Project RUBY

Robust and reliable general management tool for performance and durability improvement of fuel cell stationary units

DATA-DRIVEN PREDICTION OF THE REMAINING USEFUL LIFE OF SOFC SYSTEMS

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Introduction

Motivation:

- Remaining useful life (RUL) depends on the degradation rate;
- many techniques for RUL prognosis rely on modelling the degradation by hidden dynamic models [(1)]
- prior knowledge (or model) of the degradation can improve RUL prognosis [(2)]
- however, simple degradation models are known only for a few degradation mechanisms;
- the application to the RUL prognosis heavily relies on reliable and unambiguous isolation of the degradation mode in the diagnosis stage.

Assumptions:

- no prior knowledge about the degradation is available;
- the time evolution of a health index indicative for the RUL assessment is available (e,g, stack voltage, ASR, and others)
- Technicallly speaking, the RUL prognosis is closely related to predicting the trend of time series

Question:

- does a simple linear trend model apply?

[(1)] Cui L, Huo H, Xie G, Xu J, Kuang X, Dong Z. Long-Term Degradation Trend Prediction and Remaining Useful Life Estimation for Solid Oxide Fuel Cells. Sustainability. 2022; 14(15):9069.

[(2)] B. Dolenc, P. Boškoski, M. Stepančič, A. Pohjoranta, Đ. Juričić, State of health estimation and remaining useful life prediction of solid oxide fuel cell stack, Energy Conversion and Management, Volume 148, 2017, Pages 993-1002.

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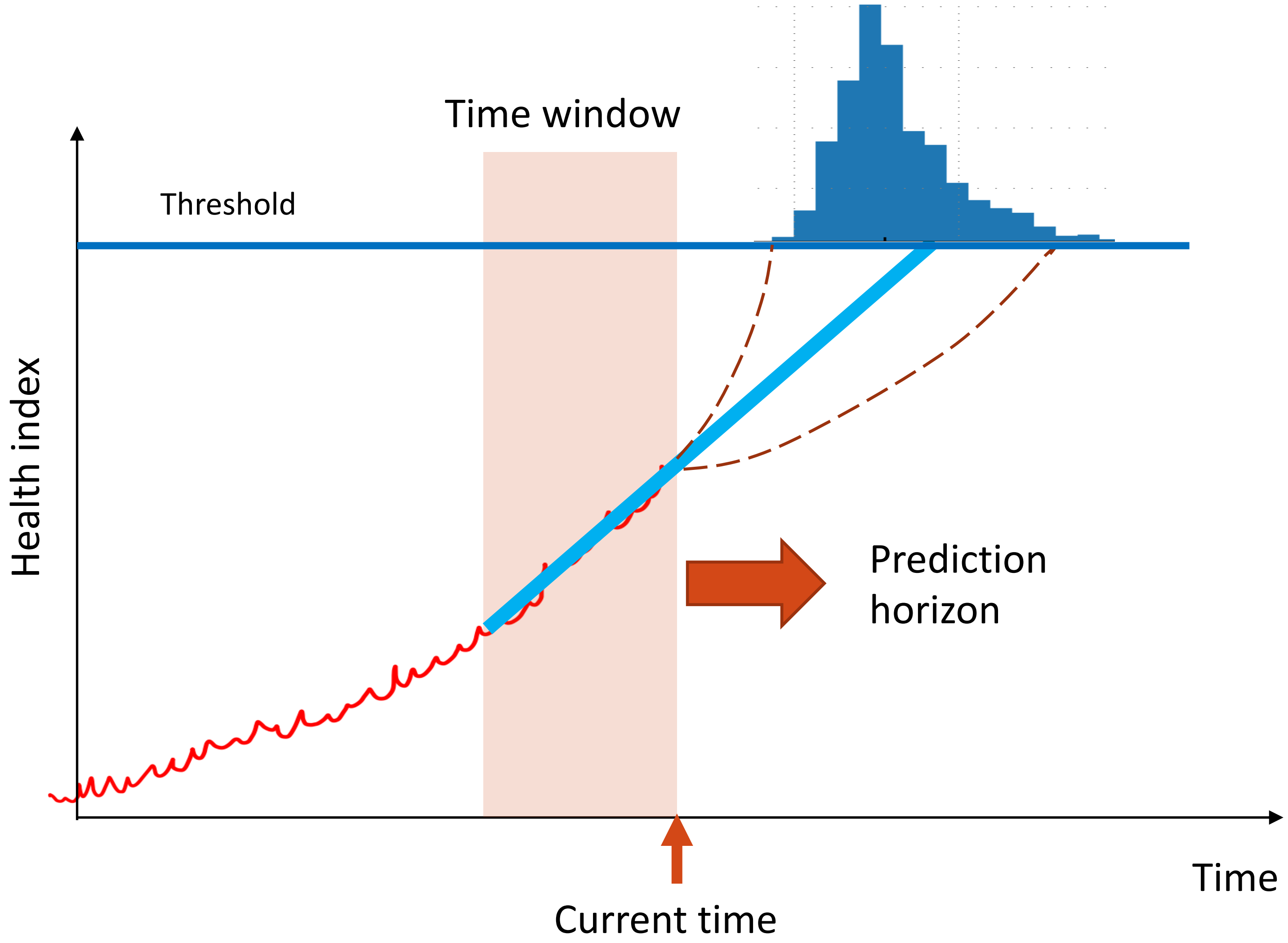
The idea



