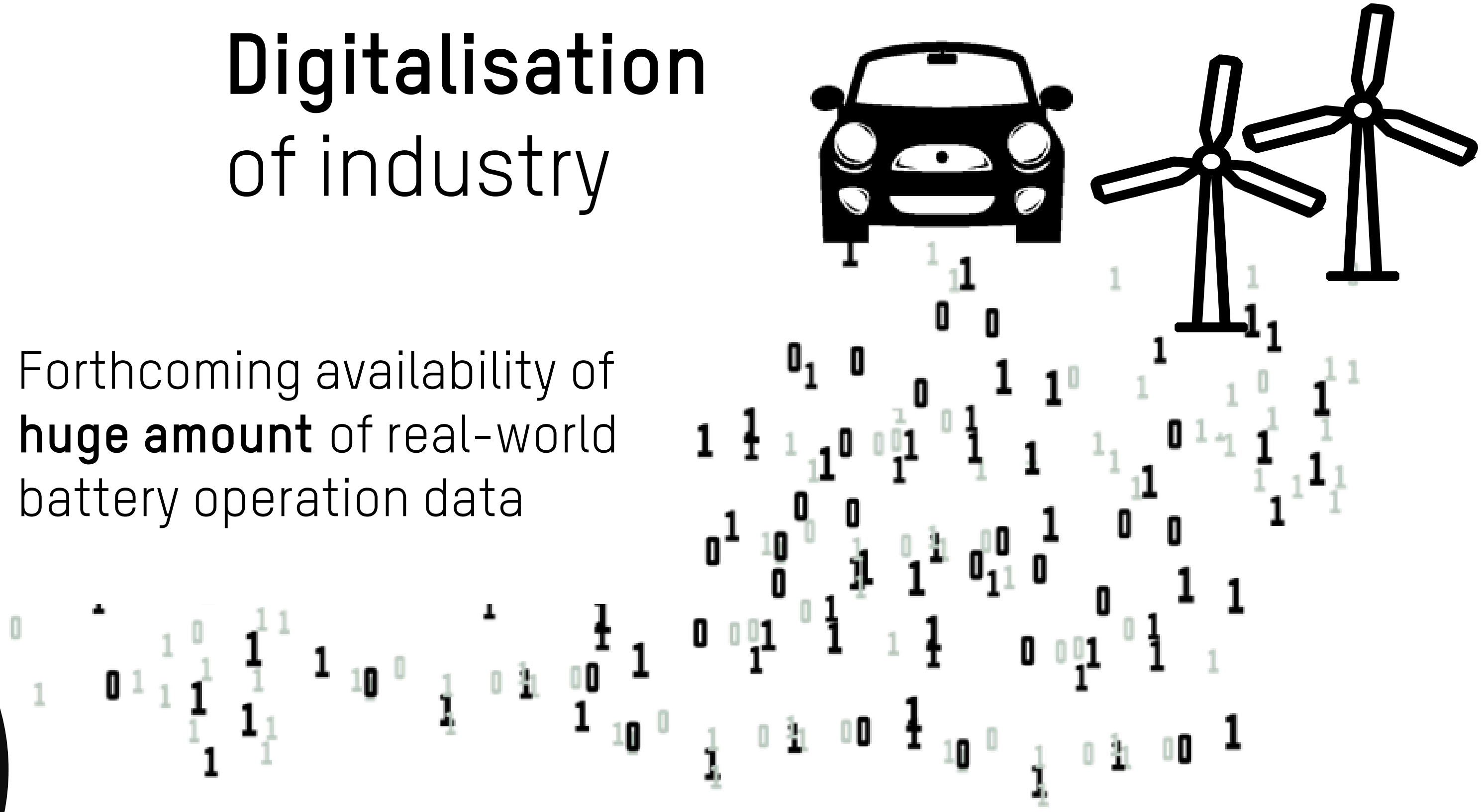
# Context



**Digitalisation**
of industry

Need to imagine models requiring **less laboratory data…**

Forthcoming availability of **huge amount** of real-world battery operation data



# Context

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Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

ELSEVIER

Review article

## A critical review on self-adaptive Li-ion battery ageing models

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[c] ESTIA Research, Ecole Supérieur des Technologies Industrielles Avancées (ESTIA), Technopole Izarbel, 64210 Bidart, France

HIGHLIGHTS

- Self-adaptive Li-ion battery ageing models are reviewed, discussed and classified.
- Specific criteria are defined for accuracy and computational cost assessment.
- Most suitable self-adaptive models for battery ageing prediction are identified.
- Recommendations for self-adaptive ageing models development are provided.

ARTICLE INFO

*Keywords:*
Lithium-ion battery
Lifetime prognosis
State of health
Remaining useful life
Adaptive models
Battery management system

ABSTRACT

The prediction accuracy of Lithium-ion (Li-ion) battery ageing models based on laboratory data is uncertain in the context of online prediction. This is due to the difficulty to reproduce realistic operating profiles in laboratory. The development of self-adaptive ageing models, which are updated using the ageing data obtained in operation, allows enhancing the online prediction accuracy and reducing the required characterisation period in laboratory. At the same time, it offers the possibility to maximise systems' profitability, providing useful information to update the energy management strategy and for predictive maintenance purposes.

The present study aims at reviewing, classifying and comparing the different self-adaptive Li-ion battery ageing models proposed in the literature. Firstly, the different characteristics influencing the ability of a model to update itself are identified, and a classification is proposed for self-adaptive Li-ion battery ageing modelling methods. Secondly, specific criteria are defined to assess and compare the accuracy and computational cost of the different models, enabling a selection of the most suitable ones. Finally, relevant conclusions are drawn considering the key features required to achieve effective ageing predictions, and concise recommendations are suggested for future self-adaptive Li-ion battery ageing model development.

Gaussian Process framework

# Gaussian Process models

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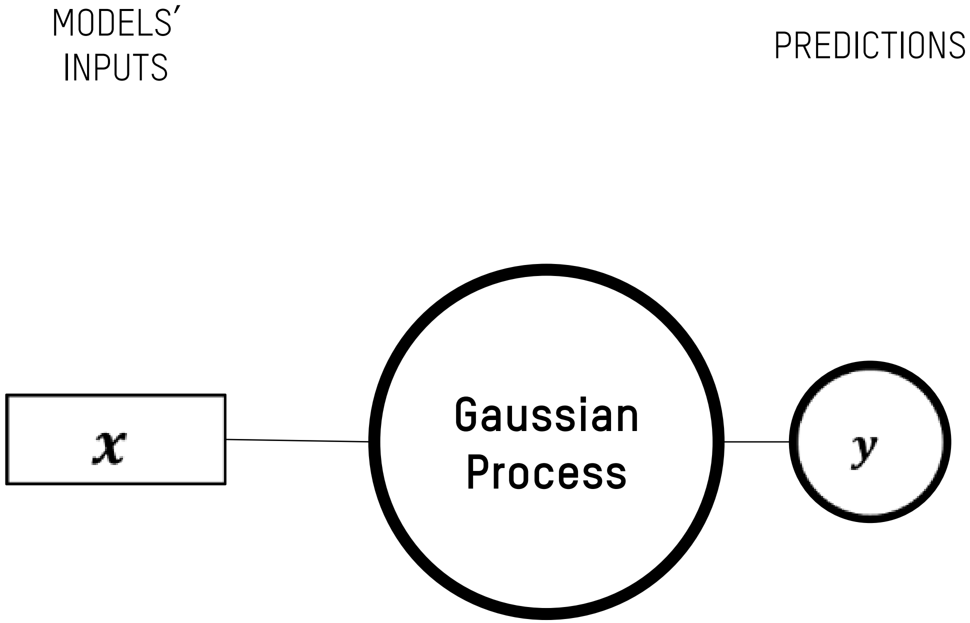
- **Probabilistic**: able to express uncertainty
- **Nonparametric**: high flexibility

REF → Lucu et al. – 2018 – A critical review on self-adaptive Li-ion battery ageing models

# Gaussian Process models

- **Probabilistic**: able to express uncertainty
- **Nonparametric**: high flexibility




GOVERNING EQUATIONS

$$f_*|X, \mathbf{y}, X_* \sim N(\bar{\boldsymbol{f}}_*, cov(\boldsymbol{f}_*))$$

- Mean prediction

$$\bar{\boldsymbol{f}}(\mathbf{x}_*) = \sum_{i=1}^{n} \alpha_i \cdot \kappa(\mathbf{x}_i, \mathbf{x}_*)$$

$$\boldsymbol{\alpha} = (\mathrm{K} + \sigma_n^2 I)^{-1} \cdot \boldsymbol{y}$$

- Confidence boundaries

$$cov(f_*) = K(X_*, X_*) - K(X_*, X)[K(X, X) + \sigma_n^2 I]^{-1} K(X, X_*)$$

Composed of:

- Mean function
- Kernel function

REF
→ Lucu et al. – 2018 – A critical review on self-adaptive Li-ion battery ageing models
→ Rasmussen and Williams – 2006 – Gaussian Processes for Machine Learning

# Modelling Li-ion battery ageing

- Inputs and outputs

- **Probabilistic**: able to express uncertainty
- **Nonparametric**: high flexibility

GOVERNING EQUATIONS

$$f_*|X, \boldsymbol{y}, X_* \sim N(\bar{\boldsymbol{f}}_*, cov(\boldsymbol{f}_*))$$

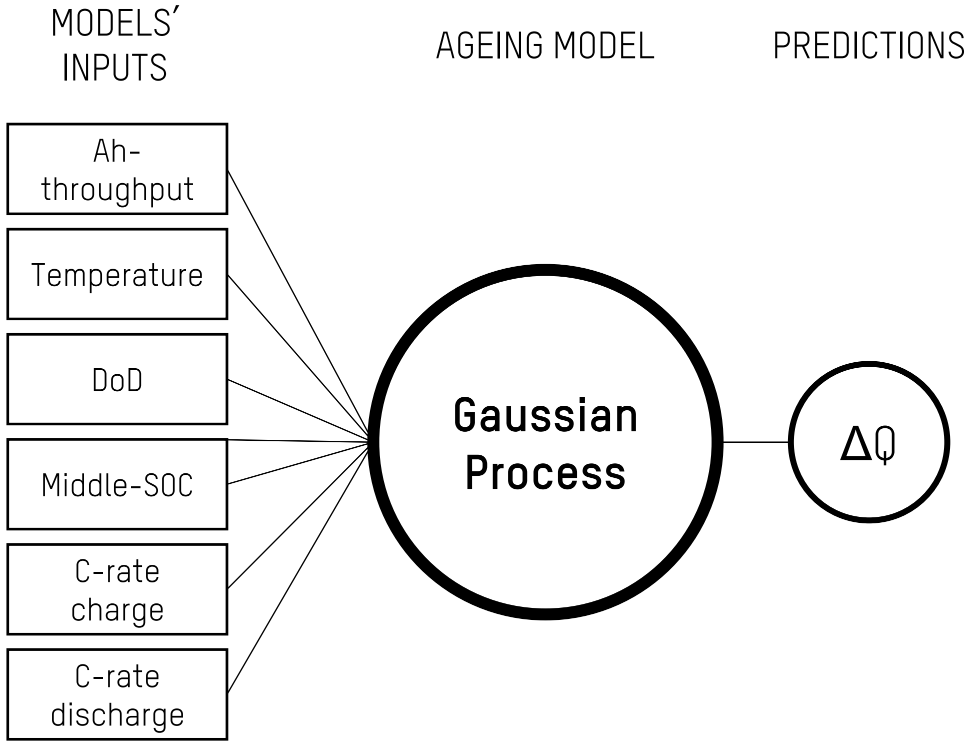
- Mean prediction

$$\bar{\boldsymbol{f}}(\mathbf{x}_*) = \sum_{i=1}^{n} \alpha_i \cdot \kappa(\mathbf{x}_i, \mathbf{x}_*)$$

$$\boldsymbol{\alpha} = (\mathrm{K} + \sigma_n^2 I)^{-1} \cdot \boldsymbol{y}$$

- Confidence boundaries

$$cov(f_*) = K(X_*, X_*) - K(X_*, X)[K(X, X) + \sigma_n^2 I]^{-1} K(X, X_*)$$




- Zero-mean function
- Compositional kernel function

# Modelling Li-ion battery ageing

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## GOAL 1

- Quantify the minimum number of required training data
- **Learning from static** ageing conditions

