IAGT
Industrial Application of Gas Turbines

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HOW STATISTICS CAN BECOME A BETTER FRIEND IN SUPPORTING EFFICIENT ISSUES MITIGATION

By
Pontus Slottner / Siemens Industrial Turbomachinery AB

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Agenda

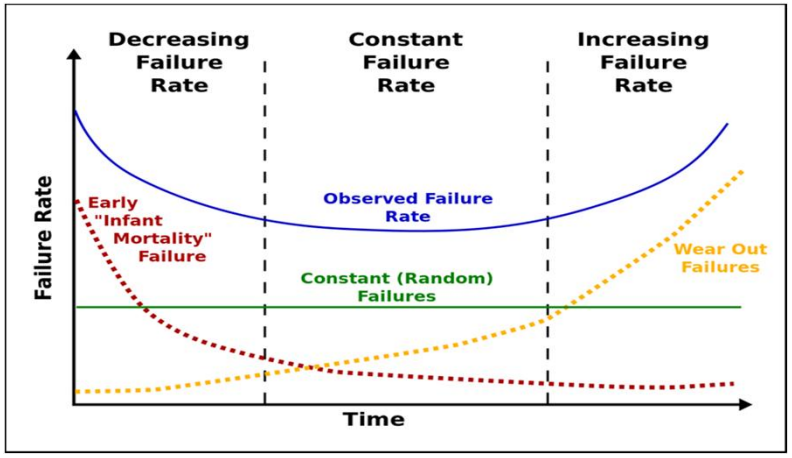
- The engineering challenge
- Weibull analysis
- Gas turbine damage mechanisms
- Traps – mixed operation
- Traps – infant failures
- Traps – early wear-out
- Conclusion and recommendations

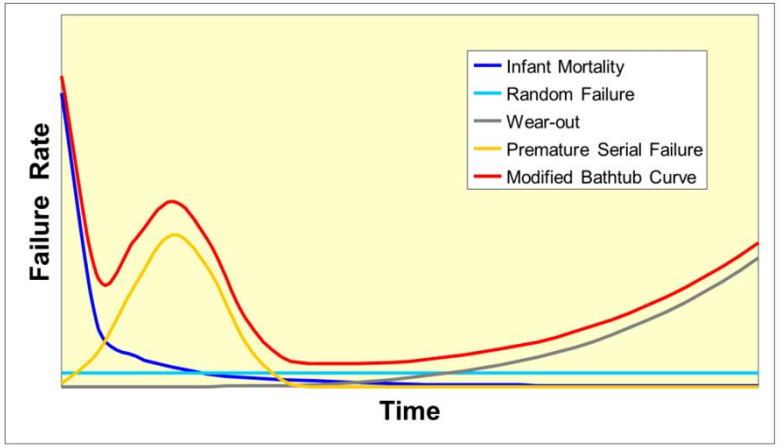
The engineering challenge

- Our goal: define improvements
  - Compare predictions/targets with data
  - Investigate why it doesn't match
  - Determine if and how targets can be met
- Our failure: stuck in analysis
  - Need to deliver solution alternatives

Weibull analysis (I)

