NTNU – Trondheim
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Rotary Machine Prognostic Based on Gamma Process

Project Introduction, Current Status and Future Plan

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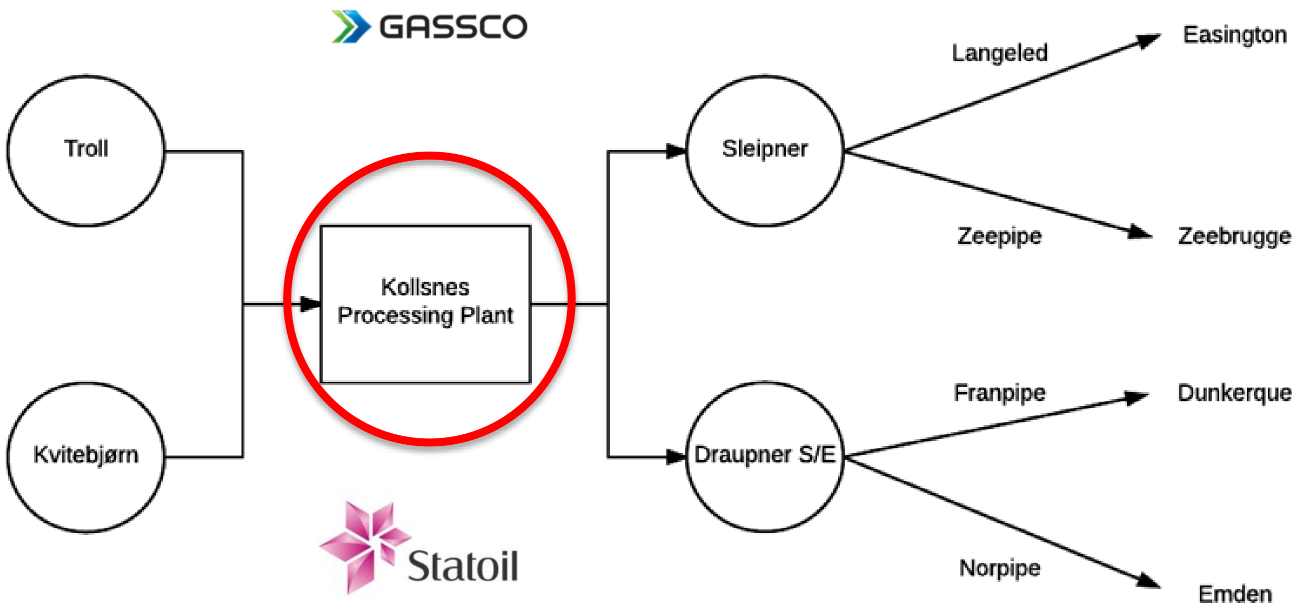
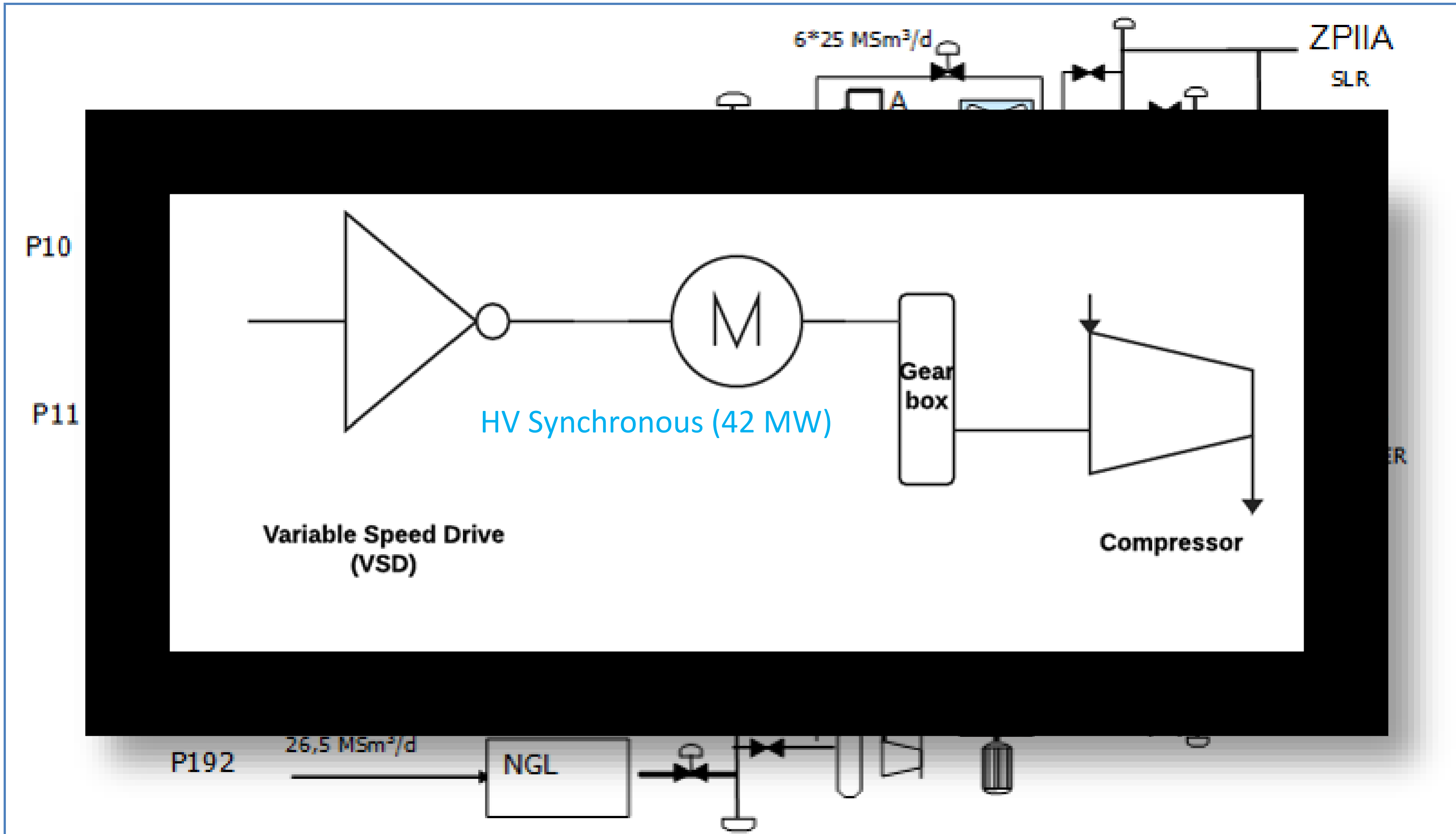
Problem Statement



Rich gas → gas, NGL, condensate

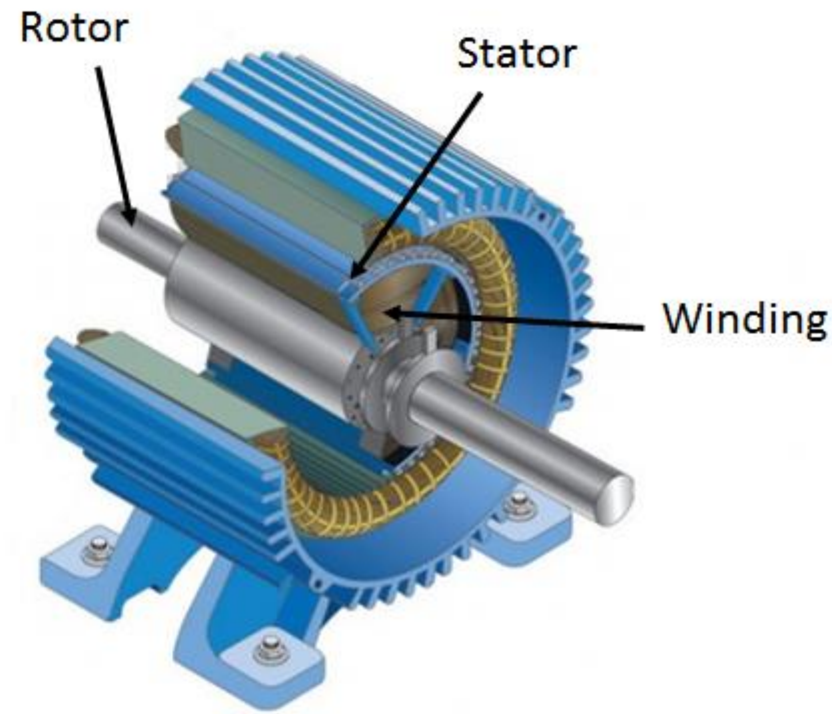
(Dewatering / Compression)

Problem Statement



Problem Statement

- Critical Component
  - Motor (Ageing of stator winding insulation)
- Requirements
  - Summer (3 units)
  - Winter (6 units)
- Current Status
  - 5 commissioned in 1996
  - 1 new (2006)