## GOAL 2

- **Validation at dynamic** ageing conditions
- **Learning from dynamic** ageing conditions

# Modelling Li-ion battery ageing

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## GOAL 1

- Quantify the minimum number of required training data
- **Learning from static** ageing conditions

## GOAL 2

- **Validation at dynamic** ageing conditions
- **Learning from dynamic** ageing conditions

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Training data / Total data [%] | TRAINING CASE |
|---|---|
| 8% | CASE 1 |
| 10% | CASE 2 |
| 15% | CASE 3 |
| 21% | CASE 4 |
| 37% | CASE 5 |
| 60% | CASE 6 |
| 64% | CASE 7 |
| 71% | CASE 8 |
| 74% | CASE 9 |
| 78% | CASE 10 |
| 80% | CASE 11 |
| 81% | CASE 12 |
| 92% | CASE 13 |
| 94% | CASE 14 |
| 98% | CASE 15 |
| 100% | CASE 16 |

## Cycle ageing matrix

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35°C | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25°C | 8% | CASE 1 |
| | 45°C | | |
| | | | |

## TRAINING CASE 1

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35°C | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |

## TRAINING CASE 2

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25°C | 8% | CASE 1 |
| | 45°C | | |
| | 35°C | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | | | |
| | | | |
| | | | |
| | | | |

## TRAINING CASE 3

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35°C | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | | | |
| | | | |
| | | | |

## TRAINING CASE 4

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | | | |
| | | | |

## TRAINING CASE 5

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | | | |

## TRAINING CASE 6

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |

## TRAINING CASE 7

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | | | |
| | | | |
| | | | |

## TRAINING CASE 8

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | | | |
| | | | |

## TRAINING CASE 9

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | | | |

## TRAINING CASE 10

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |

## TRAINING CASE 11

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25°C | 8% | CASE 1 |
| | 45°C | | |
| | 35°C | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | | | |
| | | | |

## TRAINING CASE 12

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35°C | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | 1C | 92% | CASE 13 |
| | | | |

## TRAINING CASE 13

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | 1C | 92% | CASE 13 |
| | 0.5C | 94% | CASE 14 |

## TRAINING CASE 14

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35ºC | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45ºC | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25°C | 8% | CASE 1 |
| | 45°C | | |
| | 35°C | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | 1C | 92% | CASE 13 |
| | 0.5C | 94% | CASE 14 |
| Discharging C-rate | 2C | 98% | CASE 15 |
| | | | |

## TRAINING CASE 15

| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35°C | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

## - GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25°C | 8% | CASE 1 |
| | 45°C | | |
| | 35°C | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | 1C | 92% | CASE 13 |
| | 0.5C | 94% | CASE 14 |
| Discharging C-rate | 2C | 98% | CASE 15 |
| | 0.3C | 100% | CASE 16 |

### TRAINING CASE 16

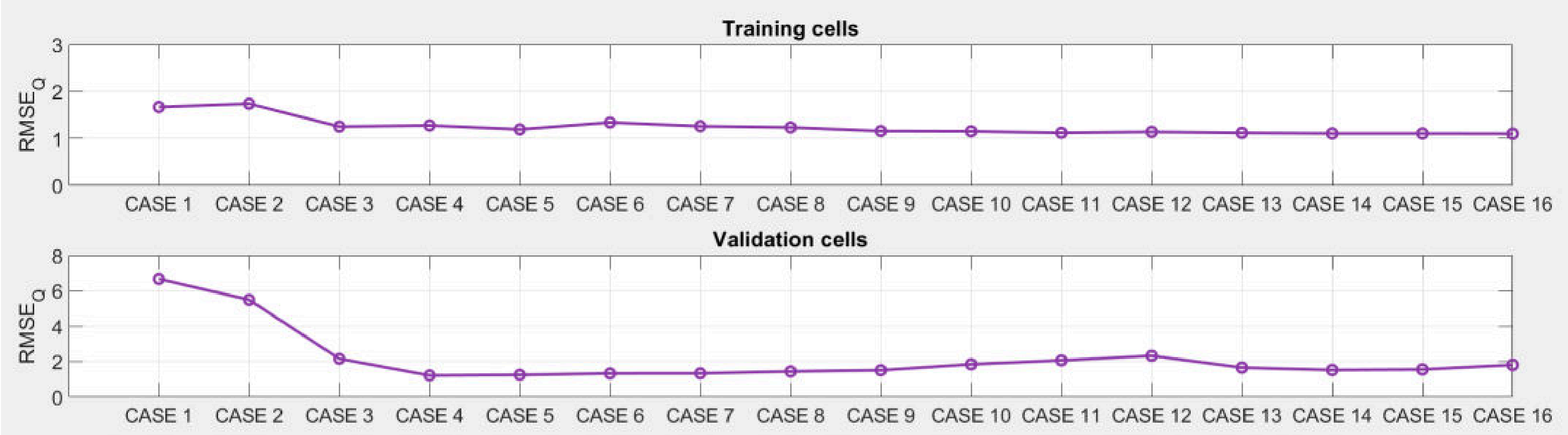
| DOD | | 100% | 80% | 65% | 50% | | | 35% | 20% | | | | | 10% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mid.SOC | | 50% | 50% | 50% | 65% | 50% | 35% | 50% | 80% | 65% | 50% | 35% | 20% | 80% | 65% | 20% |
| Temp. | Crate | | | | | | | | | | | | | | | |
| 25°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |
| | 1C-1C | | X | | | | | | | | | | | | | |
| 35°C | C/3 – C/3 | | X | | | | | | | | | | | | | |
| | C/3 – 1C | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | C/3 – 2C | | X | | | | | | | | | | | | | |
| | C/2 – 1C | | X | | | | | | | | | | | | | |
| | 1C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 1C | | X | | | | | | | | | | | | | |
| | 2C – 2C | | X | | | | | | | | | | | | | |
| 45°C | C/3 – 1C | X | X | X | | X | | X | | | X | | | | | |

# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | 1C | 92% | CASE 13 |
| | 0.5C | 94% | CASE 14 |
| Discharging C-rate | 2C | 98% | CASE 15 |
| | 0.3C | 100% | CASE 16 |

Mean of the prediction errors



# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

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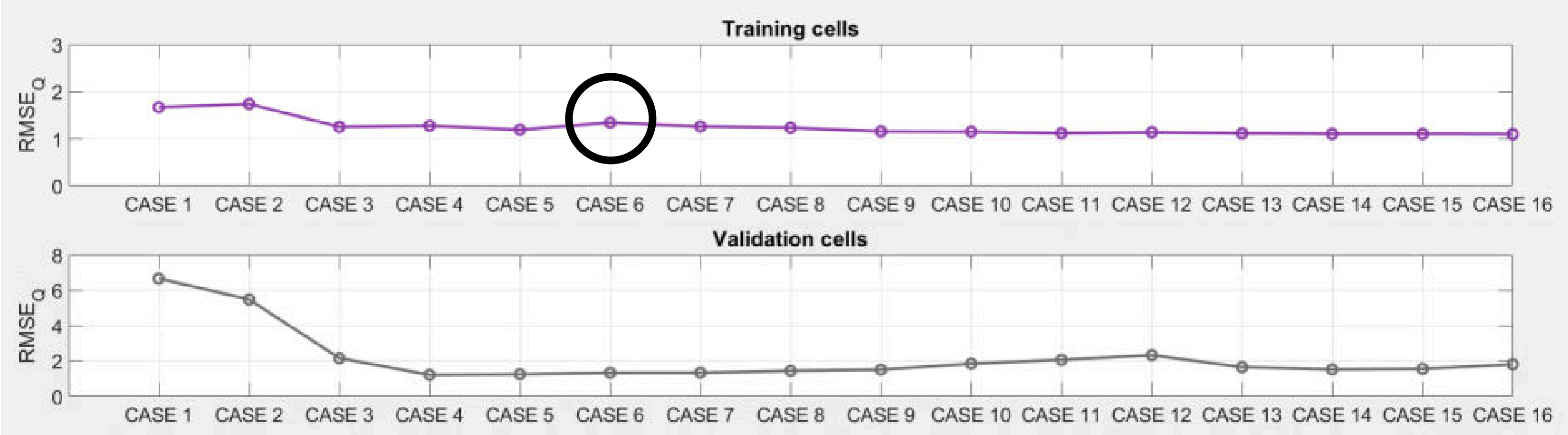
Mean of the prediction errors

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25°C | 8% | CASE 1 |
| | 45°C | | |
| | 35°C | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | 1C | 92% | CASE 13 |
| | 0.5C | 94% | CASE 14 |
| Discharging C-rate | 2C | 98% | CASE 15 |
| | 0.3C | 100% | CASE 16 |