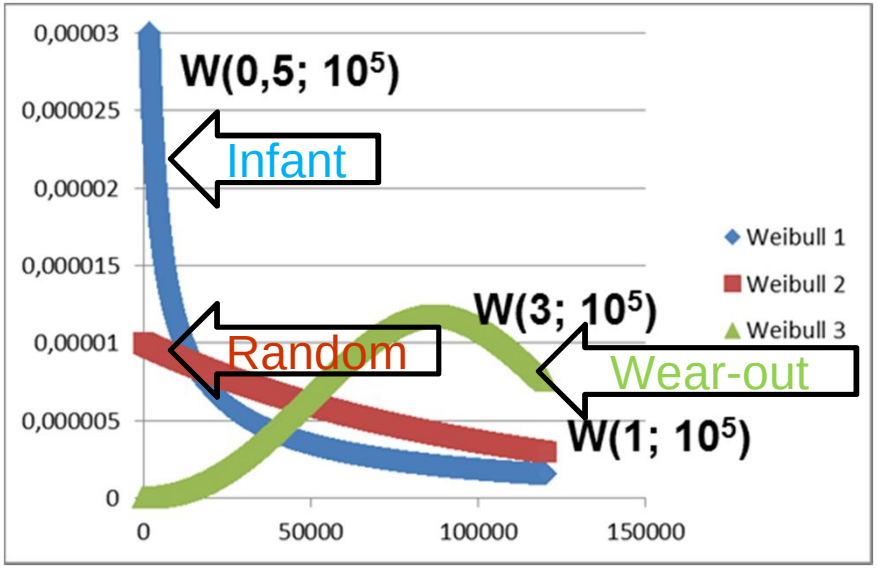
- Bathtub and rollercoaster curves





Maintenance can only mitigate wear-out failures
Maintenance can (will?) increase infant failure rate

Weibull analysis(II)



$W(\beta;\eta)$

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

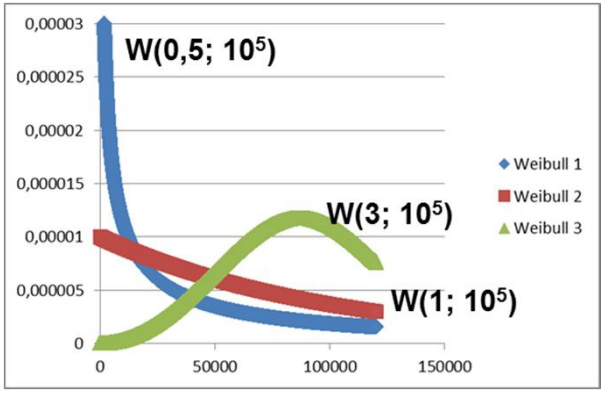
$$P(t) = \int_0^t f(t)dt$$

- Can represent all parts of the bathtub curve

Weibull analysis (IIIa)

First attempt

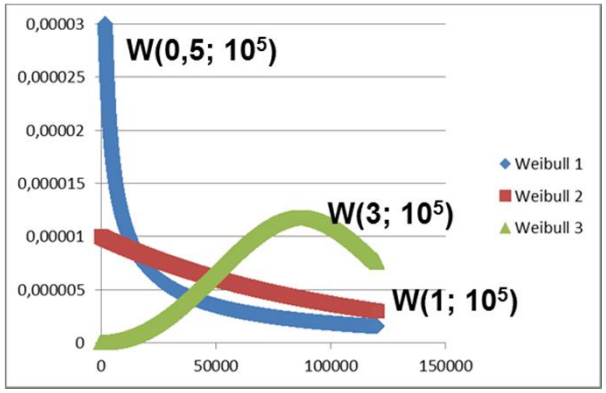
- Define metrics (X-axis)
- Collect data
- Fit parameters
- *Identify underlying failure characteristics*
- *Determine suitable mitigation strategies*



Weibull analysis (III)

Proposed approach

- **Predict failure characteristics**
- *Define metrics (X-axis)*
- Collect data
- Fit parameters
- Quantify deviations, *quantify problem*
- Define **necessary** improvement measures

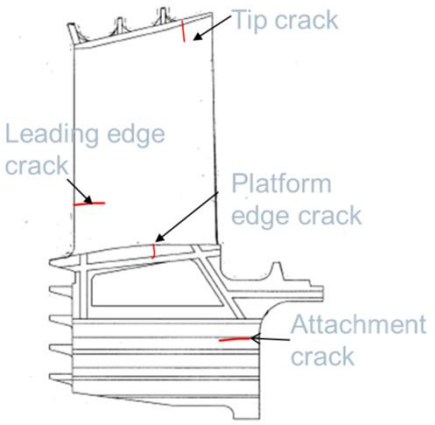


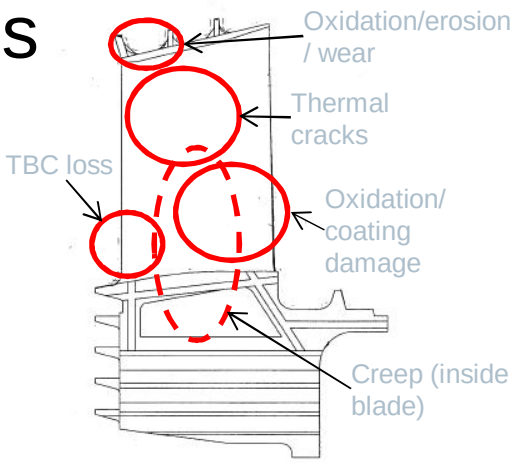
Gas turbine failure overview

- GT safety margins relatively small
  - Moderate load change -> potential high risk increase
- Hot section design failure modes include
  - creep, fatigue, oxidation (operation sensitive)
  - corrosion, vibration, wear (application sensitive)

