Modelling Uncertainties in Offshore Turbine Availability

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Overview

- General Context
- Measures of performance
- Types of uncertainty
- Availability growth problem
- Decision support example
- Estimation of uncertainty
- Summary

Offshore Wind Farm Context

Windfarm in North Hoyle (off North Wales)

- Key contributor to UK renewables target
  - 30% generation capacity by 2020
- Technical availability key performance indicator
  - UK round 1 OWF average annual availability 80.2%

    Source: Feng et al(2011)
  - Target annual OWF availability of 97%-98% for financial viability
- Wind uncertainty compounded in output uncertainty

Windfarm Availability

- Offshore challenges
  - Harsh environmental conditions
  - Limited access
  - Expensive maintenance actions
  - Relatively new systems
  - Large fleets
- Assess technological performance
  - *Reliability*, *operations* and *maintainability* drive availability

Availability Modelling Goal

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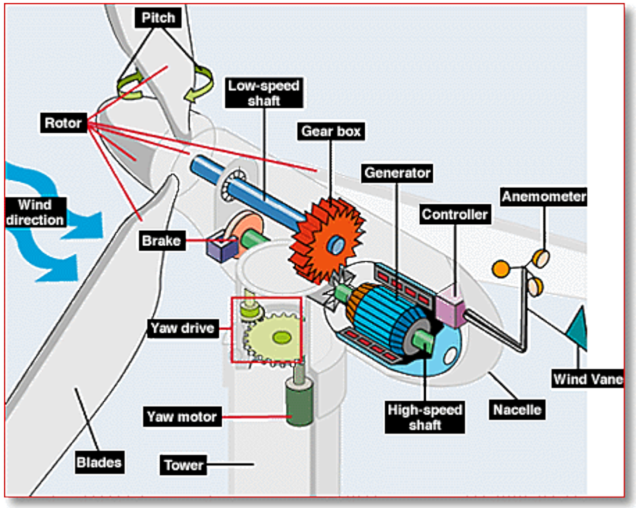
- Develop a mathematical model to:
  1. assess offshore wind farm availability growth during early operational life (up to 5 years of operation)
  2. *model state-of-knowledge uncertainty*

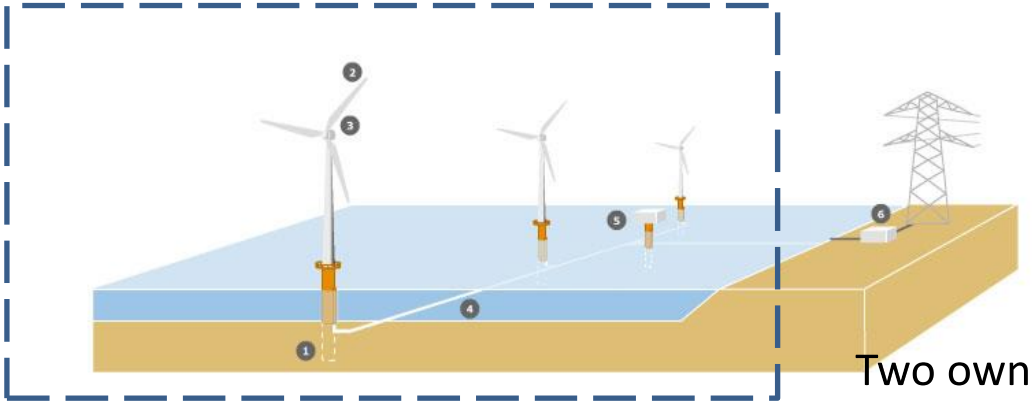
- Purpose of availability growth model is to:
  1. provide insight into interventions to achieve availability growth
  2. *understand scale of uncertainty and hence manage*

- Model to be a "tool kit" – generic and specific applications

Model Boundaries

- Offshore wind farm comprises:
  - Wind turbines - subsystems
  - Subsea cables
  - Offshore transformer





Two owners – Generator, OFTO
Risk sharing/contract

Point value models for O&M

- TU Delft
  - Assesses long-term farm availability and O&M costs
  - Uses Monte Carlo simulation
  - Simulates maintenance hourly operations over a twenty year period.
  - Uses extensive weather simulation and average failure rates
- ECN Wind Energy
  - Assesses overall O&M cost
  - Spreadsheet-based method
  - Average failure rates, availability of maintenance resources, access on site
  - Linked to @Risk to perform uncertainty analysis
- Strathclyde (EEE)
  - Empirical ROCOF used for MC simulation