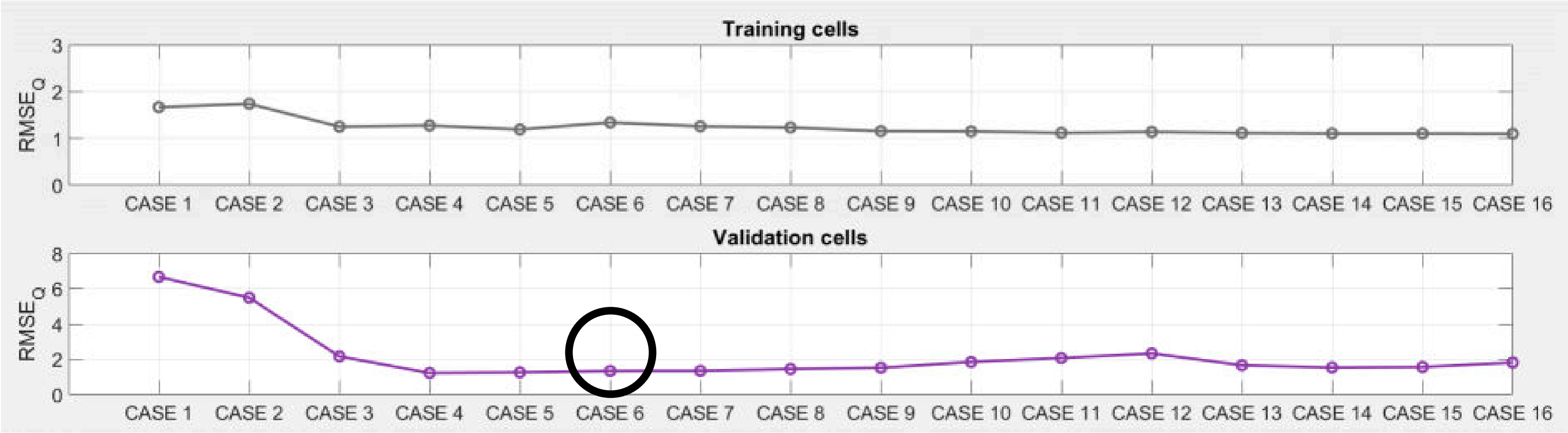


# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25ºC | 8% | CASE 1 |
| | 45ºC | | |
| | 35ºC | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | 1C | 92% | CASE 13 |
| | 0.5C | 94% | CASE 14 |
| Discharging C-rate | 2C | 98% | CASE 15 |
| | 0.3C | 100% | CASE 16 |

Mean of the prediction errors

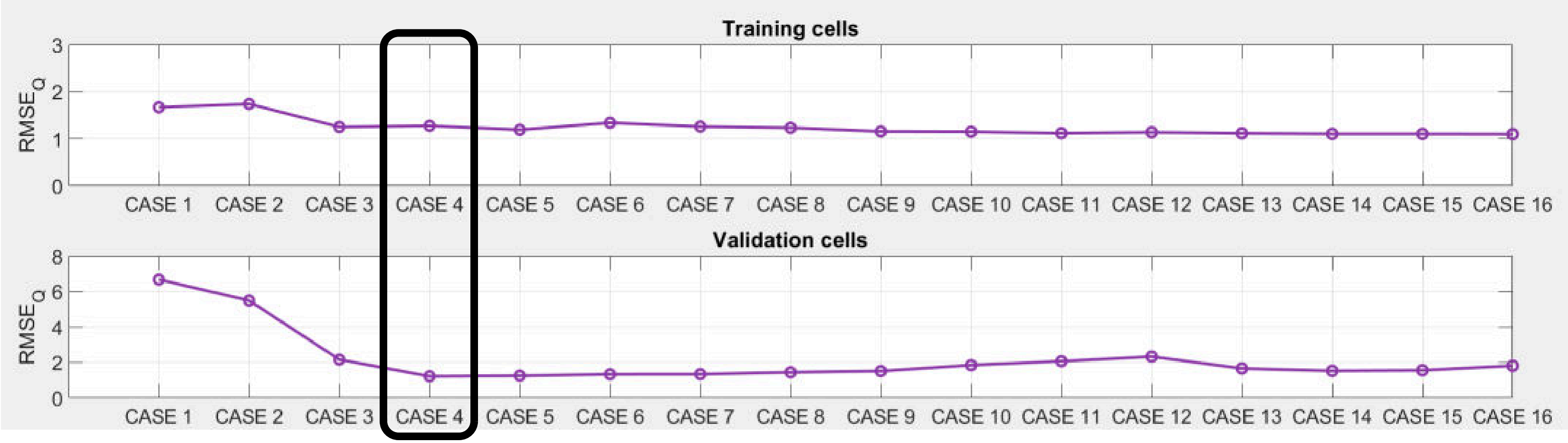


# Modelling Li-ion battery ageing

- GOAL 1: Quantifying required training data

Since TRAINING CASE 4,
not any significant improvement

Mean of the prediction errors




## Training data

- **21%** of the total data for training
- 3 temperatures: 25°C, 35°C, 45°C
- 3 DoD levels: 100%, 65%, 20%

## Accuracy

- **1.2% RMSE** in training
- **1.21% RMSE** in validation

# Modelling Li-ion battery ageing

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## GOAL 1

- Quantify the minimum number of required training data
- **Learning from static** ageing conditions

## GOAL 2

- **Validation at dynamic** ageing conditions
- **Learning from dynamic** ageing conditions

# Modelling Li-ion battery ageing

- GOAL 1: Validation and learning from static conditions

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
|---|---|---|---|
| Temperature | 25°C | 8% | CASE 1 |
| | 45°C | | |
| | 35°C | 10% | CASE 2 |
| DoD | 20% | 15% | CASE 3 |
| | 65% | 21% | CASE 4 |
| | 50% | 37% | CASE 5 |
| | 80% | 60% | CASE 6 |
| | 35% | 64% | CASE 7 |
| Middle-SOC | 80% | 71% | CASE 8 |
| | 20% | 74% | CASE 9 |
| | 65% | 78% | CASE 10 |
| | 35% | 80% | CASE 11 |
| Charging C-rate | 2C | 81% | CASE 12 |
| | 1C | 92% | CASE 13 |
| | 0.5C | 94% | CASE 14 |
| Discharging C-rate | 2C | 98% | CASE 15 |
| | 0.3C | 100% | CASE 16 |

Plotting prediction at **80% DoD**

# Modelling Li-ion battery ageing

- GOAL 1: Validation and learning from static conditions

| Learning stress-factor | New training condition | Training data / Total data [%] | TRAINING CASE |
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MODEL 1

MODEL 2

MODEL 3

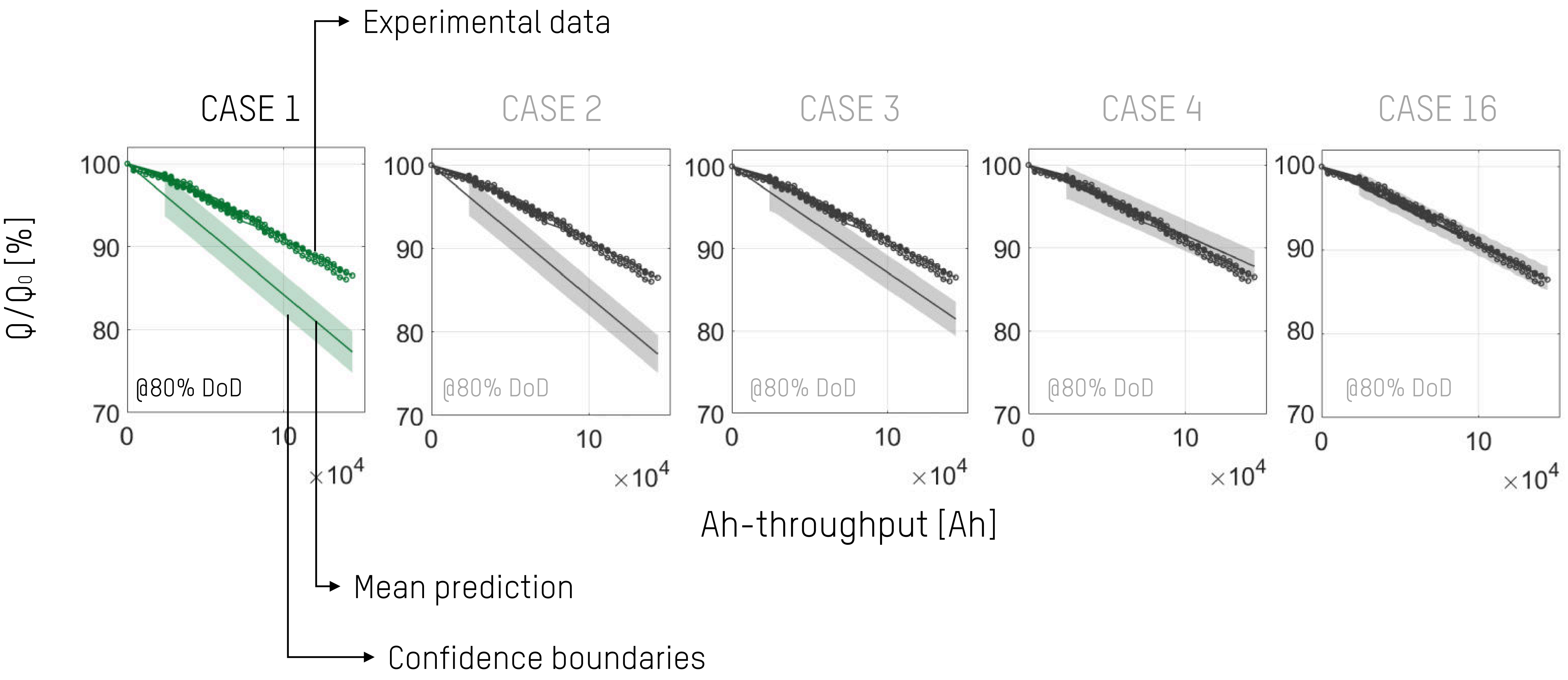
MODEL 4

MODEL 16

Plotting prediction at **80% DoD**

# Modelling Li-ion battery ageing

- GOAL 1: Validation and learning from static conditions

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# Modelling Li-ion battery ageing

- GOAL 1: Validation and learning from static conditions

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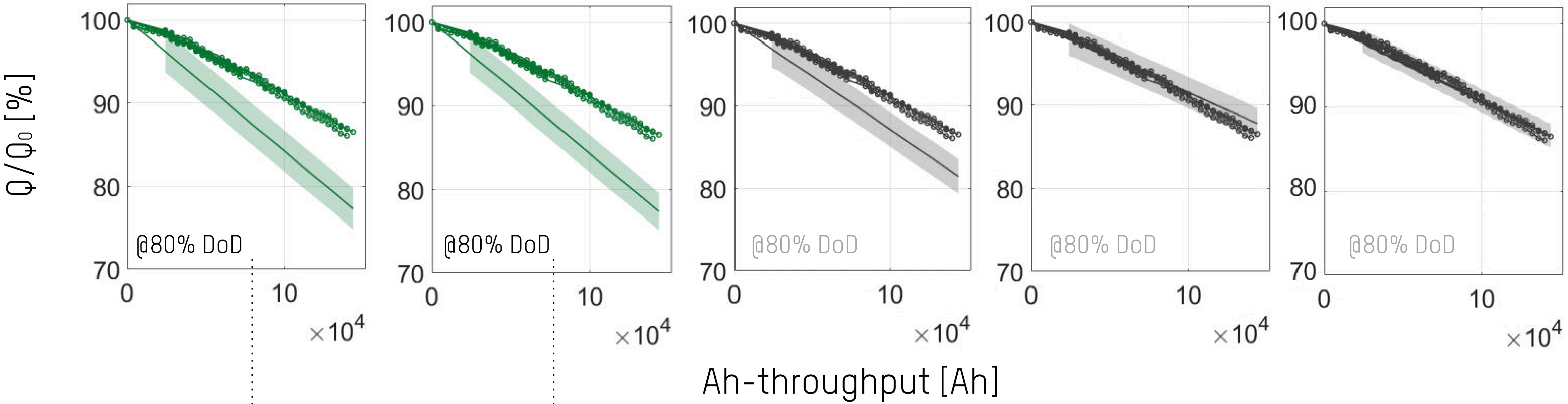
## Trained at: → 100% DoD