Gas turbine hot section blade example

- 50 blades per set
- Four failure modes
  - 3 wear-out design failure modes
  - 1 load independent infant failure mode in some blades
- Standard metrics (FFH, EOH, ES, …)





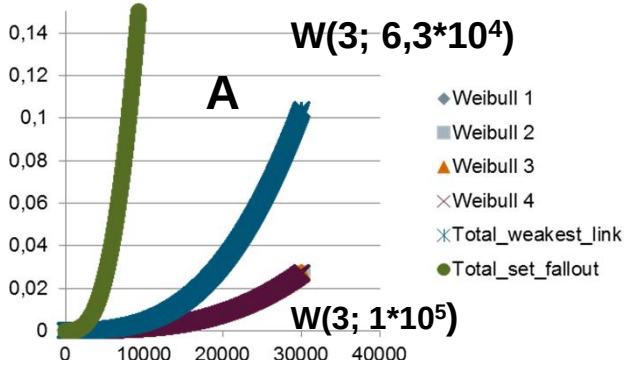
Traps - Mixed operation (I)

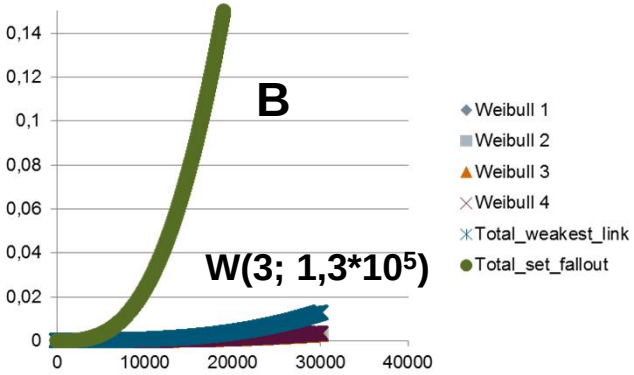
- Three operation conditions A, B, C
  - within 50 – 105% load range
  - A, B: power gen (realistic near base load)
  - C: “pipeline” part load (worst case capable)
- Population:
  - 20% A, 60% B, 20% C

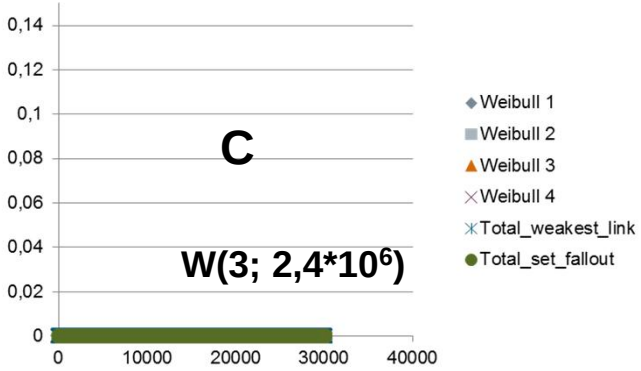
Case	FM1	FM2	FM3	FM4*
A	1,00	1,00	1,00	*
B	0,489	0,503	0,473	*
C	0,027	0,03	0,026	*

Traps - mixed operation (II)

