SUBPRO
SUBSEA PRODUCTION AND PROCESSING

Norwegian University of Science and Technology

Remaining useful life estimation for subsea choke valves:

degradation mechanism and candidate models

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Outline

- Part I: About the postdoc position
- Part II: Subsea choke valves: performance parameter and degradation mechanism
- Part III: Models and methods
- Part IV: Prototype Zero: a preliminary toolbox
- Part V: Additional remarks: sand management and production

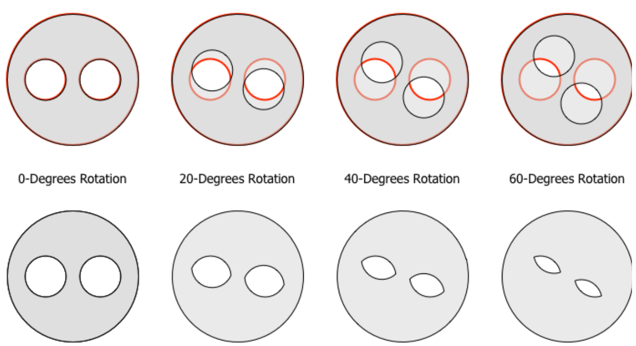
Part I: About the postdoc position

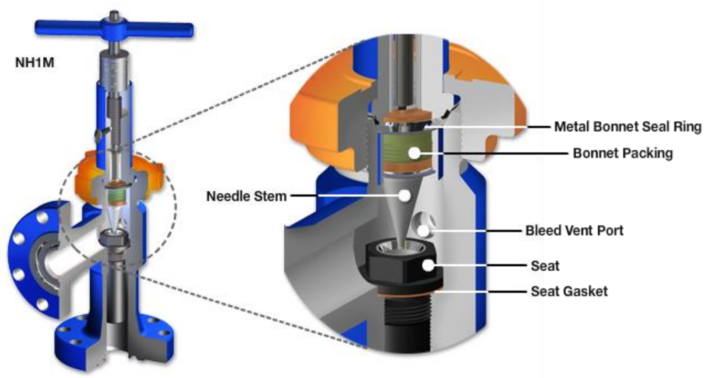
- Background: digital transformation and Industrial 4.0
- Main objective: develop prototype simulators for prediction and optimization of remaining useful life of components and systems
- Industry partners: Equinor, Lundin, DNV-GL
- Supervisor: Prof. Jørn Vatn
- Context: Yun Zhang's thesis (RUL estimation, maintenance optimization…)
- Expected outcome: toolbox, recommended procedures…

Part II: Subsea choke valves: performance parameter and degradation mechanism

Subsea choke valves

- Liquid and gas mixtures are flown through chokes to control flow rates and protect equipment from unusual pressure fluctuations.
- Production chokes generally stand out as the components in oil & gas production systems that are most susceptible to erosion, which is also reflected in the statistics on erosion failures.
- Different types of choke: multiple orifice valve (MOV), cage and plug, needle and seat…



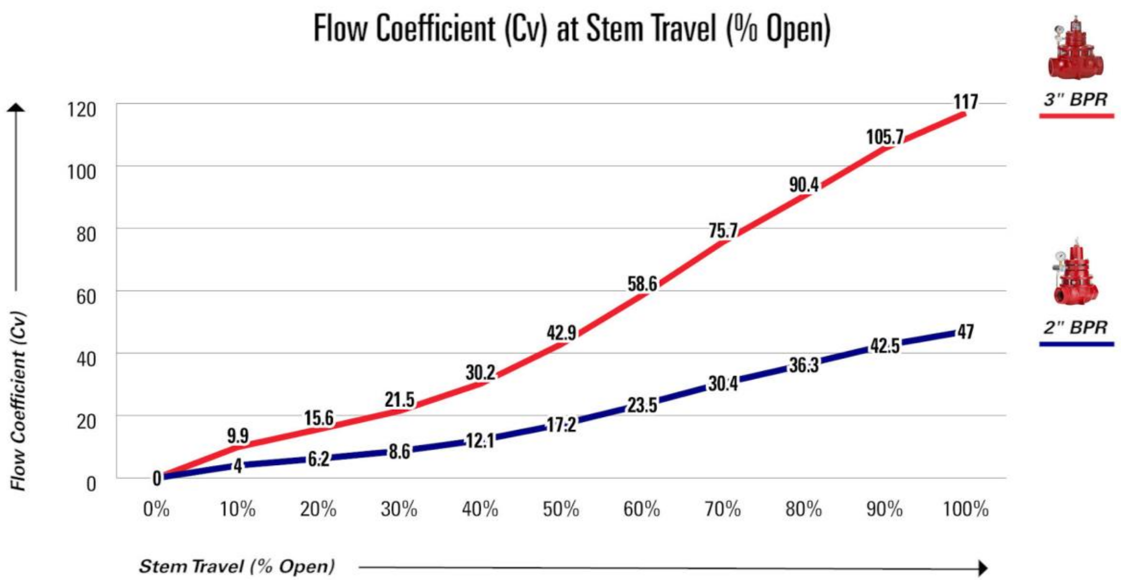


Inspection and condition monitoring

- Inspection: visual access through flanges or bonnet.
  - Topside chokes: inspection preformed at regular/specified intervals
  - Subsea chokes: inspection requires shutdown of the production and retrieval of the choke bridge and/or the XMT
- For certain chokes: detect erosive wear by monitoring changes in flow characteristics.

