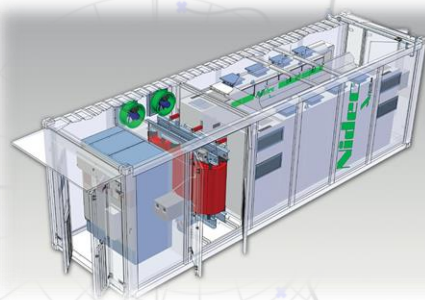




Modelos de vida útil de baterias

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Tópicos a serem abordados

☐ Classificação;

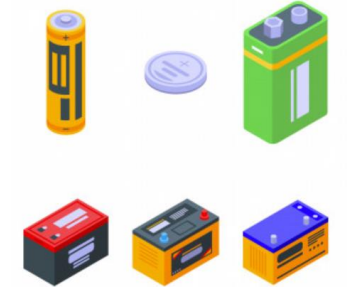


☐ Comparação de abordagens;



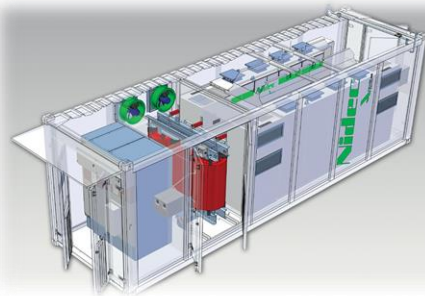
☐ Exemplos de modelos de vida útil.





Classificação de modelos de vida útil

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Critério de falha

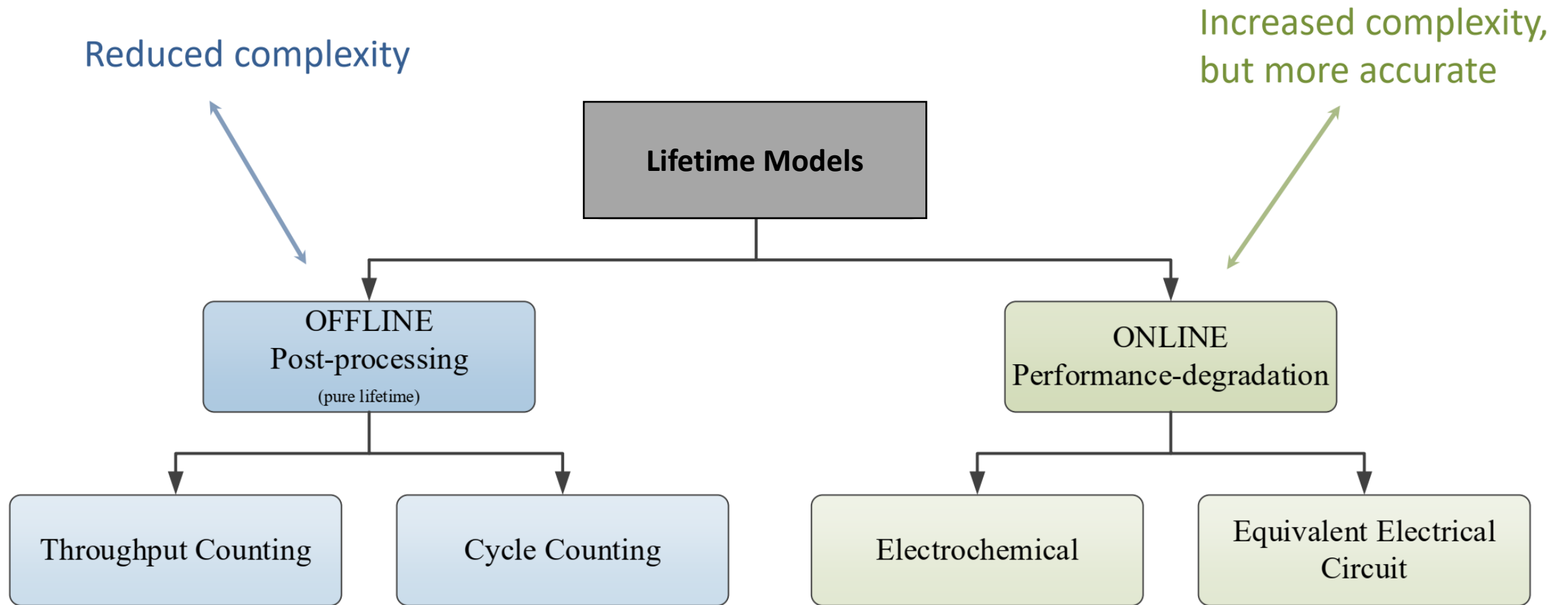
- ❑ Quando a bateria atinge o final da sua vida (EOL)?
- ❑ Definição usual: perda de capacidade de 20% ou aumento de 100% na resistência interna;
- ❑ Estado de saúde (State of Health – SOH):

$$SOH_{cap} = \frac{C}{C_o} \cdot 100$$

$$SOH_{Res} = \frac{R_o}{R} \cdot 100$$

- ❑ Conceito: baterias de segunda vida!!!

Abordagens para determinação de vida útil



Fonte: D. I. Stroe. "Storage Systems based on Lithium-Ion Batteries for Grid Support and Automotive Applications." PhD Course. Aalborg University. 2018

Modelos offline – Apenas tempo de vida!

- ❑ Baseado no cálculo do dano incremental da bateria;
- ❑ Utilizados tipicamente na etapa de planejamento e projeto;
- ❑ Modelo de performance não é incluído;
- ❑ Menor complexidade com o preço de ter uma menor precisão;
- ❑ Classificação:
 - Modelos com entradas em Ah ou Wh (Modelo de Schiffer);
 - Modelos de contagem de ciclos (Rainflow).

Modelos com entradas em Ah ou Wh

- ❑ Computa a degradação ao longo do tempo;
- ❑ Modelos teórico-empíricos são empregados;
- ❑ Considera os valores instantâneos de corrente entregue para as baterias;
- ❑ Fatores de correção para fenômenos que aceleram a degradação;

