A Value-based Maintenance Strategy for Systems under Imperfect Maintenance

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همایش
بین‌المللی مدیران فنی و نگهداری و تعمیرات

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Outline

* Introduction
* Research objective
* Basic Assumptions
* Degradation model
* Maintenance model
* Optimization model
* Numerical example
* Conclusions & future works

Value vs. Cost

"Price is what you pay, value is what you get."

Warren Buffett

Introduction

* Operations and Maintenance **Costs**
  * 60–70% of the overall generating cost in nuclear power plants [1]
  * 14%-30% of the generating cost in offshore wind farms [2]

[1] Coble, J., et al., A review of prognostics and health management applications in nuclear power plants. International Journal of Prognostics and Health Management, 2015. 6: p. 016-None.

[2] Martin, R., et al., Sensitivity analysis of offshore wind farm operation and maintenance cost and availability.

Introduction

* Focus: minimizing maintenance cost
  * Results: cost-centric models
  * Missing: contribution of maintenance to system value
    * Example: improved system reliability

Introduction

* **Maintenance as a value-generating action**
  * Scarce literature
  * **Promising results:** more sophisticated maintenance strategies
  * **Considerations:** quantifying maintenance, monitoring frequency, maintenance threshold; interacting components, …

Introduction

Imperfect Maintenance

Minimal Repair ⟷ **Renewal Process**

Research Objective

* **Objective:**
  * **A value-based maintenance strategy**
    * System is subject to degradation.
    * System receives periodic monitoring (constant monitoring interval).
    * System receive imperfect maintenance.
  * **Maximize the net value**
  * **Variables:**
    * Length of the monitoring interval (ζ)
    * Degradation level after imperfect preventive repairs (x_r)

The Major Issue

* Unlike maintenance cost, it is difficult to formulate maintenance from the value perspective.
* In this research, the revenue generated during the preventive cycles is the maintenance value.