Machinery Prognostics

- Traditional reliability approaches
  - Event data based
  - Replacement/failure times of historical units

- Prognostic approaches
  - Condition data based

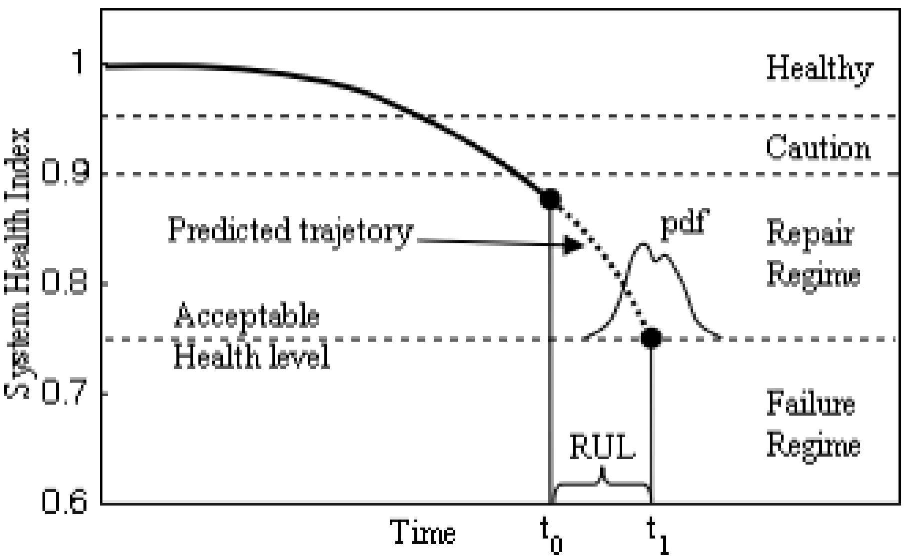
- Integrated
  - Both on event and condition data
    - Depends on the availability

Reference: Aiwina (2009)

Prognosis

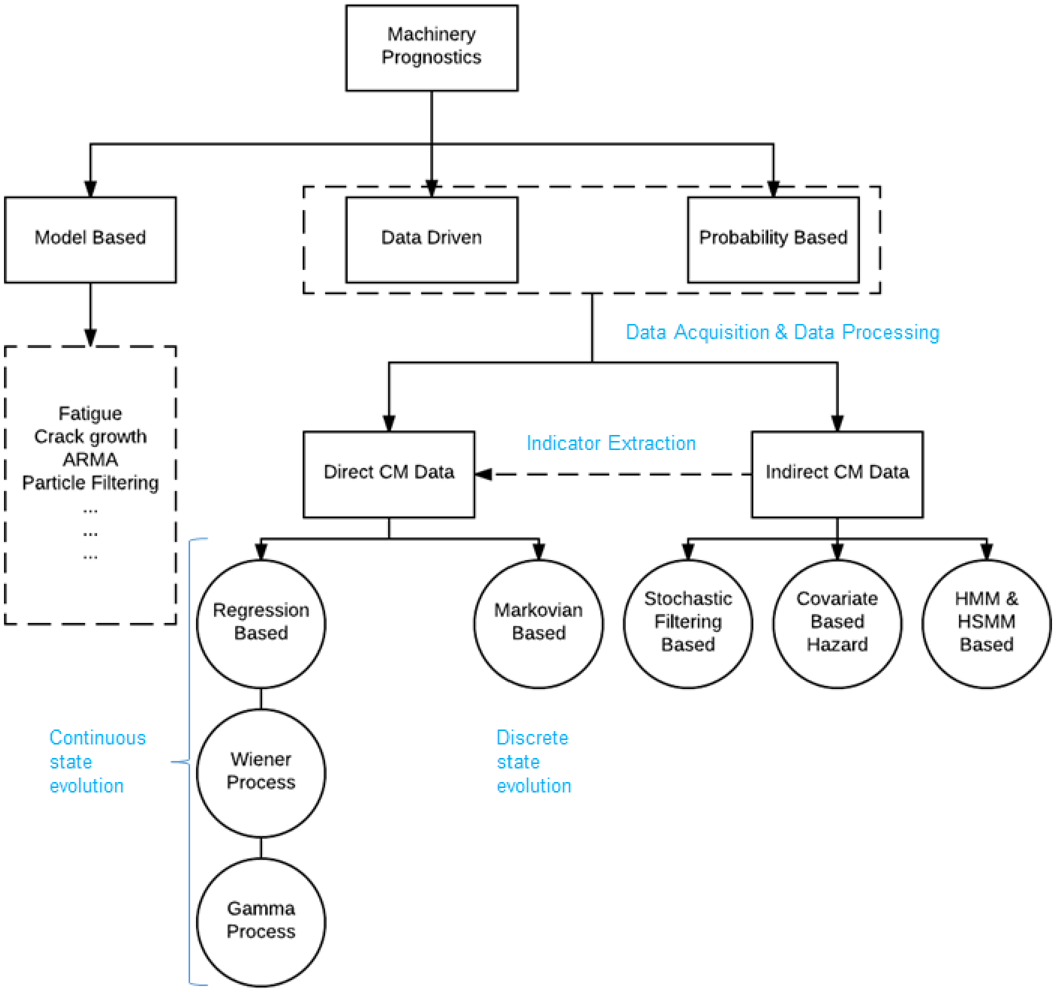
$$RUL(t) = \inf \{h: X(t+h) \in S_L | X(t) \notin S_L\}$$

$$X(t) = Random\ Variable\ (Condition)\ at\ time\ t$$
$$S_L = Set\ of\ failed\ states$$



Reference: Xiongzi (2011)

Machinery Prognostics



Under laboratory condition

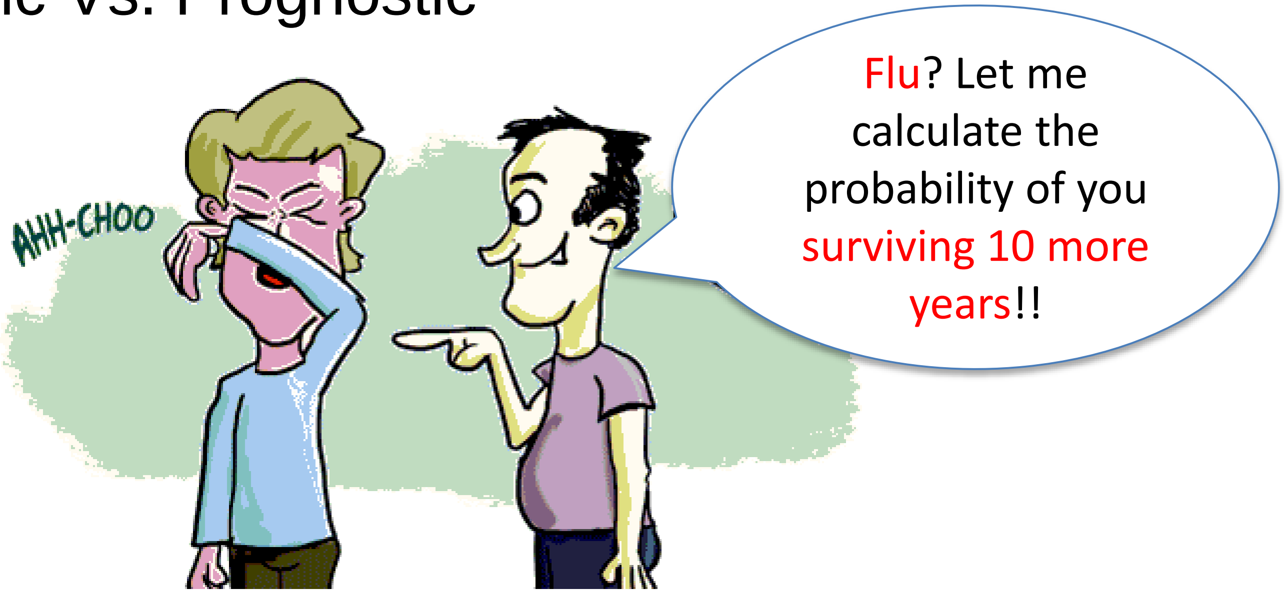
Not always practical for CM

Some tests are destructive

Reference: Based on Vachtsevanos (2006) and Si (2011)

Condition Indicator

- Diagnostic Vs. Prognostic

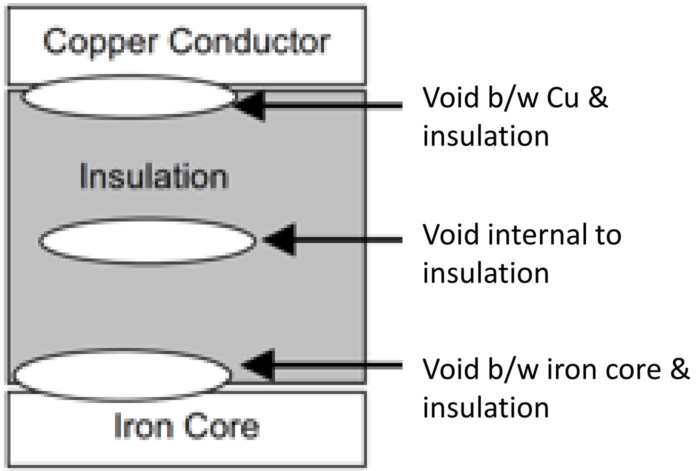


- Diagnosis- identify failure mode (cause of malfunction)
- Prognosis- generate rational estimation of RUL with available data (medical history)