Conventional approach:

1. Define the sliding window.
2. Find a (stochastic) linear model of the data from the sliding window by means of the Bayesian approach.
3. Evaluate the PDF of the first hitting times by Monte Carlo simulation of the stochastic model

Question:

Can MC simulation be avoided i.e. is there an analytical expression for PDF of RUL?

The idea (cont'd)

The model of the health index y

$$y(\tau) = k\tau + \mathrm{n} + \xi_\tau$$

The first hitting time t is such that $y(t) = C$ where C is the threshold of the health index

$$t = \frac{C - n - \xi}{k} = \frac{\zeta}{k},$$

$$\begin{bmatrix} \zeta \\ k \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mu_\zeta \\ \mu_k \end{bmatrix}, \begin{bmatrix} \sigma_\zeta^2, & \rho_{\zeta,k}\sigma_\zeta\sigma_k \\ \rho_{\zeta,k}\sigma_k\sigma_\zeta, & \sigma_k^2 \end{bmatrix} \right)$$

Variables ζ and k are correlated, normally distributed, random variables!

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Main result

The probability density function of the remaining useful life t can be found analytically

$$p(t)=\frac{\sigma_k\sigma_\zeta\left(1-\rho_{\zeta,k}^2\right)^{1/2}}{\pi\left(\sigma_k^2t^2-2\rho_{\zeta,k}\sigma_k\sigma_\zeta t+\sigma_\zeta^2\right)}\exp\left[-\frac{1}{2\left(1-\rho_{\zeta,k}^2\right)}\left(\frac{\mu_k^2}{\sigma_k^2}-2\rho_{\zeta,k}\frac{\mu_k}{\sigma_k}\frac{\mu_\zeta}{\sigma_\zeta}+\frac{\mu_\zeta^2}{\sigma_\zeta^2}\right)\right]$$
$$+\frac{\mu_k\sigma_\zeta^2-\mu_\zeta\rho_{\zeta,k}\sigma_k\sigma_\zeta+\left(\mu_\zeta\sigma_k^2-\mu_k\rho_{\zeta,k}\sigma_k\sigma_\zeta\right)t}{\sqrt{2\pi}\left(\sigma_k^2t^2-2\rho_{\zeta,k}\sigma_k\sigma_\zeta t+\sigma_\zeta^2\right)^{3/2}}$$
$$\times\exp\left(-\frac{\left(\mu_\zeta-\mu_k t\right)^2}{2\left(\sigma_k^2t^2-2\rho_{\zeta,k}\sigma_k\sigma_\zeta t+\sigma_\zeta^2\right)}\right)$$
$$\times\left[1-2Q\left(\frac{\mu_k\sigma_\zeta^2-\mu_\zeta\rho_{\zeta,k}\sigma_k\sigma_\zeta+\left(\mu_\zeta\sigma_k^2-\mu_k\rho_{\zeta,k}\sigma_k\sigma_\zeta\right)t}{\sigma_k\sigma_\zeta\left(1-\rho_{\zeta,k}^2\right)^{1/2}\left(\sigma_k^2t^2-2\rho_{\zeta,k}\sigma_k\sigma_\zeta t+\sigma_\zeta^2\right)^{1/2}}\right)\right],$$