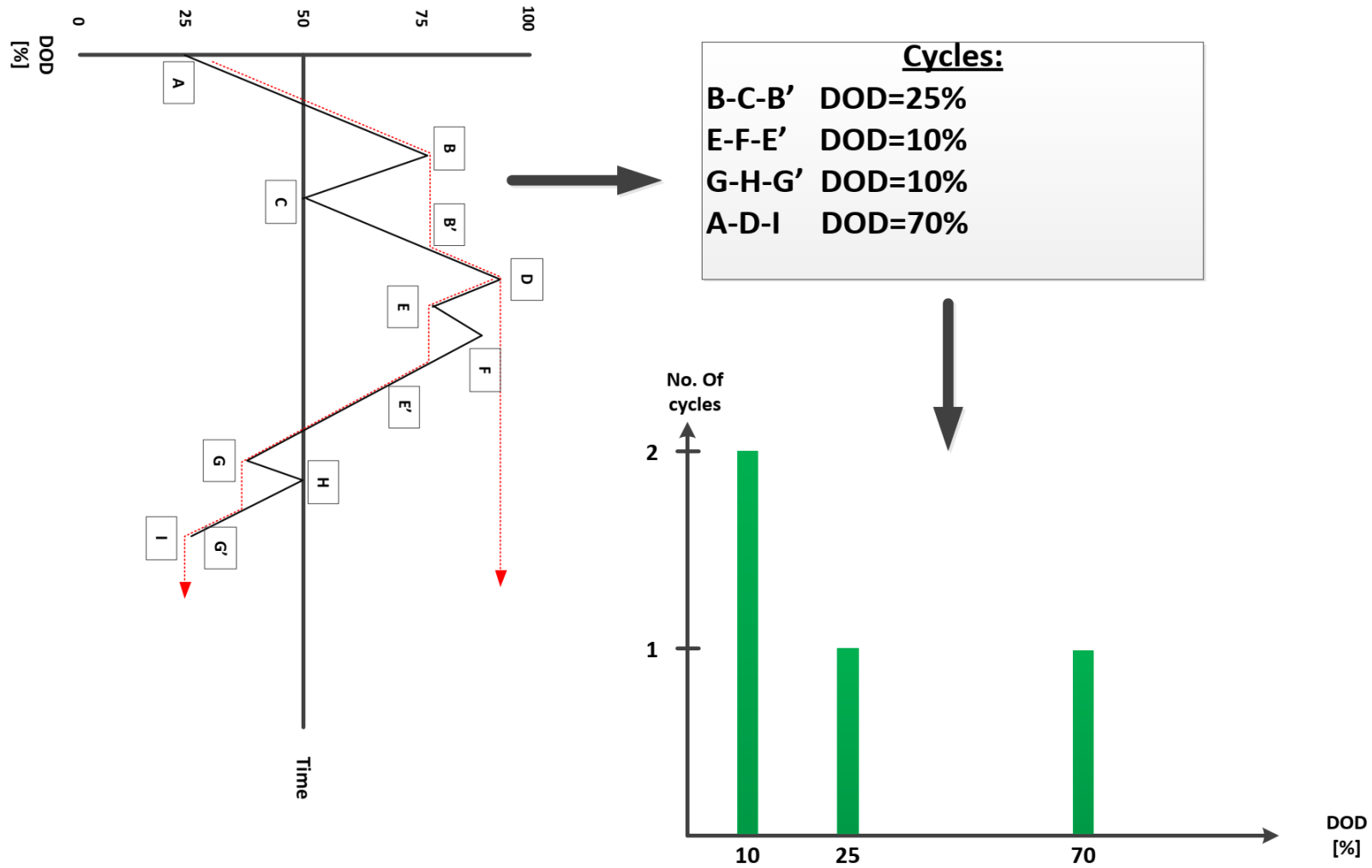
$$C_{deg}(t) = C_{deg,limit} \cdot \exp \left[-C_Z \cdot \left(1 - \frac{Z_W(t)}{1.6 \cdot Z_{IEC}} \right) \right] \quad Z_W(t + \Delta t) = Z_W(t) + \frac{|I_{disch_bat}(t)| \cdot f_{SOC}(t) \cdot f_{acid}(t) \cdot \Delta t}{C_N}$$

Modelos de contagem de ciclos

- ❑ Baseado na caracterização dos ciclos;
- ❑ Modelos empíricos do tempo de vida são empregados;
- ❑ Consideração 1: A ordem do carregamento não afeta o tempo de vida;
- ❑ Consideração 2: O acúmulo de dano é independente do nível do estresse;
- ❑ Regra de Palmgren-Miner:

$$LC = \sum_i^n \frac{1}{N_{f,i}}$$

Funcionamento do algoritmo Rainflow



Fonte: D. I. Stroe. "Storage Systems based on Lithium-Ion Batteries for Grid Support and Automotive Applications." PhD Course. Aalborg University. 2018

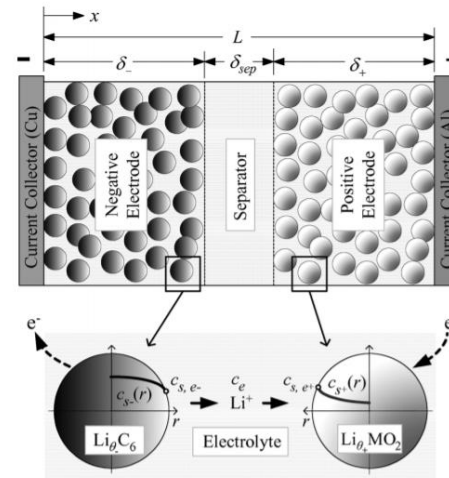
Modelos online

- ❑ Combina o modelo de vida útil e o modelo de performance;
- ❑ Considera a variação dos parâmetros ao longo da vida da bateria;
- ❑ **Exemplo:** estado de carga varia com a degradação!
- ❑ Mais preciso que os modelos offline;
- ❑ Classificação
 - Modelos físico-químicos;
 - Modelos baseados no circuito equivalente.

Modelos físico-químicos

- ❑ Modela as propriedades físicas dos eletrodos e eletrólito;
- ❑ Modelagem precisa da degradação;
- ❑ Problemas:
 - Requer conhecimento da físico-química da bateria;
 - Conhecimento de mais de 50 parâmetros!

$$\begin{aligned} \frac{\bar{V}(s)}{\bar{I}(s)} = & \frac{1}{AF} \left(\frac{\partial U_+}{\partial c_{s+}} \frac{1}{\delta_+ \varepsilon_{s+}} - \frac{\partial U_-}{\partial c_{s-}} \frac{1}{\delta_- \varepsilon_{s-}} \right) \frac{1}{s} \\ & - \frac{\frac{\partial U_-}{\partial c_{s-}} \Delta \bar{c}_{s,e}(0,s) + \bar{\eta}(0,s) - \Delta \bar{\phi}_{e-}^{jLi}(0,s)}{\bar{I}(s)} \\ & + \frac{\frac{\partial U_+}{\partial c_{s+}} \Delta \bar{c}_{s,e}(L,s) + \bar{\eta}(L,s) + \Delta \bar{\phi}_{e+}^{jLi}(L,s)}{\bar{I}(s)} \\ & + \frac{\Delta \bar{\phi}_e^{c_e}(L,s)}{\bar{I}(s)} - \frac{R_f}{A} \end{aligned}$$