Reference: Lee (2014)

Condition Indicator

- Available Test Procedures (Insulation Quality)
  - Insulation Resistance
  - Polarization Index
  - Hi-Pot Test
  - Partial Discharge
  - ….. Etc.
- Partial Discharge (PD)
  - Dielectric breakdown of electric insulation under high voltage
  - Creates small sparks in holes and bombard them

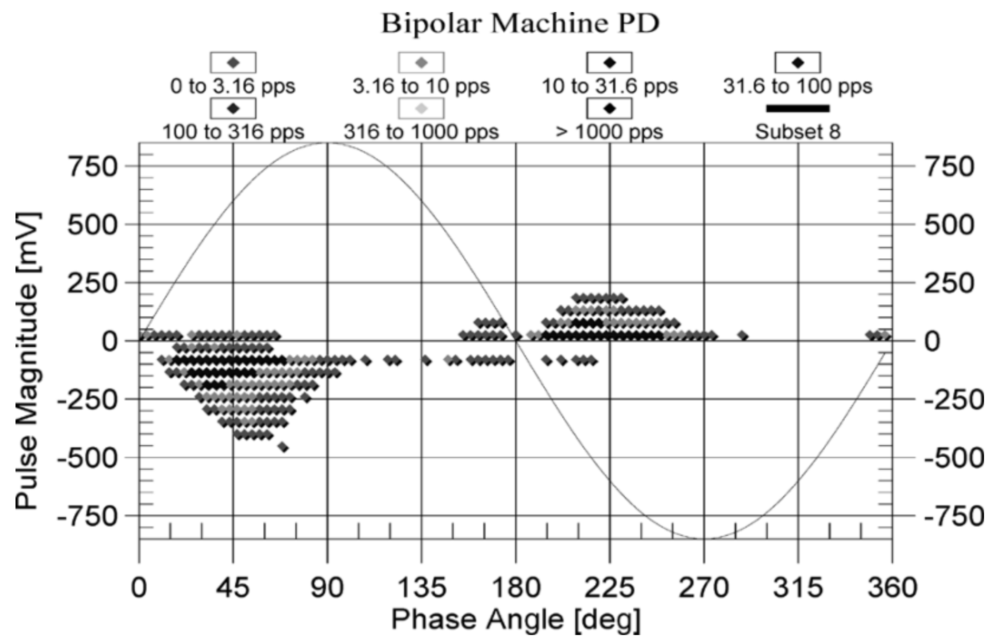


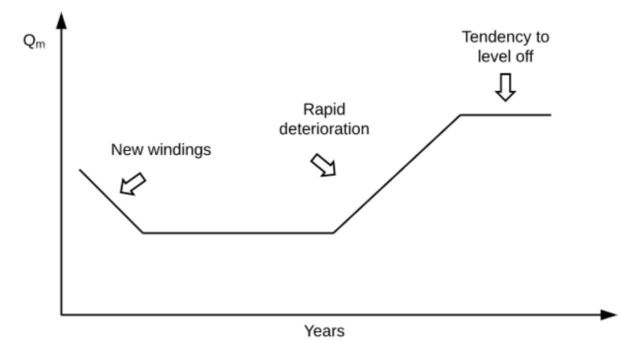
Reference: Paoletti (1999)

Online PD Monitoring

- OLPD measures-
  - Number of PD pulses
  - PD Magnitude (Qm)
  - Phase position

- PD Magnitude
  - Highest PD pulses with minimum repetition rate of 10 pulses/sec
  - Higher value indicates more deteriorated winding (Stone, 2006)





Typical trend in PD magnitude of stator windings (Stone (2012))

Preliminary Approach

- Choice of statistical model
  - Gamma process
- Reasons-
  - Strictly monotonic increasing degradation
  - Useful for optimal inspection and maintenance decisions making
- Limitations
  - Linear expected degradation

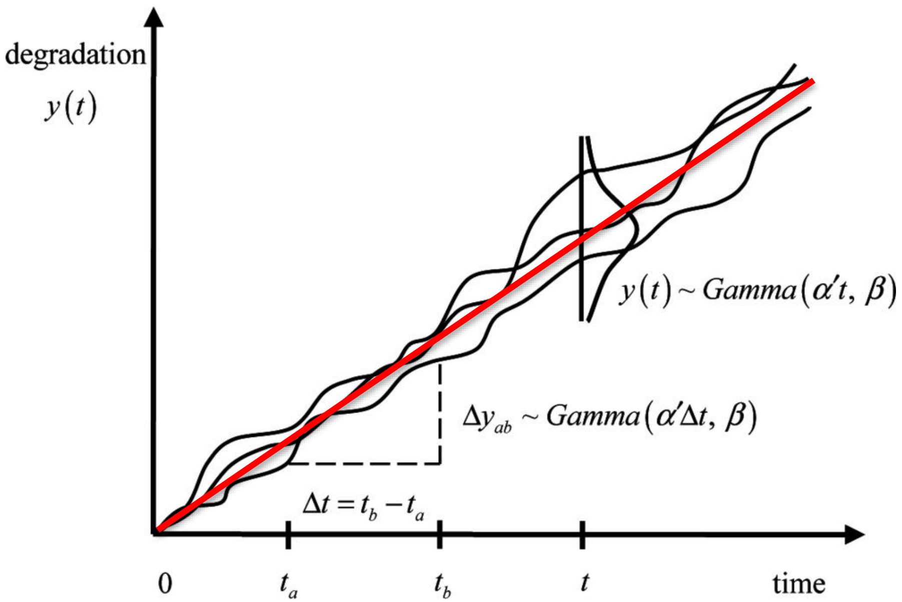


Image reference: Lim H (2015)

Gamma Process

- PDF of Gamma distribution-

$$f_{A(t),b}(x) = \frac{1}{\Gamma(A(t))} b^{A(t)} x^{A(t)-1} e^{-bx}$$

$A(t) = Shape\ function$
$b = Scalar\ parameter$

$$E(X_t) = \frac{A(t)}{b}$$

$$Var(X_t) = \frac{A(t)}{b^2}$$

Non-Homogeneous Gamma Process

- Non-homogeneous Gamma Process modeling
  - How deterioration increases over time? (Assuming temporal variability)
  - Shape function, $A(t) = c.t^{u}$ (Empirical studies)

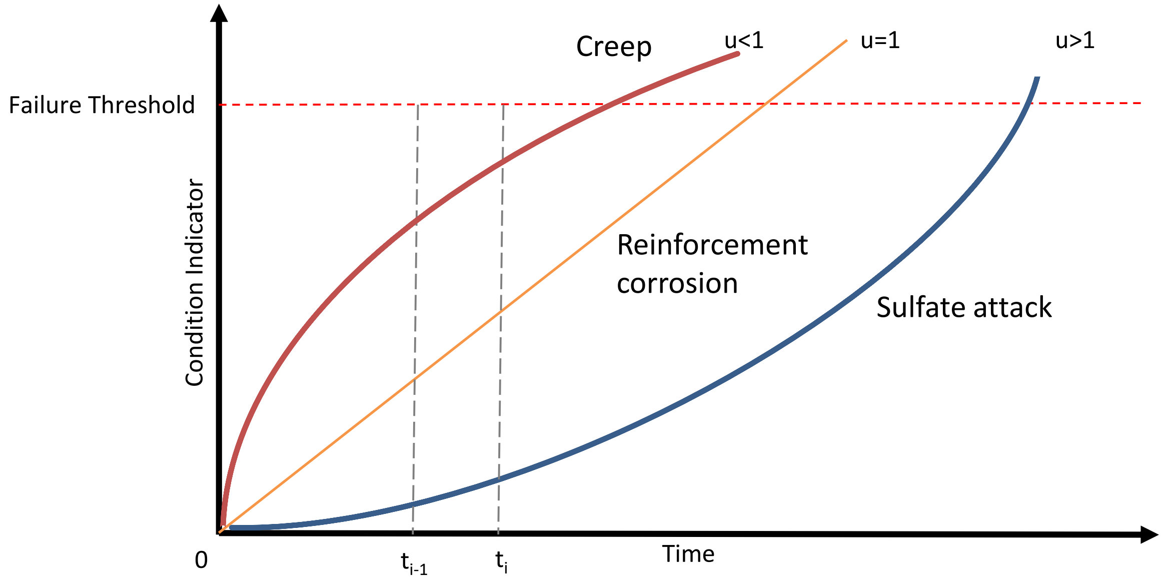


Figure: Degradation path depending on exponential parameter u
Deterioration in concrete pipes