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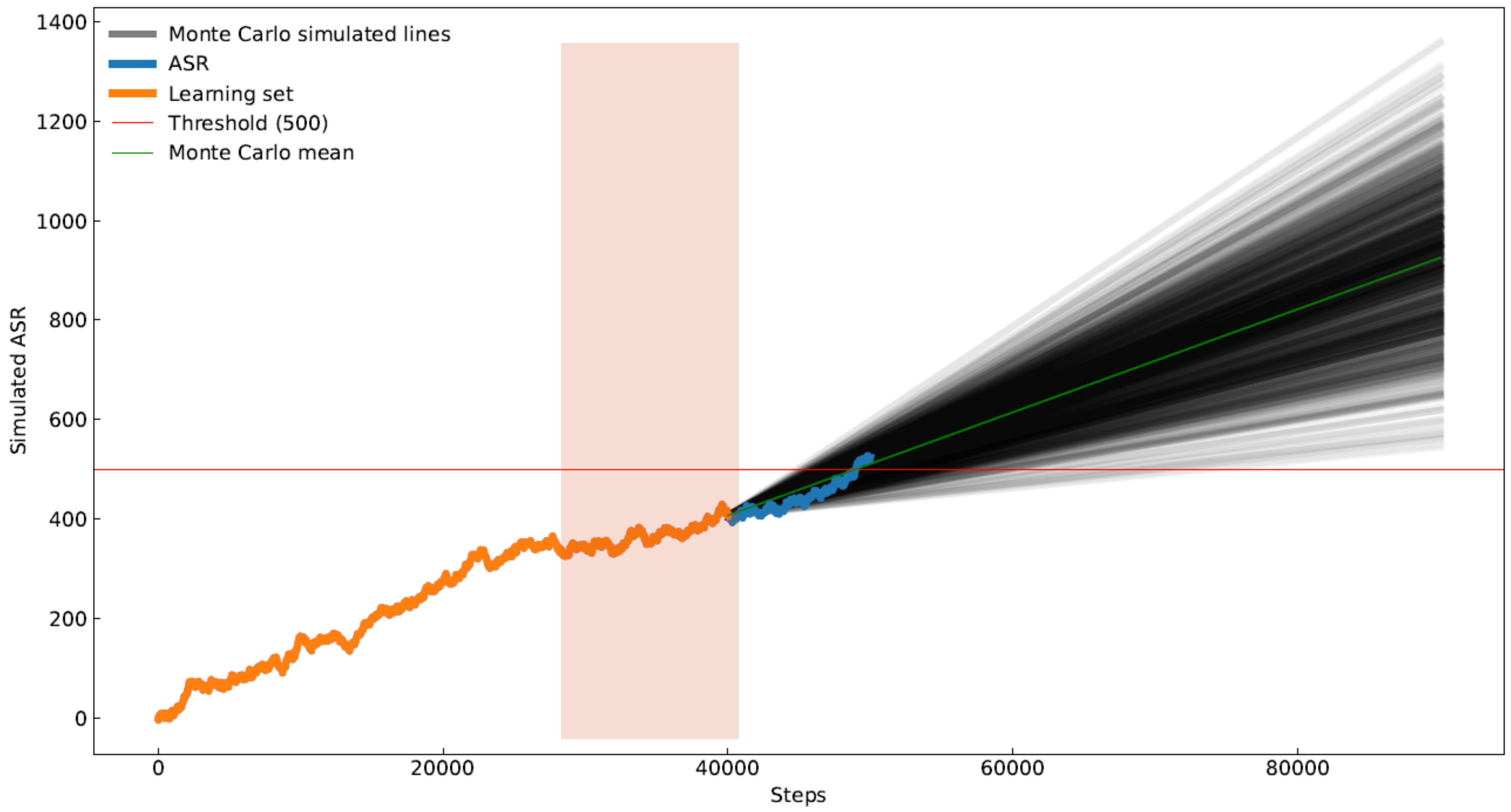
Simulated example (random walk)