Relative damage accumulation rates







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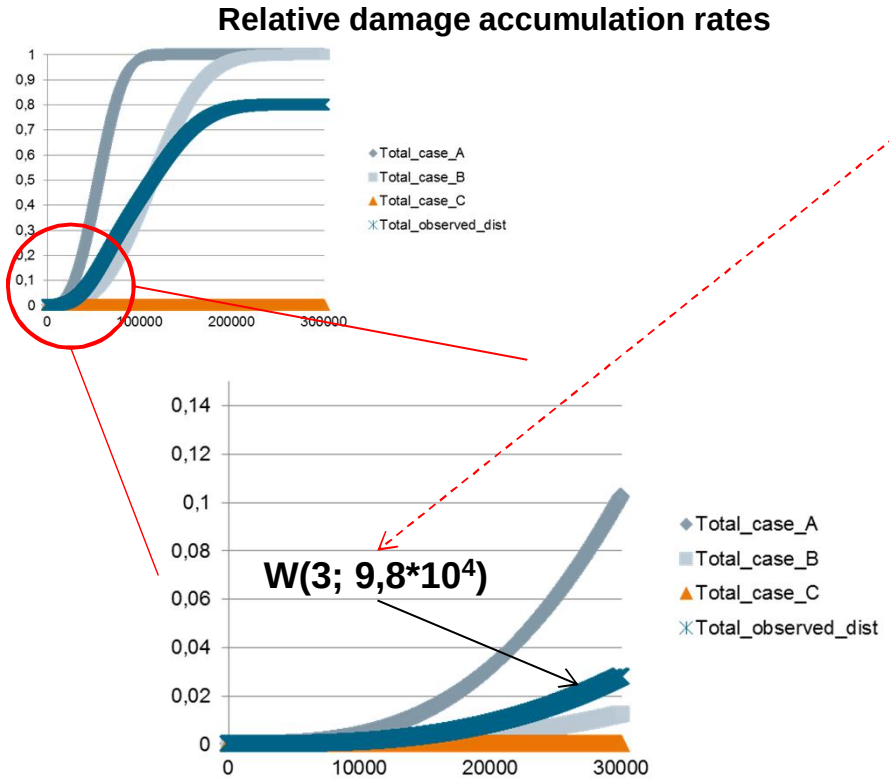
Traps – mixed operation (III)



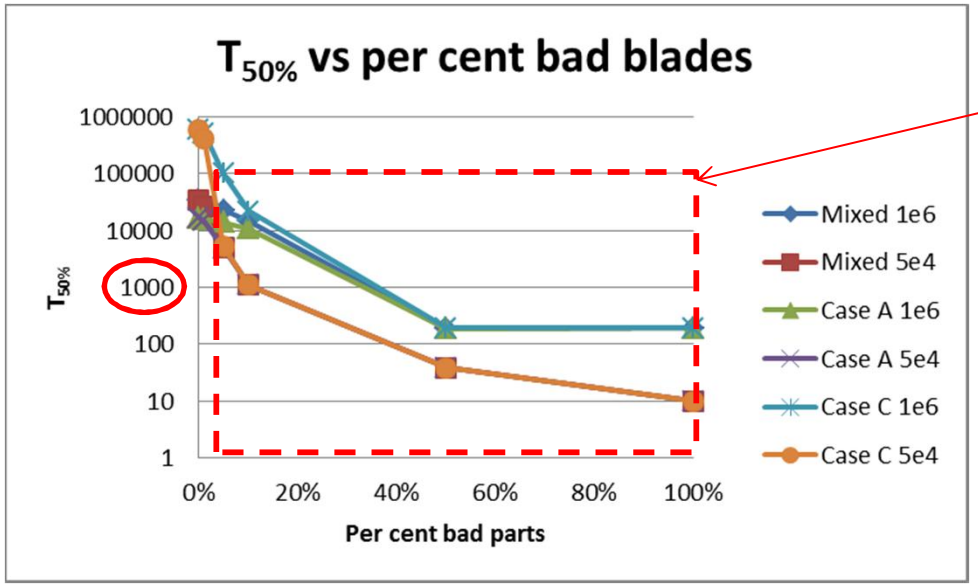
- ???
- Issues:
  - Inaccurate metric
  - Multiple failure modes
- Interpretation needed!