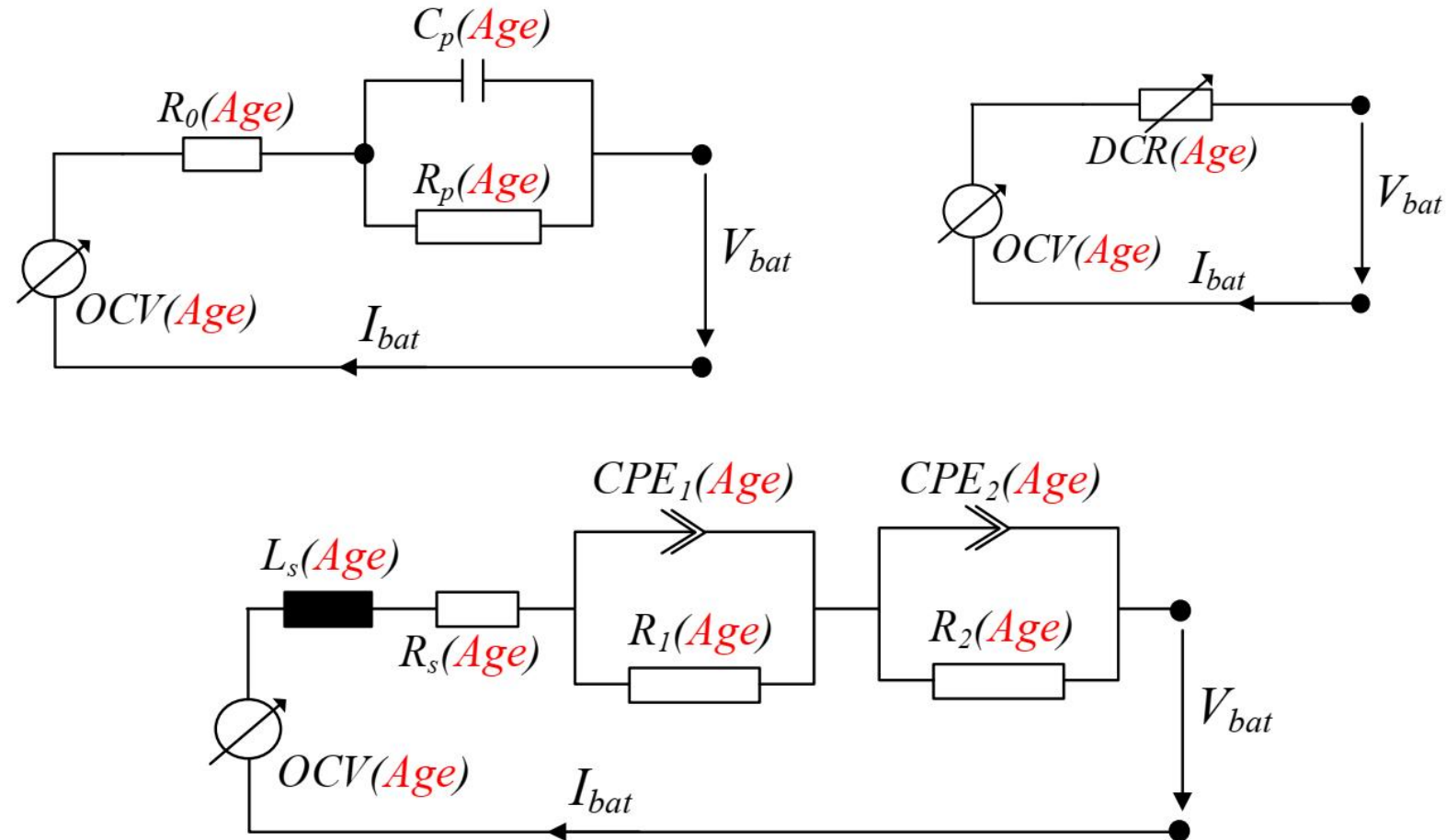


MODEL PARAMETERS FOR 6 AH LI-ION HEV BATTERY

Parameter	Symbol	Negative Electrode	Separator	Positive Electrode
Thickness [cm]	δ	50×10^{-4}	25.4×10^{-4}	36.4×10^{-4}
Particle radius [cm]	R_s	1×10^{-4}		1×10^{-4}
Solid phase Li diffusion coefficient [cm ² /s]	D_s	2.0×10^{-12}		3.7×10^{-12}
Active material volume fraction	ε_s	0.580		0.500
Solid phase conductivity [S/cm]	σ^{eff}	$1.0 \varepsilon_s$		$0.1 \varepsilon_s$
Charge transfer resistance [$\Omega \text{ cm}^2$]	R_{ct}	7.14		9.88
Maximum solid phase concentration [mol/cm ³]	$c_{s,max}$	16.1×10^{-3}		23.9×10^{-3}
Stoichiometry at 0% SOC	$\theta_{0\%}$	0.126		0.936
Stoichiometry at 100% SOC	$\theta_{100\%}$	0.676		0.442
Electrolyte volume fraction	ε_e	0.332	0.5	0.330
Bruggeman tortuosity exponent	p	1.5	1.5	1.5
Parameter	Symbol	Value		
Electrolyte phase Li ⁺ diffusion coefficient [cm ² /s]	D_e^{eff}	$D_e = 2.6 \times 10^{-4}$, $D_e^{eff} = D_e \varepsilon_e^p$		
Electrolyte phase ionic conductivity [S/cm]	κ^{eff}	$\kappa = 15.8 c_e \exp(0.85(1000/c_e)^{1.4})$, $\kappa^{eff} = \kappa \varepsilon_e^p$		
Average electrolyte concentration [mol/cm ³]	$c_{e,0}$	1.2×10^{-3}		
Li ⁺ transference number	t_e^+	0.363		
Electrode plate area [cm ²]	A	10452		
Foil contact resistance [$\Omega \text{ cm}^2$]	R_f	20		
Negative Electrode Equilibrium Potential [V]	U_-	$U_-(\theta) = 8.00229 + 5.0647\theta - 12.578\theta^{1.2}$ $- 8.6322 \times 10^{-4} \theta^{-1} + 2.1765 \times 10^{-5} \theta^{1.2}$ $- 0.46016 \exp[15.0(0.06 - \theta)]$ $- 0.55364 \exp[-2.432(\theta - 0.92)]$		
Positive Electrode Equilibrium Potential [V]	U_+	$U_+(\theta) = 85.681\theta^2 - 357.70\theta^3 + 613.89\theta^4$ $- 555.65\theta^5 + 281.06\theta^6 - 76.648\theta^7$ $- 0.30987 \exp(5.657\theta^{1.1}) + 13.1983$		

Fonte: K. A. Smith. "Model-based Electrochemical Estimation and Constraint management for Pulse Operation of Lithium-Ion Batteries." IEEE Trans. Control Systems Theory. 2010.

