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SUBSEA PRODUCTION AND PROCESSING

NTNU

Norwegian University of Science and Technology

Choke valve erosion: a new perspective

02-09-2021

Outline

- Part I: Working principle, function, and erosion of choke valve
- Part II: Flow coefficient as a degradation indicator: pitfalls and 3D representation
- Part III: Static model and Cv surface estimation: effective pass area, eigen-increment and erosion conversion
- Part IV: Dynamic model: randomization and dynamic system representation

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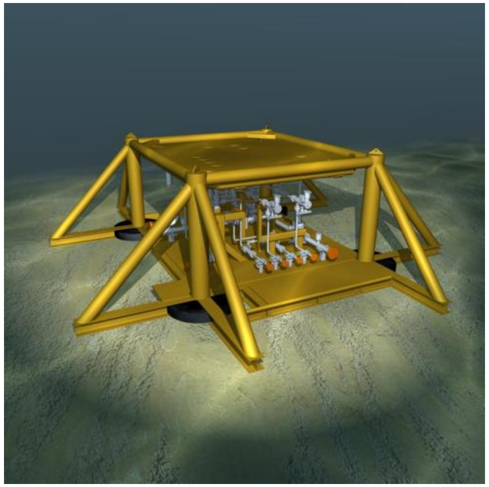
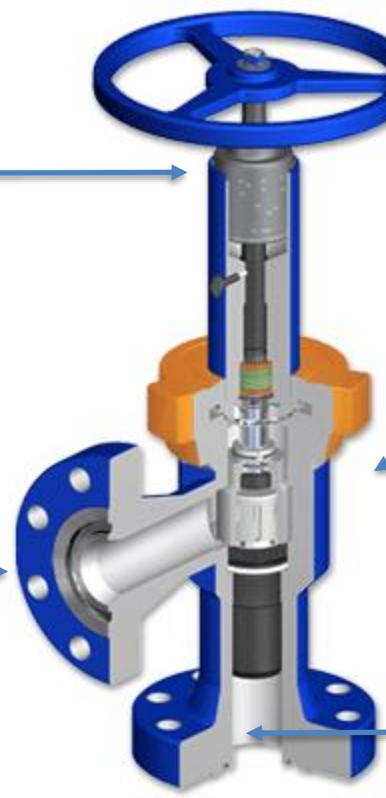
Part I: Working principle, function, and erosion of choke valve

Choke valve: overview

- Function: reduce pressure and control flow rate
- Application: production, injection, artificial lift, storage…
- Installation: Xmas tree, manifold, line heater, FPSO…

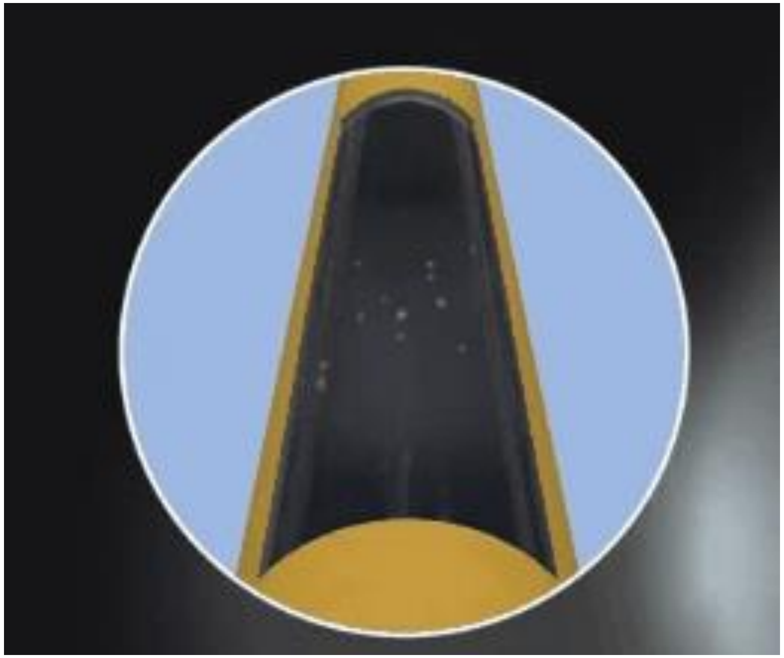


Choke valve composition

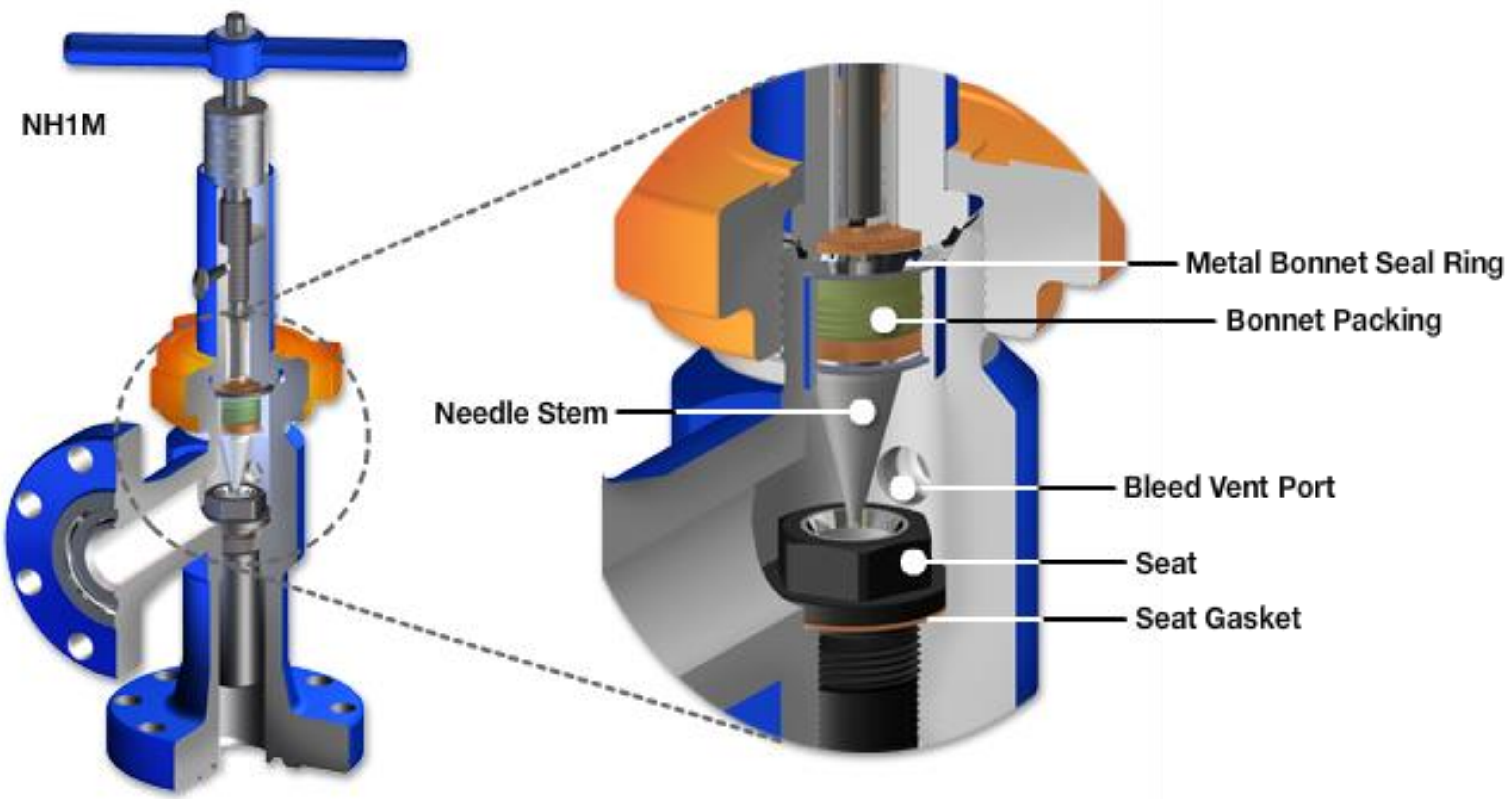


Erosion

- Erosive agents:
  - Sand
  - Barite/Calcite
  - Proppants

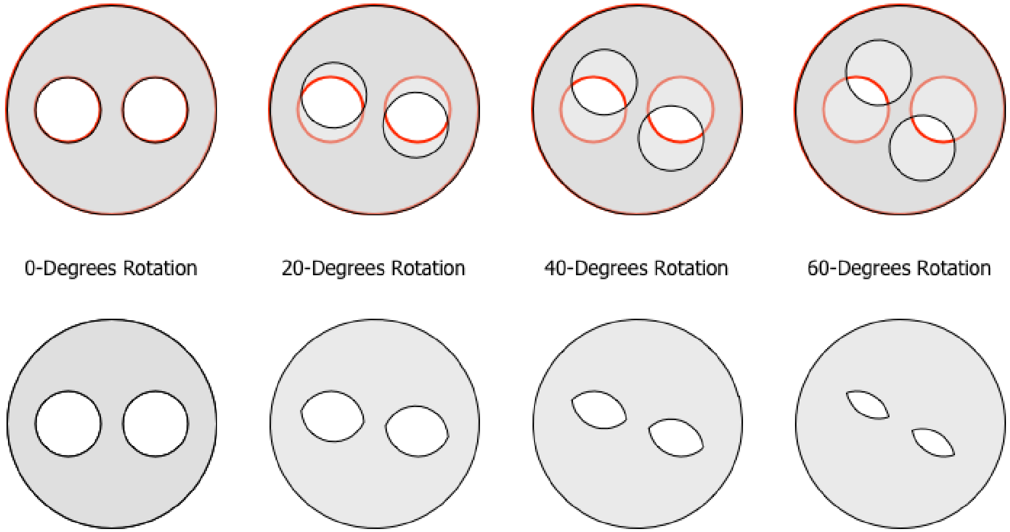


Needle & Seat choke valve

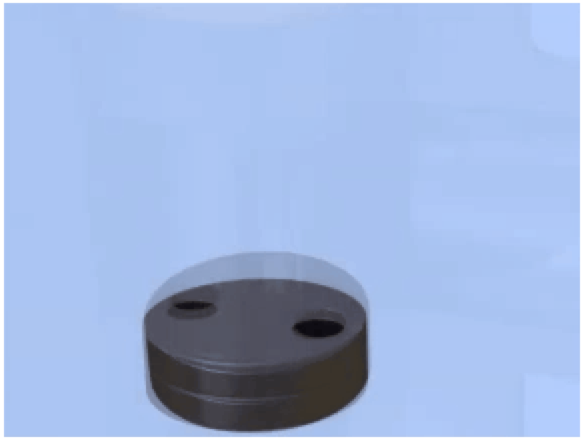


Needle & Seat choke valve: erosion

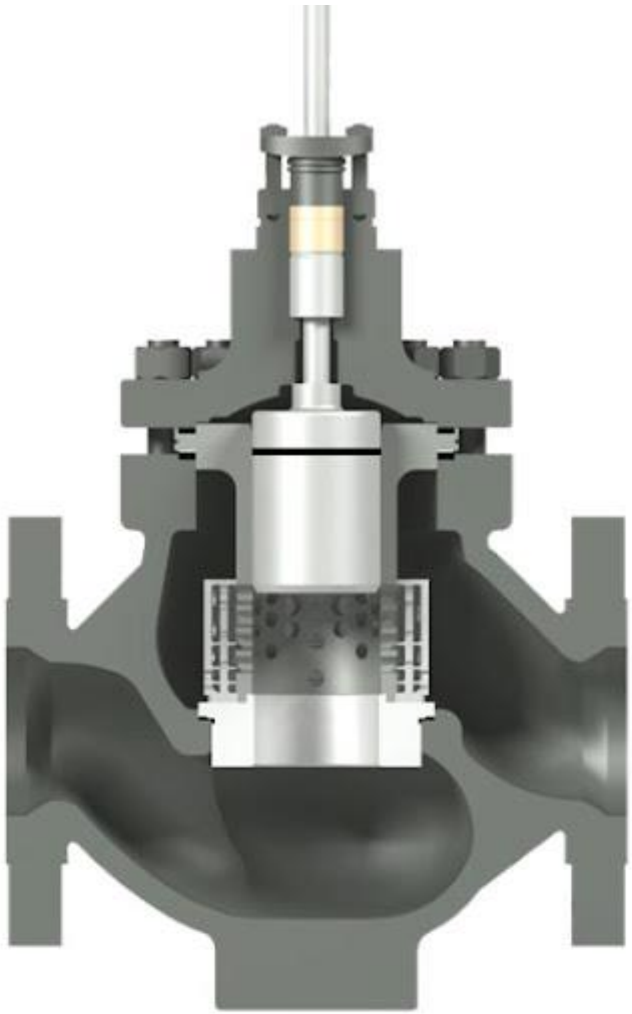
Multi-Orifice valves (disc-style)