Case	FM1	FM2	FM3	FM4*
A	1,00	1,00	1,00	*
B	0,489	0,503	0,473	*
C	0,027	0,03	0,026	*

Traps – infant failures (I)

- Investigated cases:
  - 100% A; 100% C; Mix 20% A, 60% B, 20% C
- Independent infant failure in 0 – 100% of parts, two cases:
  - 50% failed after ~5 years (5e4 shape)
  - 50% failed after ~100 years (1e6 shape)

Traps – infant failures (II)



Dominates from ~5% bad blades

- Infant failures have devastating impact

Traps – early wear-out (I)

- Some parts will obey to wear-out distribution but with shorter life
- Early wear-out life of 0 – 100% of parts
  - Triangular versus rectangular variation
  - Batch versus random distribution

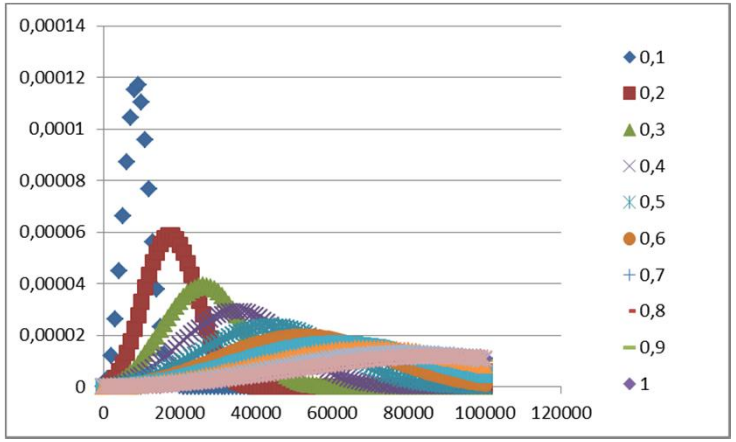
Traps – early wear-out (IIa)

- Early wear-out data – life factors and weights – triangular vs. linear distributions

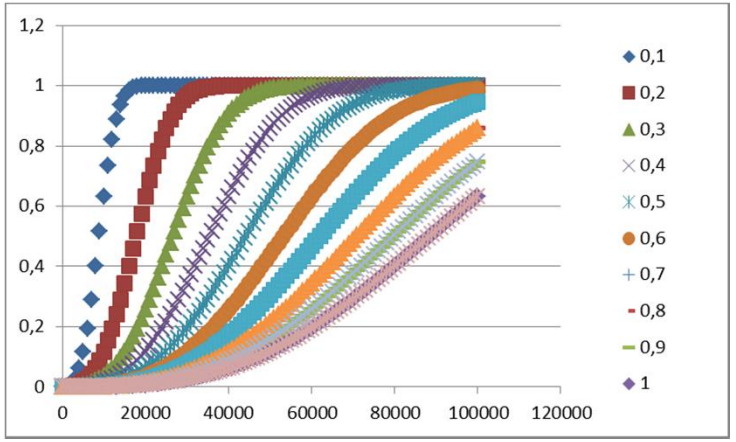
Group	1	2	3	4	5	6	7	8	9	10
Life factor	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
Group weight triang.	0,01	0,03	0,05	0,07	0,09	0,11	0,13	0,15	0,17	0,19
Group weight linear	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1

Traps – early wear-out (IIb)

- Early wear-out data – life factors and weights – triangular vs. linear distributions