Major problems - *uncertainties*

- Early life failures
- Cost of insurance/cost of finance
- Lack of performance data
- Weather/sea states/environment
- Logistics market underdeveloped
- Shifting government interest

Definition of Availability

- Performance measures for power generation systems;
  - Capacity Factor, Loss of Load Probability etc
- Technical availability;
  - failure and repair processes
- Definition (general)
  - System state

$$X(t) = \begin{cases} 1, & \text{if the system is operating} \\ 0, & \text{otherwise} \end{cases}$$

  - Point availability

$$A(t) = \Pr[X(t) = 1] = E[X(t)]$$

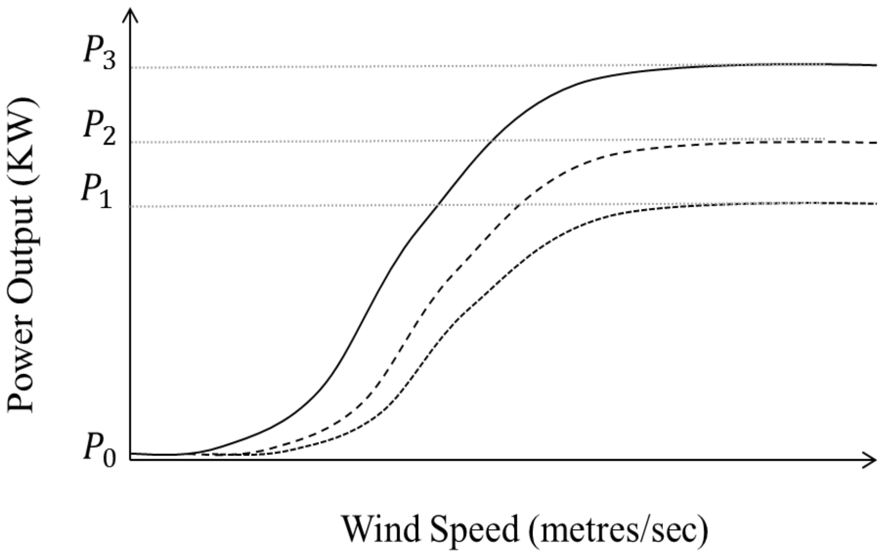
  - Time average availability, Farm availability

Definition of Availability

- But…
  - What about the farm?
  - How about when operating at a *partial* capacity?
  - Who makes the calculations?
    - Owner?
    - Manufacturer?
    - Investor?
  - What is a wind farm?
- Definition (wind industry)
  - Turbine availability
  - System availability
- There is no clearly agreed definition of availability used by all parties!

Multiple system states

Maximum output



Installed output

Availability-informed capability

- Due to the costs of repair and production loss and logistic delays an offshore wind farm will operate in degraded states.

Availability-informed capability

- Point capability

$$C(t) = \frac{\sum_{i=1}^{n} OP_i(t)}{nIP_i(t)}$$

$OP_i(t)$: maximum output power at time t of turbine i
$IP_i(t)$: installed power at time t of turbine i

- Time average capability
  - Average point availability through time

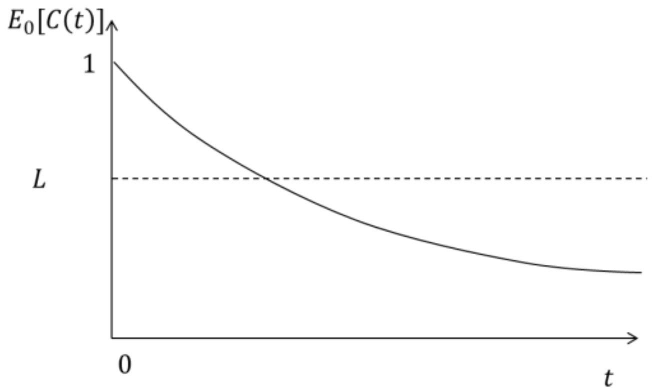
- Level capability

$$C_{(\tau_1,\tau_2)}(L) = \frac{1}{\tau_2 - \tau_1} \int_{\tau_1}^{\tau_2} \mathbf{1}\{C(t) > L\} \mathrm{d}t$$

Proportion of time system capability above some acceptable level *L*.