CASE 1 | CASE 2 | CASE 3 | CASE 4 | CASE 16




4.2% RMSE

4.1% RMSE

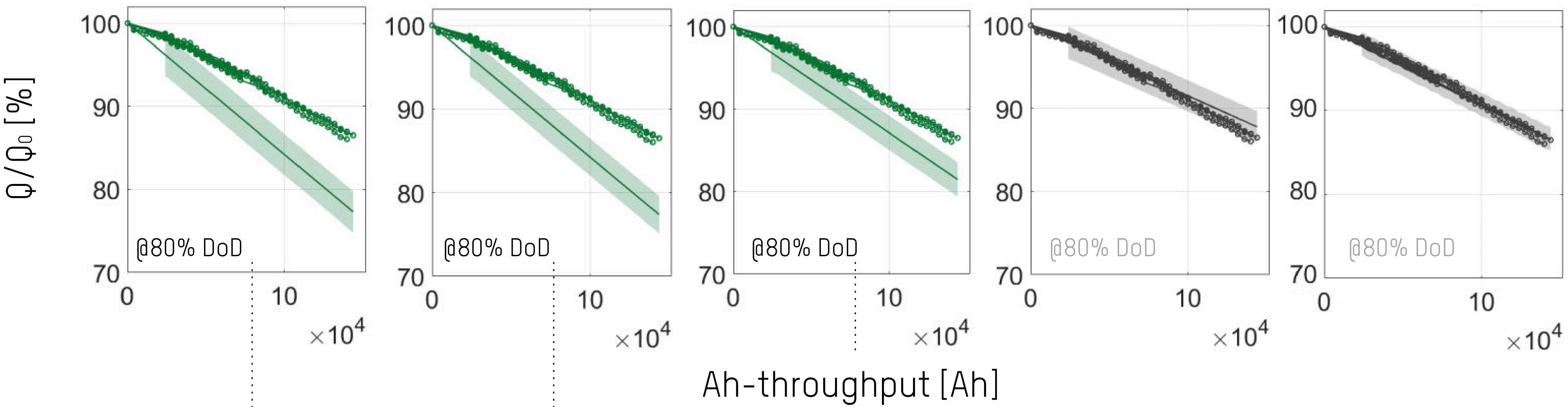
# Modelling Li-ion battery ageing

- GOAL 1: Validation and learning from static conditions



**Trained at:** → **100% DoD** → **+ 20% DoD**

CASE 1 | CASE 2 | CASE 3 | CASE 4 | CASE 16

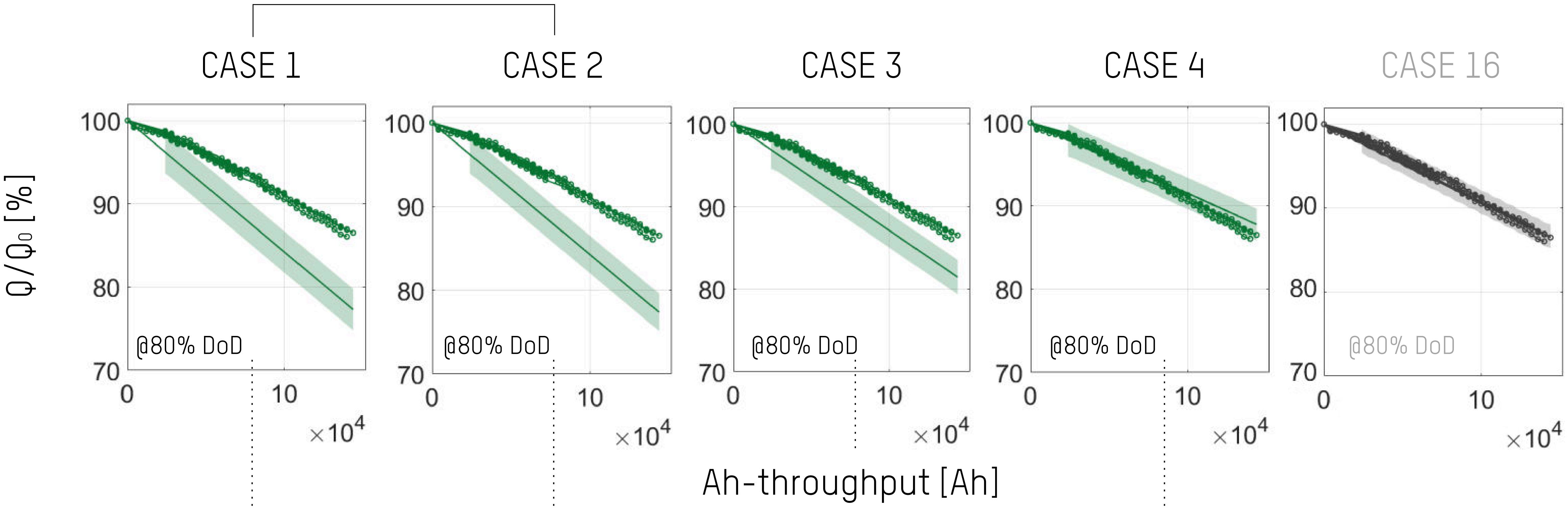



4.2% RMSE | 4.1% RMSE | 2.5% RMSE

# Modelling Li-ion battery ageing

- GOAL 1: Validation and learning from static conditions

**Trained at: → 100% DoD → + 20% DoD → + 65% DoD**




4.2% RMSE

4.1% RMSE

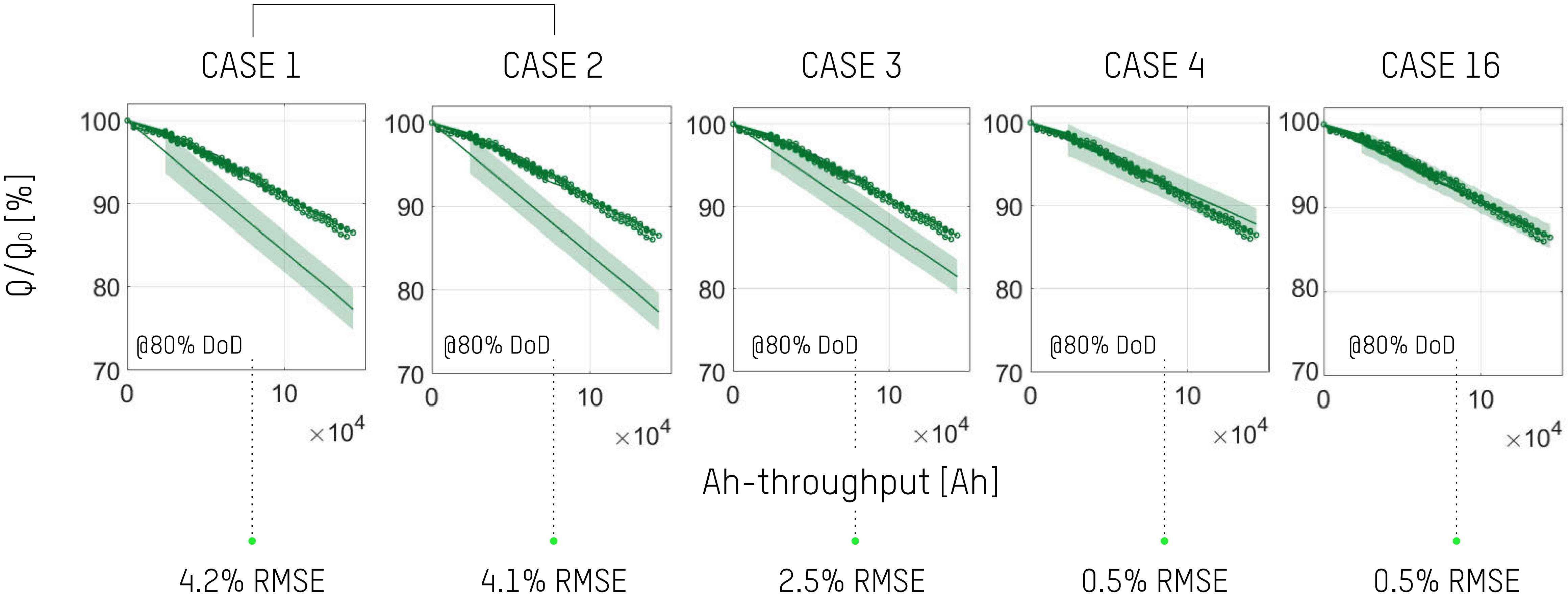
2.5% RMSE

0.5% RMSE

# Modelling Li-ion battery ageing

- GOAL 1: Validation and learning from static conditions

**Trained at:** → **100% DoD** → **+ 20% DoD** → **+ 65% DoD** → **+ 35,50,80% DoD**



# Modelling Li-ion battery ageing

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## GOAL 1 ✓

- Quantify the minimum number of required training data
- **Learning from static** ageing conditions

## GOAL 2

- **Validation at dynamic** ageing conditions
- **Learning from dynamic** ageing conditions

# Modelling Li-ion battery ageing

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## GOAL 1 ✓

- Quantify the minimum number of required training data
- **Learning from static** ageing conditions

## GOAL 2

- **Validation at dynamic** ageing conditions
- **Learning from dynamic** ageing conditions