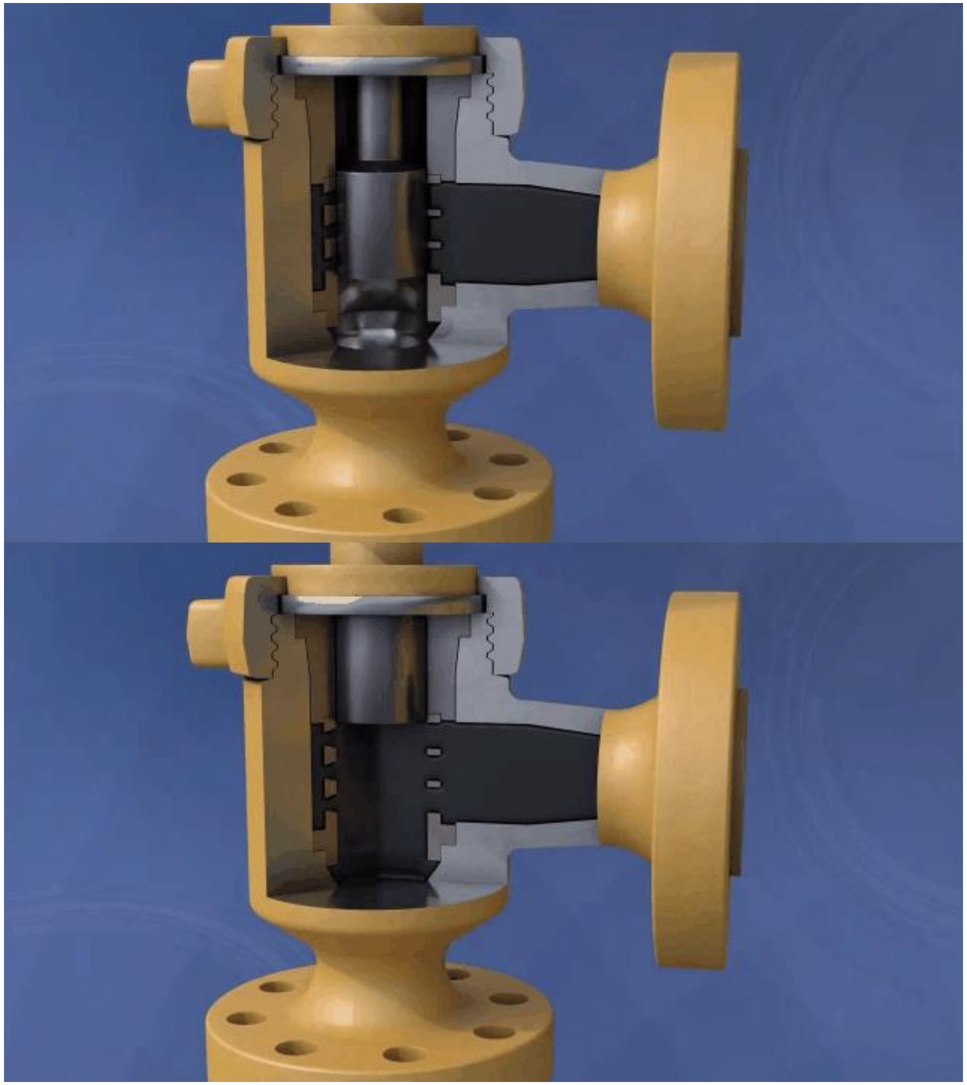


Multi-Orifice valve: erosion

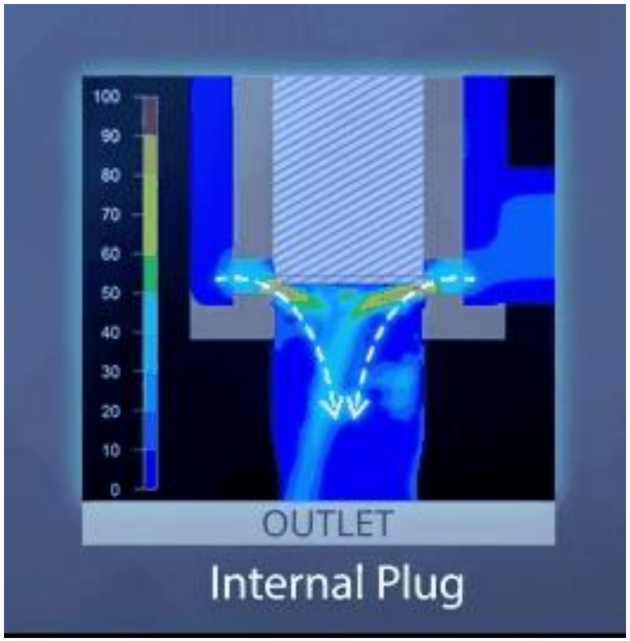


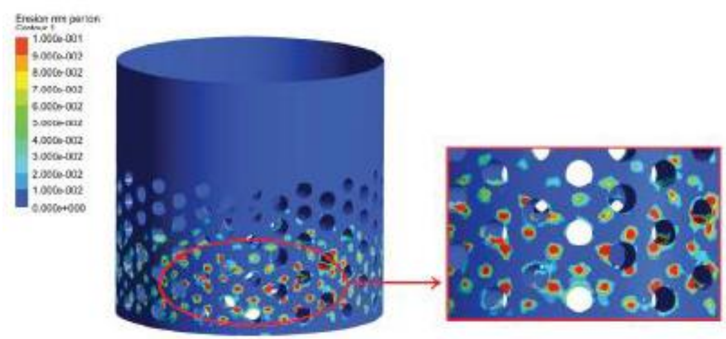
Plug & Cage choke valve





Plug & Cage choke valve: erosion





Part II: Flow coefficient as a degradation indicator: pitfalls and 3D representation

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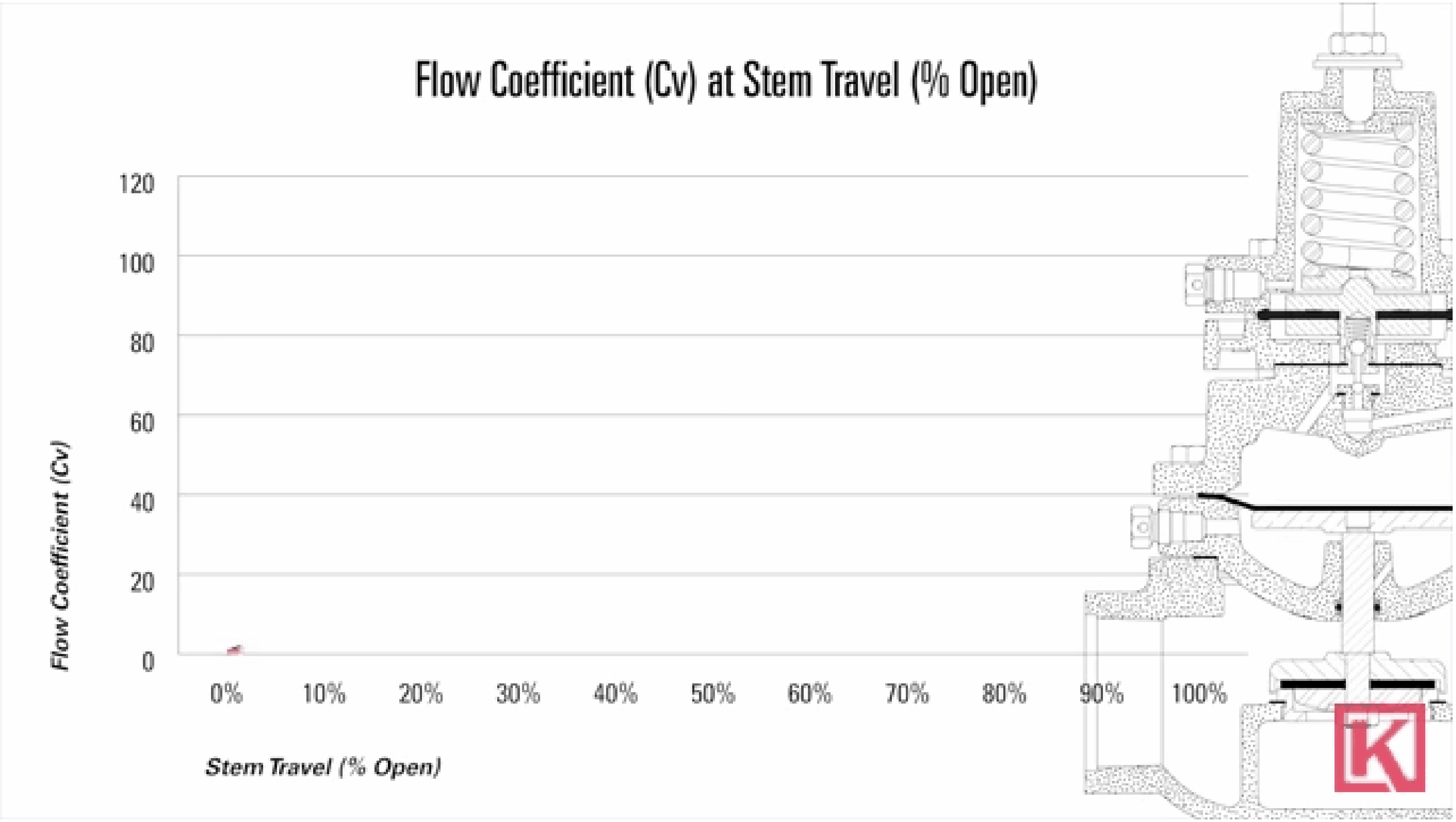
Flow coefficient (Cv): definition and calculation

Cv curve



Flow Coefficient (Cv) at Stem Travel (% Open)
120
100
80
60
40
20
0
Flow Coefficient (Cv)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Stem Travel (% Open)