Reference: Mahmoodian (2013), Van Noortwijk, J. M. (2009)

Simulation Process

- Available Methods
  - Gamma increment sampling
    - Simulate independent increments w.r.t. tiny amount of time

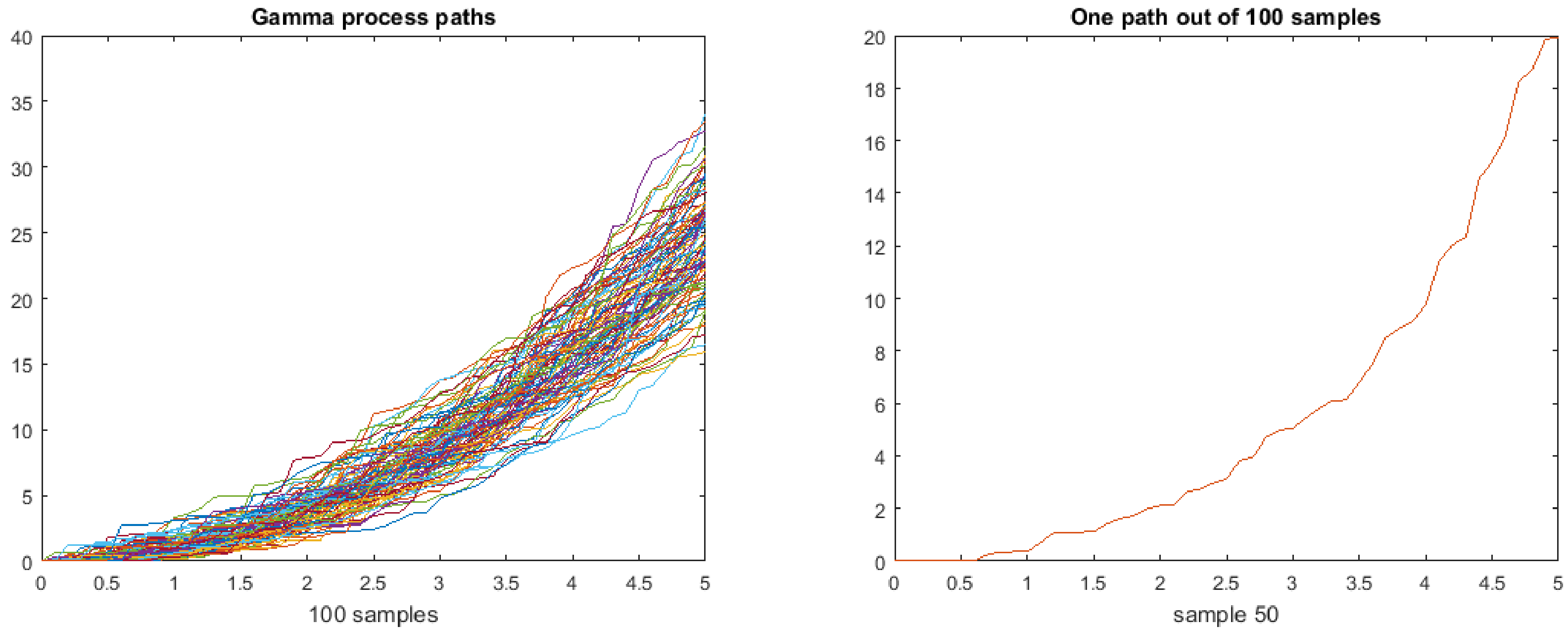
$$Ga(\delta|A(t_i) - A(t_{i-1}), b) = \frac{b^{A(t_i)-A(t_{i-1})}}{\Gamma(A(t) - A(t_{i-1}))}\delta^{[A(t)-A(t_{i-1})]-1}e^{-b\delta}$$

A.K.A – Gamma Sequential Sampling (GSS)

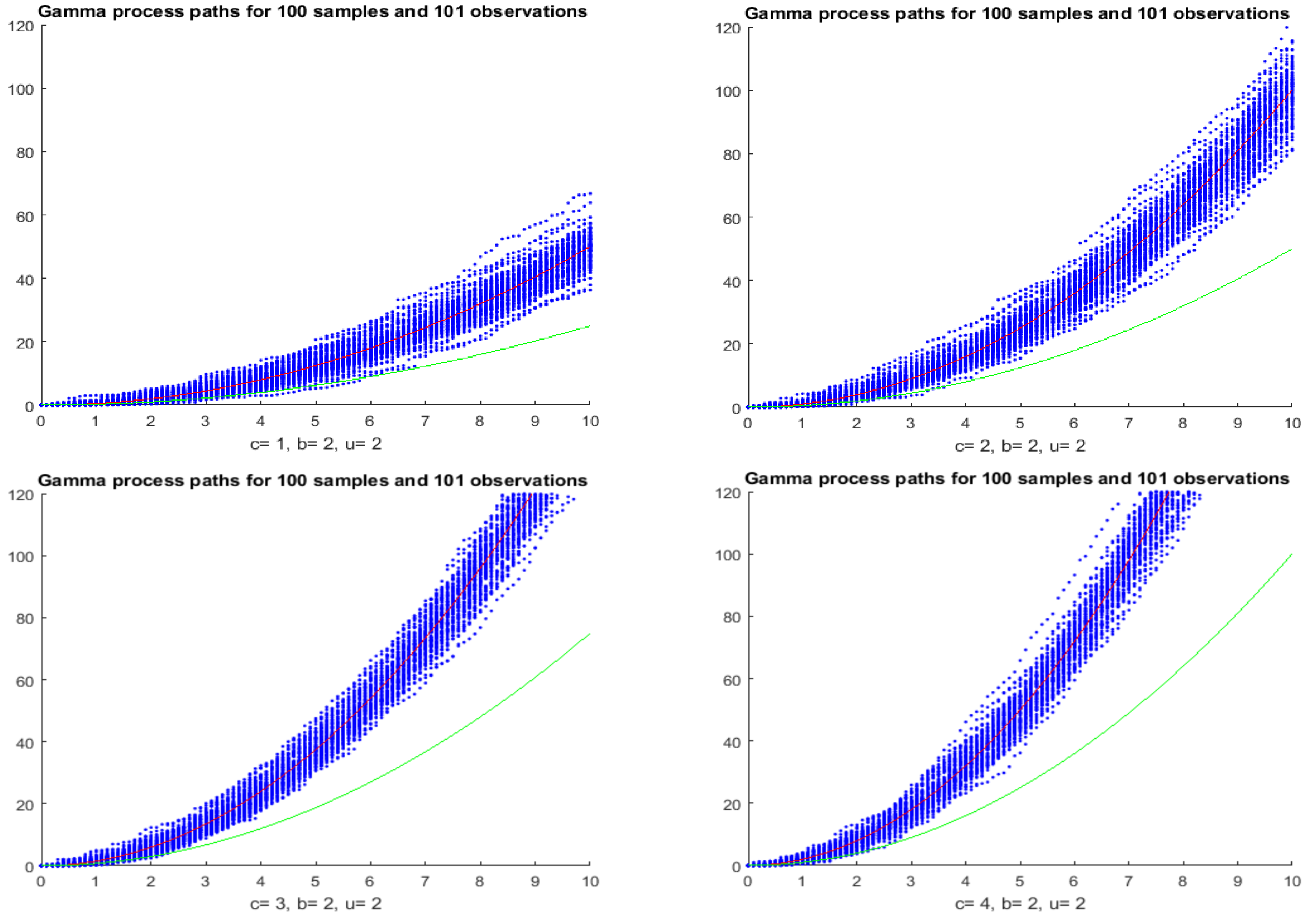
  - Gamma bridge sampling
    - Draw samples from CDF of deterioration

Reference: Van Noortwijk, J. M. (2009), A. N. Avramidis (2003)