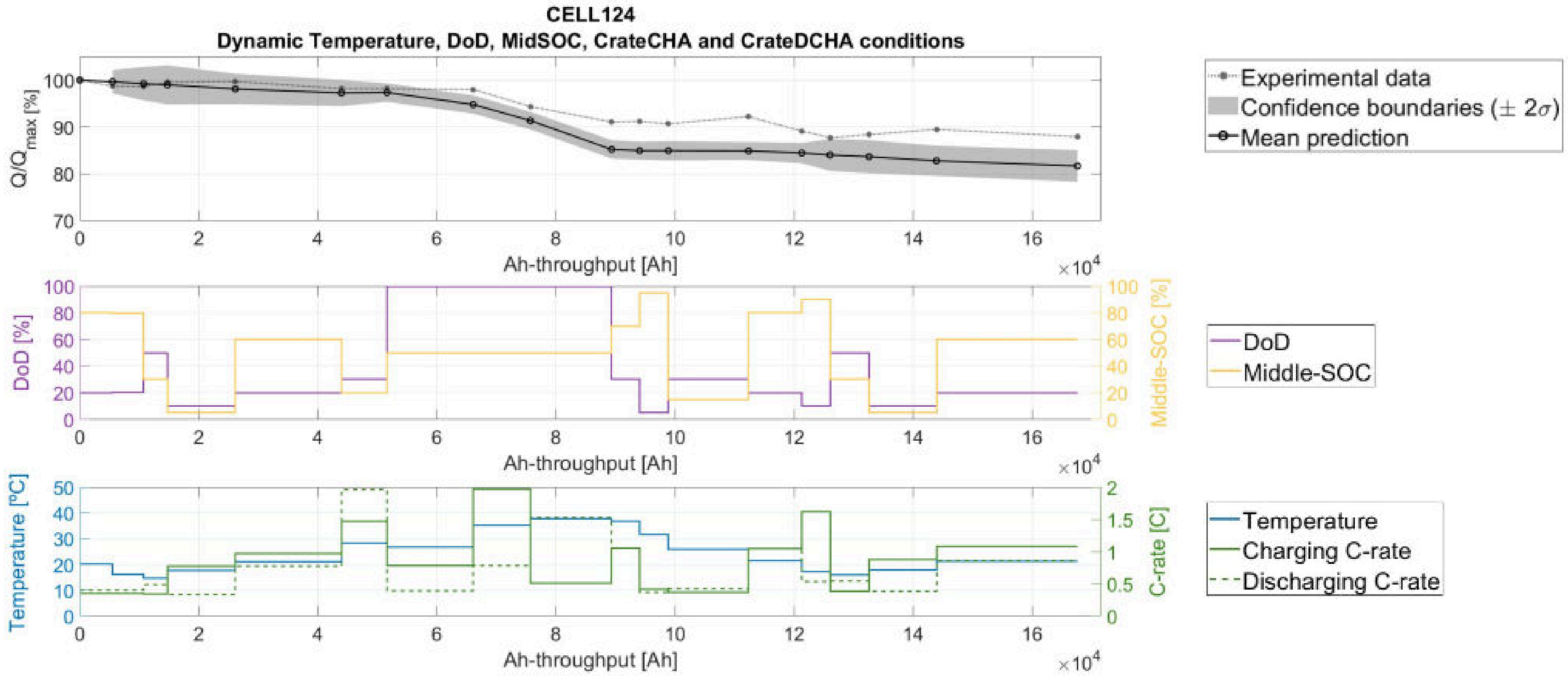
# Modelling Li-ion battery ageing

- Goal 2: **Validation at** dynamic conditions

## Training case 4

Initial model

RMSE = 4.2%



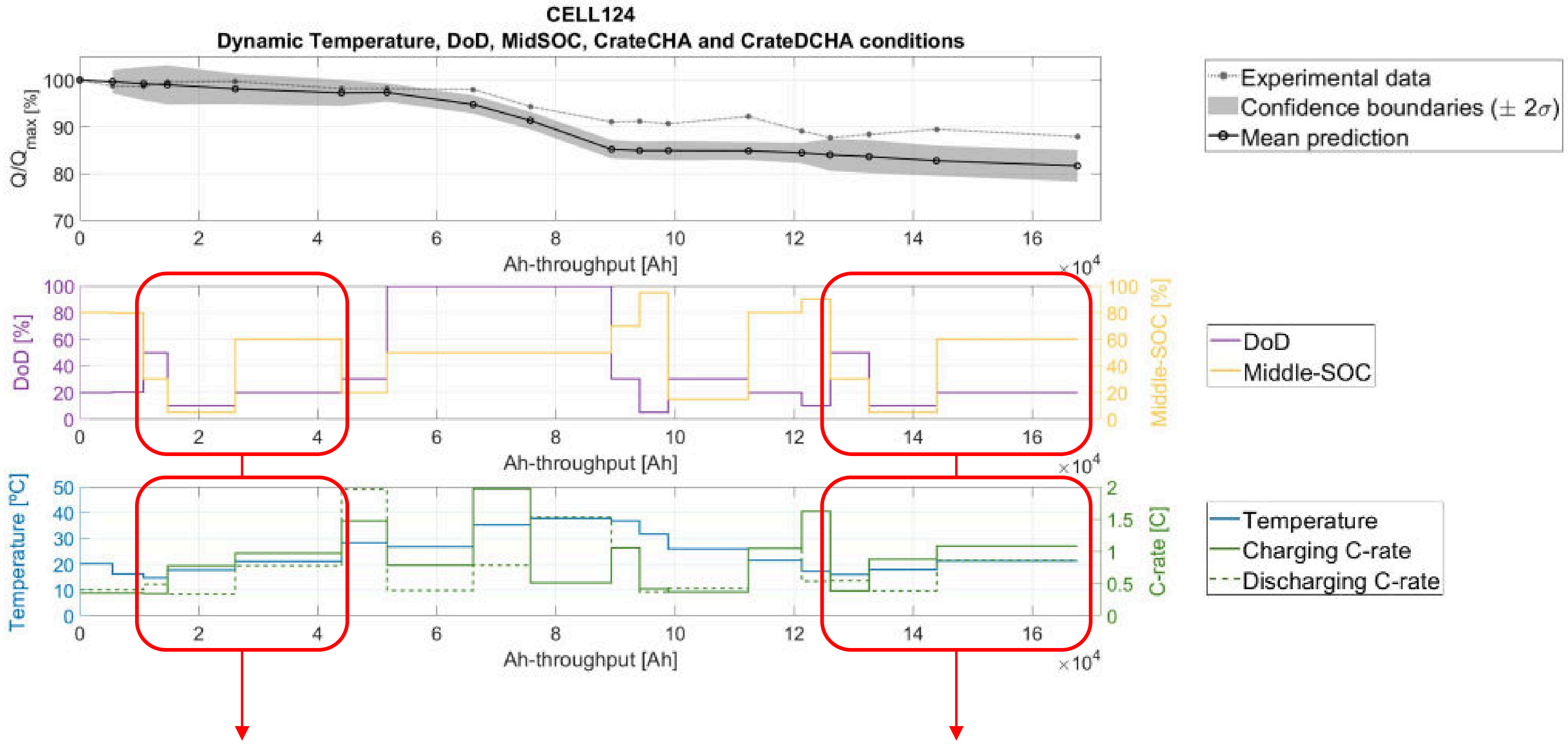
# Modelling Li-ion battery ageing

- Goal 2: **Validation at** dynamic conditions

Training case 4

Initial model

RMSE = 4.2%




Unknown combination of stress-factors

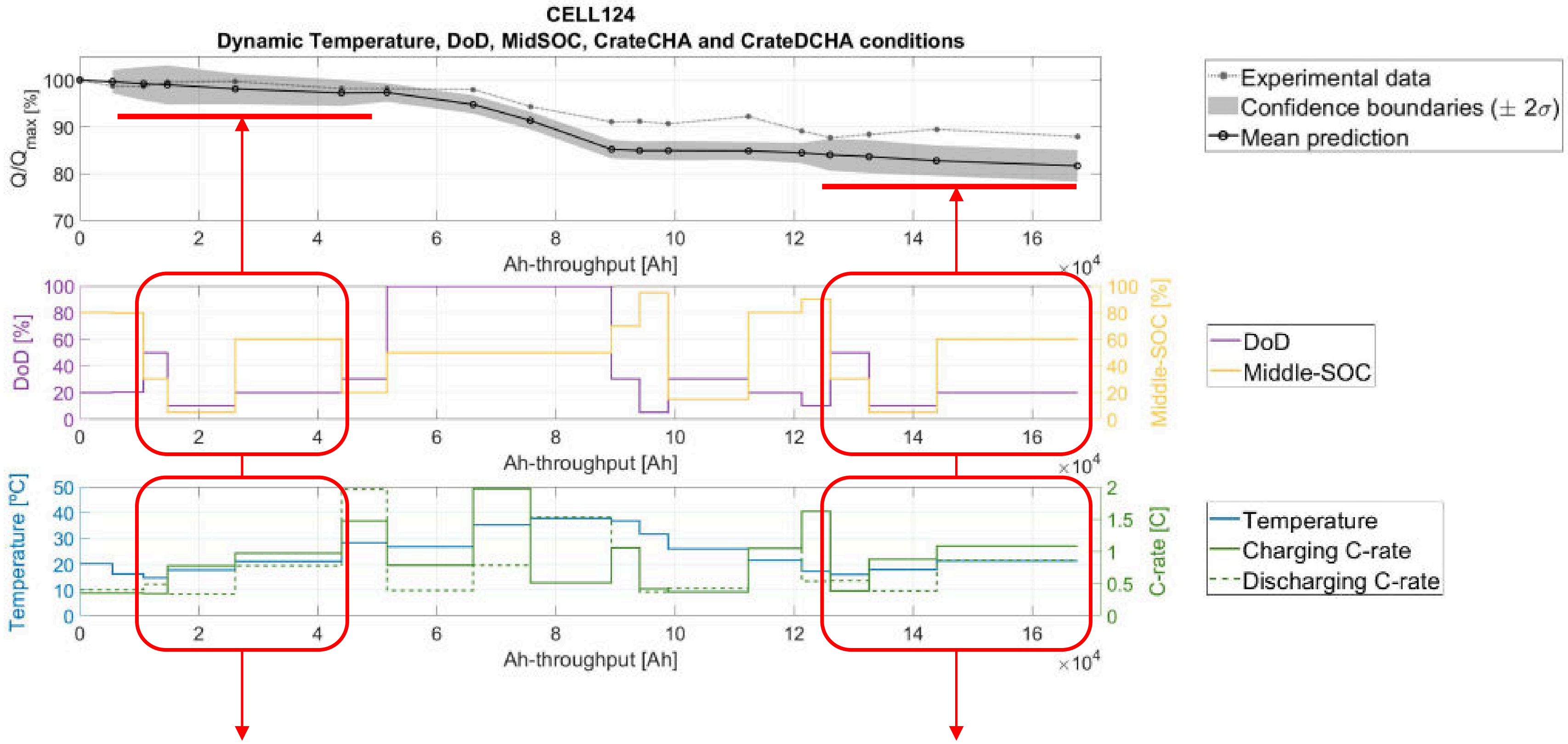
# Modelling Li-ion battery ageing

- Goal 2: **Validation at** dynamic conditions

## Training case 4

Initial model

RMSE = 4.2%




Unknown combination of stress-factors

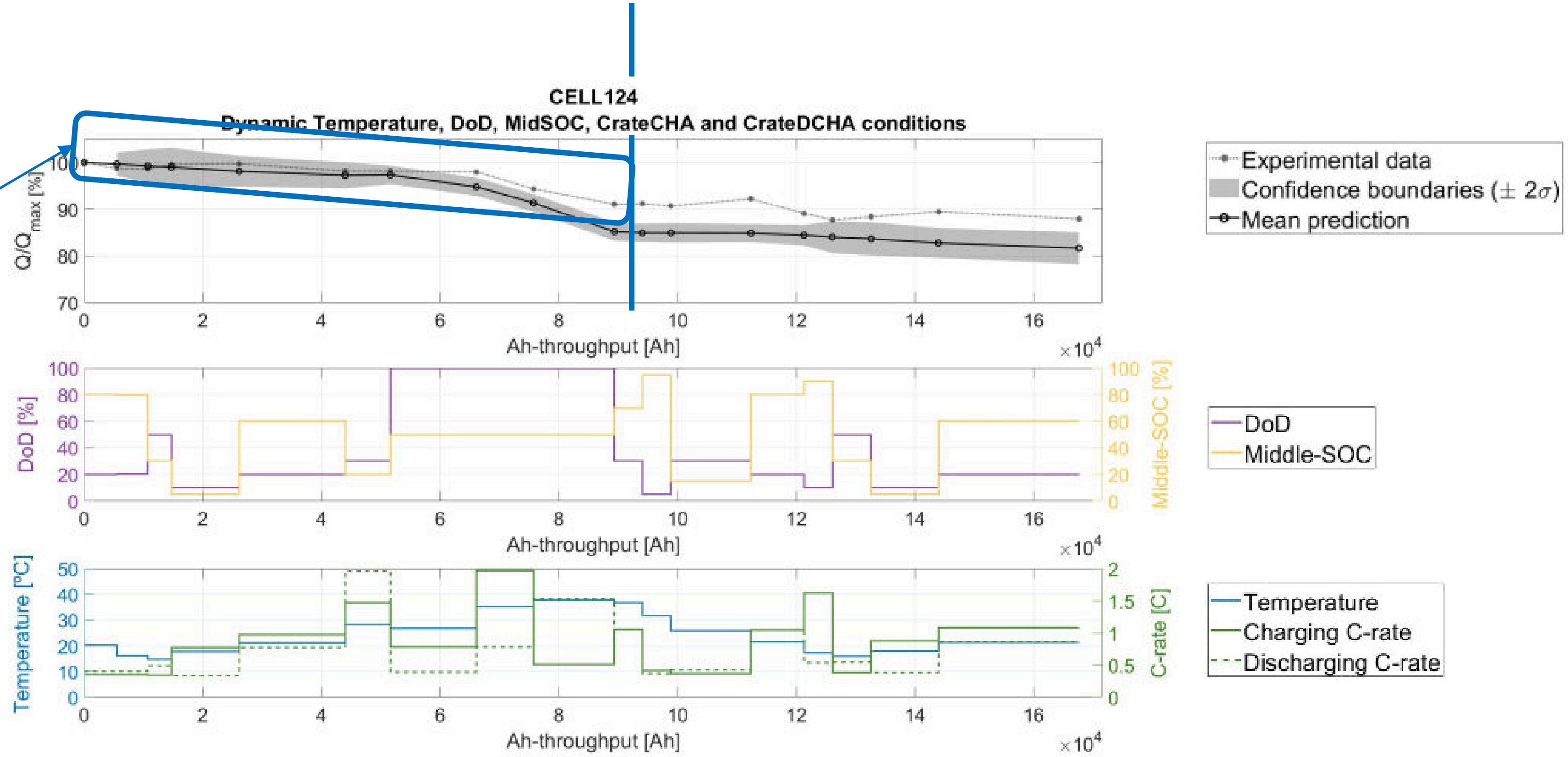
Broader confidence boundaries

# Modelling Li-ion battery ageing

- Goal 2: **Learning from** dynamic conditions

Training case 4

Incorporate in training data