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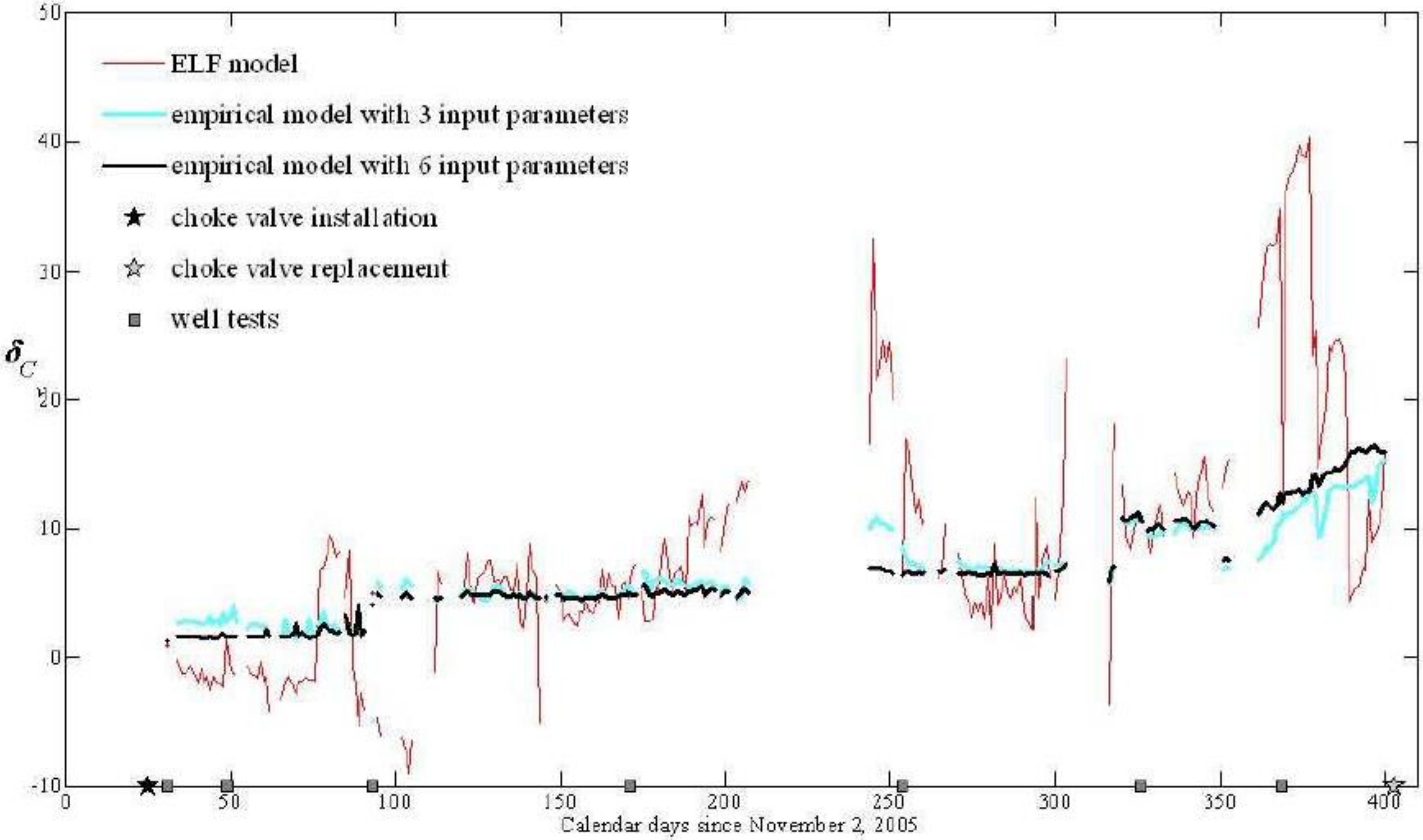
Cv deviation as erosion occurs



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Pitfall

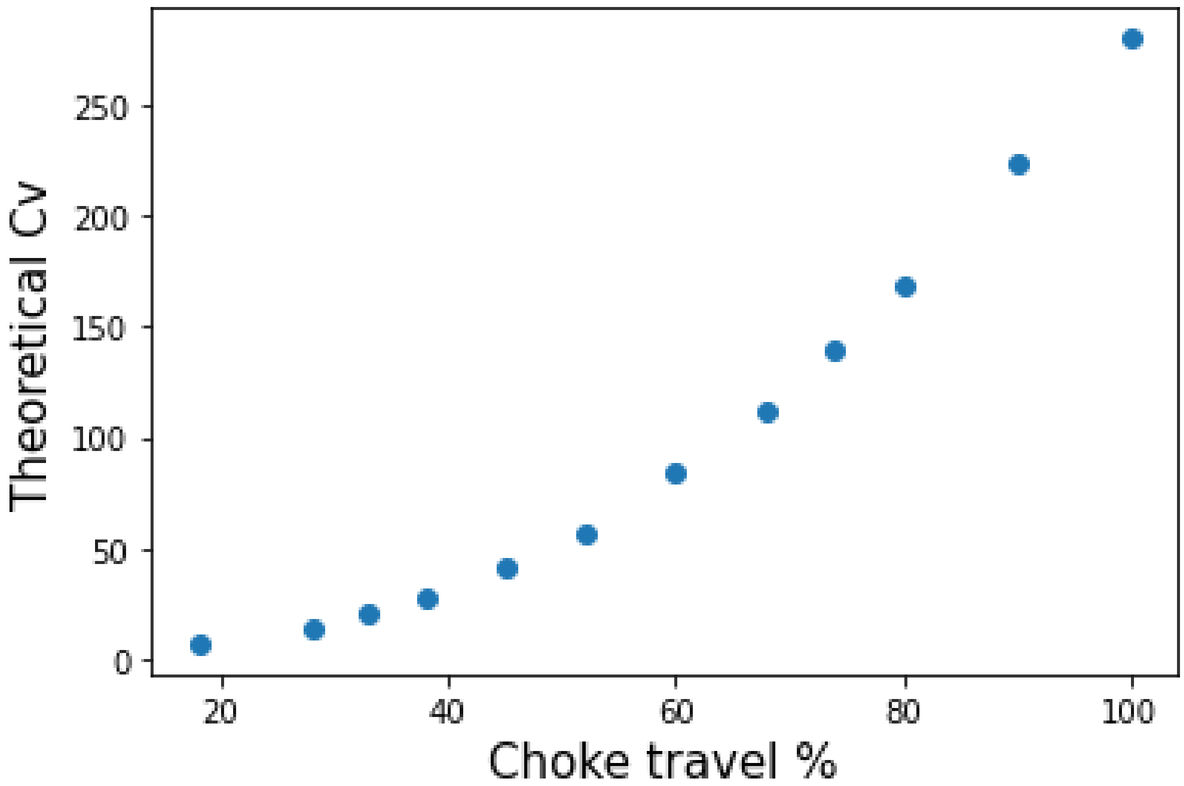
- The Cv is a function of both time and opening
- Non-monotonic Cv deviation growth

Case study

Data source	Equinor
Horizon	17 Sep to 31 Dec
Working starts at	Unknown
Number of data points	46
Available data types	Timestamp, Calculated Cv, choke travel, pressure drop

Theoretical Cv as a function of opening

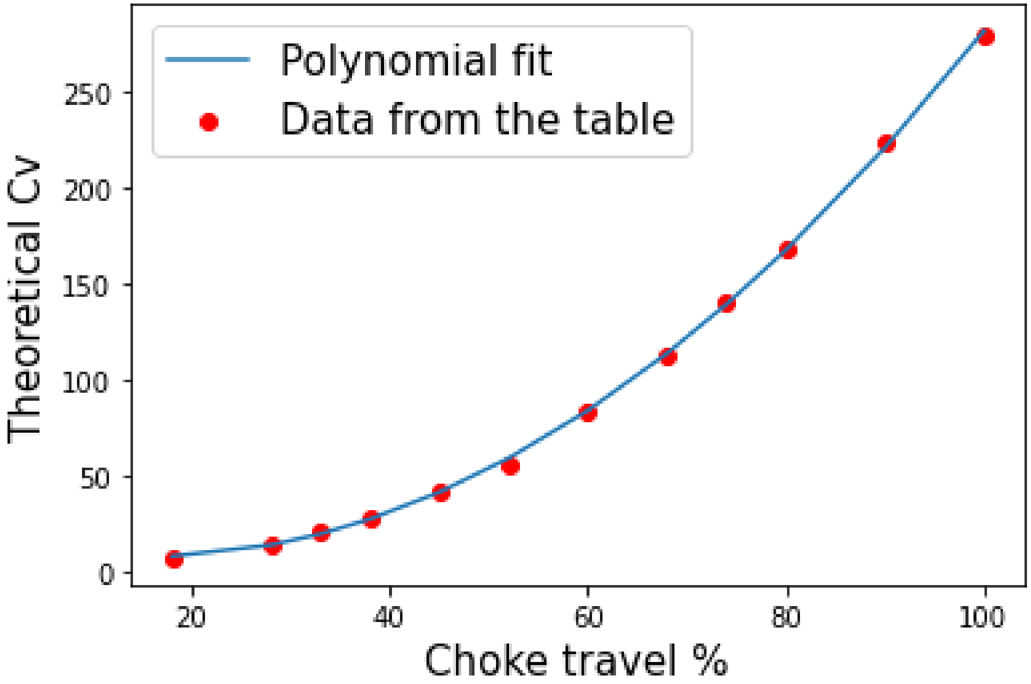
Choke Cv	Choke travel (% or °)
280	100
224	90
168	80
140	74
112	68
84	60
56	52
42	45
28	38
21	33
14	28
7	18



Interpolation/regression

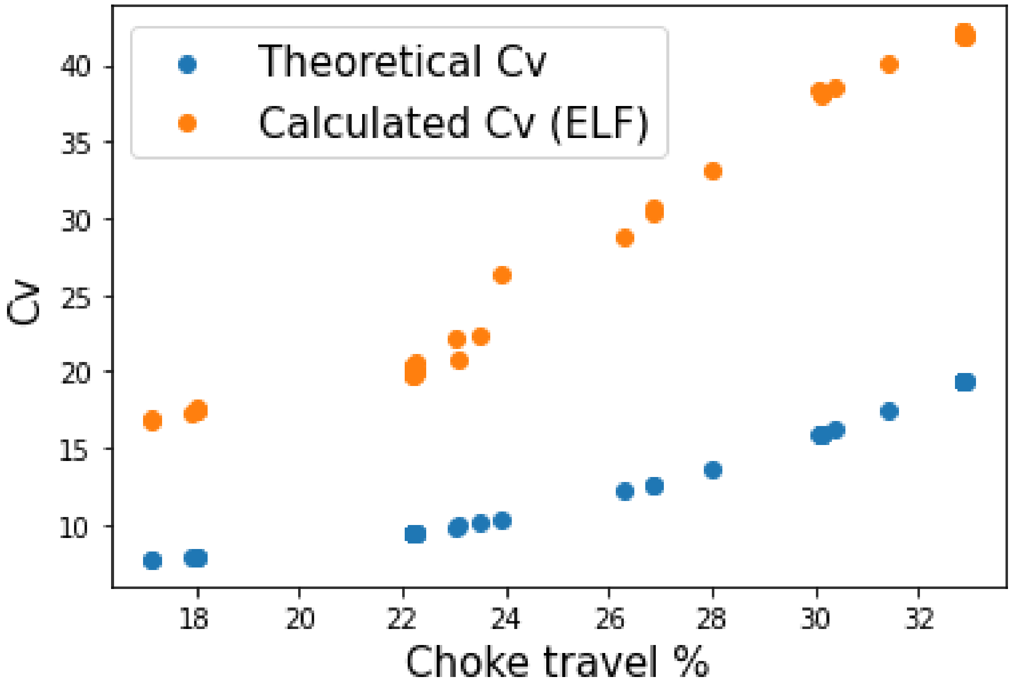
- During operation, the actual valve travel are not always integer
- Regression: Cv as a polynomial function of opening
- $Cv = 16.64-1.18x+0.038x^2$

Choke Travel_CalcInput
32.88107147
32.88134081
32.88371517
32.88327449
32.87886203
32.8777763
32.88026494
32.88148215
32.88160827
32.88171191
32.88128229
31.38321662



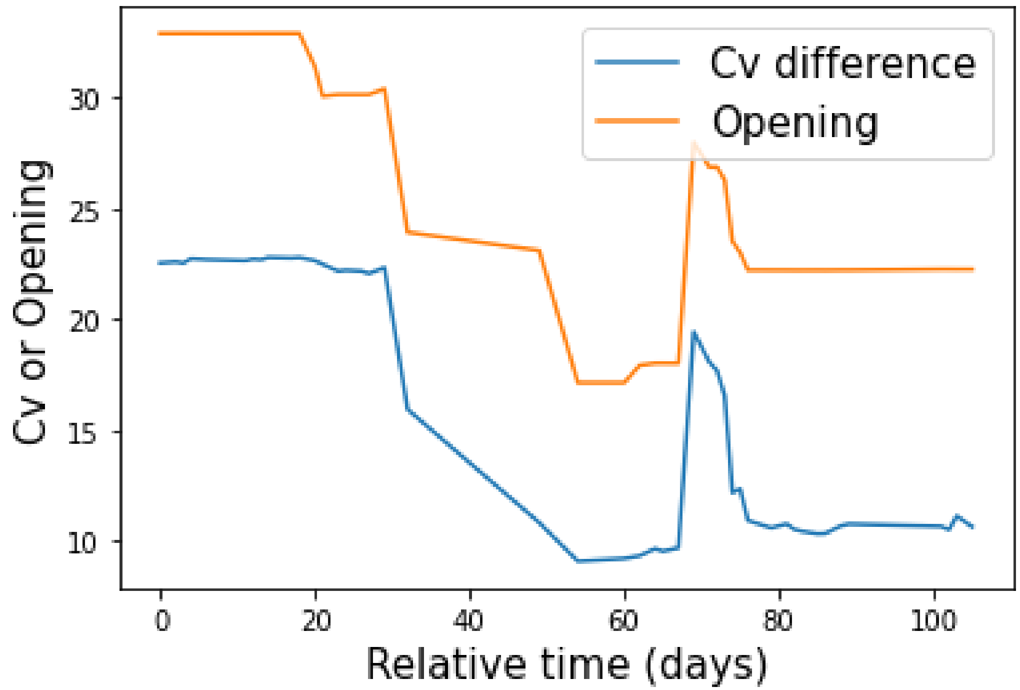
Overall degradation

- From 17 Sep to 31 Dec, the valve has been operated at moderate openings: <=35%
- If we ignore the time dimension, then the erosion is captured in the following snapshot.