Performance parameter

- Flow coefficient (Cv): describes the relationship between the pressure drop across a valve and the corresponding flow rate
- The theoretical Cv: provided by vendors, depends on choke type and opening



$$C_v = Q\sqrt{\frac{SG}{\Delta P}}$$

Q: flow rate
SG: relative density
ΔP: drop of pressure

Degradation indicator

- Estimated Cv: depends on the choke opening and other process parameters
  - Allocated oil/water/gas flow rate
  - Upstream and downstream well head pressure
  - Choke opening

$$C_v^{calc} = \frac{w}{N_6 F_p \sqrt{\Delta P \rho_E}}$$

- Cv calculation:
  - Insight Erosion management system (ABB)
  - Erosion Monitor Application (DNV-GL)

$$\rho_E = \left(\frac{f_g}{\rho_g \cdot J^2} + \frac{f_w}{\rho_w} + \frac{f_o}{\rho_o} \right)^{-1}$$

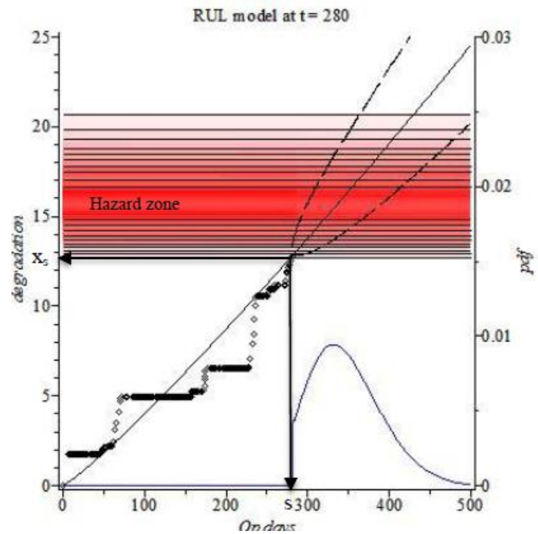
- Degradation indicator:

Δ Cv = Estimated Cv – Theoretical Cv

- Δ Cv is monotone
- Credibility of the estimated Cv: well test

Failure threshold

- Failure threshold is determined based on
  - Expert judgement: in some early studies, a threshold of 7 has been used
  - Choke characteristics: "*For Gullfaks, the choke should be inspected when the Cv difference passes 7… the limit should be higher for a large choke (e.g. max Cv = 250) than for a small choke (e.g. max Cv = 15)*"----IOHN report.
- The threshold could also be random with a specific distribution.