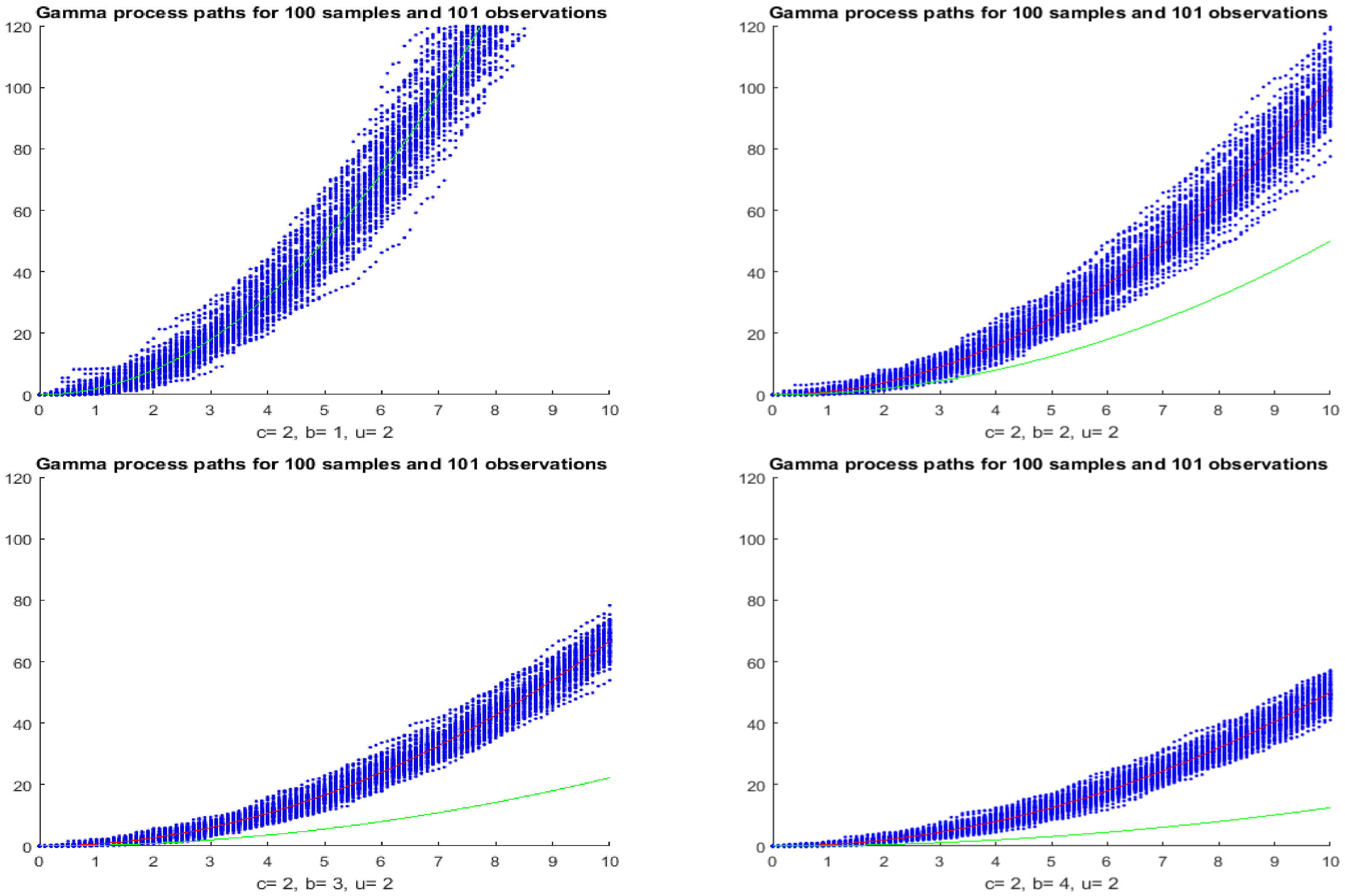
Simulated NHGP Paths



Changes in Shape



Changes in Scaler Parameter



Parameter Estimation

- Maximum Likelihood Estimation

$$\mathcal{L}(\delta_i|c,b) = \prod_{i=1}^{n} f_{X(t_i)-X(t_{i-1})}(\delta_i)$$

$$= \prod_{i=1}^{n} \frac{b^{c(t_i^u - t_{i-1}^u)}}{\Gamma[c(t_i^u - t_{i-1}^u)]} \delta_i^{c[t_i^u - t_{i-1}^u]-1} e^{-b\delta_i}$$

$$\psi(x) = \frac{d}{dx} ln\Gamma(x)$$

$$= \frac{\Gamma'(x)}{\Gamma(x)}$$

$$\hat{b} = \frac{m\hat{c}t_n^u}{\sum_{j=1}^{m} x_{n,j}}$$

$$\sum_{i=1}^{n}[t_i^u - t_{i-1}^u]\psi(\hat{c}[t_i^u - t_{i-1}^u]) - \frac{\sum_{j=1}^{m}\sum_{i=1}^{n}[t_i^u - t_{i-1}^u]ln(\delta_{i,j})}{m} = t_n^u ln(\frac{m\hat{c}t_n^u}{\sum_{j=1}^{m} x_{n,j}})$$

Ĉ Must be computed iteratively (Newton-Raphson Method)

Test Result (Example)

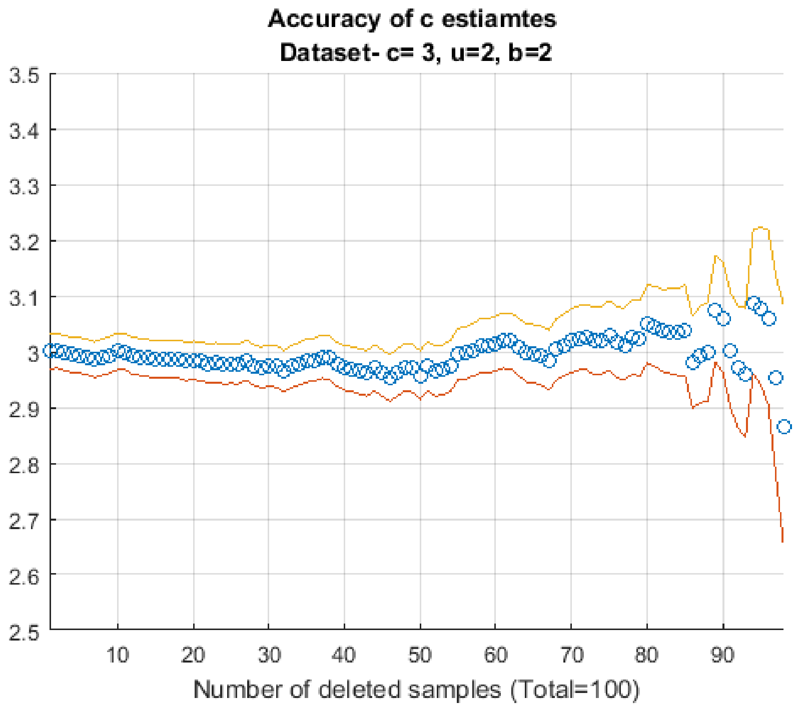
$$Shape\ function, A(t) = c.t^u$$
$$Scaler\ parameter = b$$

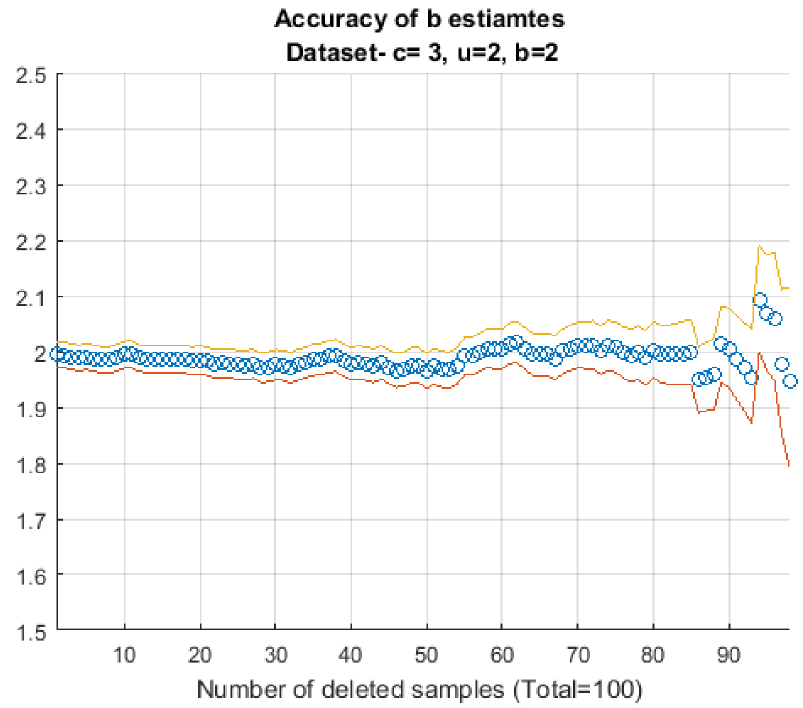
$$Number\ of\ components, M = 100$$
$$Total\ time, T = 10\ unit$$
$$Time\ increment = 0.1$$