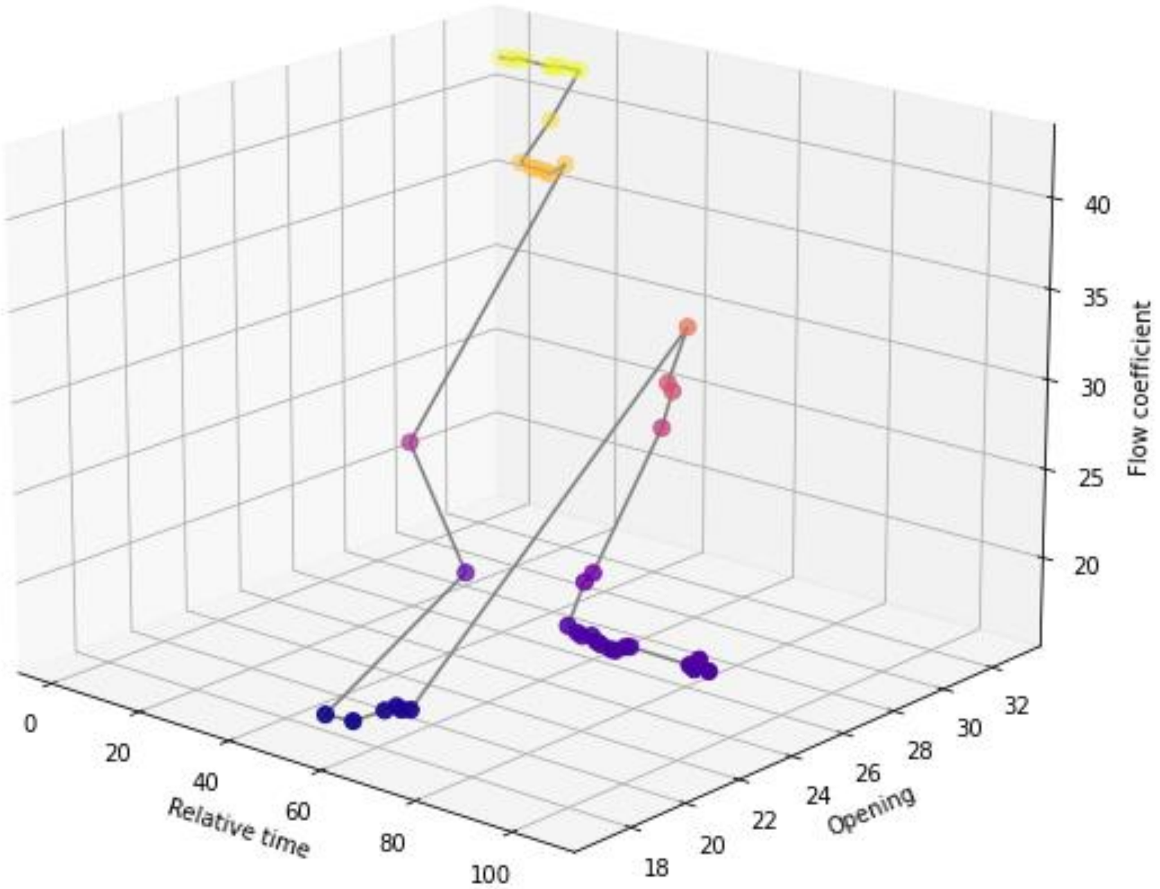


Cv deviation vs relative time

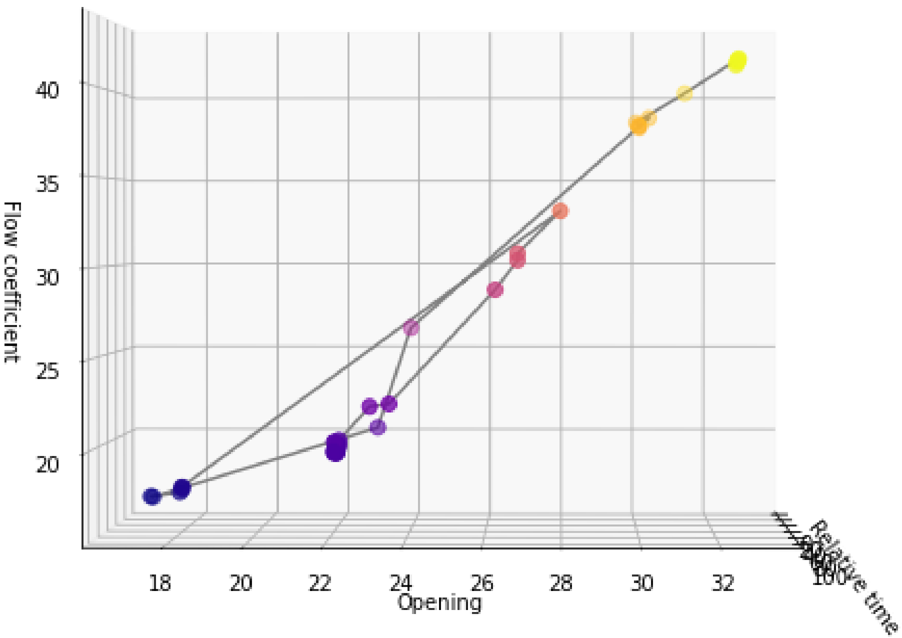
- Correlation between the Cv difference and the valve travel