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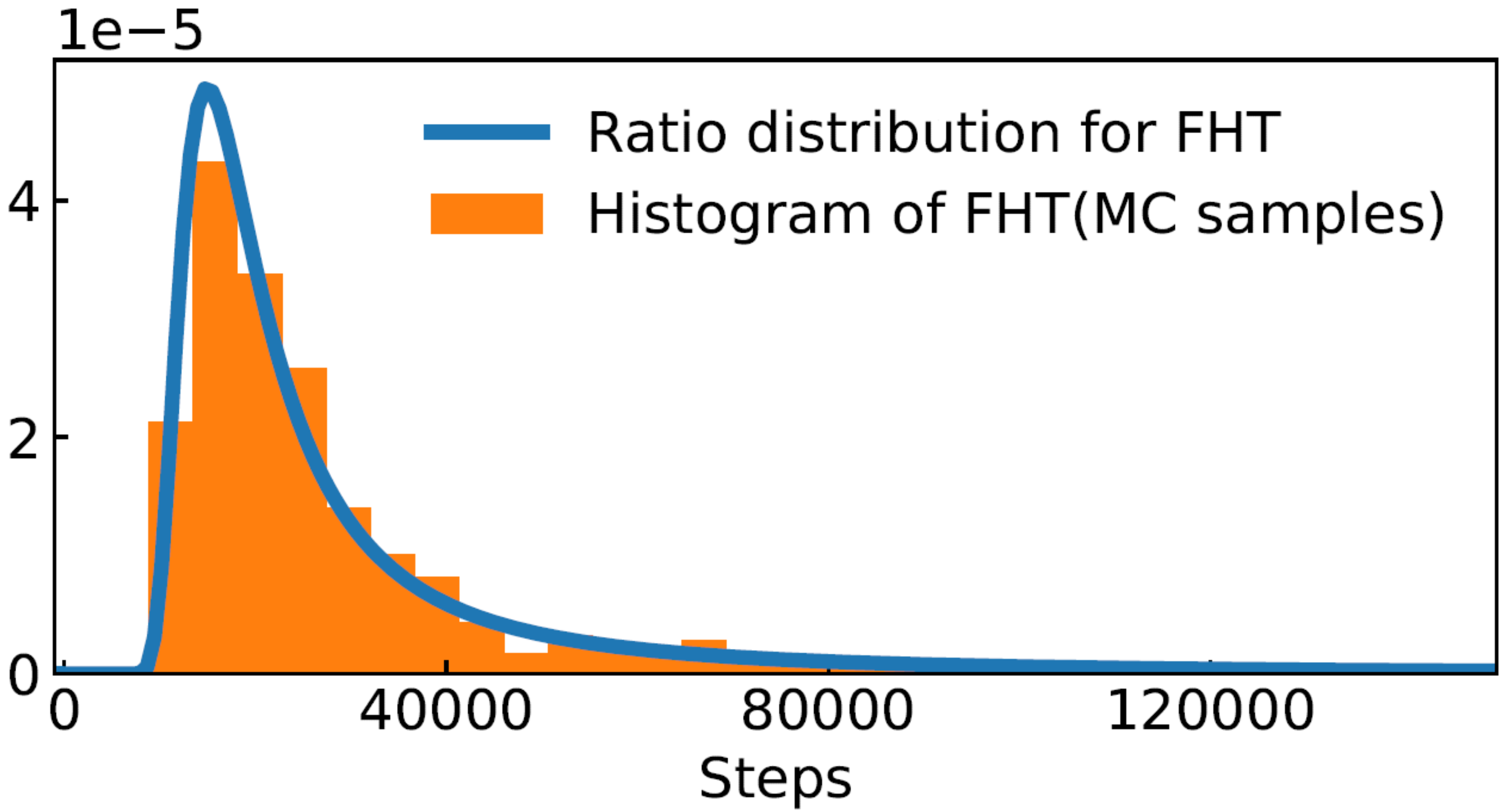
Simulated example (cont'd)

Comparison between Monte Carlo evaluation of the first hitting times and the analytical PDF