$$Parameter\ value\ of\ generated\ data, b = c = u = 2$$

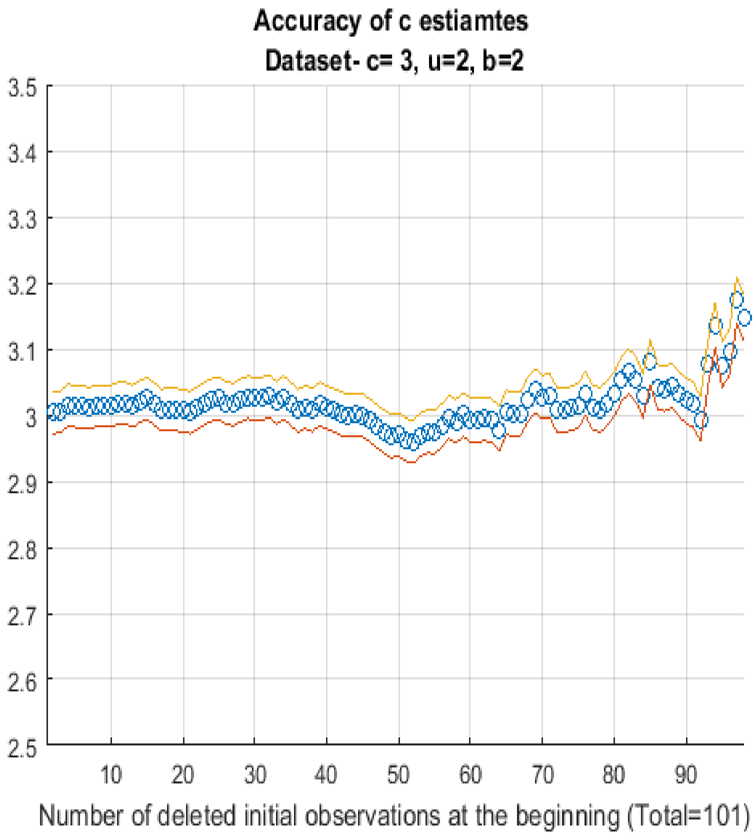
Parameter	Estimate	Confidence Level	Lower Bound	Upper Bound
c	2.0919	95%	2.0146	2.1722
b	2.0441		1.9584	2.1336

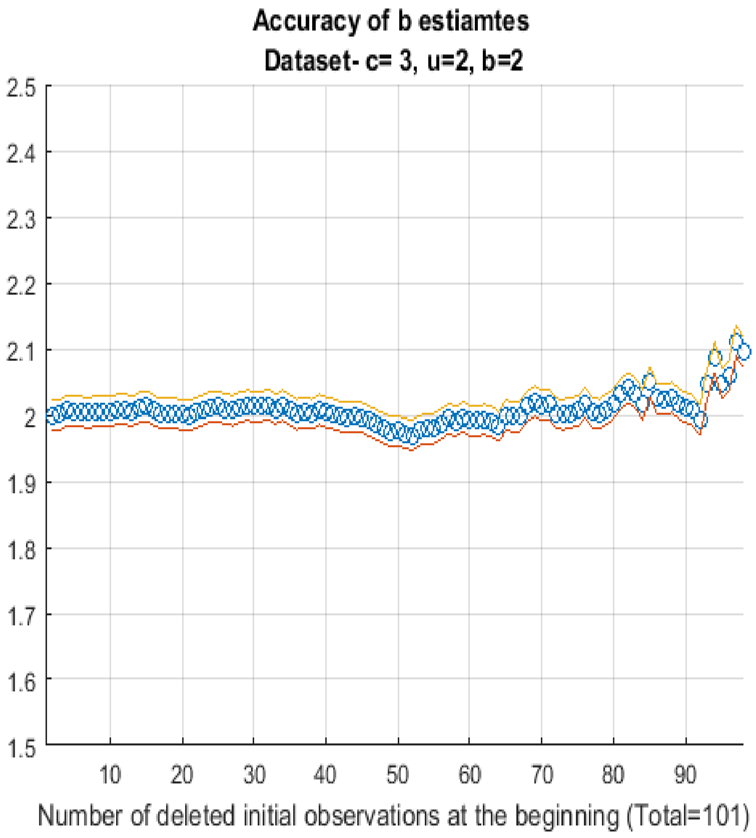
Estimation Accuracy- Sample size



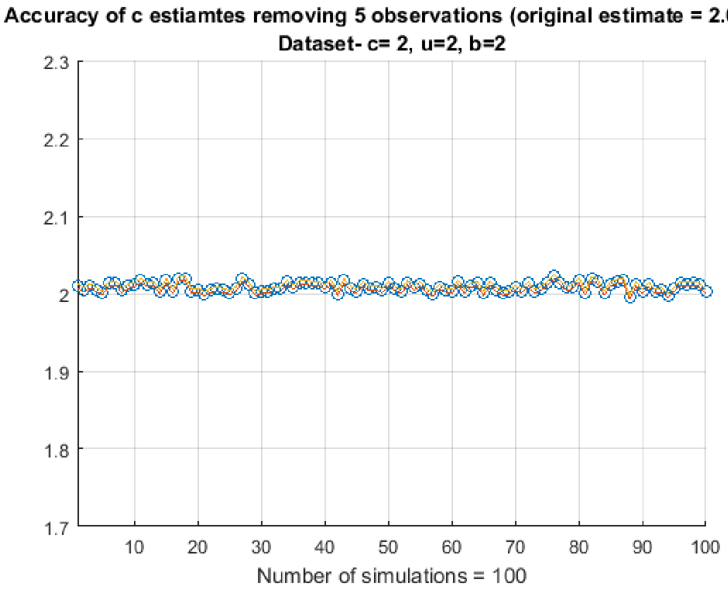


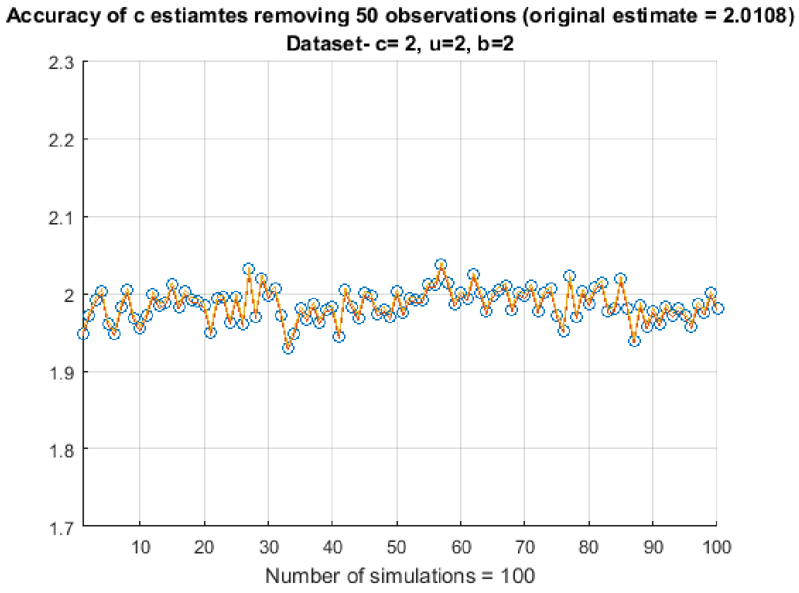
Estimation Accuracy- Initial Observation