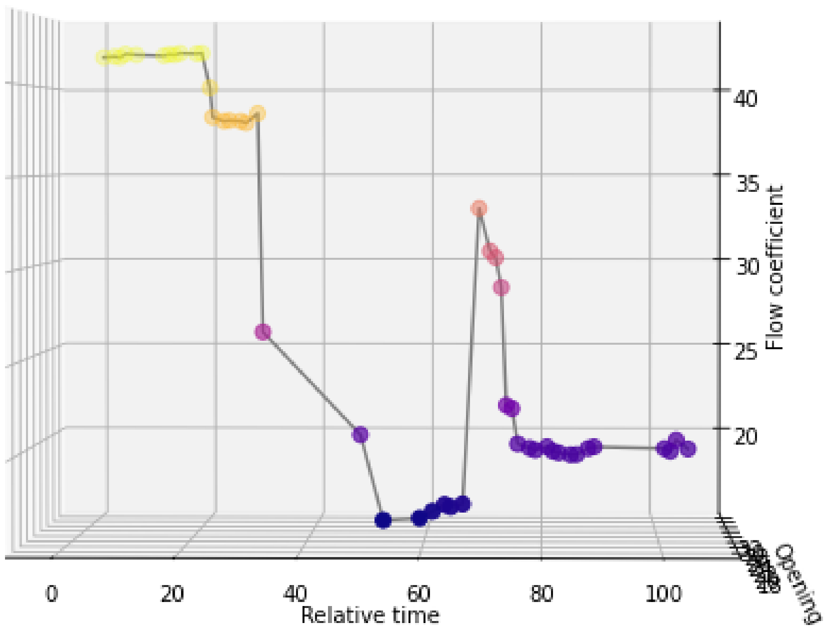


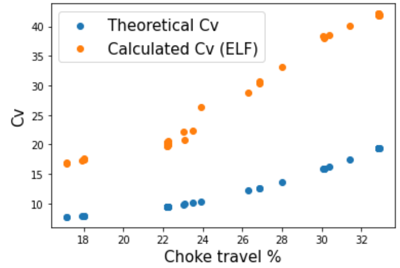
Observed Cv in 3D

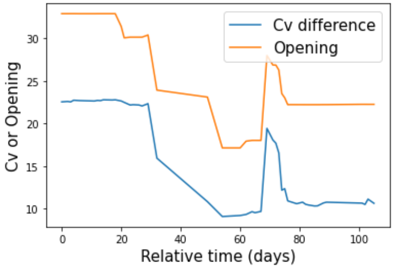


Observed Cv projected into x-z and y-z plane

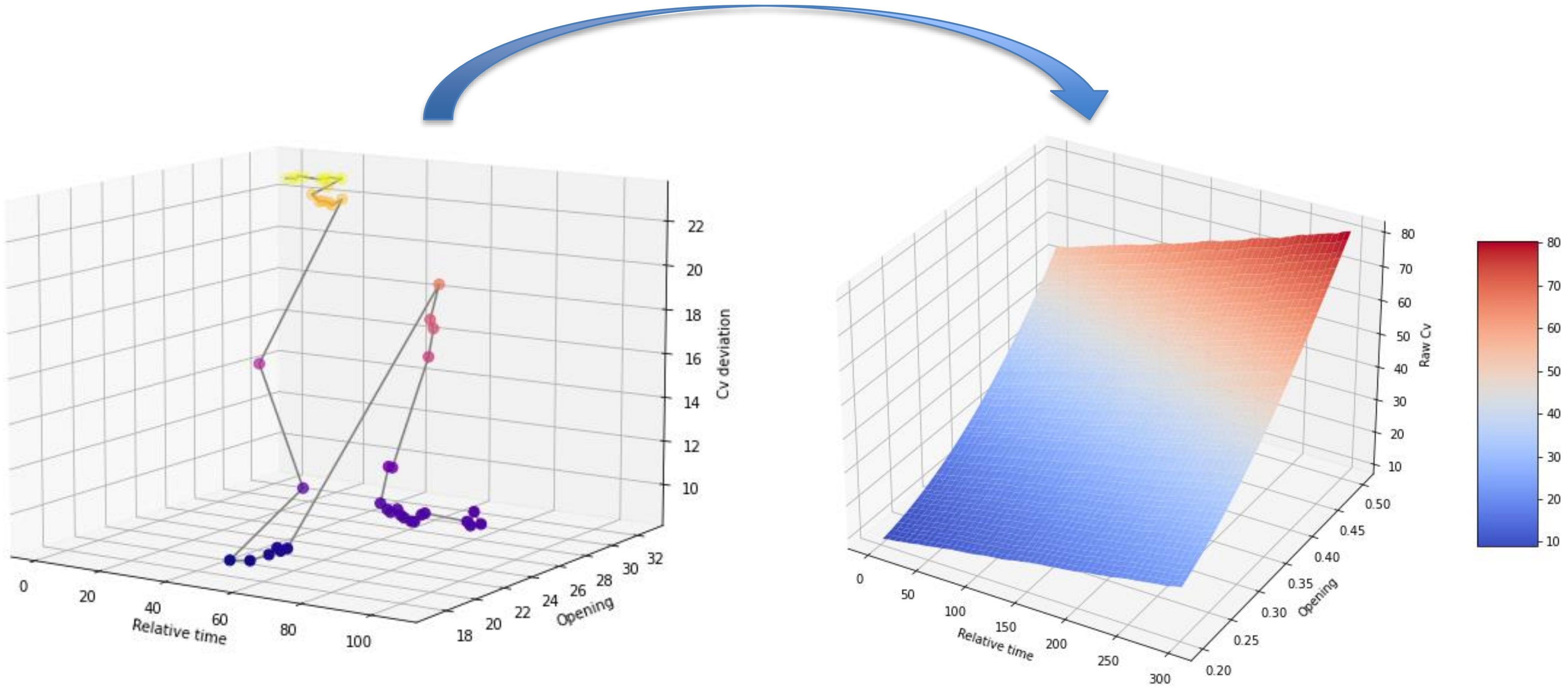








Challenge: Cv surface estimation



Failure threshold: a vector, not a scalar

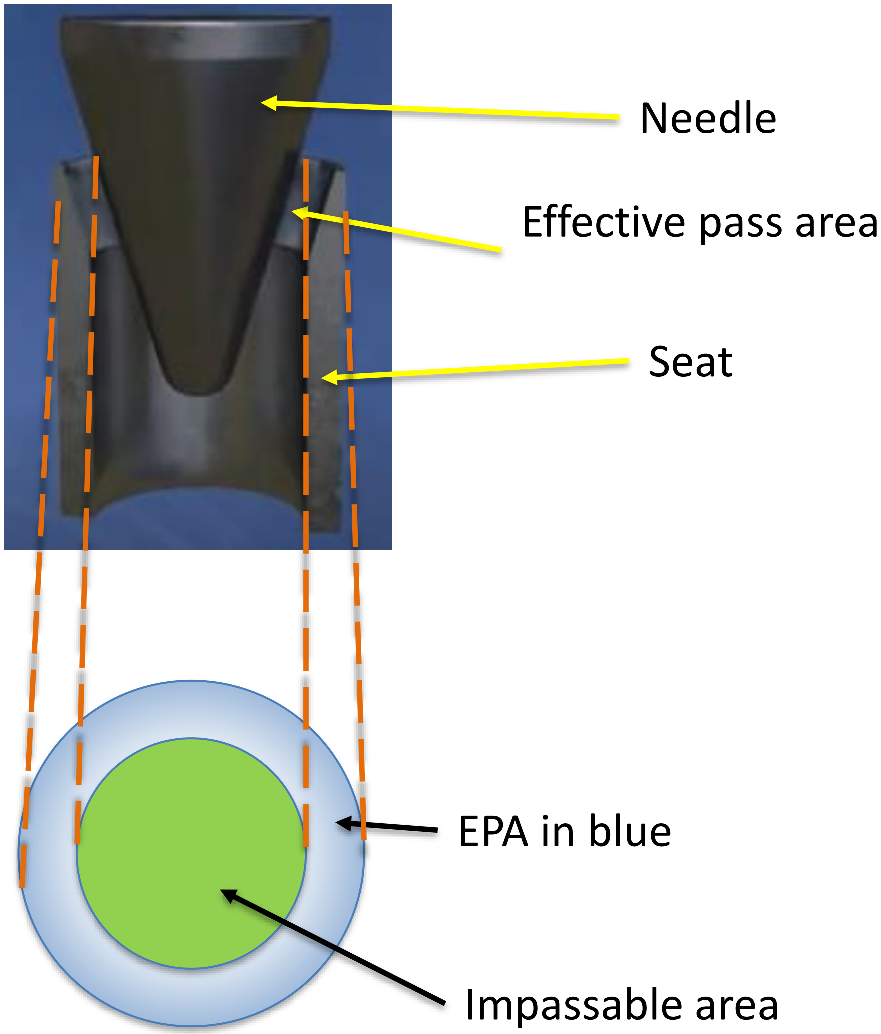
- When defining the failure threshold, the opening should be specified
- A set of constraints:
  - For opening=0%, $\Delta Cv \leq 5$
  - For opening = 50%, $\Delta Cv \leq 20$
  - For opening = 100% $\Delta Cv \leq 50$
  - …

Part III: Static model and Cv surface estimation: effective pass area, eigen-increment and erosion conversion

Hidden erosion state: Effective Pass Area

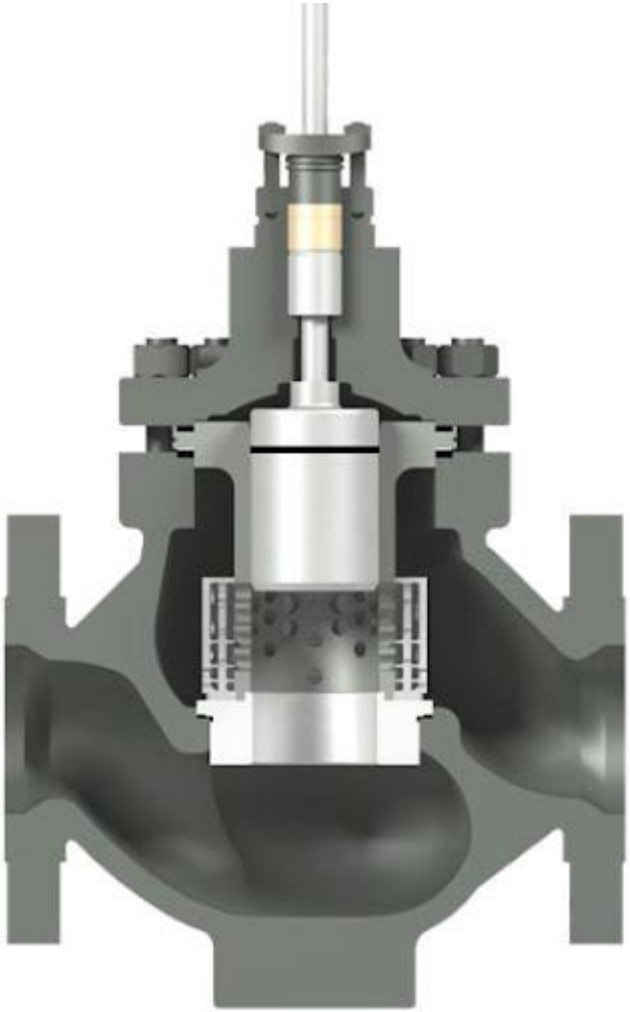
- In normal operation, EPA is controlled by changing the valve opening (changing the position of internal plug/external sleeve/rotation angle/needle lift)
- EPA could be, for different types of choke valve:
  - Unblocked cage port area
  - Orifice area
  - Area between needle and seat
- When the valve is good as new, EPA is known or can be measured
- For a given opening, EPA increases monotonically as the valve degrades
- EPA can temporarily decrease due to plugging
- For most valves, EPA is directly proportional to Cv

Effective pass area: needle & seat

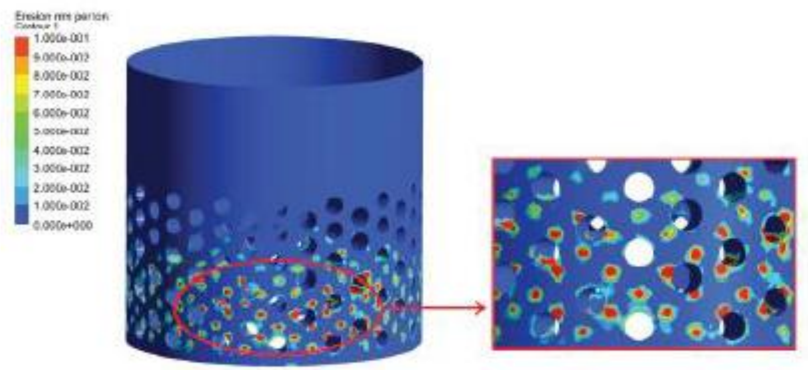


Seat and needle erosion: enlarged effective pass area

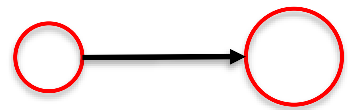
Cage & plug



Cage & plug choke valve: enlarged EPA

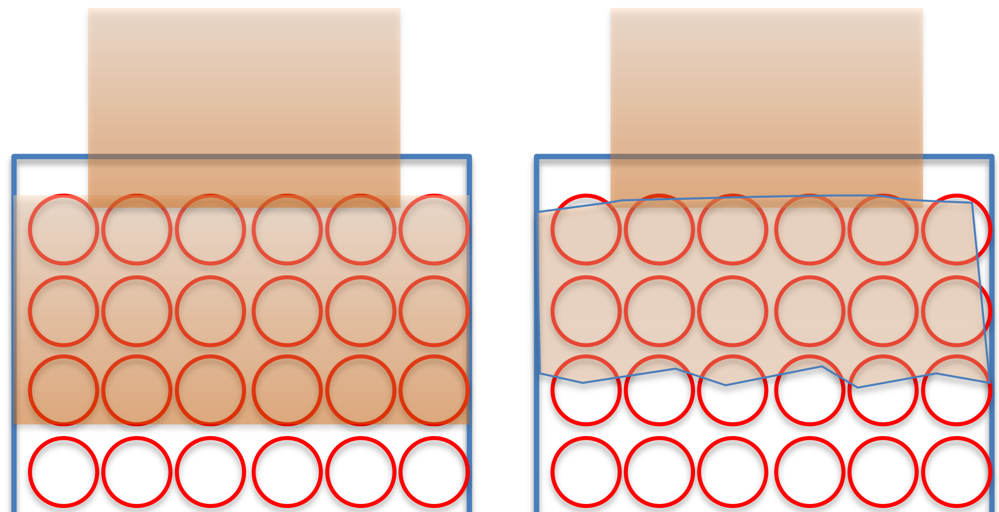


Cage port erosion



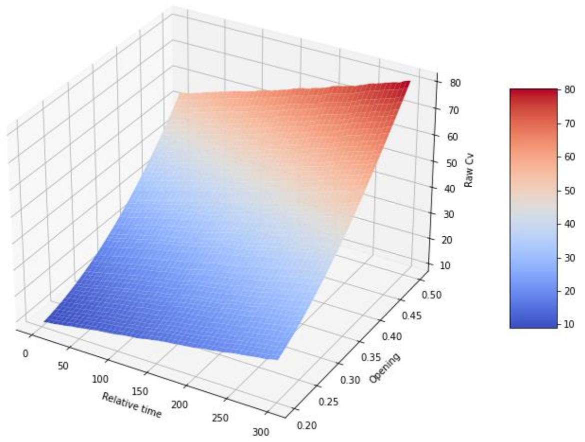
Enlarged cage ports

Plug head erosion



More cage ports are unblocked

Eigen-increment $\Delta A(h_k, k)$



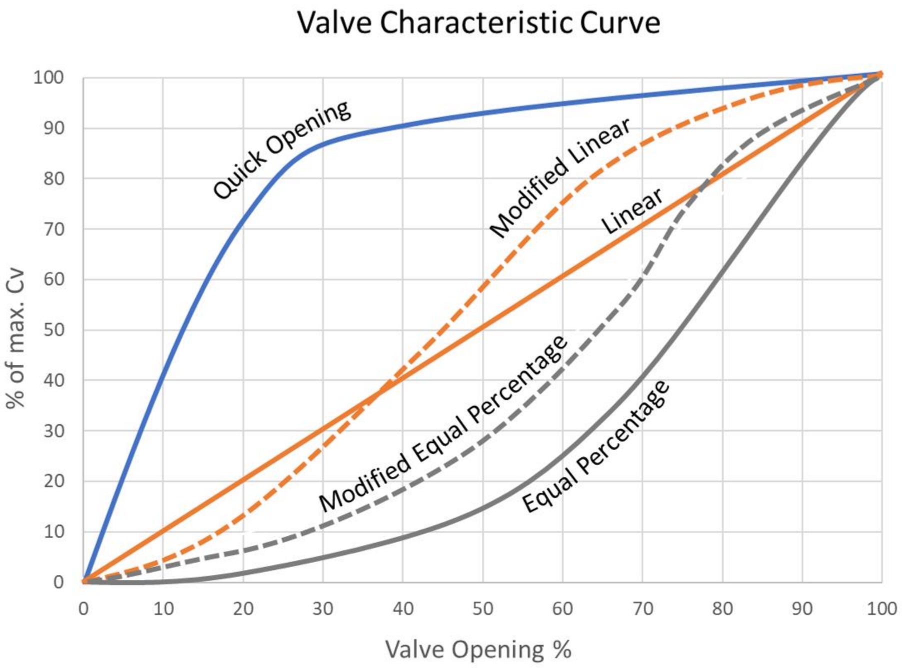
- T: the operation horizon
- k: day index, $k = 0,1,2 \ldots T$
- h_k: the valve opening at day k, in [0%, 100%]
- h: an arbitrary opening in [0%, 100%]
- $A(h, k)$: EPA at the end of day k at opening h
- Eigen-increment:

$$\Delta A(h_k, k) = A(h_k, k) - A(h_k, k-1)$$

- $\Delta A(h, k)$, $A(h, k)$ and Cv surface are computed based on eigen-increments