Modelos baseados em circuitos equivalentes



Fonte: D. I. Stroe. "Storage Systems based on Lithium-Ion Batteries for Grid Support and Automotive Applications." PhD Course. Aalborg University. 2018

Comparação de abordagens

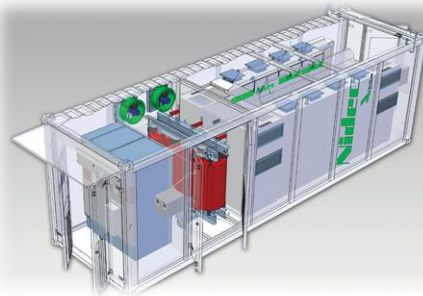
Condition	Lifetime Modelling Approach			
	<i>Cycle Counting</i>	<i>Throughput Counting</i>	<i>Electrochemical</i>	<i>EEC</i>
<i>Complexity</i>	Reduced	Reduced	High	Medium
<i>Computation Time</i>	Reduced	Reduced	High	Medium
<i>Accuracy</i>	Medium	Reduced	Very High	High
<i>Parametriz.</i>	Data-sheet	Data-sheet	Complex lab. measurements	Lab. measurements
<i>Output</i>	RUL	RUL	RUL, SOH, Voltage	RUL, SOH, Voltage
<i>Transfer to other chemistry</i>	No	No	Yes	No

Fonte: D. I. Stroe. “Storage Systems based on Lithium-Ion Batteries for Grid Support and Automotive Applications.” PhD Course. Aalborg University. 2018

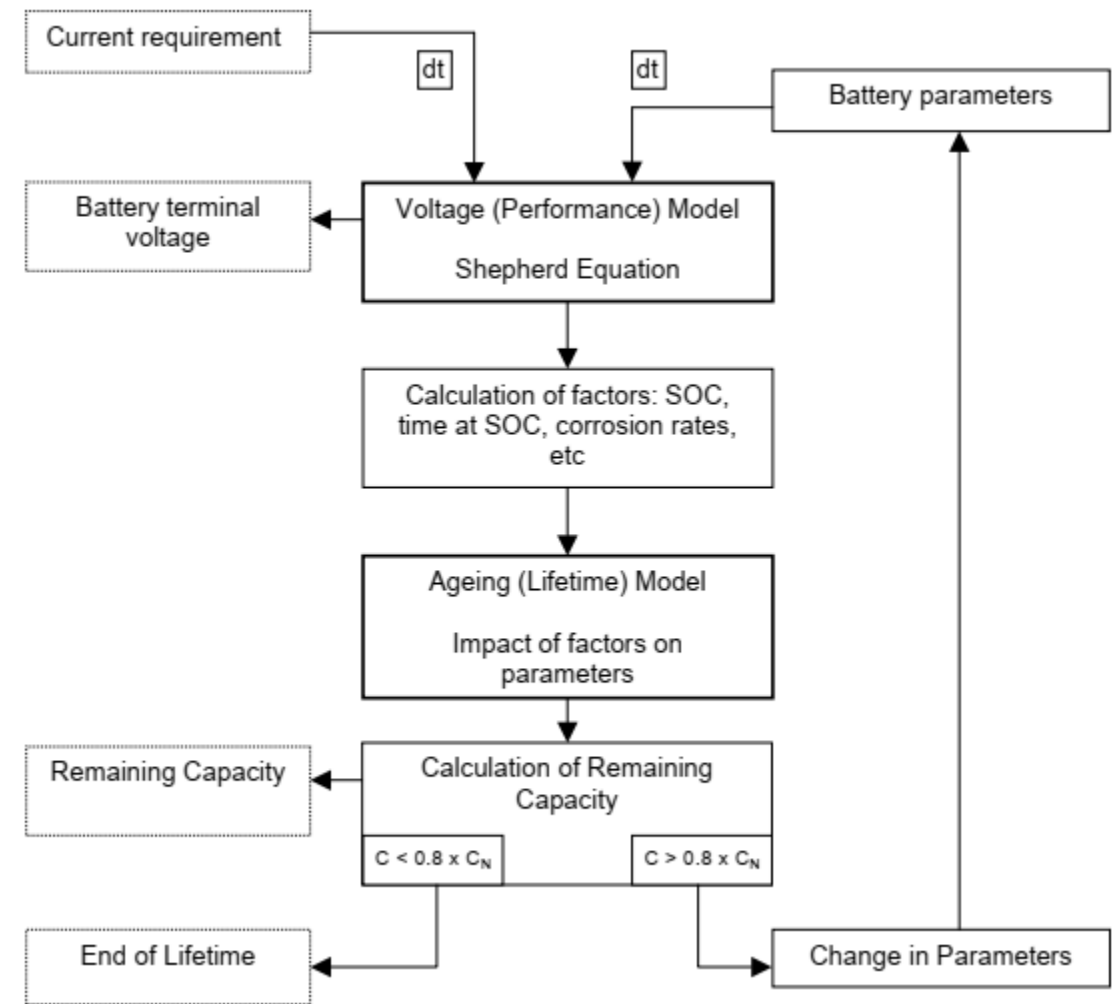
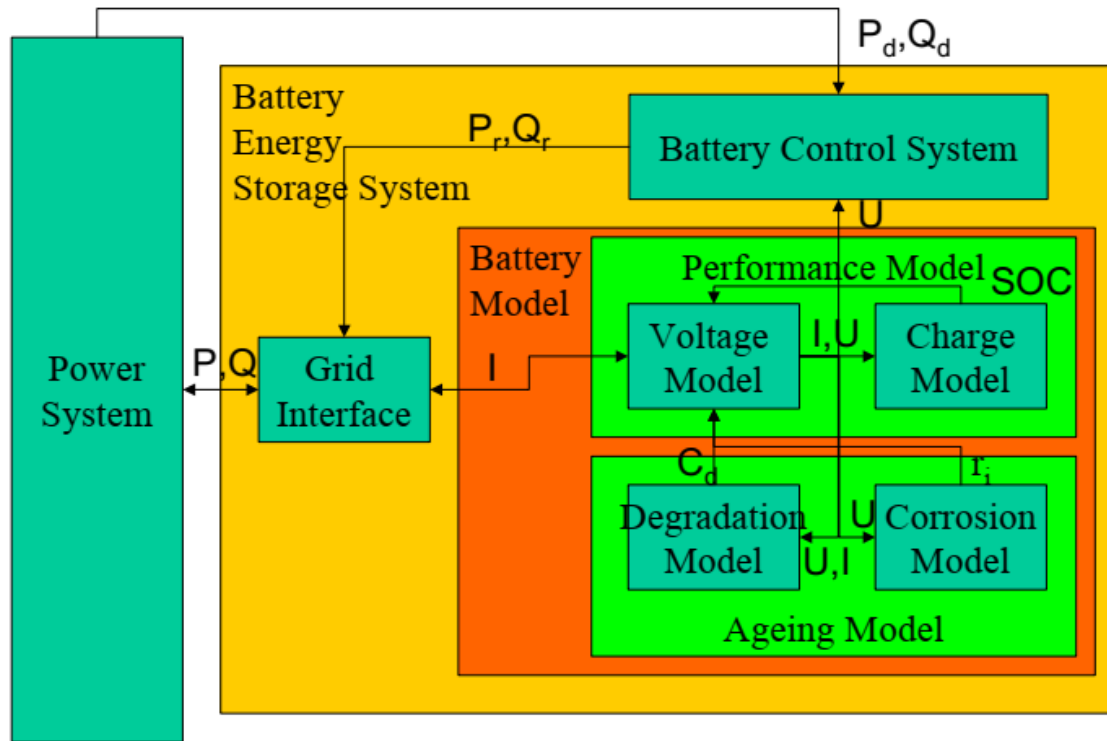