An example of the degradation path

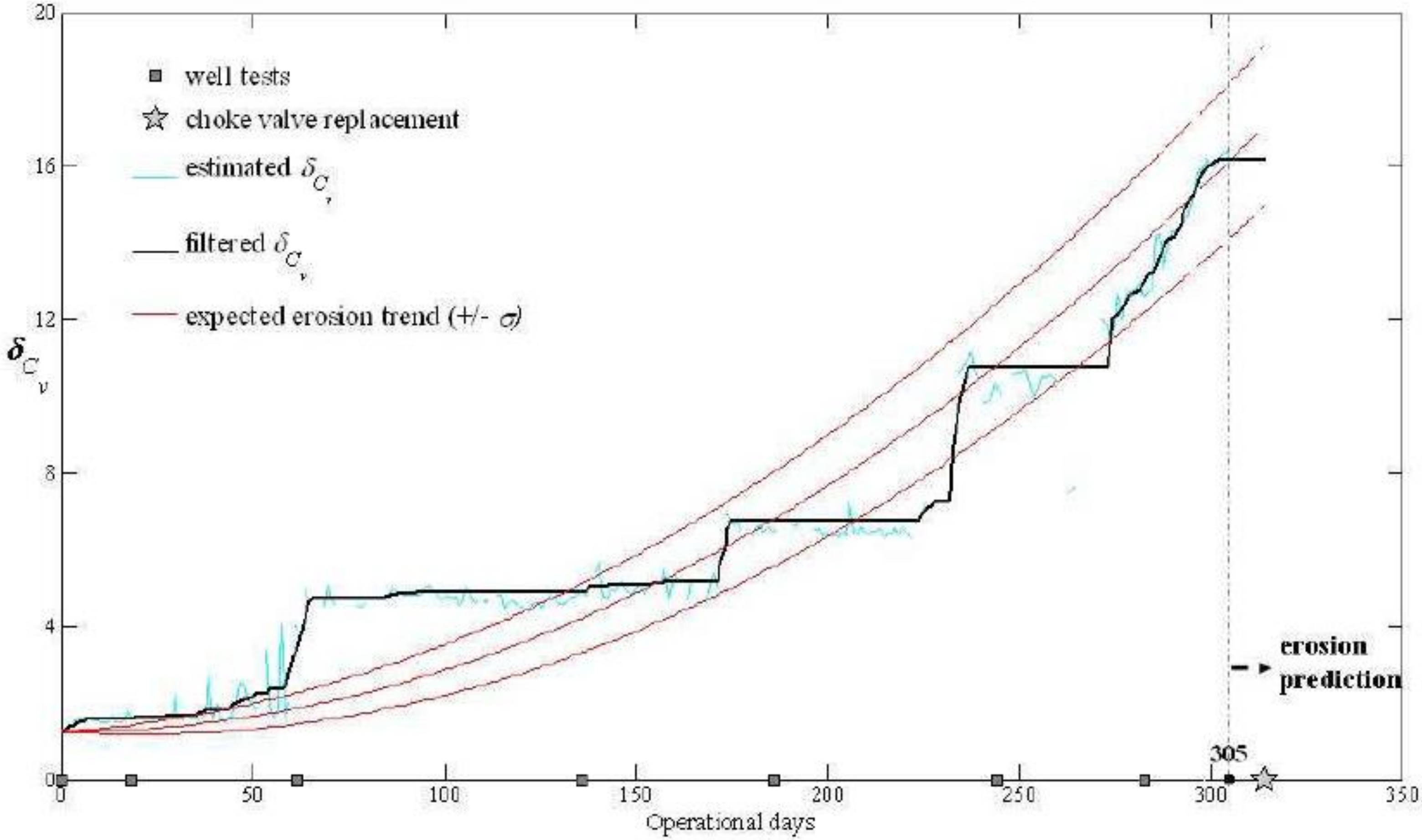


Figure 5: Expected functional shape of the erosion process using data up to 305 operational days ($\hat{b}$=2, $\hat{u}$=3.65543, $\hat{c}$=0.00059)

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Choke valve type

- Two types of choke valve are under consideration:
  - Multistage or labyrinth cage (production choke)
  - MOV (surface choke)

- According to RP-O501*: For multiphase operating conditions in combination with single stage trim designs, the use of Cv has proven to be difficult. For multistage or labyrinth cage designs where internal wear of the cage gives a significant effect on the flow capacity of the choke the approach is considered feasible.*

Degradation mechanism

- High sand load contributes to erosions to choke body, flange and cage port holes (RP-O501)
- Sand production depends on production rate, rock and fluid properties, completion design…
  - Continuous production
  - Sand burst: when the well is suddenly exposed to sand loosening from the reservoir

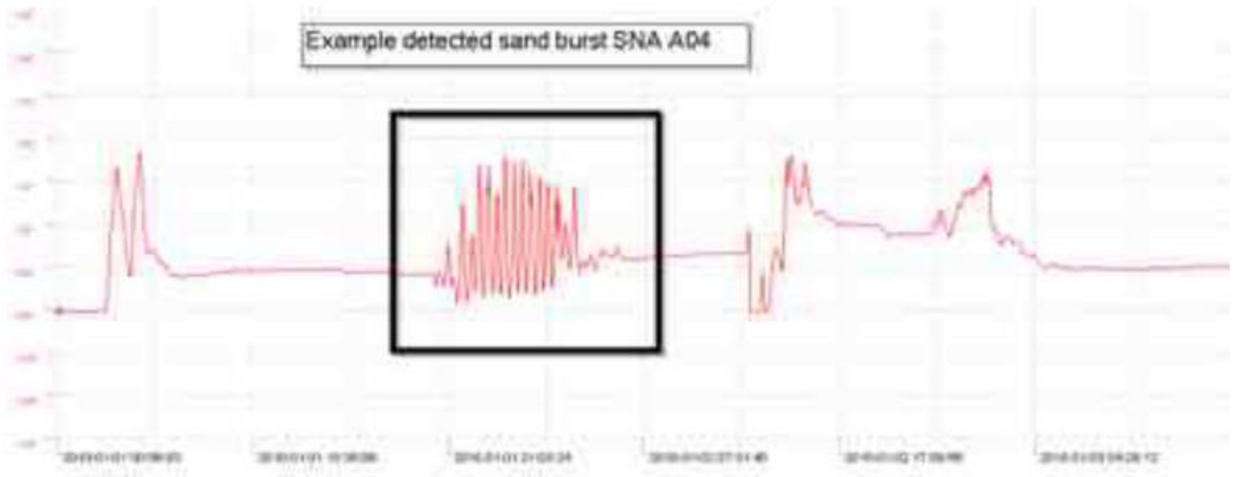
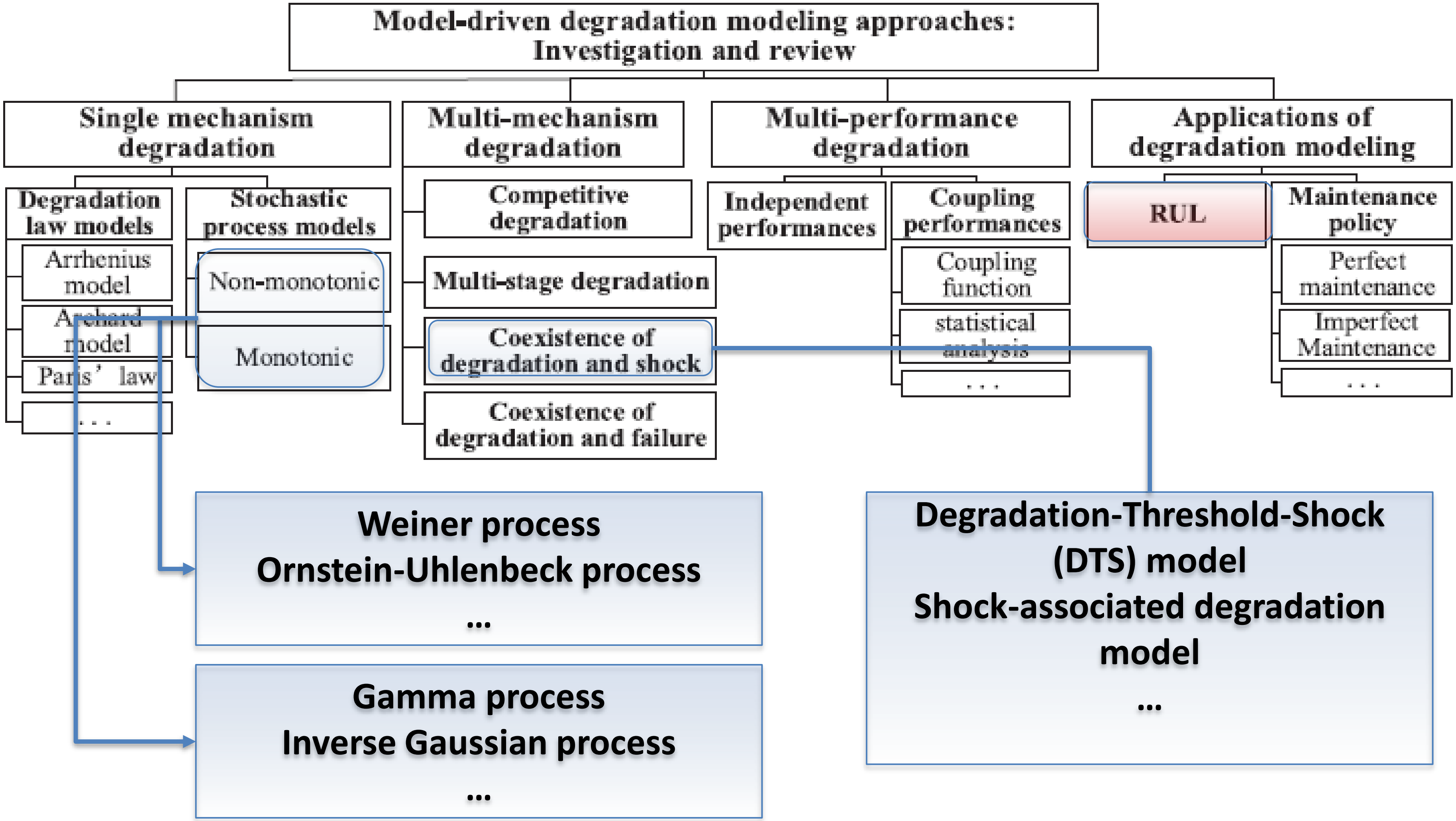