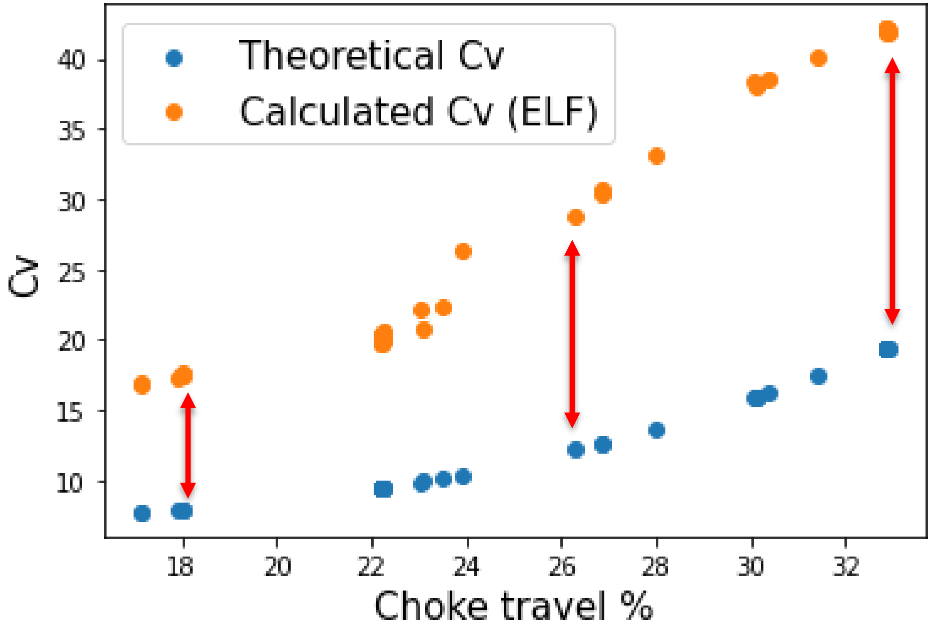
Inherent flow characteristics: $f(h)$

- Defines the relationship between valve opening and flowrate under constant pressure conditions
- Defines the relationship between opening and “vulnerable area”
- Linear: $f(h) = h$
- Equal percentage: $f(h) = R^{h-1}$,
- R: rangeability
- Fast opening: $f(h) = h^{\frac{1}{\alpha}}$

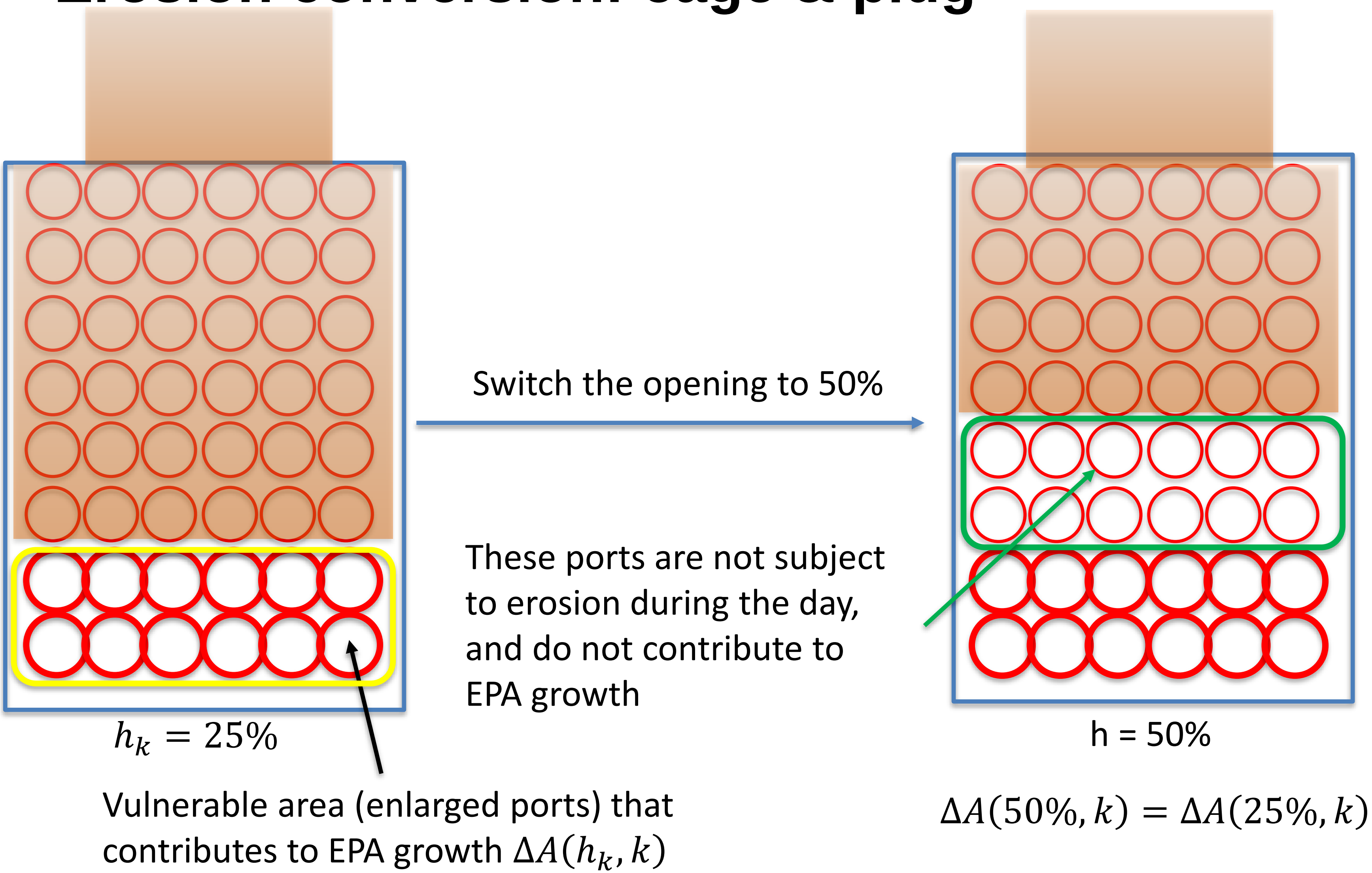


Erosion conversion

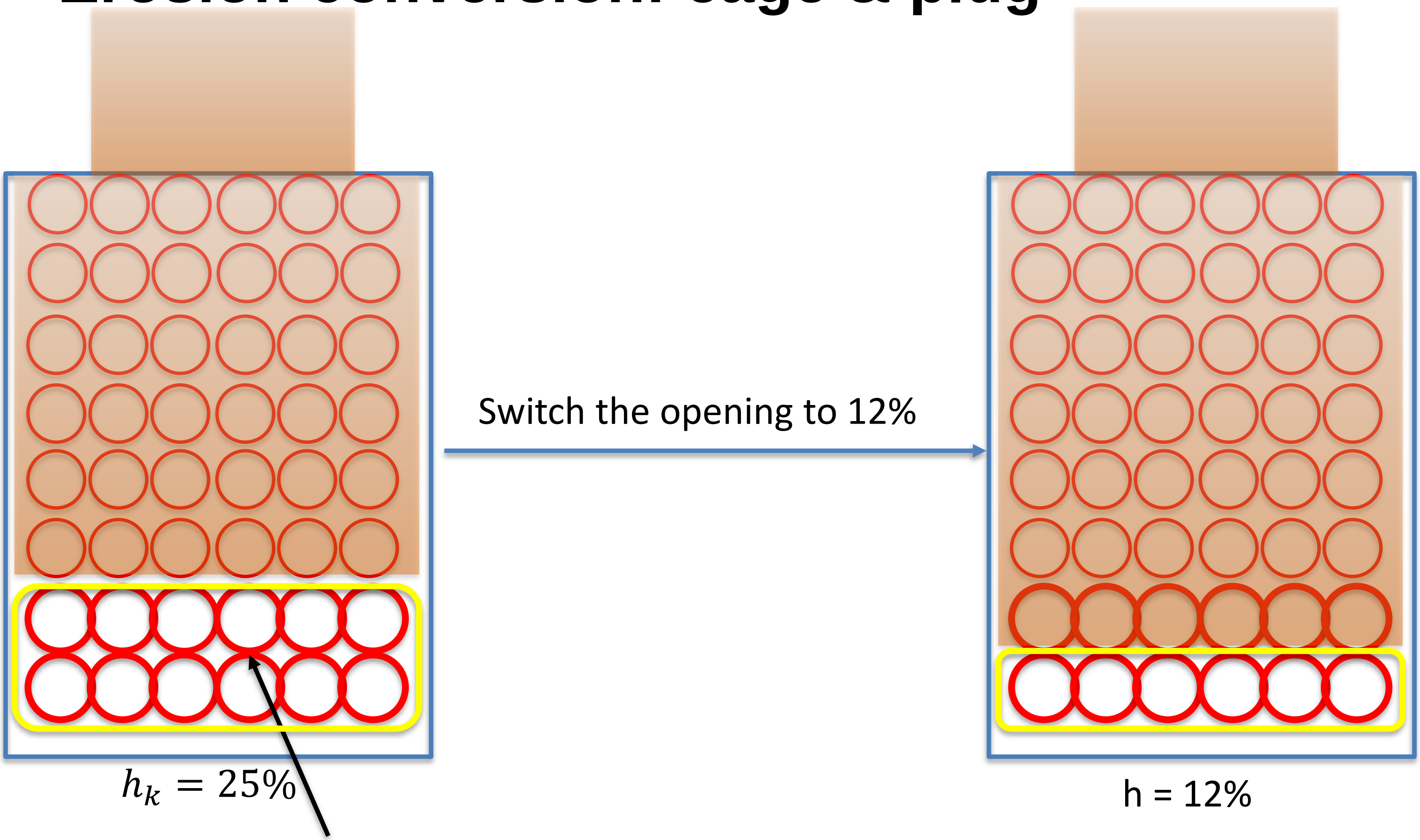
- $\Delta A(h,k) = \min\left(\frac{f(h)}{f(h_k)}, 1\right)\Delta A(h_k,k)$
- For an arbitrary opening h and an operational opening h_k, if $h > h_k$ the increment is preserved; if $h < h_k$ the increment is proportional to $\Delta A(h_k,k)$



Erosion conversion: cage & plug



Erosion conversion: cage & plug



Vulnerable area (enlarged holes) that contributes to EPA growth $\Delta A(h_k, k)$

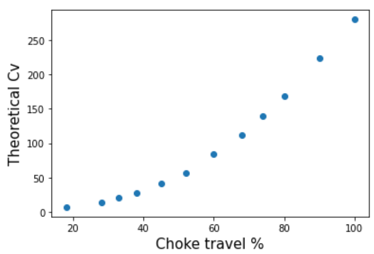
$$\Delta A(12.5\%, k) = \frac{f(12\%)}{f(25\%)} * \Delta A(25\%, k)$$

Erosion conversion: EPA deviation

- $A(h,k) = A(h) + \sum_{j=1}^{k} \min\left(\frac{f(h)}{f(h_j)}, 1\right) \Delta A\left(h_j, j\right)$

EPA deviation: surface estimation

- Initial EPA + daily openings + flow characteristics +Eigen-increment = EPA surface/ EPA deviation surface
- How to infer eigen-increments?