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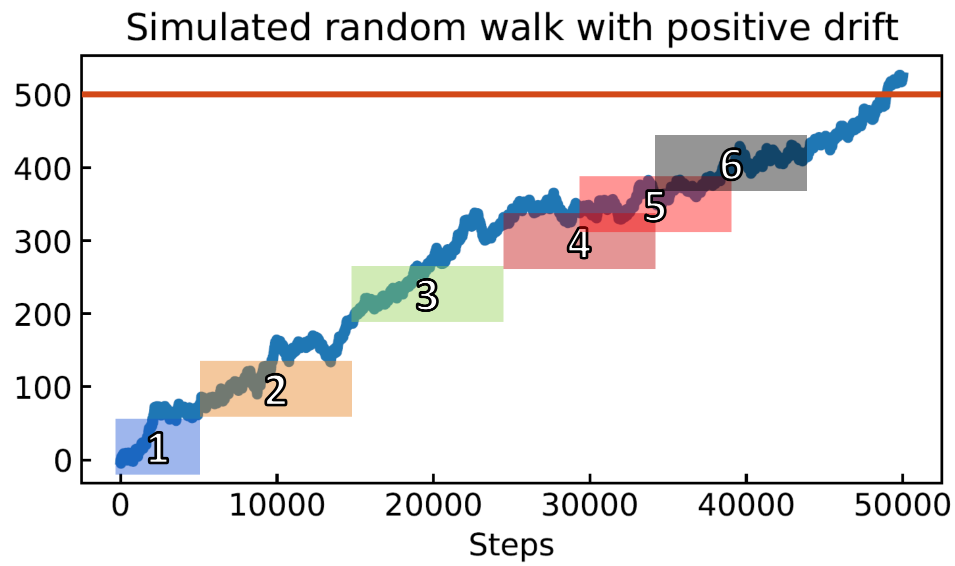
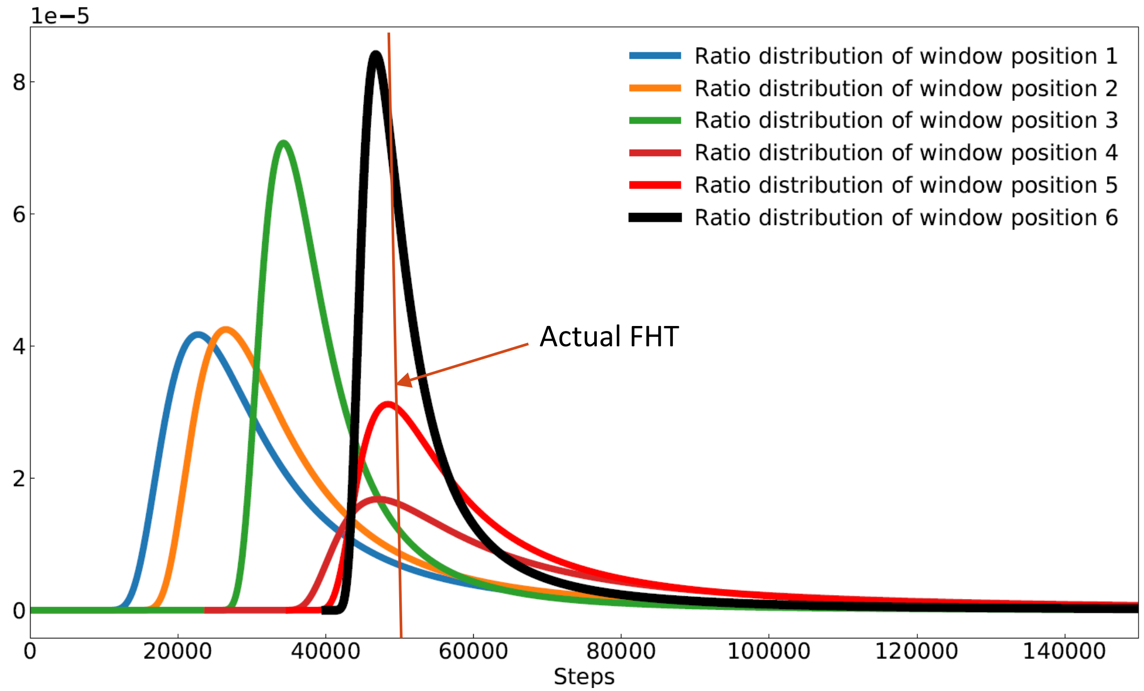
Simulated example (cont'd)