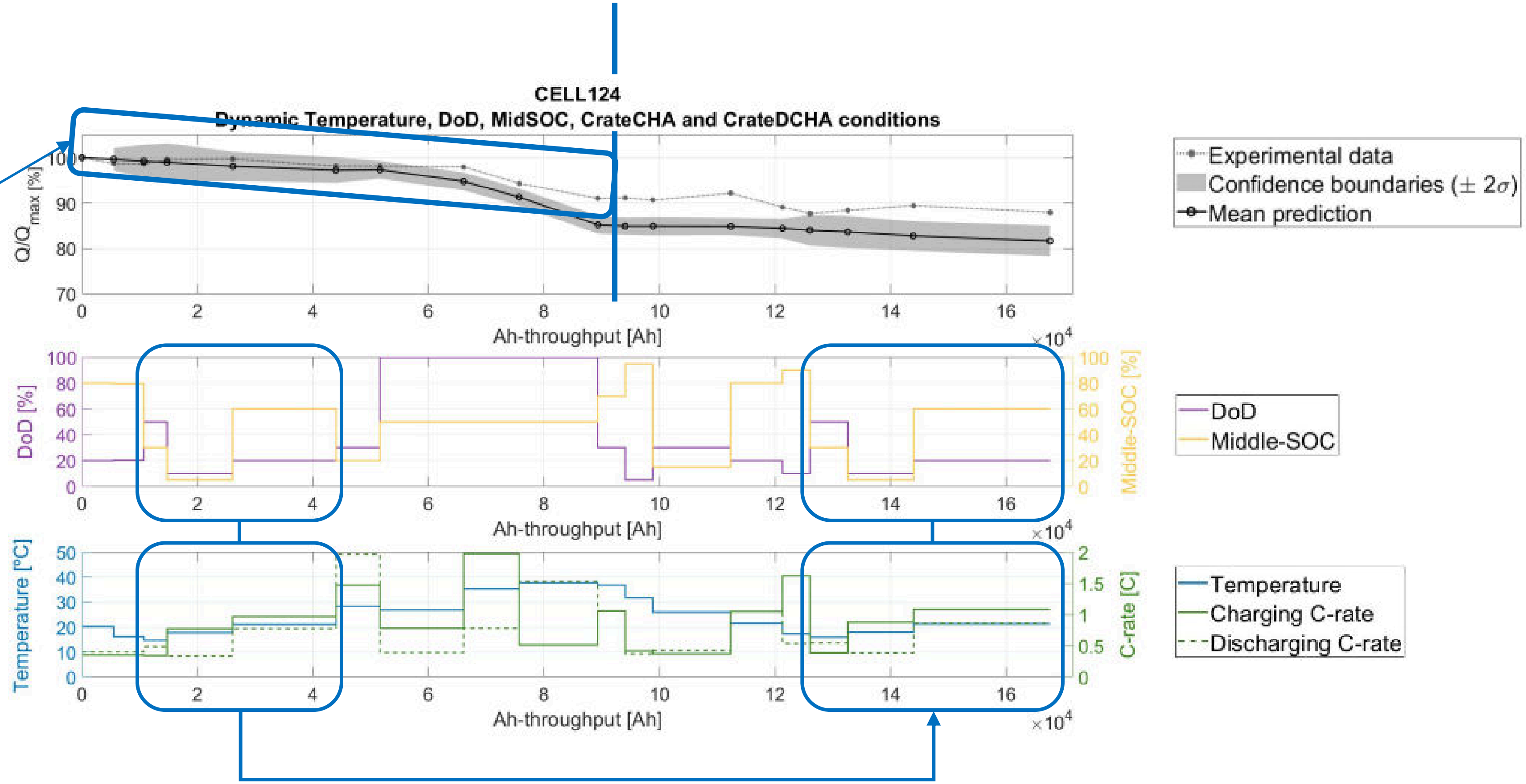


# Modelling Li-ion battery ageing

- Goal 2: **Learning from** dynamic conditions

Training case 4

Incorporate in training data

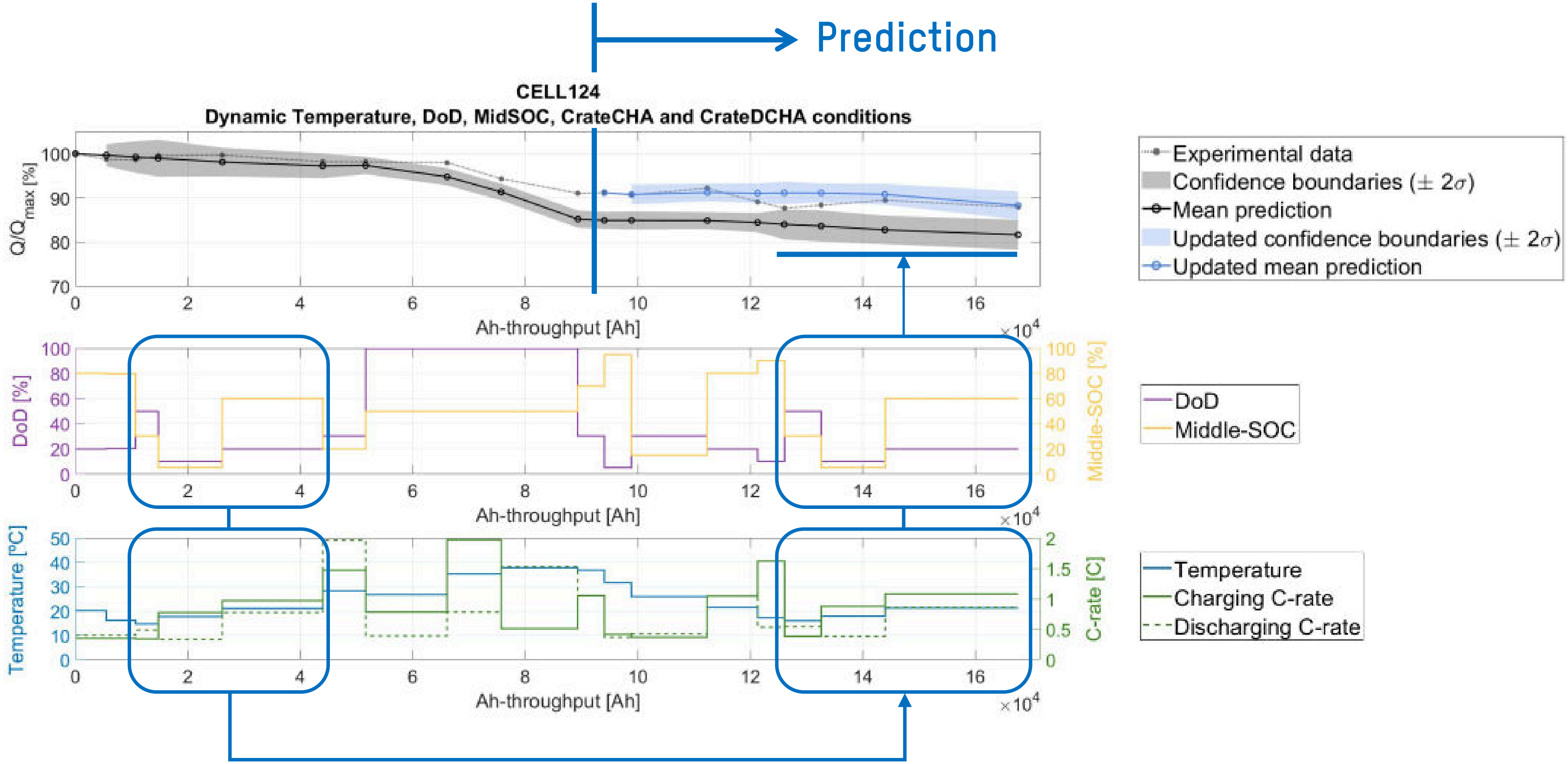



Learning new operating conditions

# Modelling Li-ion battery ageing

- Goal 2: **Learning from** dynamic conditions

Training case 4




Learning new operating conditions

Reduction of confidence boundaries

# Modelling Li-ion battery ageing

- Goal 2: **Learning from** dynamic conditions

Training case 4

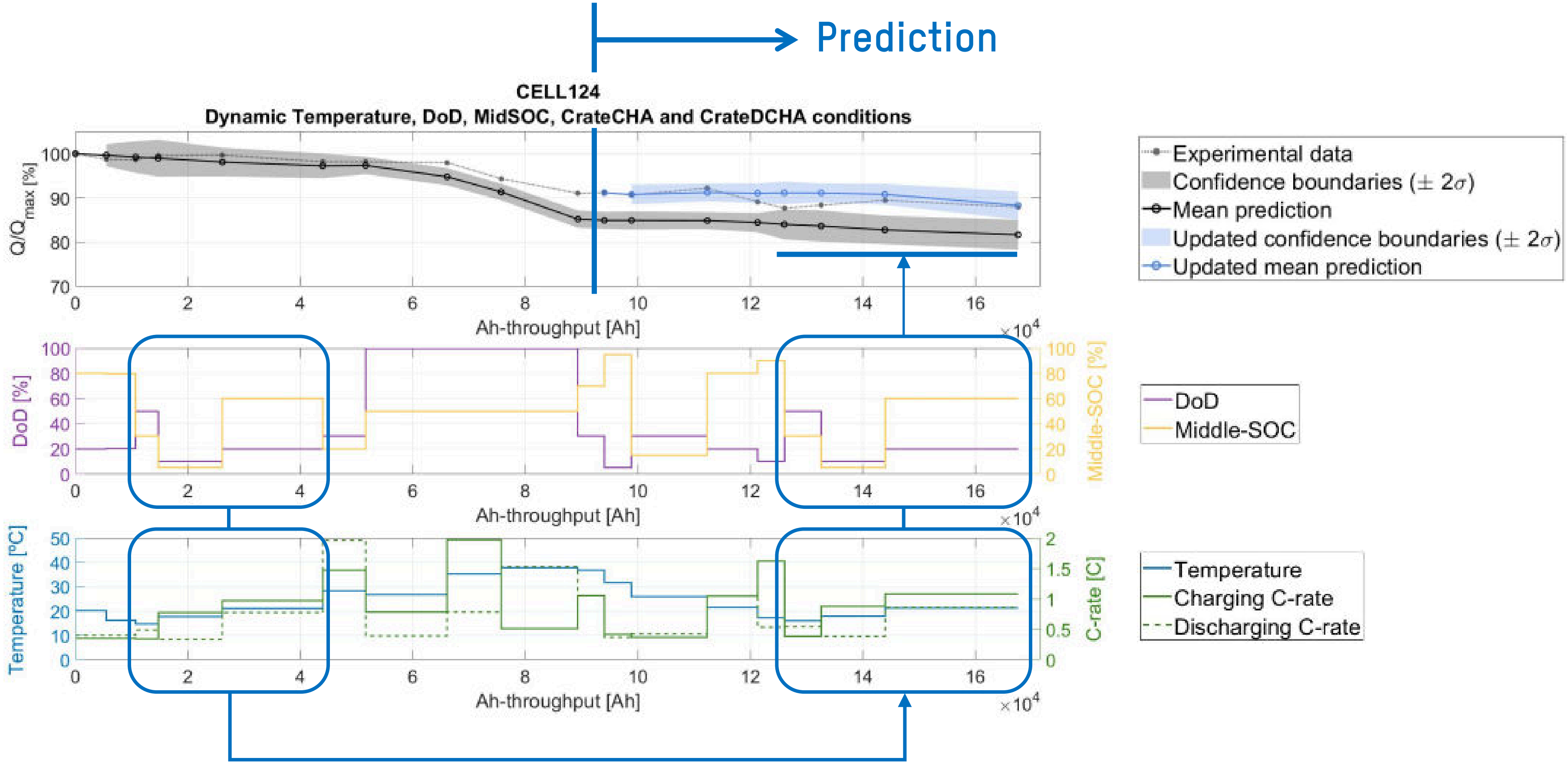
Errors from **updating point**:

Initial model

RMSE = 5.7%

Updated model

RMSE = 1.8%




Learning new operating conditions

Reduction of confidence boundaries

# Modelling Li-ion battery ageing

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## GOAL 1 ✓