Exemplos de modelos de vida útil

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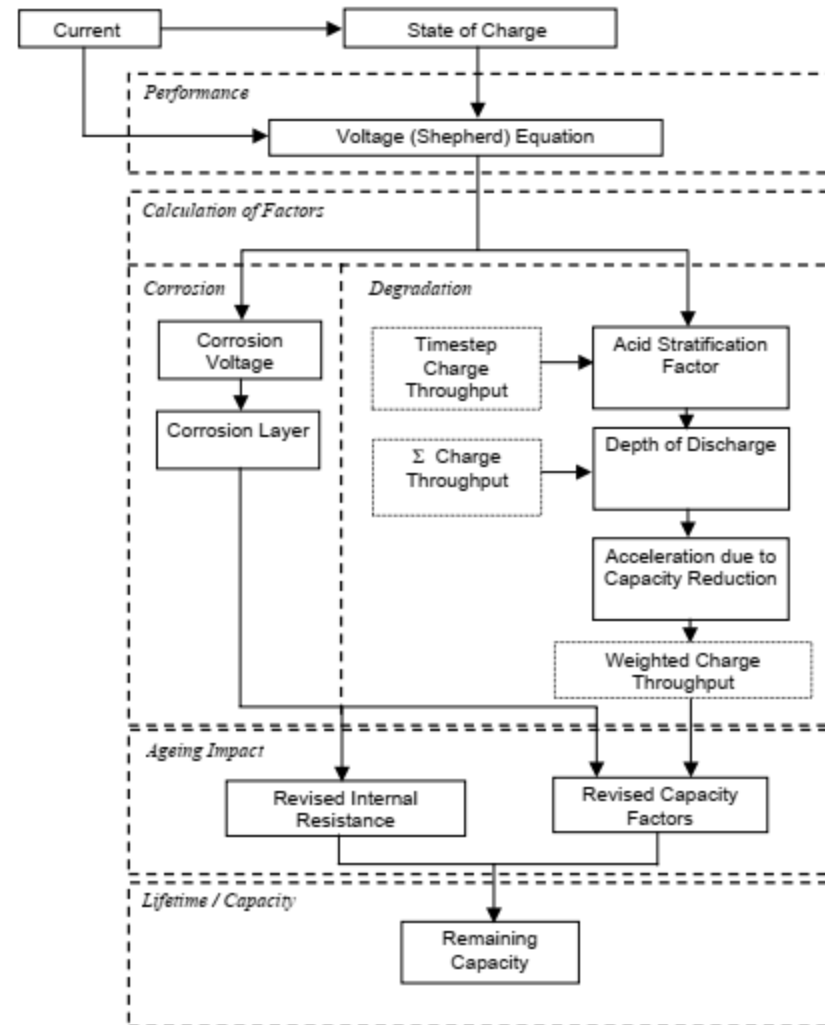


Modelo de vida útil para baterias de chumbo ácido (1)



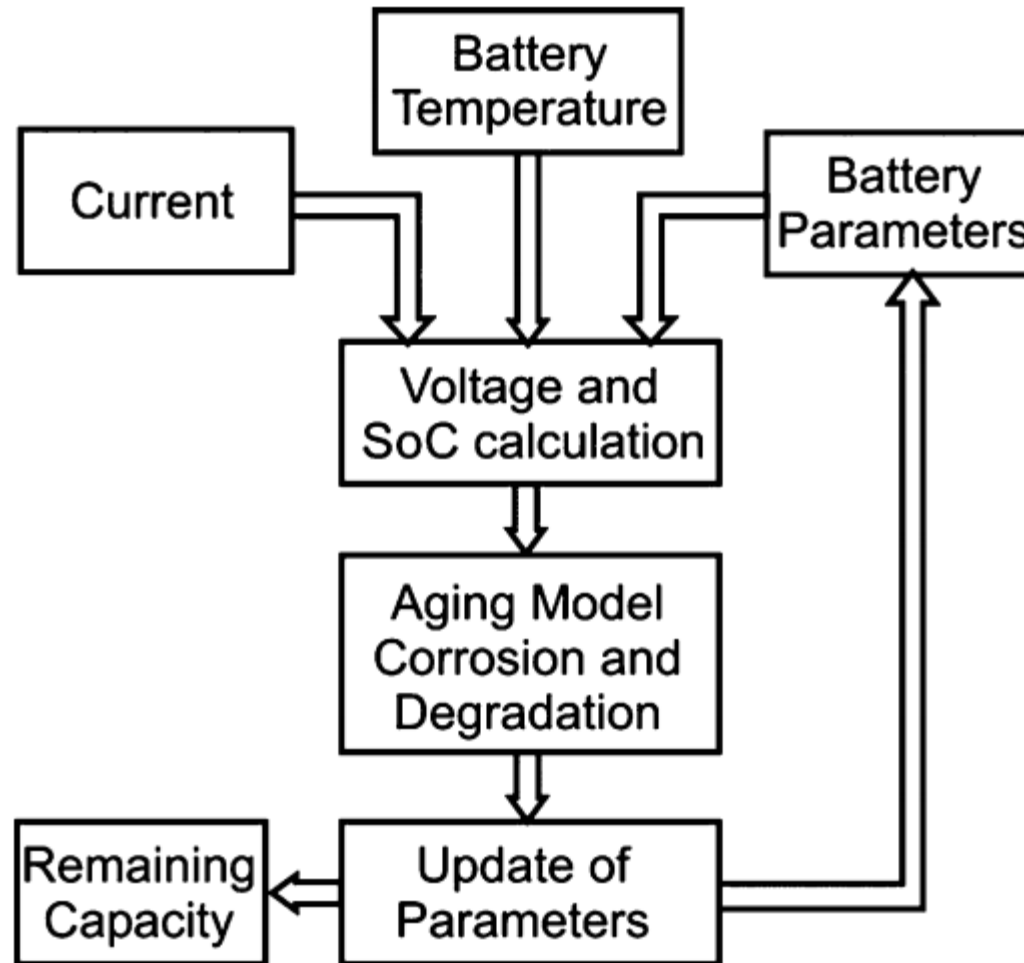
Fonte: H. Bindner et. al. "Lifetime Modelling of Lead Acid Batteries". Risø National Laboratory. 2005.

Modelo de vida útil para baterias de chumbo ácido (1)