Evolution of the prognosis over time





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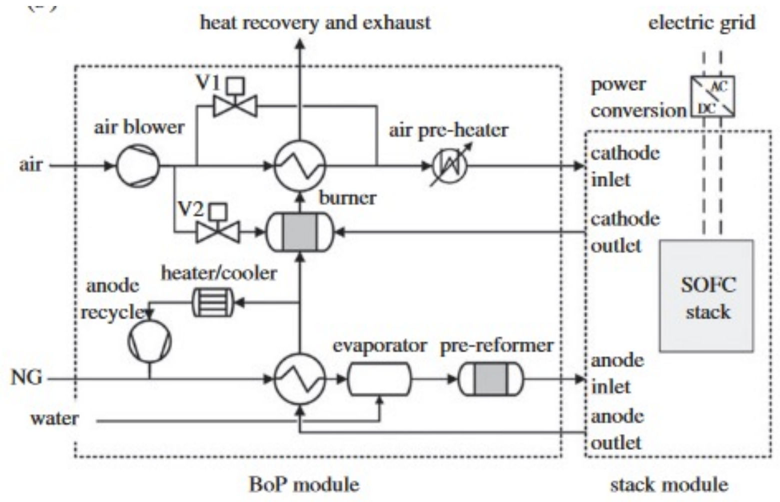
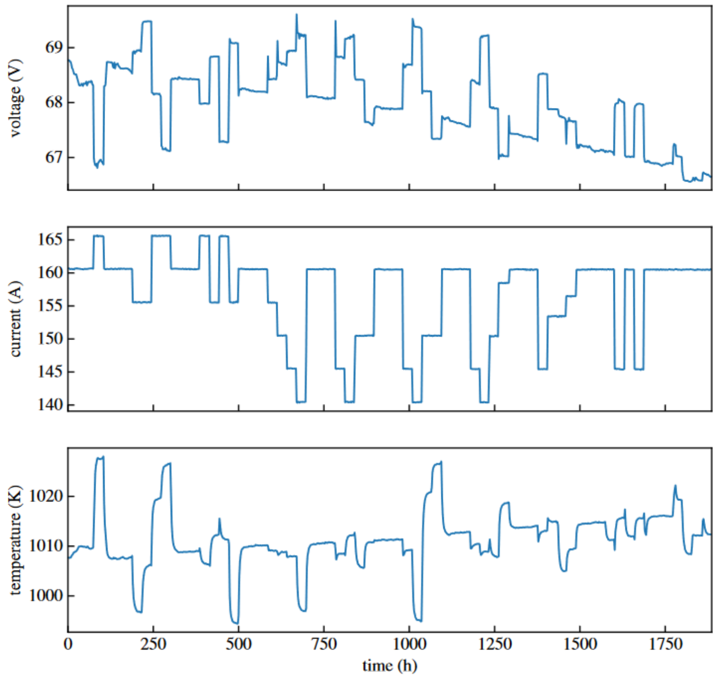
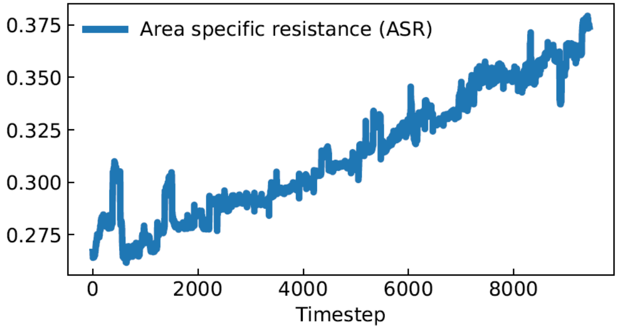
Experimental evaluation

- data from Diamond project are used
- from available process data ASR γ is estimated

$$K_s \frac{dT}{dt} = \dot{E}_{\text{in}}(T_{\text{in}}) - \dot{E}_{\text{out}}(T) - IN_0\left(1.2586 - 0.000252T + \frac{RT}{2F}\ln\frac{p_{H_2}p_{O_2}^{0.5}}{p_{H_2O}} - \gamma\exp\left[\frac{30000}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \times \frac{I}{A}\right)$$