- Quantify the minimum number of required training data
- **Learning from static** ageing conditions

## GOAL 2 ✓

- **Validation at dynamic** ageing conditions
- **Learning from dynamic** ageing conditions

# Conclusions

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Accurate Gaussian Process model:

- Reduced laboratory training data (3 temperatures, 3 DODs)
- Large operating window of the model
- Validated at dynamic operating conditions

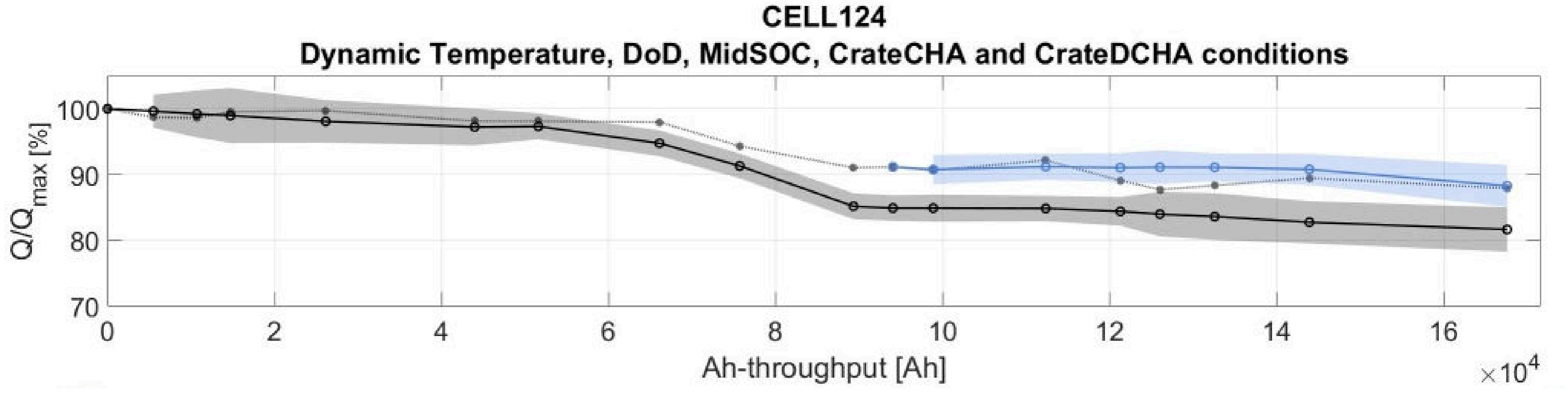
1.2% RMSE

↓

OPERATING WINDOW

| | |
|---|---|
| Temperature | [25ºC – 45ºC] |
| DoD | [10% – 100%] |
| Middle-SOC | [20% – 80% ] |
| Charging C-rate | [C/3 – 2C] |
| Discharging C-rate | [C/3 – 2C] |

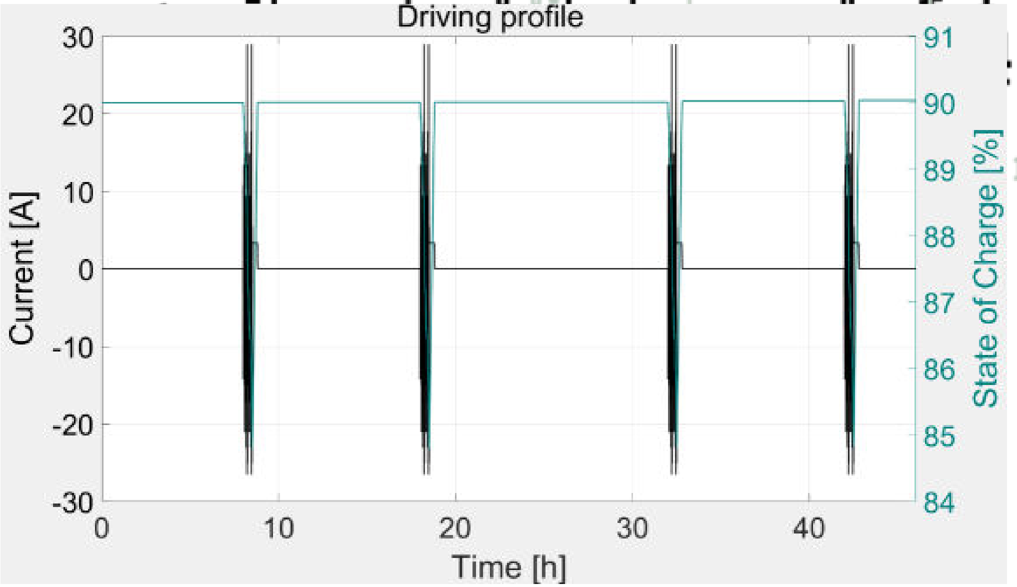
# Conclusions

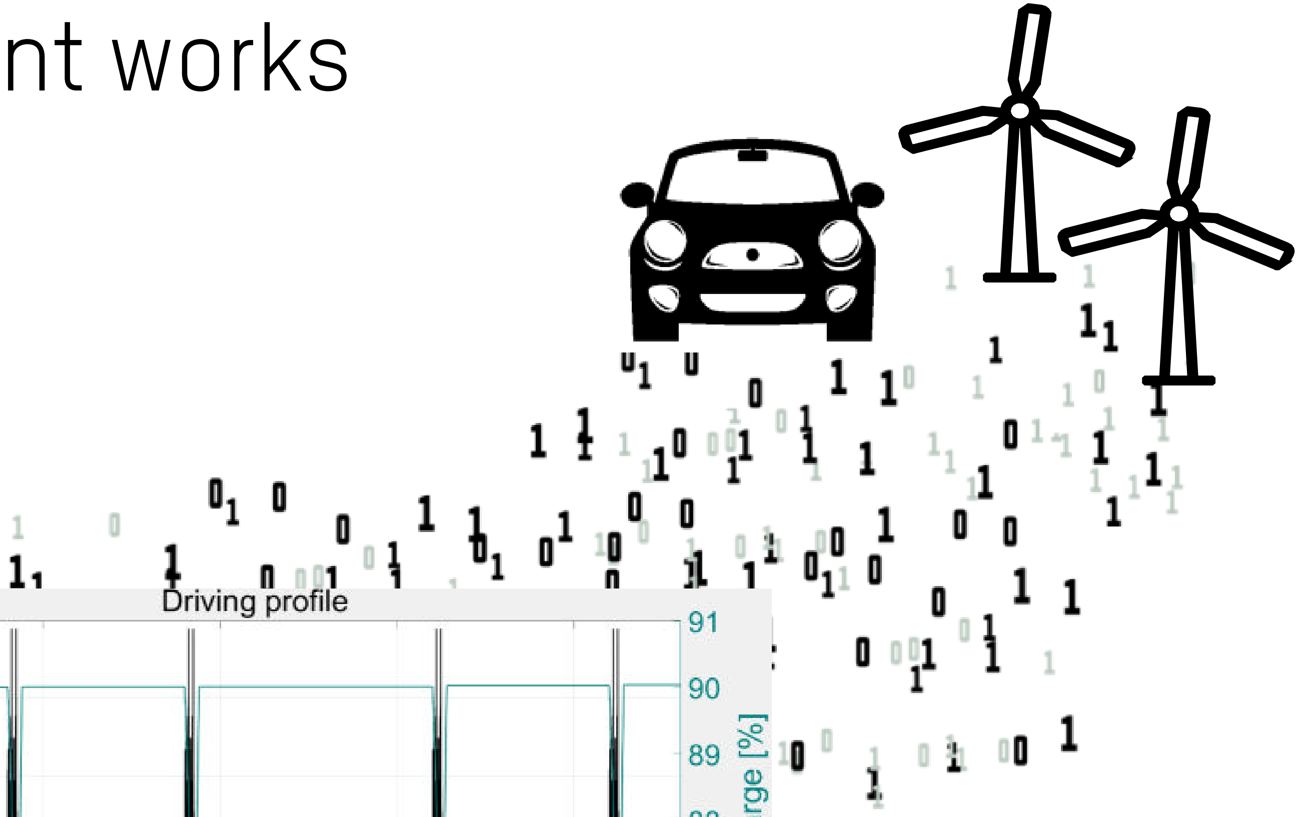



Able to **learn from new data**:

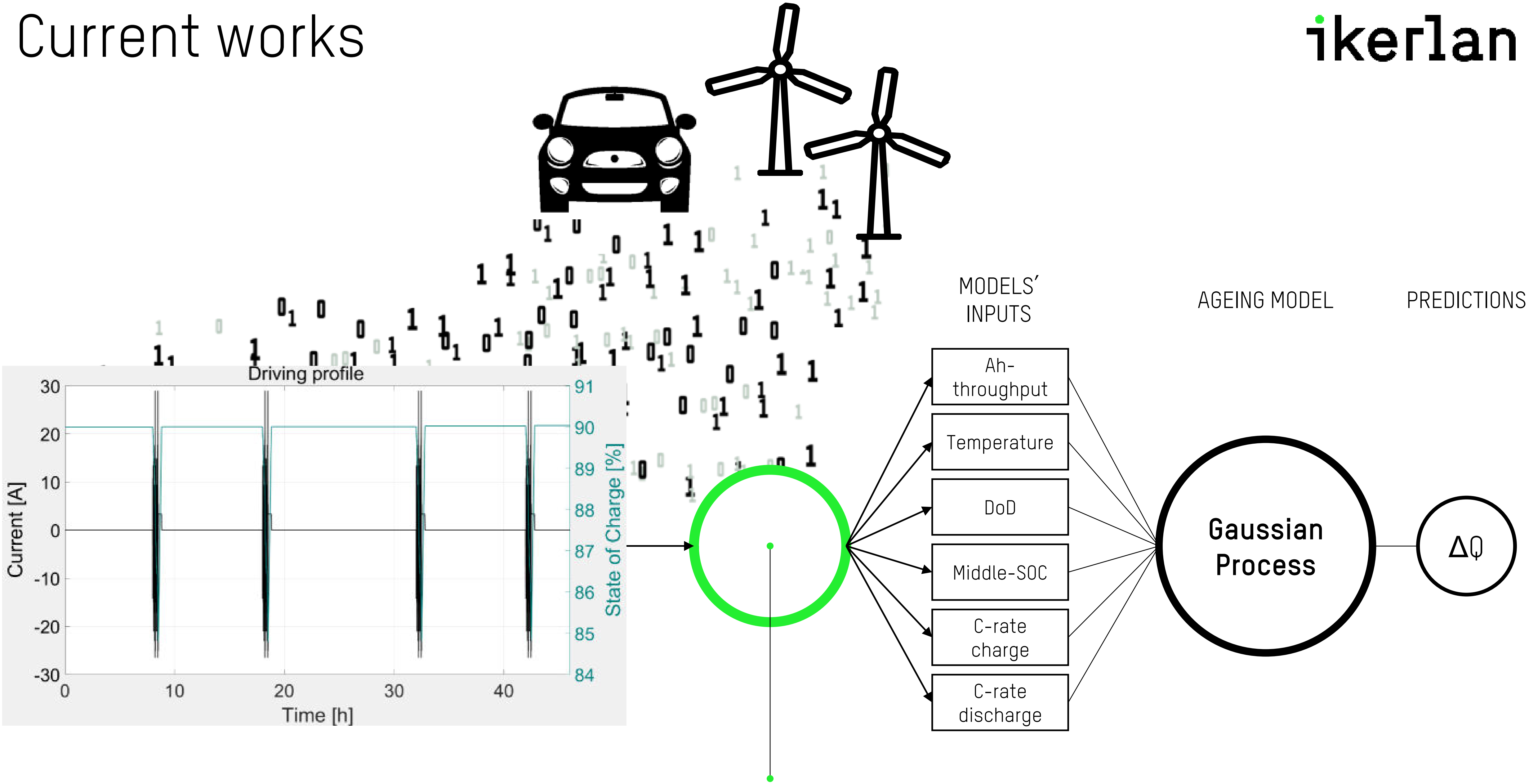
- Obtained from **static** & **dynamic** profiles
- Increasingly **accurate** and **confident** prediction
- Increasingly large **operating window** of the model

# Current works



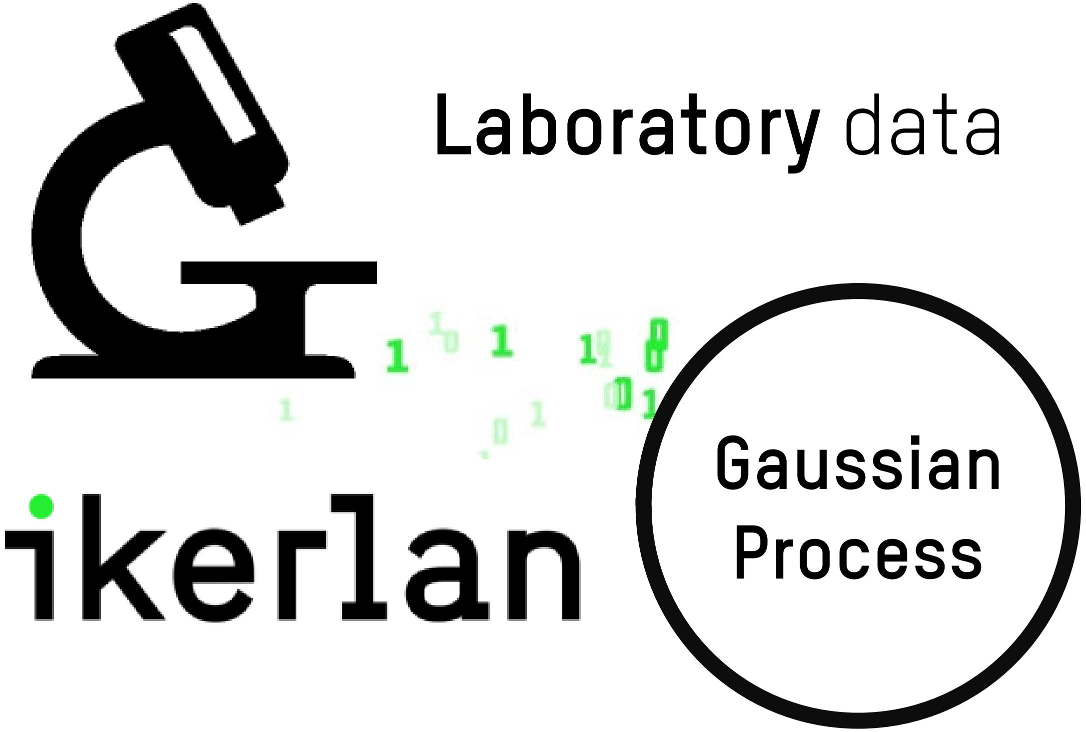



# Current works




Profile conversion algorithm

# Final words…




Data makes our models **strong**…

# Final words…

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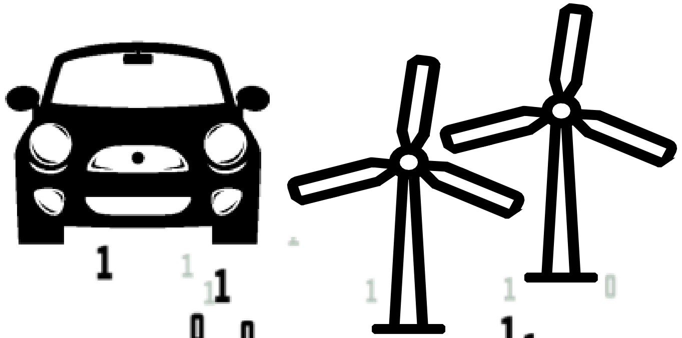
**Laboratory** data



**Real-world** data?

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**Gaussian Process**

What about you?

Data makes our models **strong**…

# Contact us

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WHERE TECHNOLOGY IS AN ATTITUDE

Milesker

Thank you

Merci

# Previous works

More details about related **previous** works:

- Lucu et al. – 2018 – A critical review on self-adaptive Li-ion battery ageing models
  Journal of Power Sources - DOI / link: https://doi.org/10.1016/j.jpowsour.2018.08.064

- Lucu et al. – Under review – Journal of Power Sources
  Data-driven calendar ageing model for NMC/graphite Lithium-ion battery: a nonparametric approach to learn from real-world operation data

# Kernel composition

$$\kappa(\mathbf{x}, \mathbf{x}') = \kappa(\Delta \mathrm{Ah}) \,.\, \kappa(\mathrm{DOD}) \,.\, \kappa(\mathrm{MidSOC}) \,.\, \kappa(\mathrm{T}) \,.\, \kappa(\mathrm{CrateCHA}) \,.\, \kappa(\mathrm{CrateDCH})$$

- One **kernel component** for each stress factor
- **Tensor product:** assuming a **strong interaction** between input dimensions

Rasmussen and Williams – 2006 – Gaussian Processes for Machine Learning

# Kernel composition

$$\kappa(\mathrm{x},\mathrm{x}') = \kappa(\Delta\mathrm{Ah})\,.\,\kappa(\mathrm{DOD})\,.\,\kappa(\mathrm{MidSOC})\,.\,\kappa(\mathrm{T})\,.\,\kappa(\mathrm{CrateCHA})\,.\,\kappa(\mathrm{CrateDCH})$$

Non-limited range
(longterm prediction)

Conceptually limited range
[0% – 100%]

We assume a local modelling problem
e.g. [-30°C – +40°C]
e.g. Max 2C charge (datasheet 1C)
e.g. Max 10C discharge

**ANISOTROPIC**
KERNEL
COMPONENT

→ Linear kernel

**ISOTROPIC**
KERNEL
COMPONENTS

→ Matérn 5/2

Rasmussen and Williams – 2006 – Gaussian Processes for Machine Learning