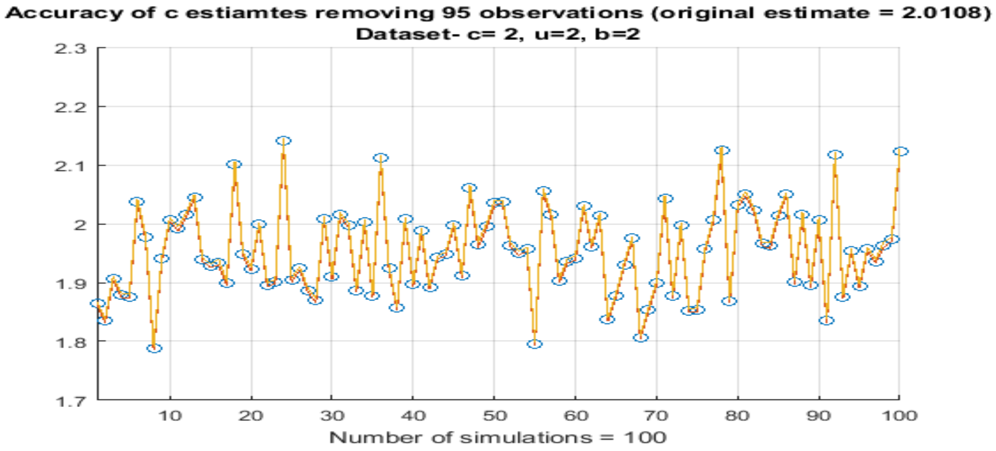




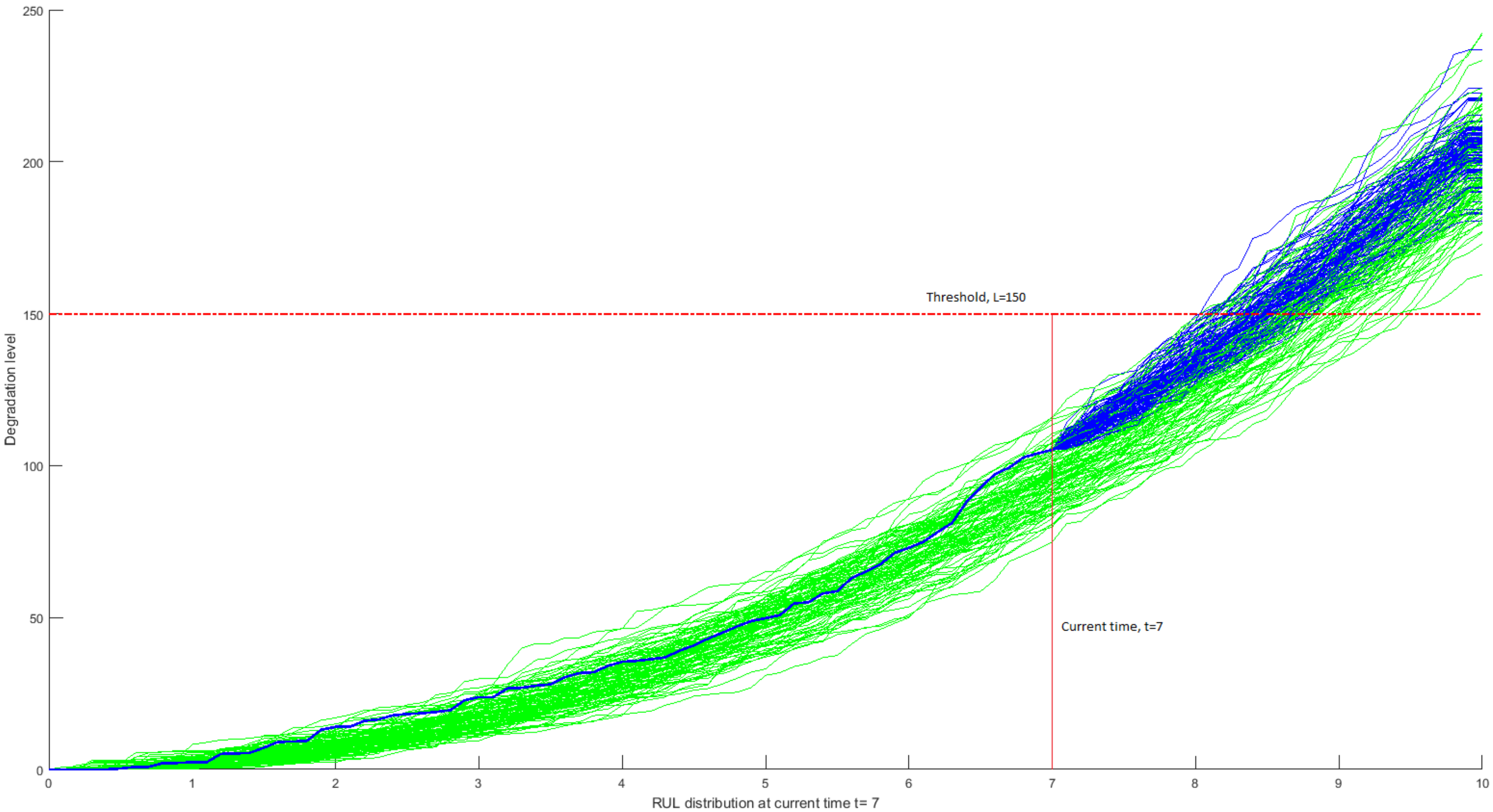
Opportunistic Observation







RUL (Illustration)



RUL Estimation

First Hitting Time, T_L

$$T_L = \inf(t > 0 : X(t) \geq L)$$

CDF of FHT,

$$F(t) = \Pr(T_L < t) = \Pr(X(t) \geq L)$$

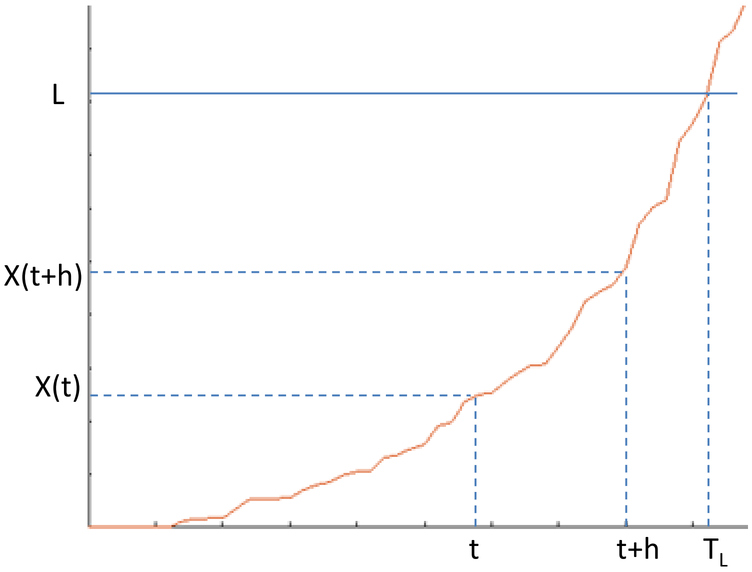
$$= \int_{x=L}^{\infty} f_{X(t)}(x)dx = \frac{\Gamma(A(t), Lb)}{\Gamma(A(t))}$$

At time t when X(t)=x(t), RUL< h

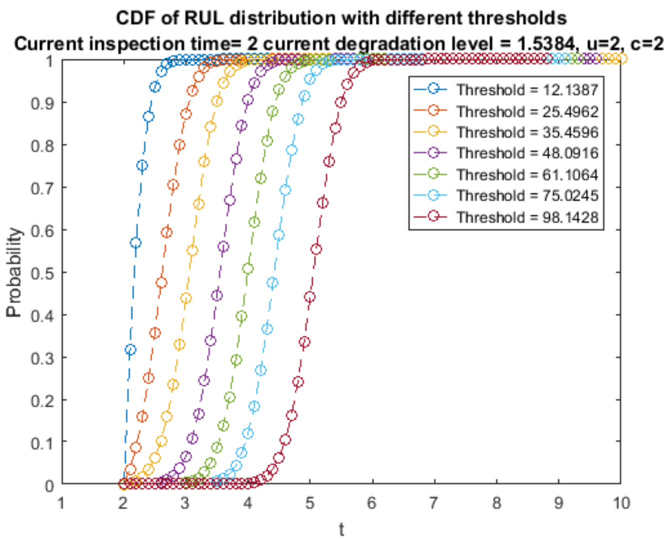
$$P(RUL \leq h) = 1 - P(RUL > h)$$

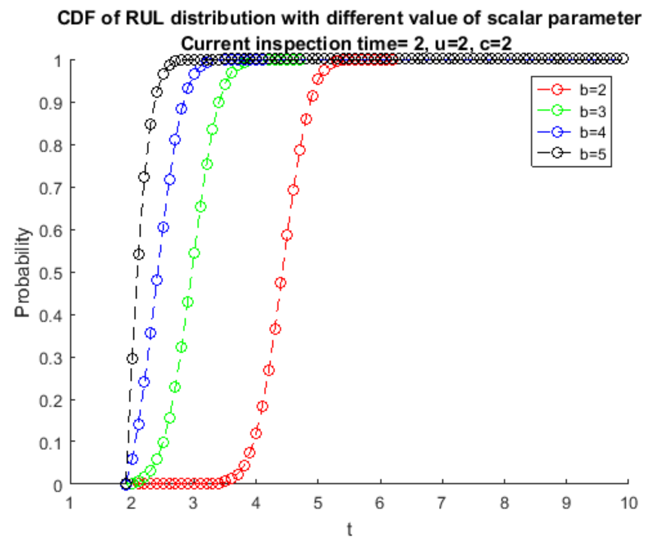
$$= 1 - P[X(t+h) < L | X(t) = x(t)]$$

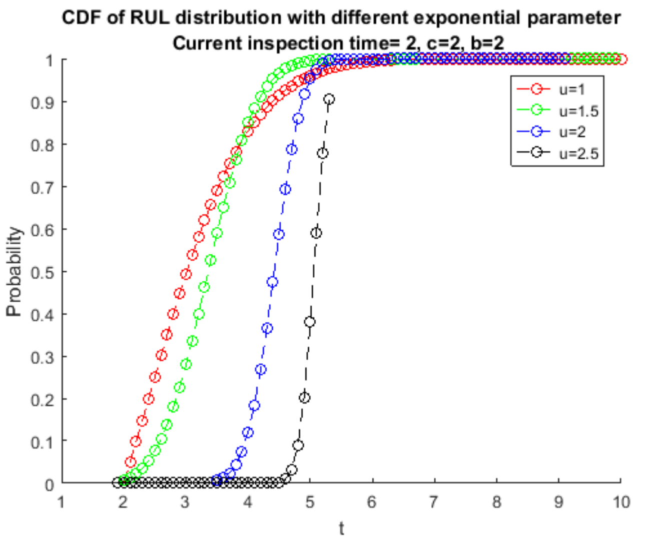
$$= 1 - \frac{P[X(t+h) - x(t) < L - x(t)]}{P(X(t) < L)}$$