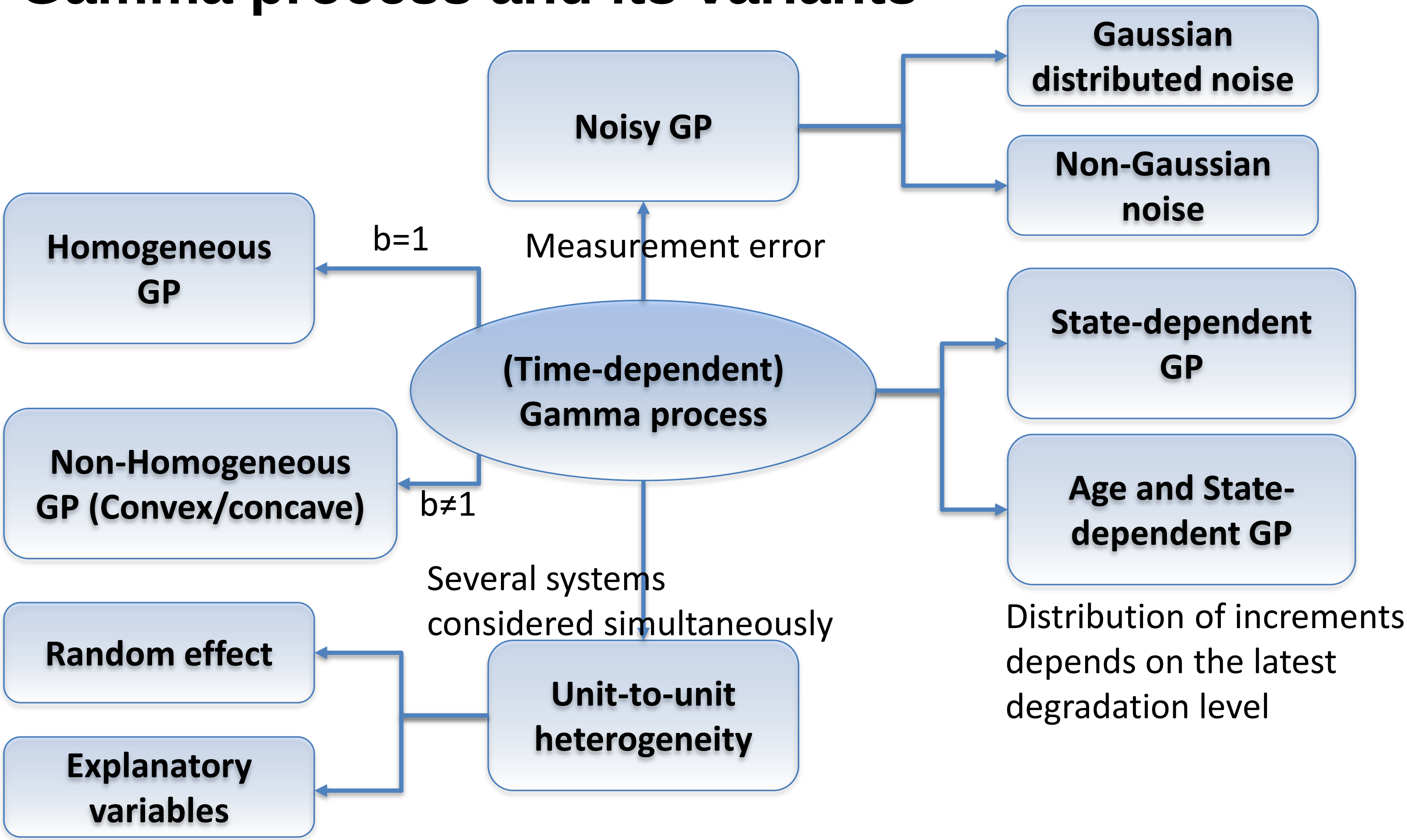
Figure 6.19: Sand detection example from calculated sand rate