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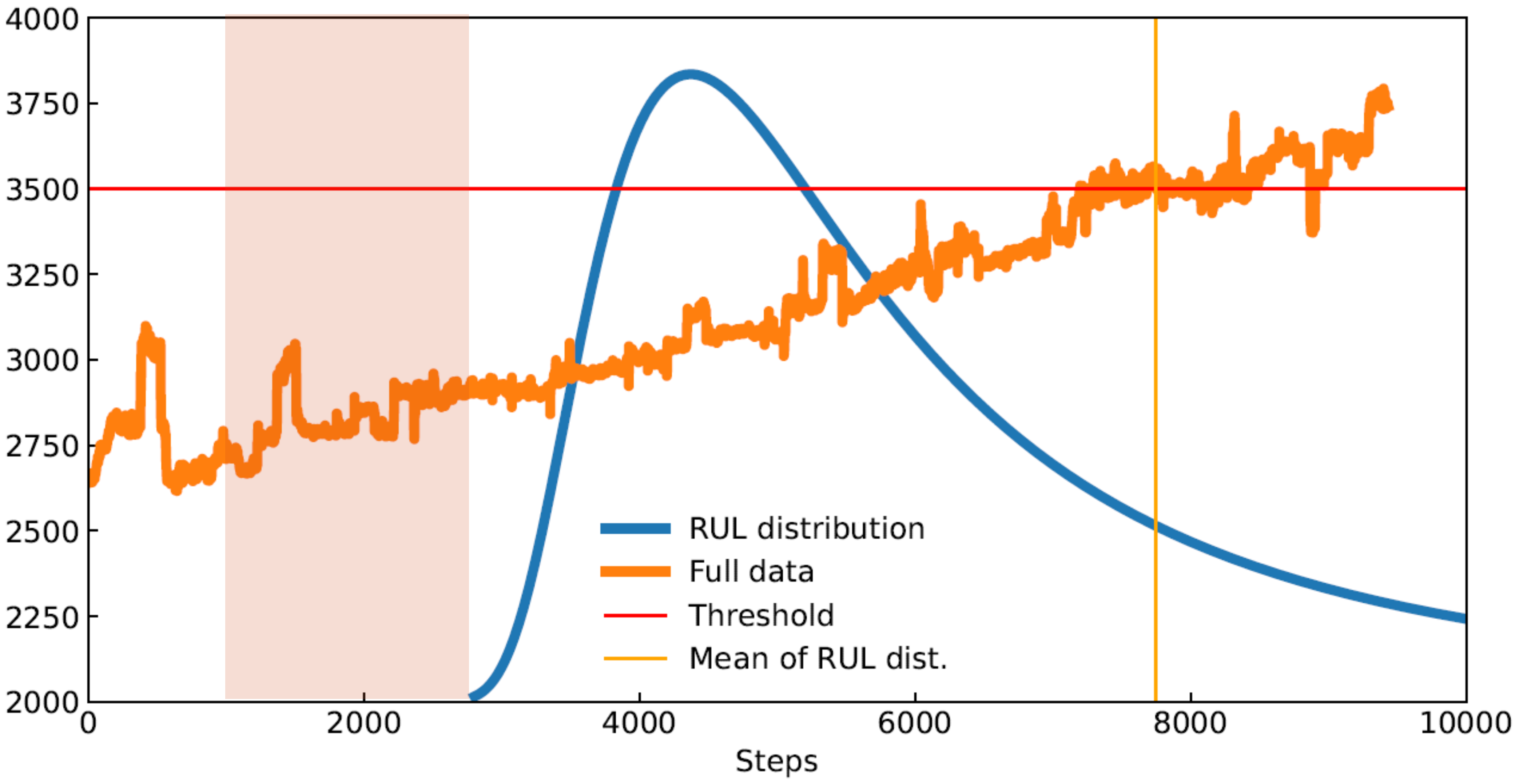
Experimental evaluation (cont'd)