Choke Travel_Calcl
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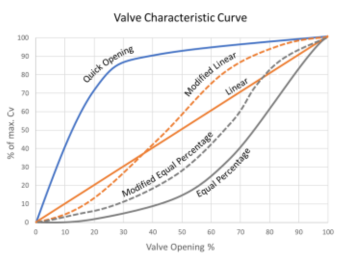
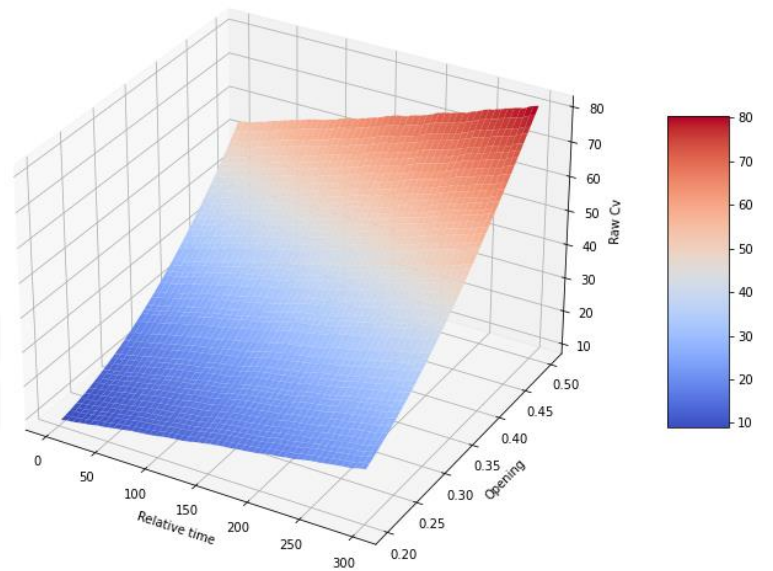


Eigen-increments



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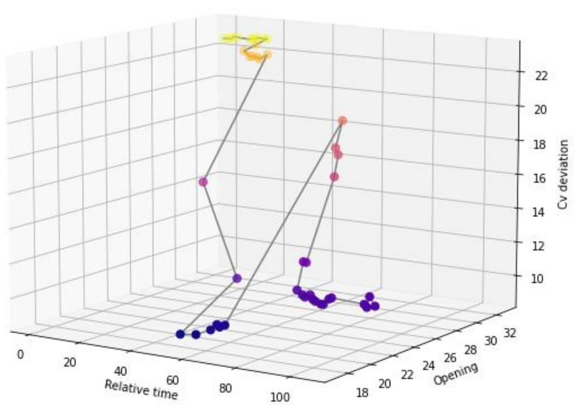
Estimation of eigen-increments: least squares

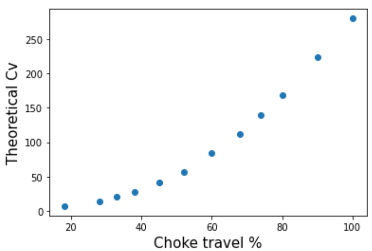
- Observations: $y_1, y_2 \dots y_T$
- Cv conversion function: $Cv(h) = \lambda\big(A(h)\big) = \lambda A(h)$
- Observation model: $y_k = \lambda A(h_k, k) + \epsilon$
- Loss function: $L = \sum_{k=1}^{T}\big(y_k - \lambda A(h_k, k)\big)^2$ With $A(h_k, k) = A(h_k) + \sum_{j=1}^{k} \min\left(\frac{f(h_k)}{f(h_j)}, 1\right) \Delta A(h_j, j)$
- Find $\Delta A(h_k, k), k = 1 \dots T$ that minimizes L



Eigen-increments

Cv deviation: surface estimation

- Initial Cv + daily openings + flow characteristics +Observed Cv+ Cv Conversion function = Cv surface/ Cv deviation surface



Choke Travel_Calcl
32.88107147
32.88134081
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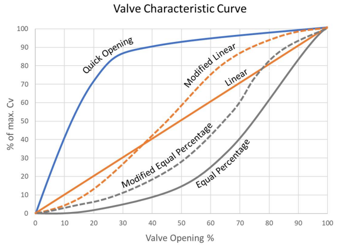

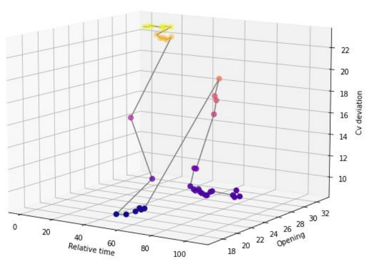

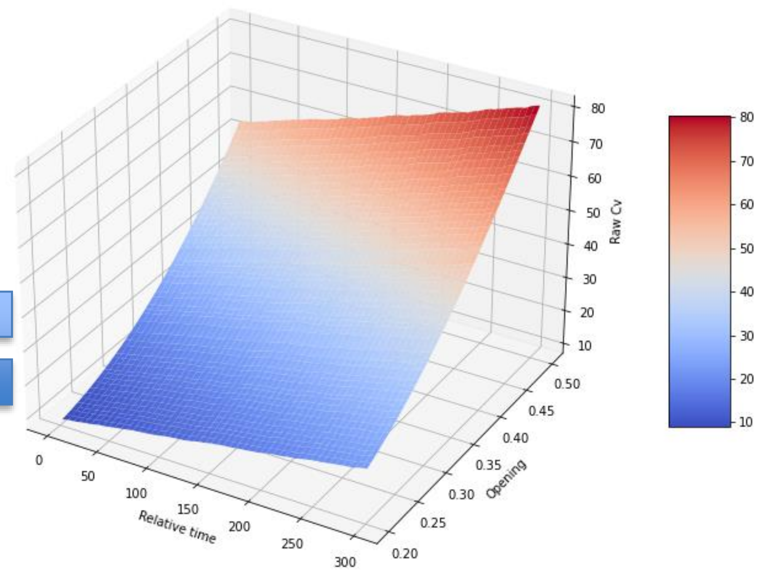

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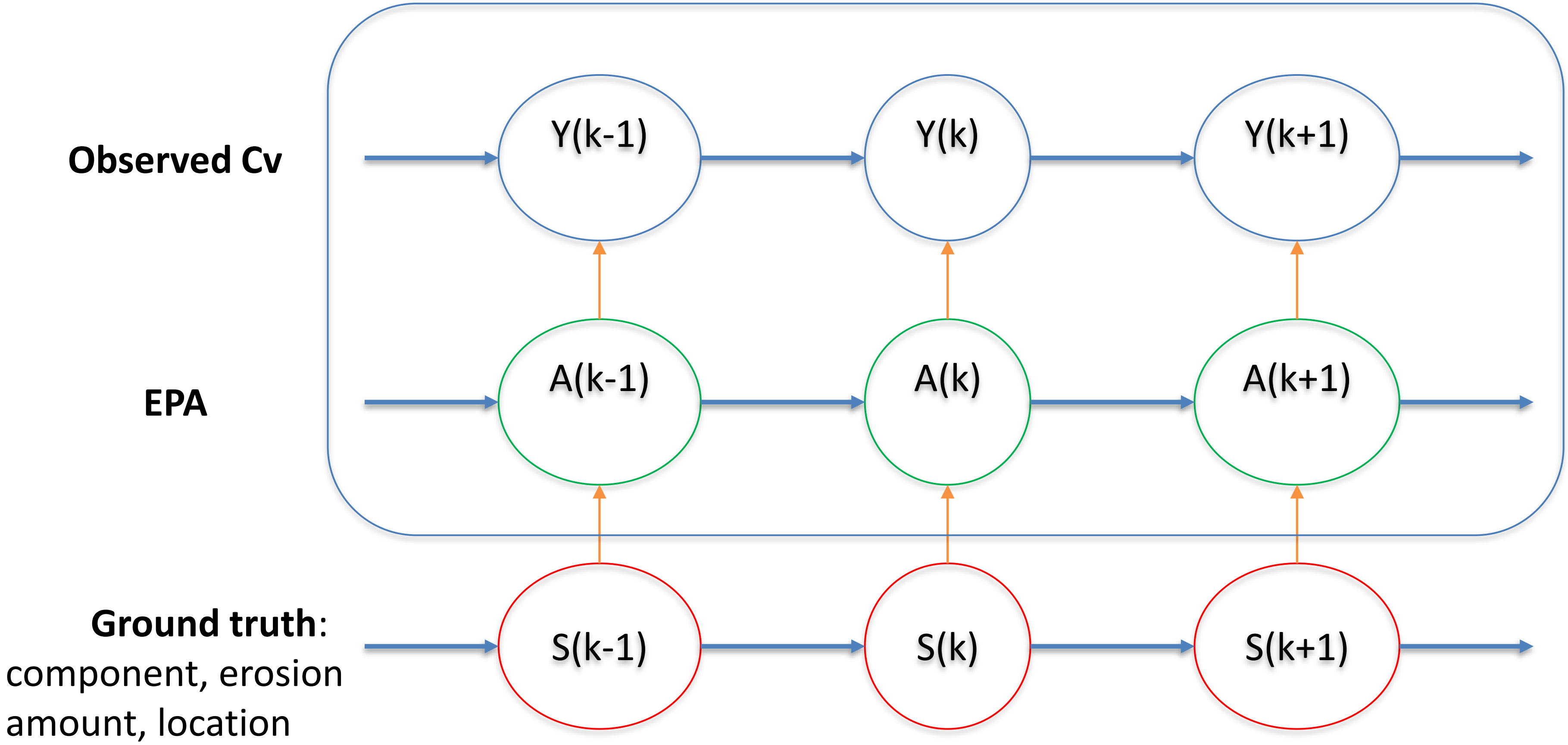
Part I-III: Summary

- Cv, recorded as 1D array, should be perceived and used in combination with the openings
- Failure threshold should be defined for each opening
- Effective Pass Area is the hidden erosion state
- Using the inherent flow characteristic, we can establish a “conversion rule” that converts the eigen-increments to increments at an arbitrary opening
- Least squares method can be used to estimate the eigen-increments from the observed Cv
- The obtained Cv deviation surface shows the erosion state for any opening
- Up to now, everything is deterministic, and no process parameters are taken into account. So the RUL cannot be predicted based on this model.

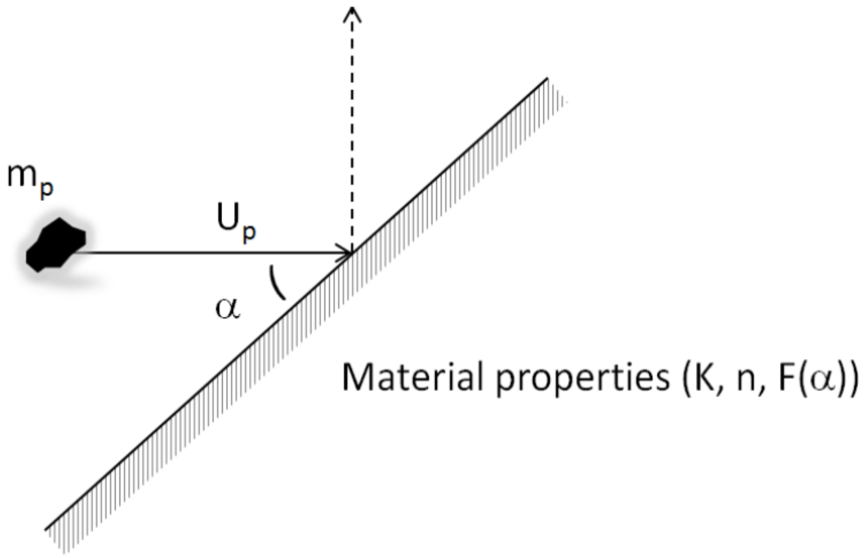
Part IV: Dynamic model: randomization and dynamic system representation

Markovian dependencies between states and observations



Erosion response model

- $E = K * U^n * F(\alpha) * m$
- E: material loss rate (kg/s)
- α: impact angle
- n: velocity exponent
- F: material ductility function
- U: particle impact velocity (m/s)
- m: mass rate of sand (kg/s)