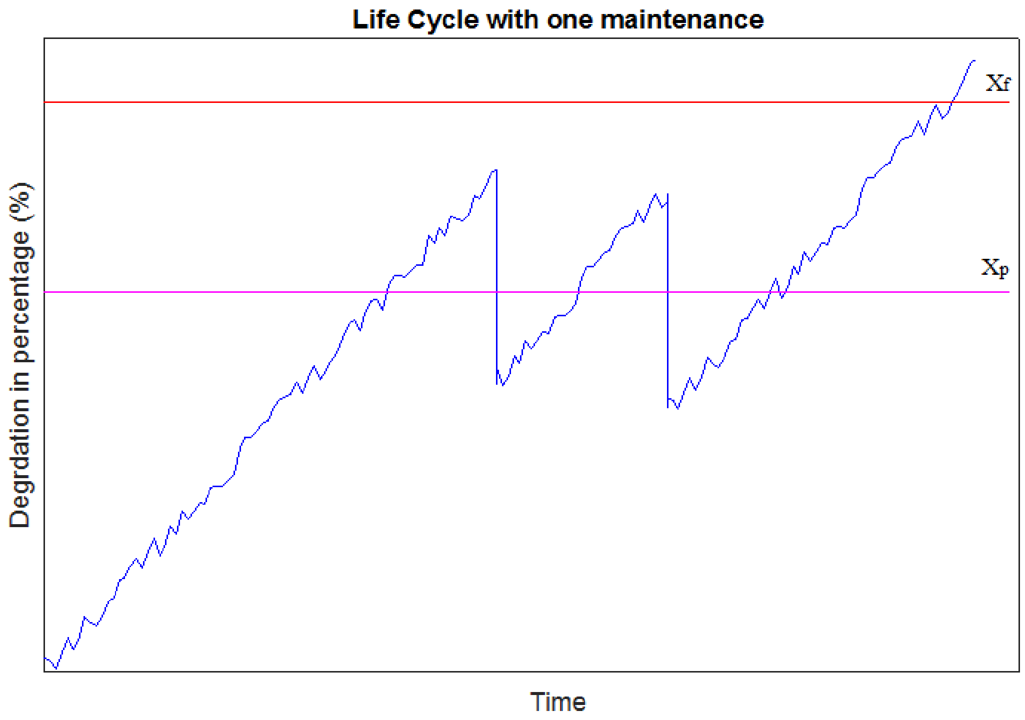
Net Value = Revenue – Costs

$$Z = V - C$$

Basic Assumptions

* X_p: threshold between normal state and potential failure

* X_f : threshold between potential and functional failure



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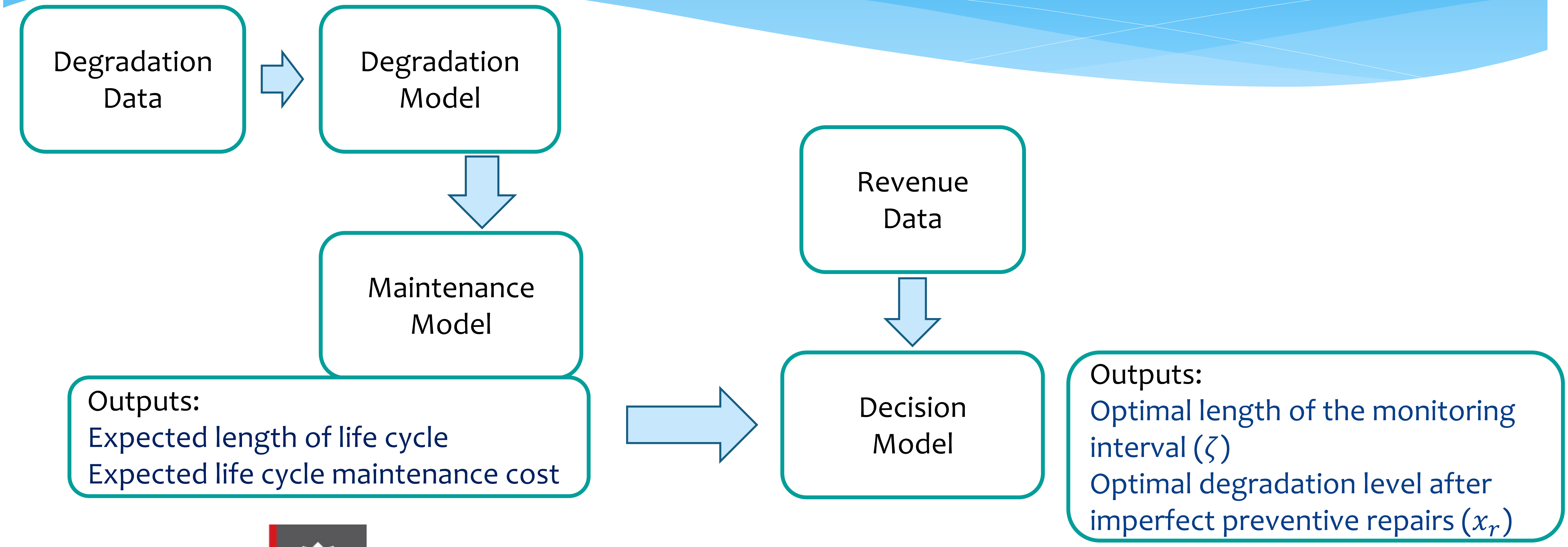
Basic Assumptions

* Duration of imperfect repair is negligible.
* The only cause of system failure is degradation.
* Degradations before and after repair are independent.
* Degradation is monotonic.
* Cost of imperfect maintenance depend on the maintenance degree.
* Degradation threshold are pre-determined.
* Functional failures are detected only by monitoring.

[3] Wu, F., et.al, **A cost effective degradation-based maintenance strategy under imperfect repair**. Reliability Engineering & System Safety, 2015. 144: p. 234-243

Methodology



Degradation Model

* Cumulative degradation:

$$D(t_i) = \Phi + \theta e^{\beta t_i + \varepsilon(t_i)} \quad i = 1,2, \ldots ; \; 0 \le t_1 \le t_2 \le ..$$

* Log form:

$$L(t_i) = \ln(D(t_i) - \Phi) = ln\theta + \beta t_i + \varepsilon(t_i)$$

  * Common characteristics: ϑ and β (mutually independent)
  * $ln\theta$ has a normal distribution
  * Unique characteristics: $\varepsilon(t_i)$. The error term follows a Markov process
* Let $L(t_0) = 0$ and $\theta' = ln\theta$:

$$\boldsymbol{L(t_i) = \theta' + \beta t_i + \varepsilon(t_i)}$$

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Maintenance Model
Expected length of life cycle

- Three cycles: the first cycle, repair cycles, failure cycle.
- The first cycle and the failure cycle are not affected by maintenance activities (no value for maintenance).
- From value perspective

$$LC(x_r, \zeta) = E[Preventive\ cycles] * (E[Np] - 1)$$

- Two cases, two probabilities for
  - Case 1: at least one repair before the failure

$$P_P(i, x, \zeta) = P\{D_1 < x_p, \dots, D_{i-1} < x_p, x_p < D_i < x_f \mid D_0 = x\}$$

  - Case 2: failure occurs before the first repair

$$P_F(i, x, \zeta) = P\{D_1 < x_p, \dots, D_{i-1} < x_p, x_f < D_i \mid D_0 = x\}$$

Maintenance Model
Expected length of life cycle

$$P_f(x,\zeta) + P_P(x,\zeta) = 1$$

$$E[Length\ Repair\ Cycles] = \sum_{i=1}^{\infty}(i\zeta)P_P\,(i, x_r, \zeta)$$

$$(Np) \sim Geom\left(P_f(x_r,\zeta)\right) \rightarrow E[Np-1] = \frac{1}{P_f(x_r,\zeta)} - 1 = \frac{P_P(0;\zeta)}{P_f(x_r;\zeta)}$$

$$\boldsymbol{LC(x_r,\zeta) = \left(\frac{P_P(0;\zeta)}{P_f(x_r;\zeta)}\right)\sum_{i=1}^{\infty}(i\zeta)P_P\,(i, x_r, \zeta)}$$