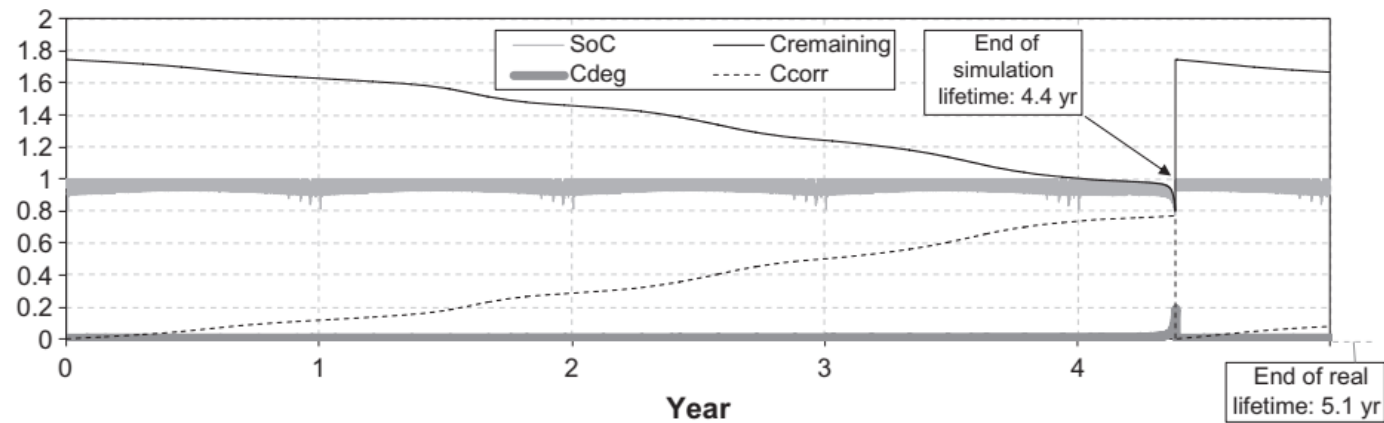
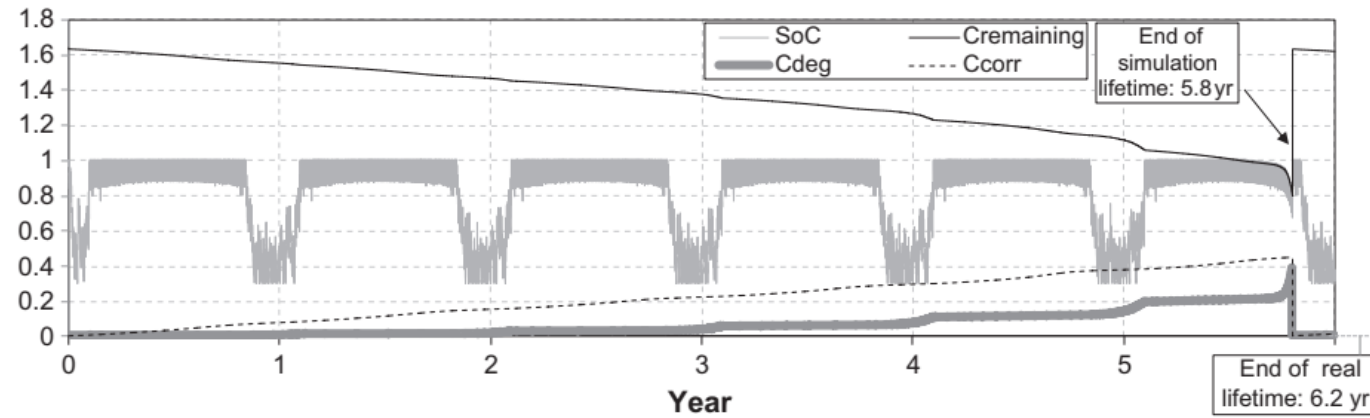
Fonte: H. Bindner et. al. "Lifetime Modelling of Lead Acid Batteries". Risø National Laboratory. 2005.

Modelo de vida útil para baterias de chumbo ácido (2)



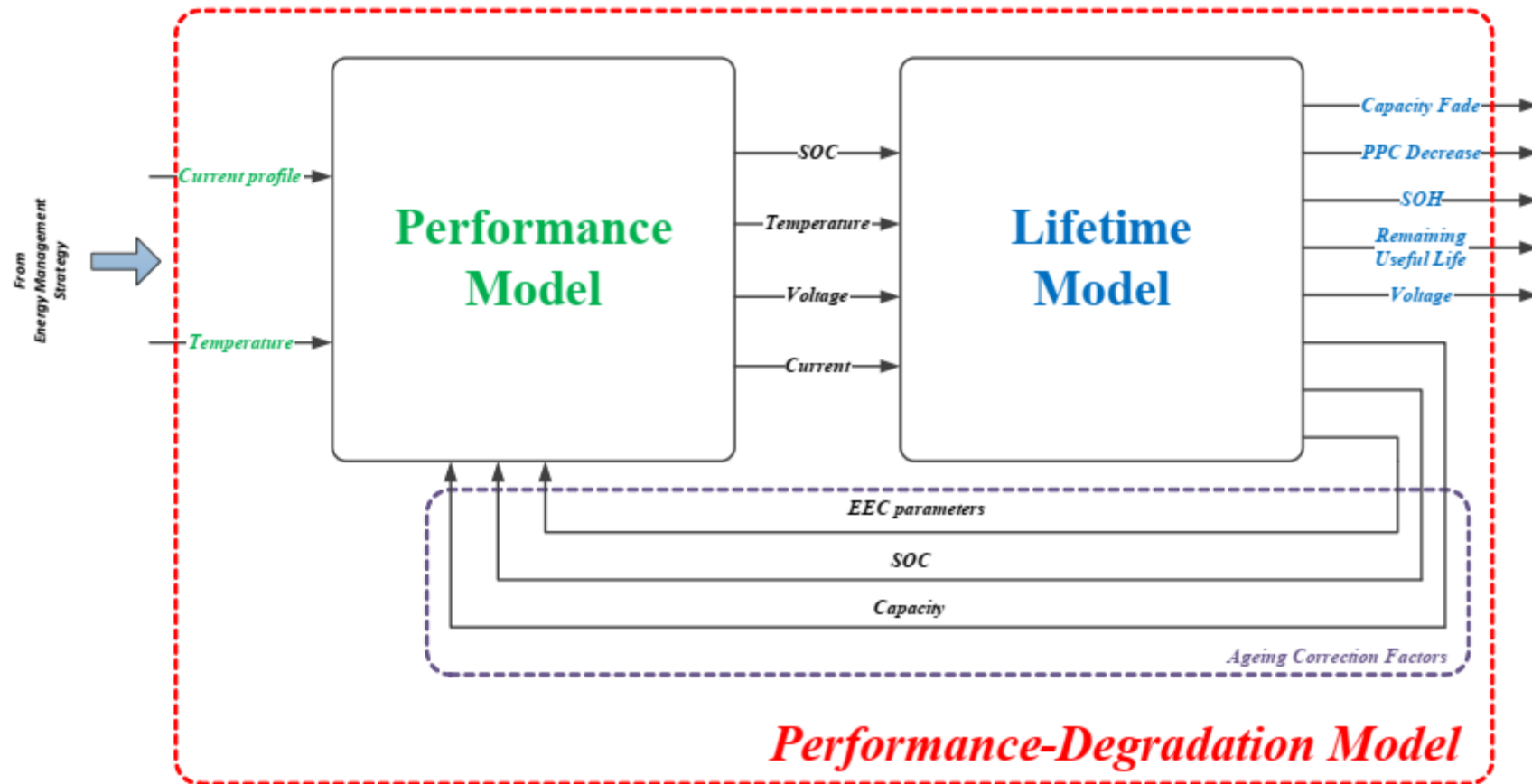
Fonte: J. Schiffer et. Al. “Model prediction for ranking lead-acid batteries according to expected lifetime in renewable energy systems and autonomous power-supply systems”. Journal of Power Sources. 2007.