Part III: Models and methods

Degradation modeling: an overview



Gamma process and its variants



Candidate models for choke valve

- Δ Cv is theoretically increasing
- Presence of noise due to sensor measurement errors
- Observed degradation path is not monotonic
- Candidate models
  - Weiner process
  - Noisy Gamma process
  - Noisy Inverse Gaussian (IG) process
- Both IG and Gamma process can be regarded as the limit of compound Poisson process (suitable for modeling degradation due to continuous external shocks)
- State-dependent models and random effect will be considered later

Gaussian noise

- True degradation levels are hidden, and the likelihood (necessary for parameter estimation) involves a n-dimension integral.

- $y_j = x_j + e_j$: observation is perturbed by noises
- $\Delta y - \Delta e = \Delta x$: (unobserved) true increments

$$L_i(\alpha, \beta \mid \Delta y_i) = f_{\Delta Y_i}(\Delta \mathbf{y}_i; \alpha, \beta)$$

$$= \int_D f_{\Delta X_i}(\Delta \mathbf{y}_i - \Delta \mathbf{e}_i; \alpha, \beta) f_{\Delta \mathbf{E}_i}(\Delta \mathbf{e}_i) d\Delta \mathbf{e}_i$$

$$f_{\Delta \mathbf{E}_i}(\Delta \mathbf{e}_i) = \frac{1}{(2\pi)^{m_i/2} |\boldsymbol{\Sigma}_{\Delta \mathbf{E}_i}|} \exp\left(-\frac{1}{2} \Delta \mathbf{e}_i \boldsymbol{\Sigma}_{\Delta \mathbf{E}_i}^{-1} \Delta \mathbf{e}_i^T\right)$$

$$\boldsymbol{\Sigma}_{\Delta \mathbf{E}_i} = \sigma_E^2 \mathbf{J} \mathbf{I}_{m_i+1} \mathbf{J}^T = \sigma_E^2 \mathbf{J} \mathbf{J}^T$$

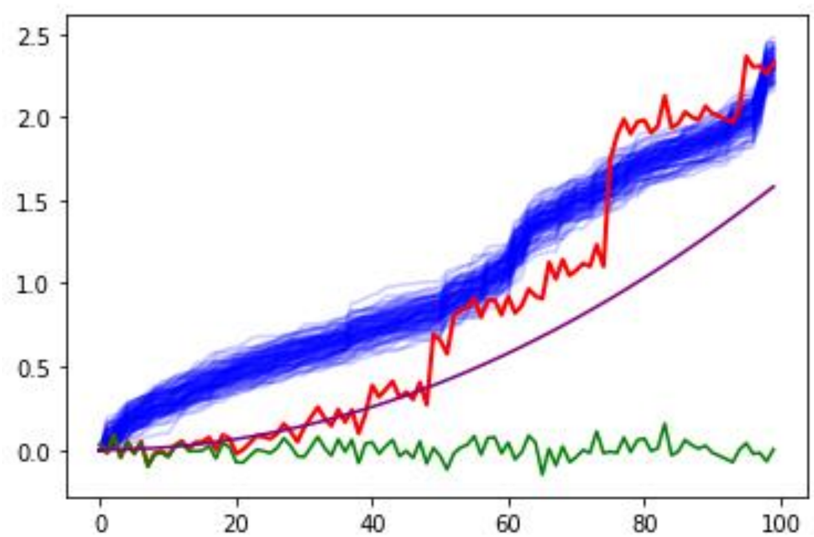
$$= 2\sigma_E^2 \begin{pmatrix} 1 & -1/2 & & 0 \\ -1/2 & \ddots & \ddots & \\ & \ddots & 1 & -1/2 \\ 0 & & -1/2 & 1 \end{pmatrix}_{m_i \times m_i}$$

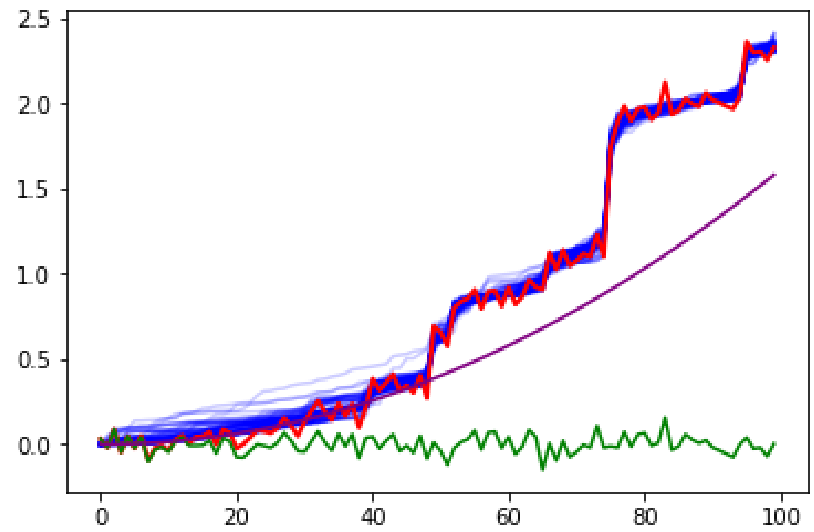
How to deal with noise?