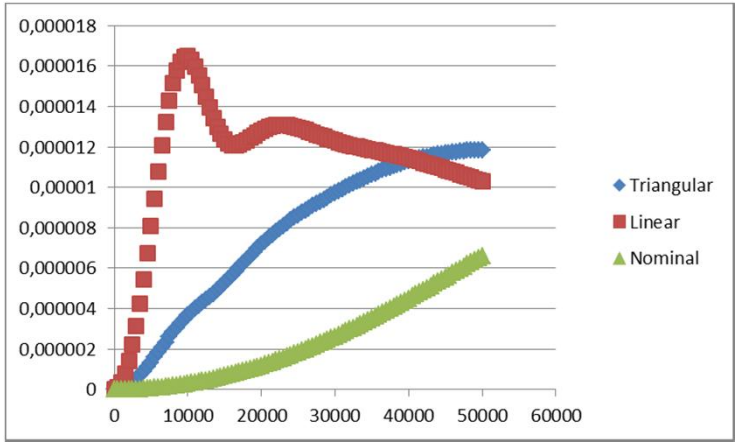
Frequency domain



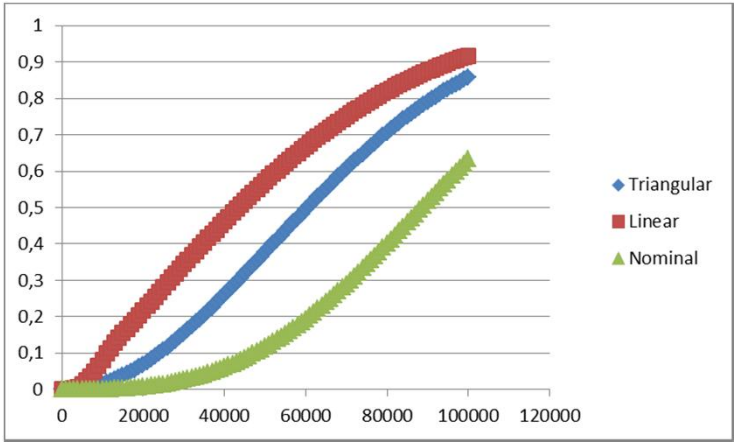
Probability domain

Traps – early wear-out (IIc)

- Early wear-out data – life factors and weights – triangular vs. linear distributions

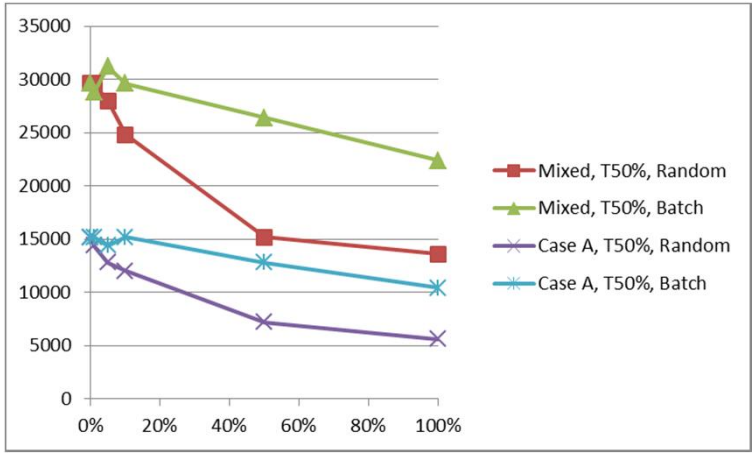


Frequency domain

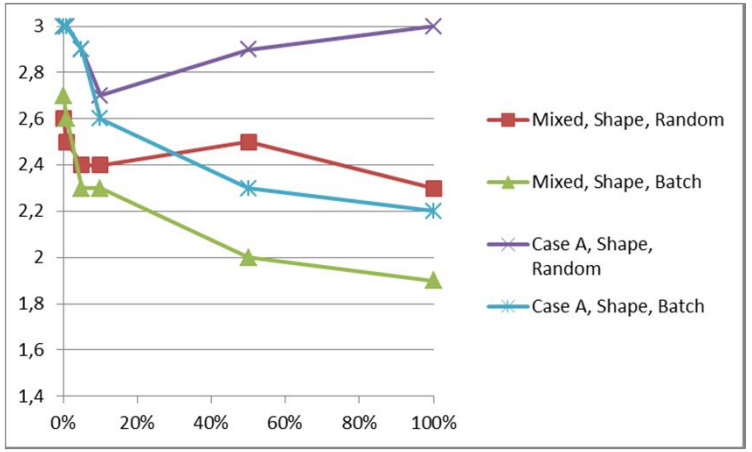


Probability domain

Traps – early wear-out (III)



Scale vs per cent early wear-out



Shape vs per cent early wear-out

- Already 5 – 10% underperforming parts changes picture
- No clear pattern; batch changes picture

Conclusions

- Weibull easily adapts to almost any data
  - X-axis metric is key
- OEM will find and fix infant failures
- Findings in data have to be tested against domain knowledge
- Shape, scale and time interval together can help strengthen conclusions

Recommendations

- Focus strictly on “painful” failure modes
- Failure mode specific metrics helpful
- Document facts that caused rejections
- Partner up with domain expertise
- Don’t stop until data and physics agree