Exemplo de utilização do modelo (2)



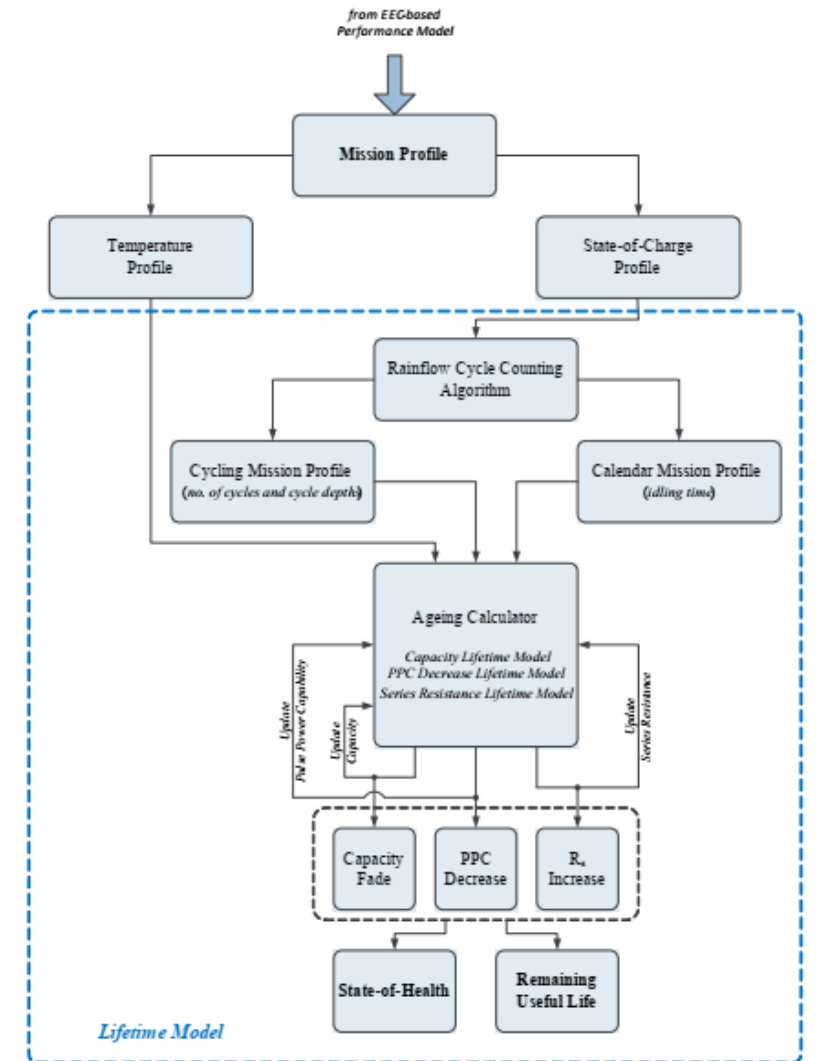
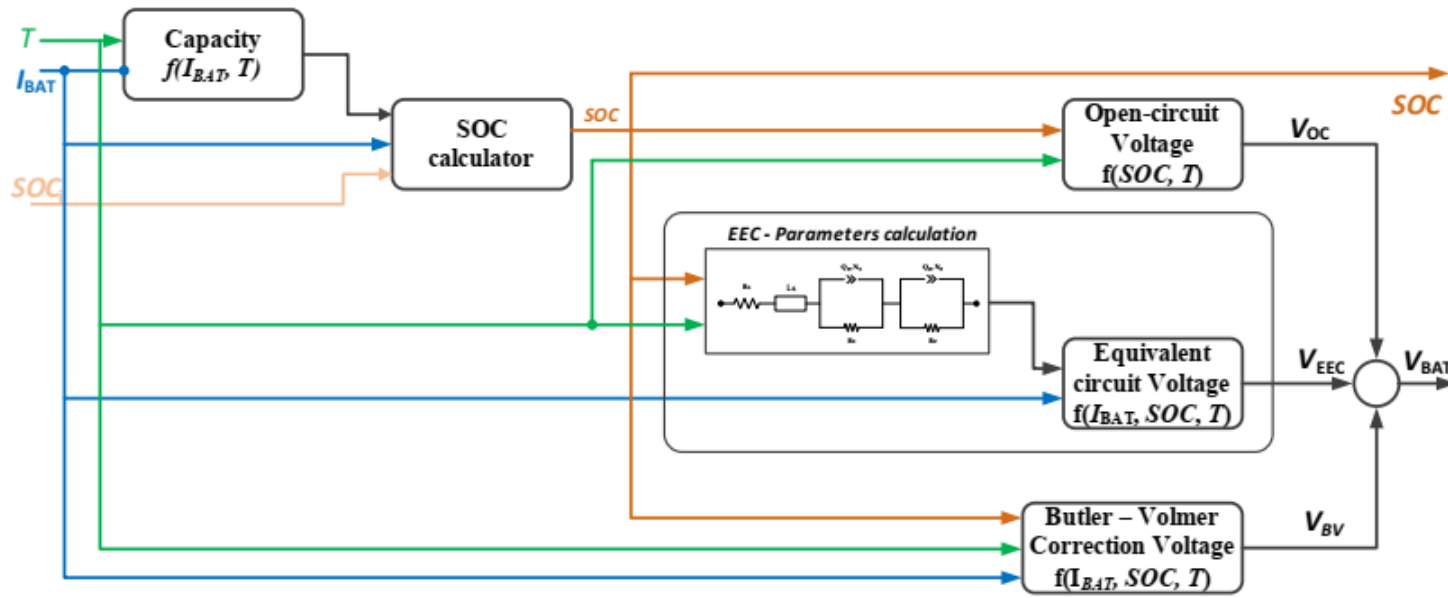
Fonte: R. Dufo-López et. al. “Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems”. Applied Energy. 2014.