- Monte Carlo integration:
  - For each observation y_j, a noise e_j is sampled from $N(0, \sigma^2)$
  - Easily understood and implemented
  - Inefficient when many negative increments exist
- Genz transform:
  - Convert the original multivariate normal integration domain into a unit hypercube
  - Avoid ineffective sampling
  - Sampled paths are biased under certain situations
- Markov Chain Monte Carlo: Gibbs sampling
  - Generates a Markov chain of samples
  - Each of which is correlated with nearby samples
  - Applied to noisy Gamma process (A. Barros 2016)
- Stochastic filtering: Kalman filter, Particle filter…
  - Rarely used in degradation modeling

Genz transform (left) vs Gibbs sampling (right)

- Gamma parameters: ($c = 0.00059, b = 2, u = 3.65543, \sigma = 0.05$)
- 100 sampled paths are drawn in blue
- For Genz transform, the difference between the sampled path and the observation results in erroneous likelihood and inconsistent estimates





Model selection

- The *corrected Akaike information criterion* (AICc) is used to estimates the relative amount of information lost by a given model: the less information a model loses, the higher the quality of that model

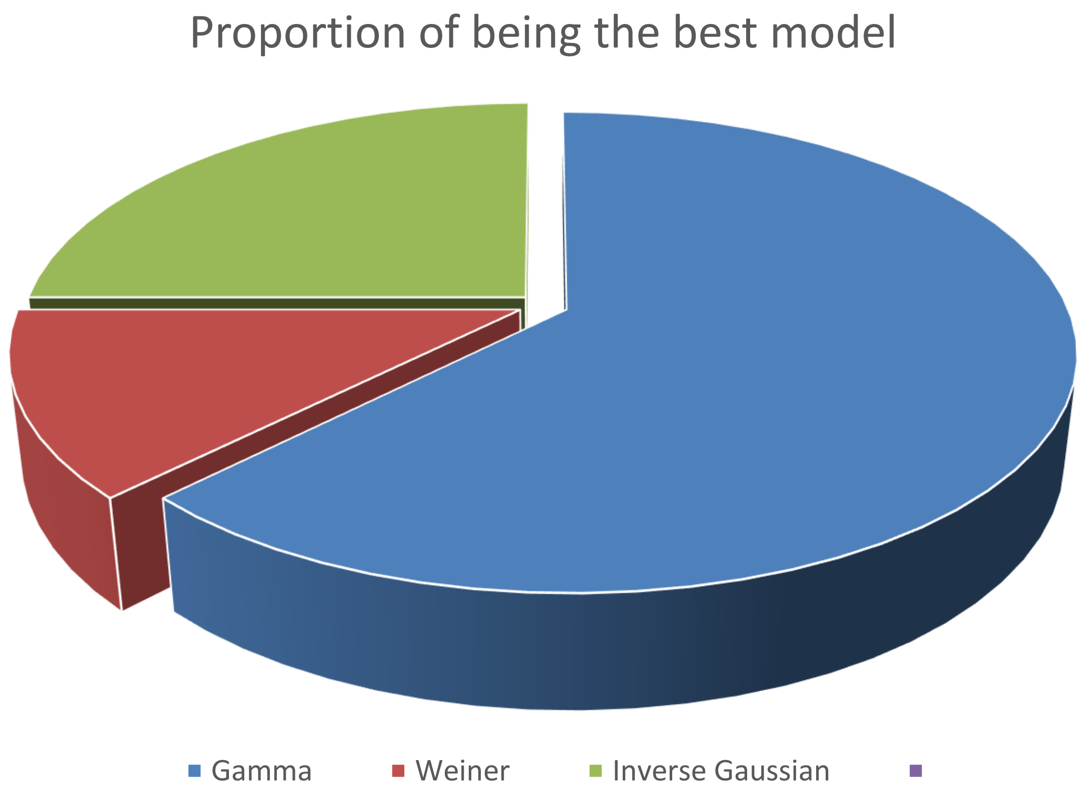
$$\mathrm{AIC} = 2k - 2\ln(\hat{L}) \qquad \mathrm{AICc} = \mathrm{AIC} + \frac{2k^2 + 2k}{n - k - 1}$$

- *Akaike weights* are than computed from the raw AICc values, showing the strength of evidence in favor of one model over the others

$$\Delta_i(\mathrm{AIC}) = \mathrm{AIC}_i - \min \mathrm{AIC}. \qquad w_i(\mathrm{AIC}) = \frac{\exp\left\{-\frac{1}{2}\Delta_i(\mathrm{AIC})\right\}}{\sum_{k=1}^{K} \exp\left\{-\frac{1}{2}\Delta_k(\mathrm{AIC})\right\}}.$$