Eigen-increments, flow rate and sand rate

- Eigen-increments: $\Delta A(h_k, k) = A(h_k, k) - A(h_k, k-1)$
- $Q(k)$: flow rate of day k
- $m(k)$: sand mass rate of day k in kg
- $\Delta A(h_k, k)$ considered as a positive random variable with expectation
- $E[\Delta A(h_k, k)] = E[A(h_k, k) - A(h_k, k-1)] = \ K \ * \left(\frac{Q(k)}{A(h_k, k-1)}\right)^n * m(k)$
- Variance to mean ratio: $\frac{\mathrm{Var}[\Delta A(h_k, k)]}{E[\Delta A(h_k, k)]} = \theta$
- The eigen-increments are modeled as gamma distributed r.v.
- $\Delta A(h_k, k) \sim Gamma(K \ * \left(\frac{Q(k)}{A(h_k, k-1)}\right)^n * m(k), \theta)$

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System model and observation model

- Evolution of eigen-increment :

$$\Delta A(h_k, k) \sim Gamma\left(K * \left(\frac{Q(k)}{A(h_k, k-1)}\right)^n * m(k), \theta\right)$$

- EPA evaluation:

$$A(h, k) = A(h) + \sum_{j=1}^{k} \min\left(\frac{f(h)}{f(h_j)}, 1\right) \Delta A\left(h_j, j\right)$$

- Convert the EPA to Cv with measurement error

$$y_k = \lambda(A(h_k, k)) + \epsilon \text{ , } \epsilon \sim N(0, \sigma)$$

- Inference on model parameters (K, n, θ, σ ...):
- expectation-maximization + particle filter

Prediction of erosion growth and of RUL based on production plan

Cv records, initial Cv, flow characteristics, opening, flow rate, sand rate

+

Particle filter EM

=

Model parameters

Model

+

Production plan(Openings and corresponding flow rate)

=

Prediction of Cv growth and estimation of RUL

Conclusion

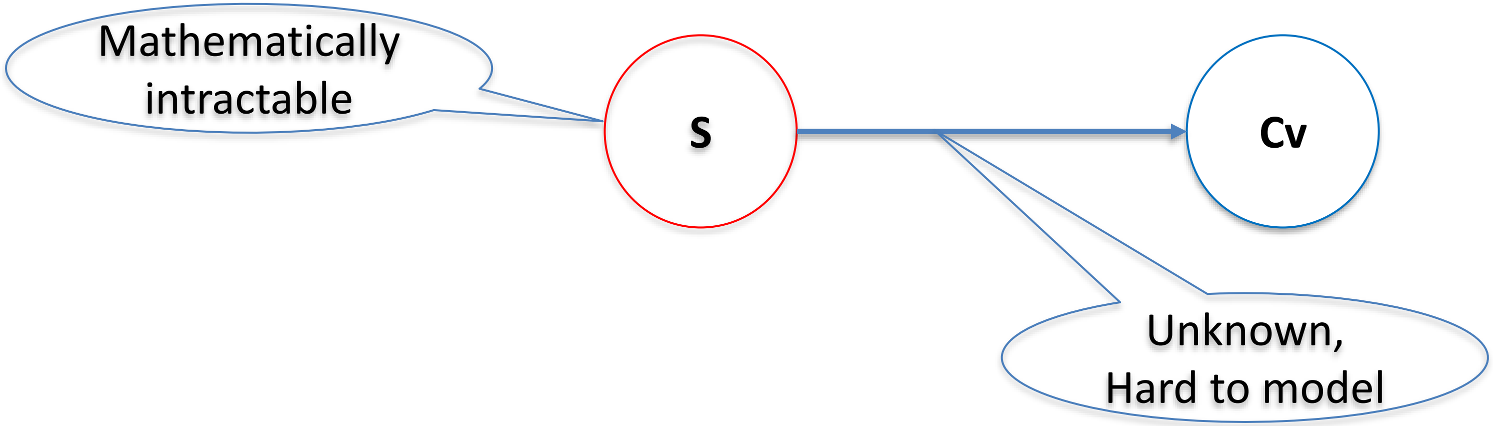
- Cv evolves as a surface, and failure threshold is a curve
- Static model: estimate the Cv surface in the past
- Dynamic model: predict the Cv evolution in the future

Erosion state described by a triplet S

- Three elements define the erosion state:
  - Eroded component
  - Erosion amount (material loss, thickness loss)
  - Erosion location
- Obtained by visual inspection and measurements
- Example: plug and cage control choke
  - S_1 = {cage, material loss: 12g, most at the bottom}
  - S_2 = {cage ports, total enlarged area: 5cm^2, middle and bottom}
  - S_3 = {plug, material loss: 5g, plug head}
  - S_4 = {seat, material loss: 3g, on top}
  - S_5 = {gallery, thickness loss: 2mm, uniformly distributed}
  - …
- $S = \{S_1, S_2, \ldots\}$

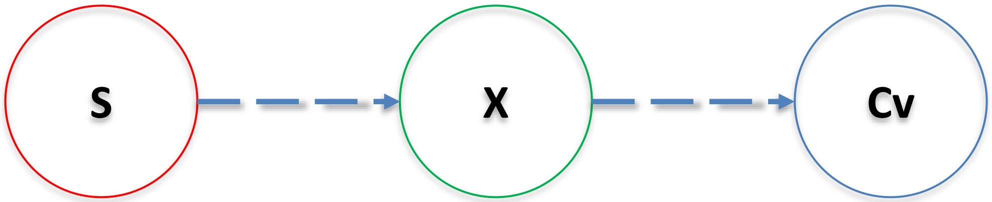
Triplet S

- The triplet S represents the ground truth
- S is unobservable during production
- S involves descriptive text
- S and its evolution do not have a tractable mathematical representation
- Cv is exclusively determined by S and the opening, independent of process parameters such as flow rate, sand rate, pressure drop

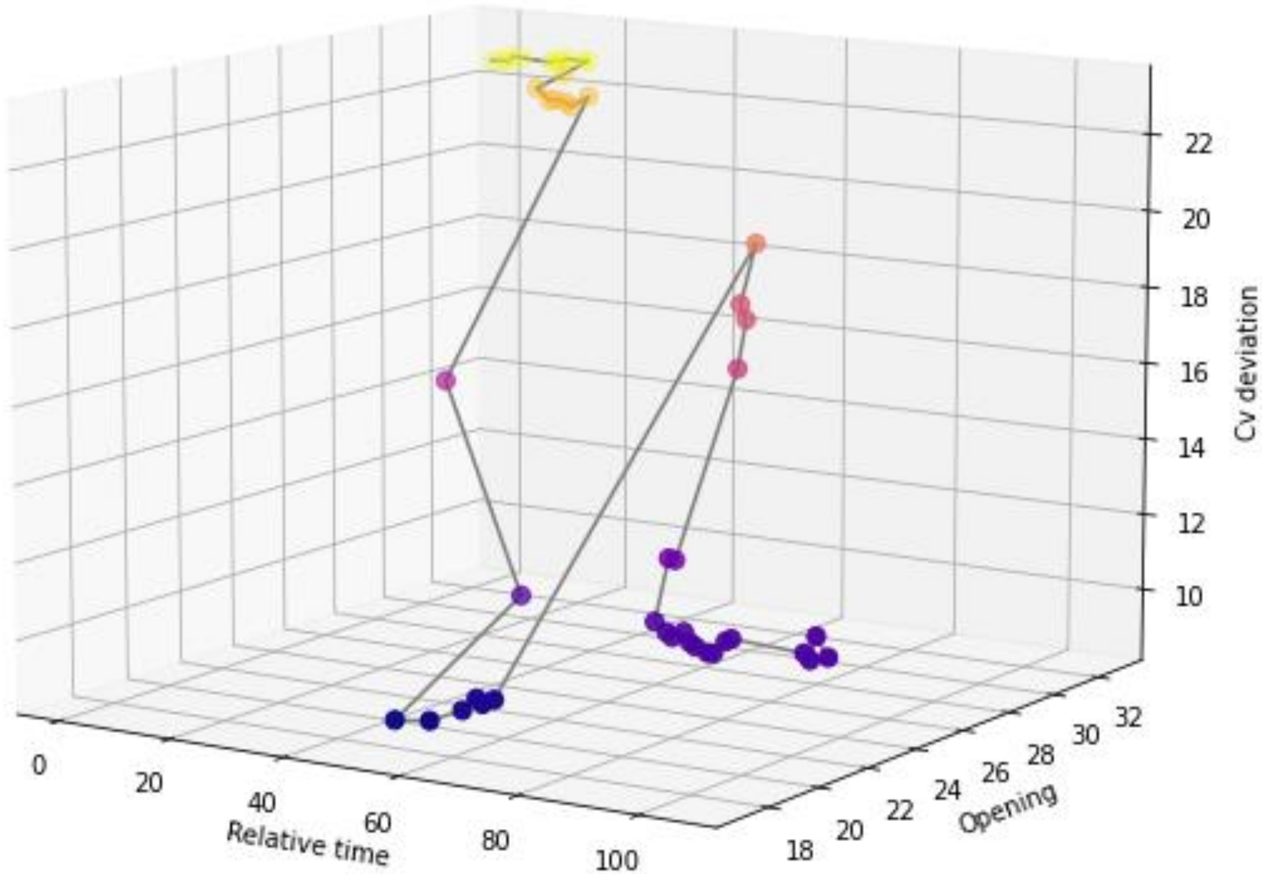


An intermediate state variable: X

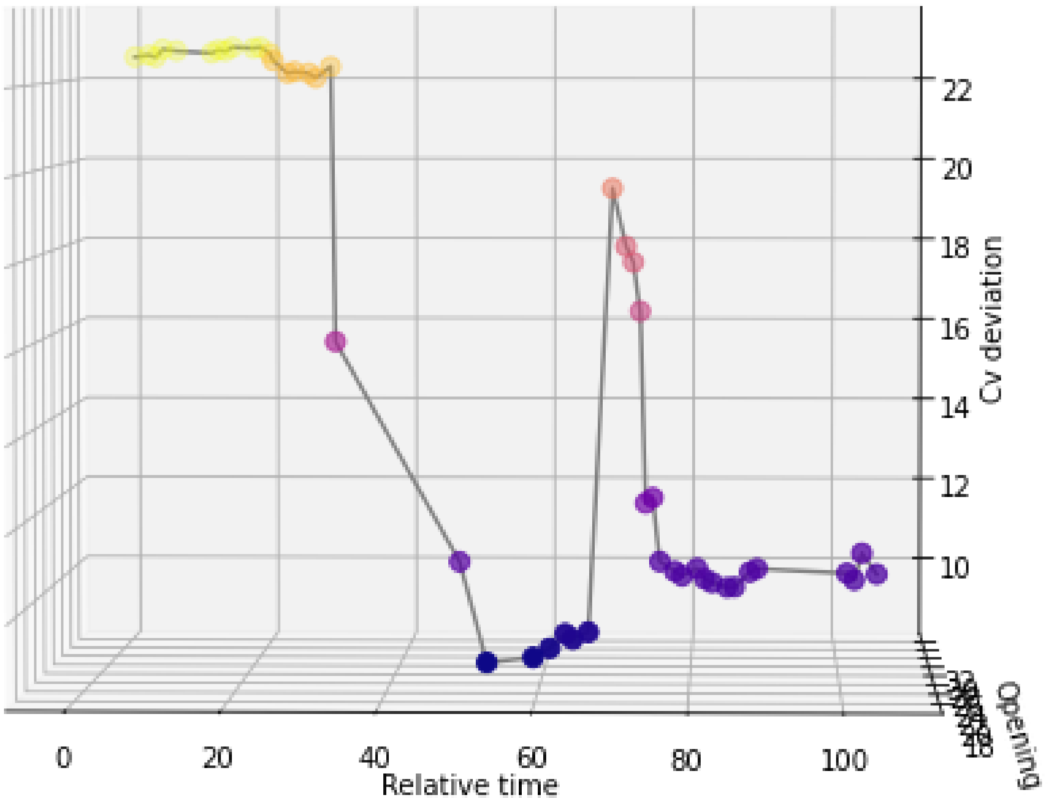
- X should satisfy:
  - Exclusively determined by S
  - Has a physical interpretation, understandable by domain experts
  - When S evolves, X should response and trigger changes in Cv
  - The relation between X and Cv should be knowable or measurable
  - Mathematically representable



Cv deviation in 3D



Cv deviation projected into x-z plane



Cv deviation projected into y-z plane