Modelo de vida útil para baterias lítio-íon



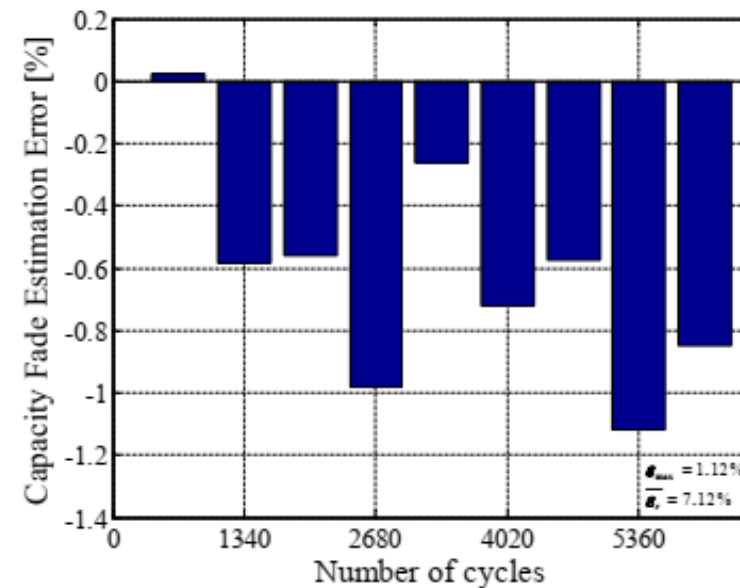
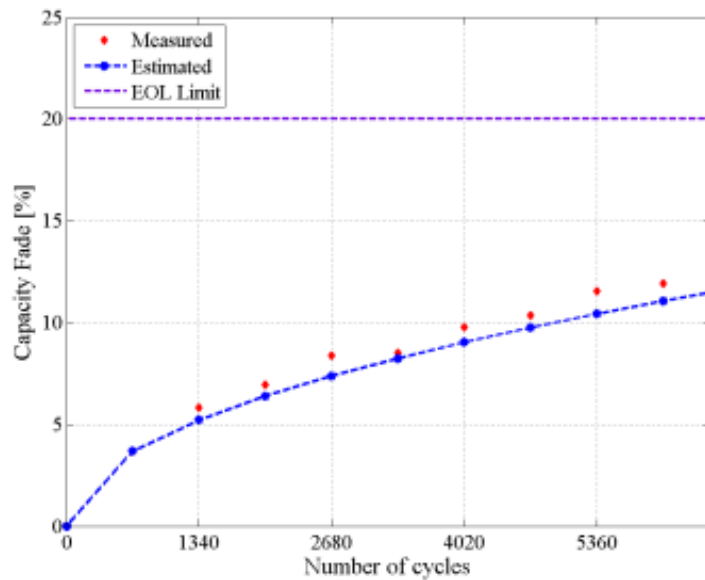
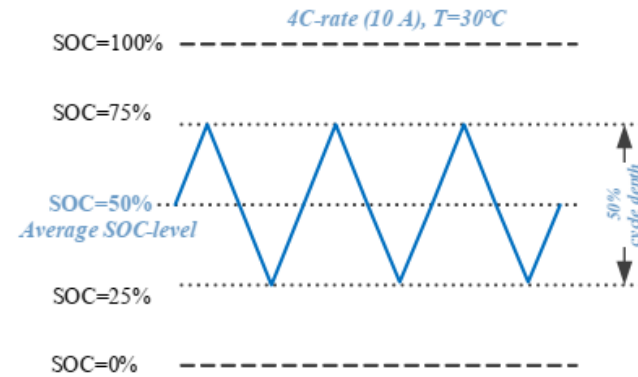
Fonte: D. I. Stroe. "Lifetime Models for Lithium Ion Batteries used in Virtual Power Plants". PhD Thesis. Aalborg University. 2014

Modelo de vida útil para baterias lítio-íon



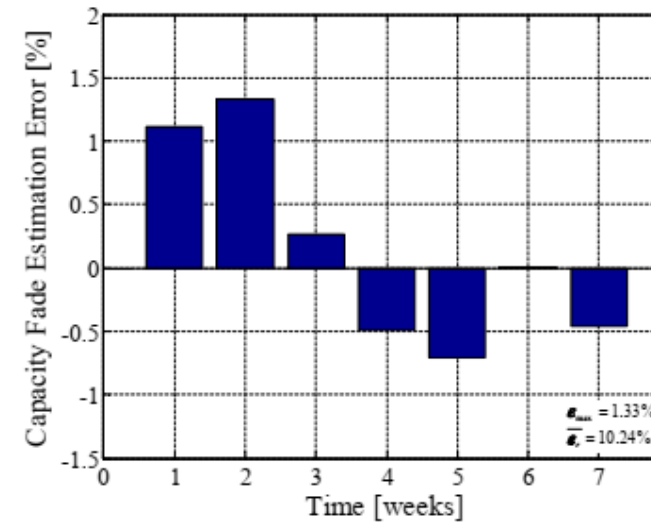
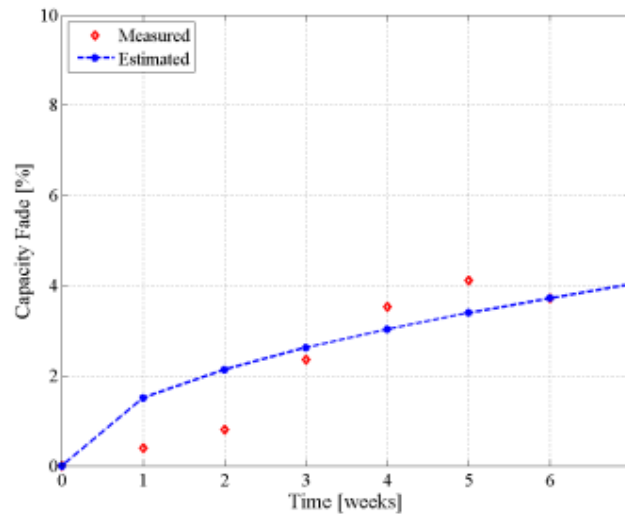
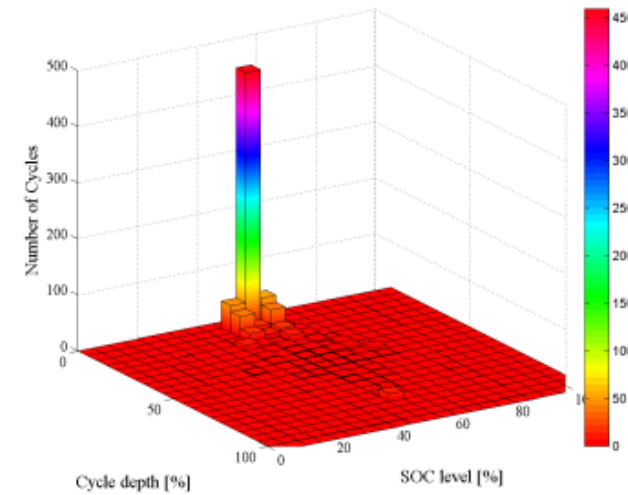
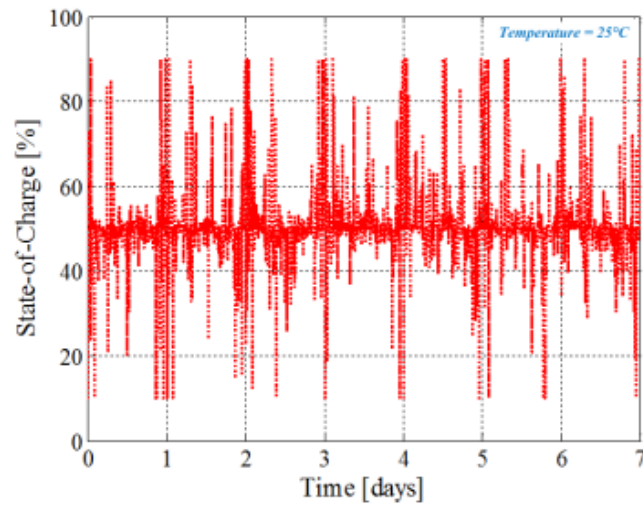
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Modelo de vida útil para baterias lítio-íon



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Modelo de vida útil para baterias lítio-íon



Fonte: D. I. Stroe. “Lifetime Models for Lithium Ion Batteries used in Virtual Power Plants”. PhD Thesis. Aalborg University. 2014

Obrigado pela Atenção



Bons estudos!



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