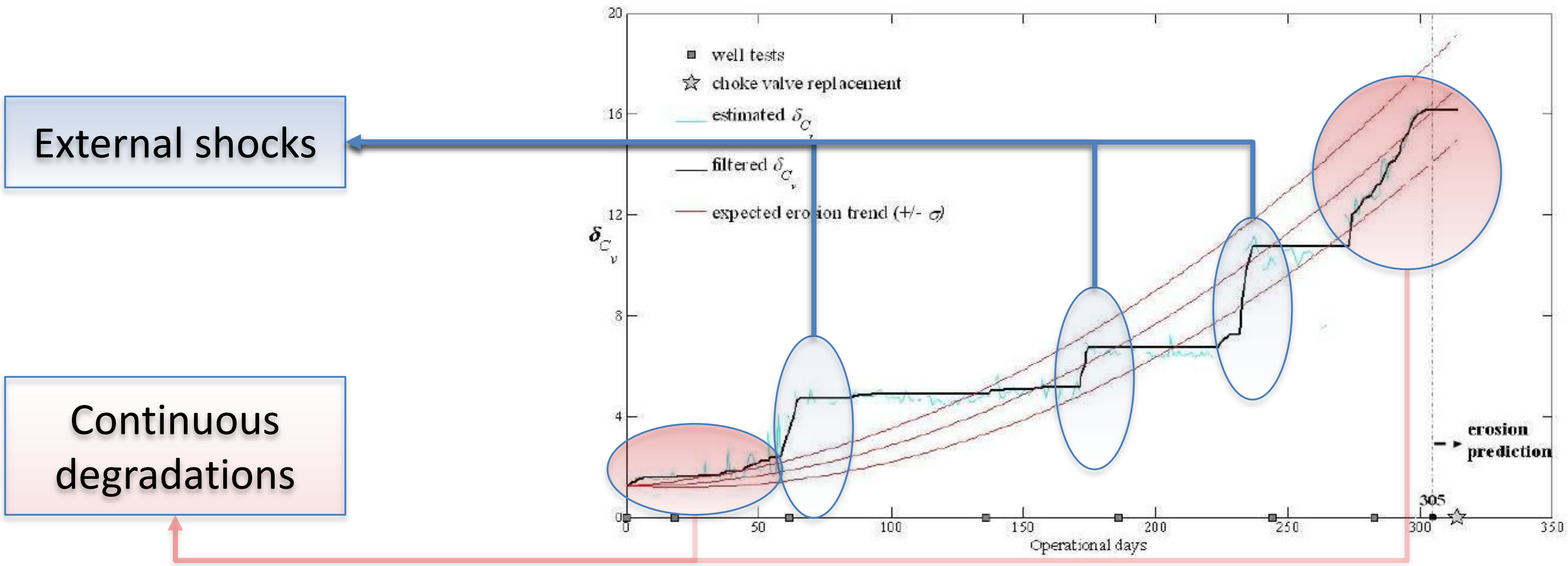
Uniformly Best Model

- Test the models on real data
- Find the model that performs the best for most of the cases



Shock-associated degradation model

- Separate continuous degradation from large jumps which may result from sand bursts: compound Poisson process + Gamma process
- Chokes installed at the same well should be considered together
- Sand data (time and amount of sand burst, sand rate) is required



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Part IV: Prototype Zero

Prototype Zero: a preliminary toolbox

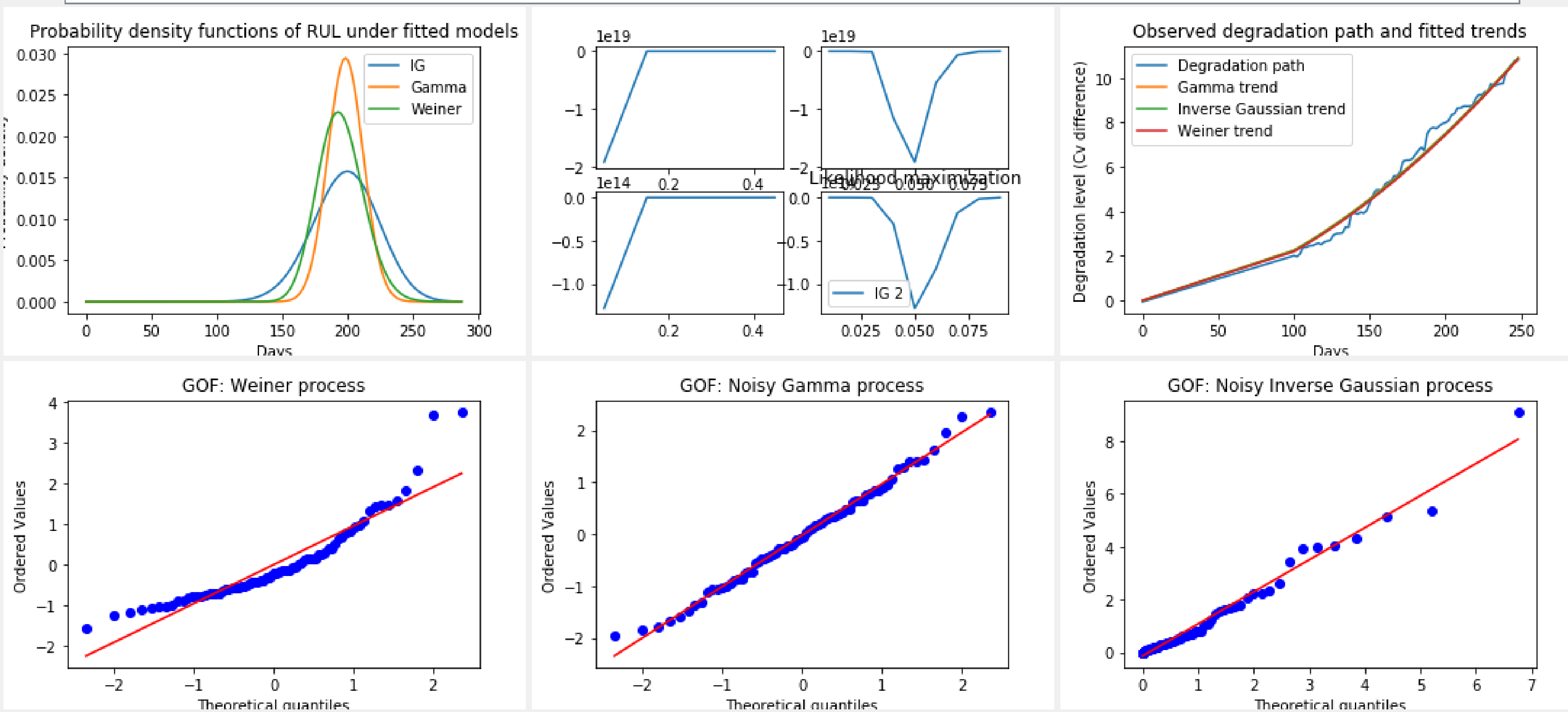
- Implemented models: Weiner, noisy IG, noisy Gamma
- Coding Language: Python