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Maintenance Model
Expected life cycle maintenance cost

$$\boldsymbol{TC(\zeta, x_r) = C_f + E[N_p + 1]C_m + E[N_p]E[C_p]}$$

* C_f: cost of failure
* C_m: cost of monitoring
* C_p: cost of repair = $M \cdot E[R] + C_s$
  * C_s: fixed cost of repair
  * M: a known proportional constant
  * $E[R]$: expected degradation reduction after repair

$$E[R] = \ln\theta + \beta \sum_{i=1}^{\infty} (i\zeta) P_P(i, x_r, \zeta) - x_r$$

Optimization Model

$$\boldsymbol{Max\ Z = LC(x_r, \zeta) * RV - TC(\zeta, x_r)}$$

s.t. $\boldsymbol{0 < E[R] < X_p}$

- The constraint implies that the degradation level after a repair cannot be greater than $\mathrm{X_p}$.

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Numerical Example

- $\mu_\theta = 1$ and $\sigma_\theta{}^2 = 0.01$.
- $\beta = 0.125$
- Error: univariate autoregressive–moving-average (ARMA) process for error terms with lag = k (k = 1,2,…).
  - Centered at zero.
  - Two settings are examined: lag = 2, and lag = 3.
- 1000 sets of degradation data generated.
- The discrete values of the length of monitoring interval and the degradation reduction after preventive repair:

$$\zeta = [25, 50, 75, 100, 125, 150], \quad x_r = [2, 4, 6, 8, 10]$$

Numerical Example

LAG = 2						
Number of monitoring		Xr				
		2	4	6	8	10
Zeta	25	17	1175	1266	1312	1350
	50	7	8	23	227	288
	75	4	4	5	7	17
	100	3	3	3	3	4
	125	2	3	3	3	3

LAG = 3						
Number of monitoring		Xr				
		2	4	6	8	10
Zeta	25	18	997	997	997	997
	50	7	9	34	498	498
	75	4	5	5	9	46
	100	3	3	3	4	5
	125	3	3	4	4	4

Numerical Example

LAG = 2

Cost		Xr 2	Xr 4	Xr 6	Xr 8	Xr 10
Zeta	25	84.5	5295.5	5705	5912	6083
	50	63.5	72	199.5	1933.5	2452
	75	50	50	62.5	87.5	212.5
	100	45.5	45.5	45.5	45.5	62
	125	33	53.5	53.5	53.5	53.5

LAG = 3

Cost		Xr 2	Xr 4	Xr 6	Xr 8	Xr 10
Zeta	25	75.5	4236.3	4236.3	4236.3	4236.3
	50	52.75	69.25	275.5	4103.5	4103.5
	75	40	52.25	52.25	101.25	554.5
	100	35.75	35.75	35.75	52	68.25
	125	43.75	43.75	64	64	64

LAG = 2

Net Value		Xr 2	Xr 4	Xr 6	Xr 8	Xr 10
Zeta	25	-4.5	574.5	620	643	662
	50	-3.5	-2	20.5	326.5	418
	75	-5	-5	-2.5	2.5	27.5
	100	-5.5	-5.5	-5.5	-5.5	-2
	125	-8	-3.5	-3.5	-3.5	-3.5

LAG = 3

Net Value		Xr 2	Xr 4	Xr 6	Xr 8	Xr 10
Zeta	25	9.5	743.75	743.75	743.75	743.75
	50	7.25	10.75	54.5	866.5	866.5
	75	5	7.75	7.75	18.75	120.5
	100	4.25	4.25	4.25	8	11.75
	125	6.25	6.25	11	11	11

Expected costs and net values for lag of 2 and 3

Numerical Example

Net Value (high degradation rate)		Xr				
		2	4	6	8	10
Zeta	25	-7.75	-6.25	13.25	423.5	431
	50	-8.75	-8.75	-8.75	-7	-5.25
	75	-9.5	-9.5	-9.5	-9.5	-9.5
	100	-8.5	-8.5	-8.5	-8.5	-8.5
	125	-7.5	-7.5	-7.5	-7.5	-7.5

Expected net value for higher degradation rate

Conclusions & future works

* Longer monitoring intervals increase the risk of shorter life.
* The optimal net value might be insensitive to the degradation level after repair.
* Thresholds can play a decisive role.

Conclusions & future works

* Important factors including: rate of degradation, accurate calculation of the cost associated with the degradation. reduction, and revenue calculation especially in the case of partial failure.
* Relaxing the limiting assumptions; shocks and the duration of maintenance based on the required repair level.
* Need for an appropriate optimization method.

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