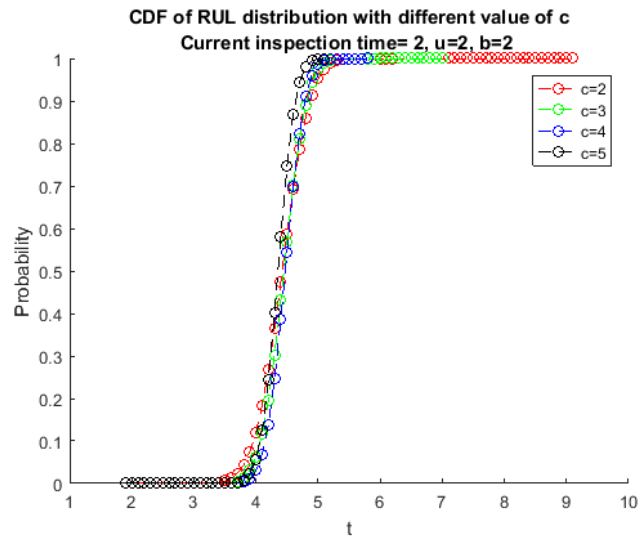


RUL Results

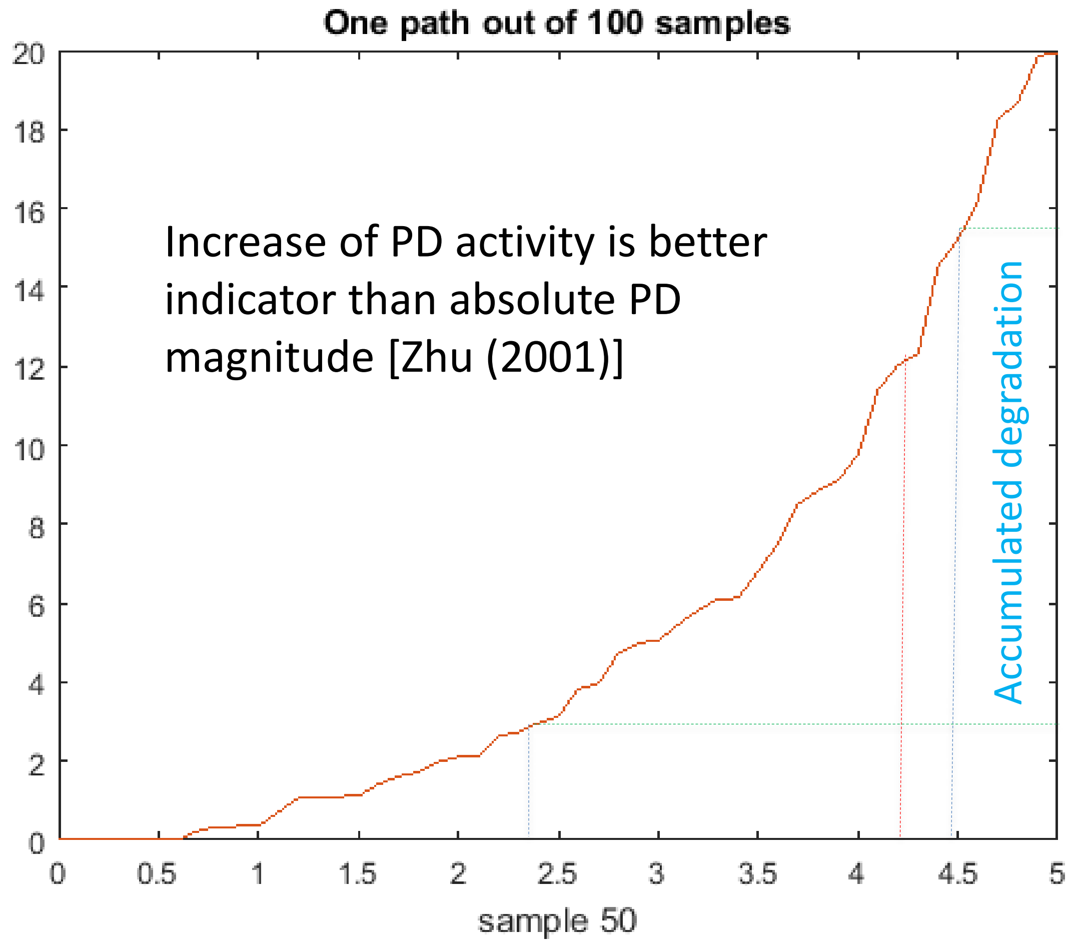

CDF of RUL distribution with different thresholds
Current inspection time= 2 current degradation level = 1.5384, u=2, c=2
Probability
t
Threshold = 12.1387
Threshold = 25.4962
Threshold = 35.4596
Threshold = 48.0916
Threshold = 61.1064
Threshold = 75.0245
Threshold = 98.1428


CDF of RUL distribution with different value of scalar parameter
Current inspection time= 2, u=2, c=2
Probability
t
b=2
b=3
b=4
b=5


CDF of RUL distribution with different exponential parameter
Current inspection time= 2, c=2, b=2
Probability
t
u=1
u=1.5
u=2
u=2.5


CDF of RUL distribution with different value of c
Current inspection time= 2, u=2, b=2
Probability
t
c=2
c=3
c=4
c=5

An Insight



One path out of 100 samples
20
18
16
14
12
10
8
6
4
2
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
sample 50
Increase of PD activity is better indicator than absolute PD magnitude [Zhu (2001)]
Accumulated degradation

Further Workplan

- Compare RUL estimations
  - Inspection intervals
  - Interpretations
- Discuss improvement
  - Adaptive model (update parameter)
  - Stochastic threshold
- Discuss System level RUL
  - Implementations
  - Challenges
- Data collection
  - Requirements
  - Conditions
  - PD? Misinterpretation?

References

- A. N. Avramidis, P. L'ecuyer and P. A. Tremblay, "Efficient simulation of gamma and variance-gamma processes," *Proceedings of the 2003 Winter Simulation Conference, 2003.*, 2003, pp. 319-326 Vol.1.
- IEEE Guide to the Measurement of Partial Discharges in Rotating Machinery," in *IEEE Std 1434-2000* , vol., no., pp.1-64, Aug. 15 2000
- Stone, G. C., & Warren, V. (2006). Objective methods to interpret partial-discharge data on rotating-machine stator windings. *IEEE Transactions on Industry Applications*, *42*(1), 195-200.
- Stone, G. C. (2012). A perspective on online partial discharge monitoring for assessment of the condition of rotating machine stator winding insulation. *IEEE Electrical Insulation Magazine*, *28*(5).
- Paoletti, G., & Golubev, A. (1999, June). Partial discharge theory and applications to electrical systems. In *Pulp and Paper, 1999. Industry Technical Conference Record of 1999 Annual* (pp. 124-138). IEEE.
- Zhu, H., Green, V., Sasic, M., & Jakubik, A. (2001). Partial discharge database: its benefits and limitations on assessment of stator insulation deterioration. In *Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference, 2001. Proceedings* (pp. 405-409). IEEE.
- Aiwina Heng, Sheng Zhang, Andy C.C. Tan, Joseph Mathew, Rotating machinery prognostics: State of the art, challenges and opportunities, Mechanical Systems and Signal Processing, Volume 23, Issue 3, April 2009, Pages 724-739, ISSN 0888-3270
- Xiongzi, C., Jinsong, Y., Diyin, T., & Yingxun, W. (2011, August). Remaining useful life prognostic estimation for aircraft subsystems or components: A review. In *Electronic Measurement & Instruments (ICEMI), 2011 10th International Conference on* (Vol. 2, pp. 94-98). IEEE.
- Si, X. S., Wang, W., Hu, C. H., & Zhou, D. H. (2011). Remaining useful life estimation–A review on the statistical data driven approaches. *European journal of operational research*, *213*(1), 1-14.
- Mahmoodian, M., & Alani, A. (2013). Modeling deterioration in concrete pipes as a stochastic gamma process for time-dependent reliability analysis. *Journal of pipeline systems engineering and practice*, *5*(1), 04013008.
- Lim, H. (2015). Optimum Accelerated Degradation Tests for the Gamma Degradation Process Case under the Constraint of Total Cost. *Entropy*, *17*(5), 2556-2572
- Van Noortwijk, J. M. (2009). A survey of the application of gamma processes in maintenance. *Reliability Engineering & System Safety*, *94*(1), 2-21.
- Vachtsevanos, G., Lewis, F., Roemer, M., Hess, A., & Wu, B. (2006). BOOK TOOLS.
- Lee, J., Wu, F., Zhao, W., Ghaffari, M., Liao, L., & Siegel, D. (2014). Prognostics and health management design for rotary machinery systems—Reviews, methodology and applications. *Mechanical systems and signal processing*, *42*(1), 314-334.