- Input: dates and observed Cv difference
- Output:
  - RUL estimation (median, mean, PDF, 90% confidence interval)
  - Akaike Weights
  - Visualization：
    - Degradation path and expected trends
    - Graphical goodness of fit (Q-Q plot)
    - Validation of parameter estimation (compute likelihoods with unknown sigma)

RUL Prediction: demo

Generate data | Open file and run

	Akaike weights	Mean RUL	Median RUL	90% Confidence Interval
Weiner process	4.602474090876463e-07	194.63820927095279	193.94873260914966	167.07053453509585 224.5585094699
Noisy Gamma process	0.999992814848092	198.3811651366932	198.34473592960134	176.17694407675805 220.709544817
Noisy Inverse Gaussian process	6.724904499072529e-06	198.19421134821854	198.70241166513276	155.5154051505286 239.14066849733



Part V: Additional remarks

Improve the Cv estimation

RP-O501: *“Interpretation of any changes in Cv that is perceived to be due to erosion needs to consider the accuracy of the theoretical Cv model…”*

- Different models exist
  - TOTAL model
  - Perkins model
- Cv difference value is more uncertain for chokes with low pressure drop

$$C_V = \frac{w_o + w_w + w_g}{N_6 F_p \sqrt{\Delta p}} \sqrt{\frac{f_o}{\rho_o} + \frac{f_w}{\rho_w} + \frac{f_g}{\rho_g J^2}}$$

Improve the Cv estimation

- A series of studies conducted by Nystad et al., in collaboration with Statoil from 2010 to 2014 addressed the Cv estimation with
  - Physical models
  - Kernel regression models (data-driven)
  - Hybrid models
- The latest models have not been implemented in DNV EMA or ABB Erosion Insight

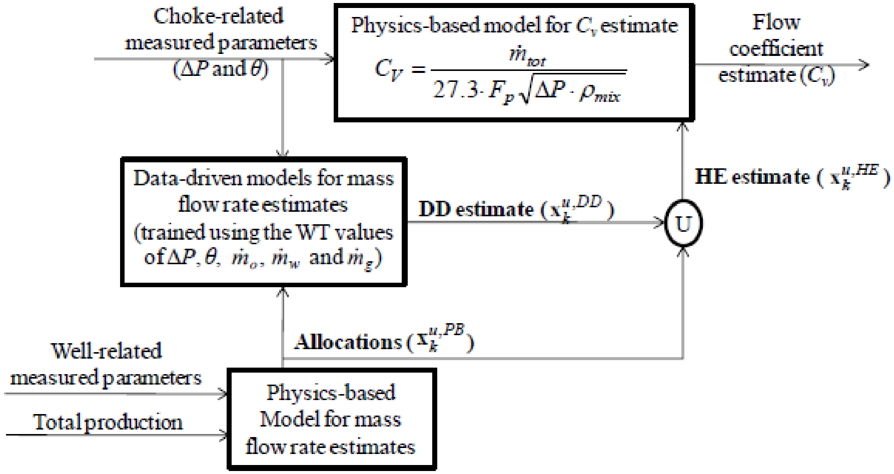


Figure 3: Schematic of the Proposed Hybrid Modelling Approach.

Sand management and Choke RUL prediction

- Sand production depends on production rate, rock and fluid properties, completion design…
- Forecast the Cv difference trend based on the monitoring and prediction of sand production and sand event
- More data is needed:
  - Operational data
  - Well test data
  - Topology and configuration data
  - Choke data
  - PVT data
  - Sand data

Combine the RUL estimation with production

- Both DNV EMA and ABB Insight have the What-if analysis: Forecast production profiles can be utilized to analyze the expected consequences of different future production scenarios and the impact of the production scenarios will have on the inspection and maintenance strategy.
- Collaboration with SUBPRO System Control
  - Control for extending component life (Adriaen Verheyleweghen)
  - Validation of methods for optimizing remaining useful life (Jose Matias)
    - An experimental rig was set up
    - Abrasive flow: mixture of water and air
    - Choke valve represented by an intrusive probe

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