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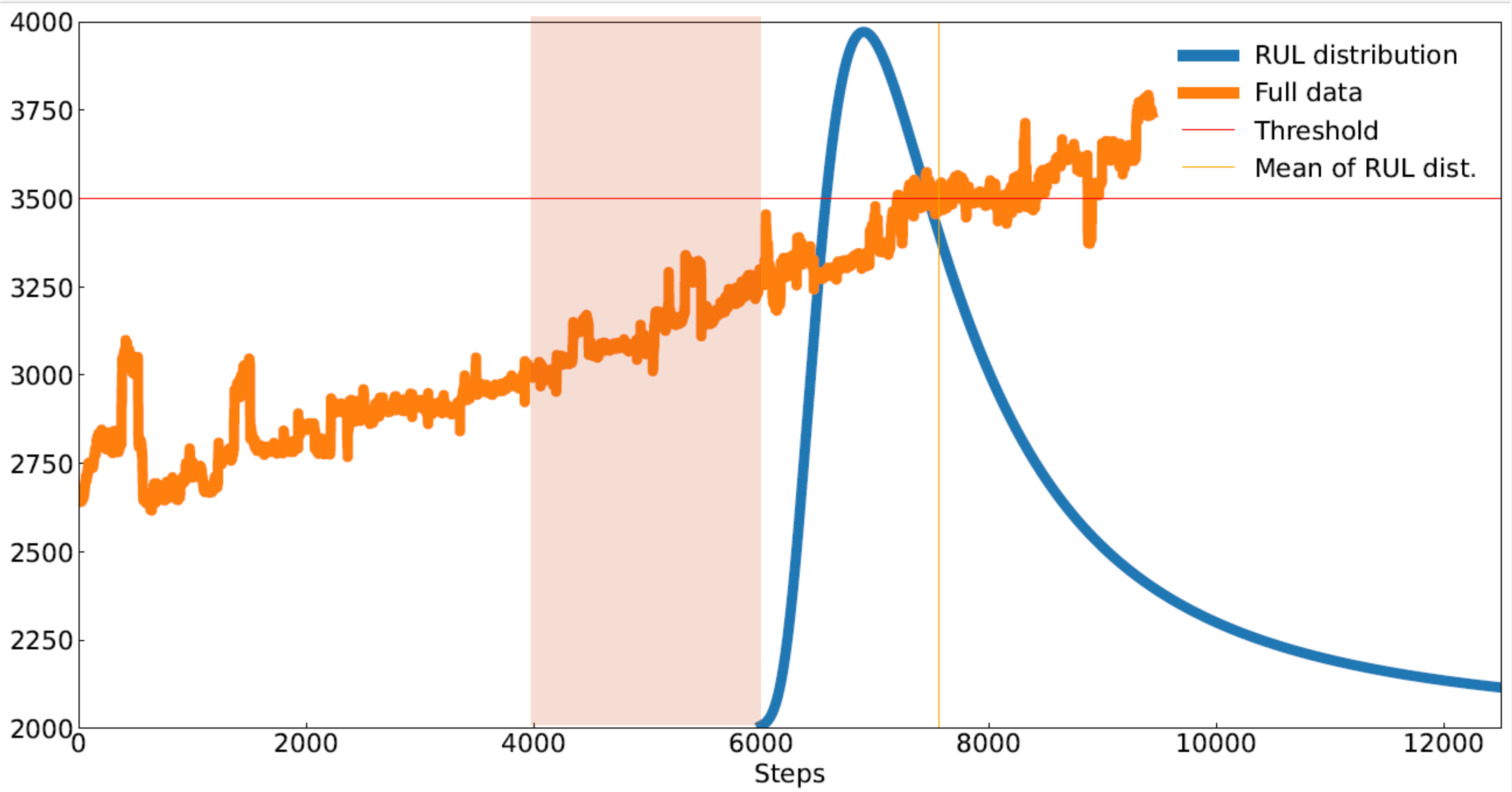
Experimental evaluation (cont'd)



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Conclusions

- a simple algorithm for predicting the remaining useful life is proposed
- it assumes no prior model of the degradation is available and therefore relies on linear trend estimation of a health index
- the key contribution is the analytical expression for the distribution of the RUL
- evaluation is fast and appropriate for implementation on the Bitron platform
- in the demonstrated case the quality of the prediction depends on the quality of the ASR estimates obtained from the lumped stack voltage model
- The quality of the predicted RUL improves when approaching the dead end (acceptable quality of the prediction is achieved usually in the last 30-40% of the overall life

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