Estimate capability

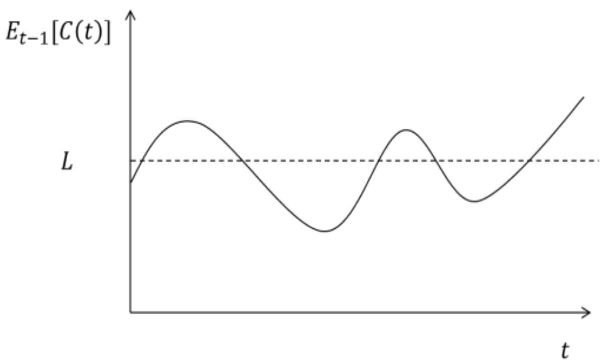
Long -term
(from time t$= 0$)



(a) Expected availability-informed capability over $(0, \tau)$

Metric to judge overall capability

Short-term
(from time $s > 0$)



(b) One-step ahead expected availability-informed capability over $(0, \tau)$

Metric to judge short term variability and controlability through maintenance strategy

Uncertainty & Assessments

- Role of uncertainty
  - Need to represent in availability models and explore implications in reliability/availability assessments
- Aleatory uncertainty
  - Natural variability in the system
  - Failure times, repair times….
  - Irreducible
- Epistemic/state of knowledge uncertainty
  - Lack of knowledge of the system and environment
  - Limitations in assessing parameters of key elements
  - Reducible by better information

Policy interest in epistemic uncertainty

- Nuclear power plants (NPPs)
- WASH 1400 report gave the probability of a frequency…of core melt
- Difficult to understand what this means – imagine a notional large population of NPPs of same design and ask about number of core melts in 1000 years…

One persons epistemic uncertainty…

- …is another persons aleatory uncertainty

- Farm level variability arising from epistemic uncertainties are of interest to financiers/insurers

Stiesdal and Madsen, 2005

- Stiesdal is Chief Technology Officer at Siemens Wind Power.
- Discuss three stage Weibull failure rate model for offshore wind farms, giving bathtub curve.
- Argue that there should be fourth element to failure rate curve; serial failures from premature wear-out.
- This element due to component immaturity in early life – result of rapid product development.

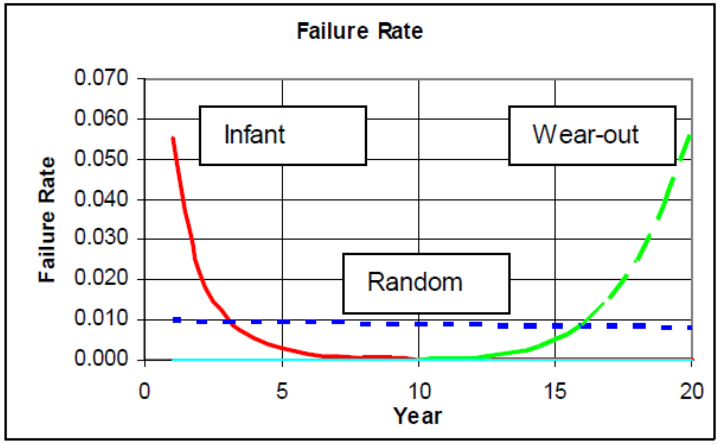


Fig. 2: Elements of bathtub curve

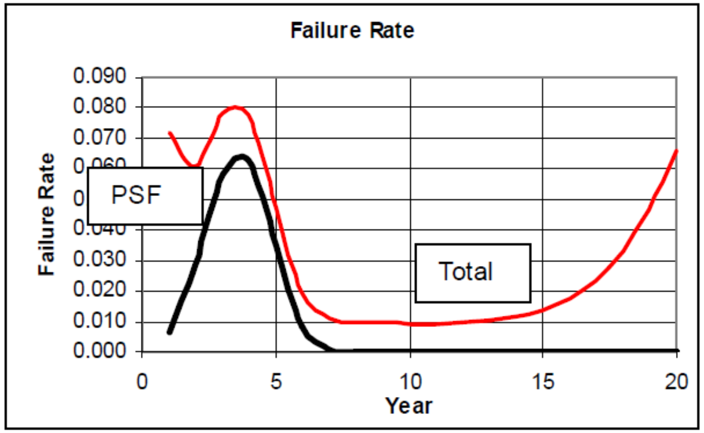
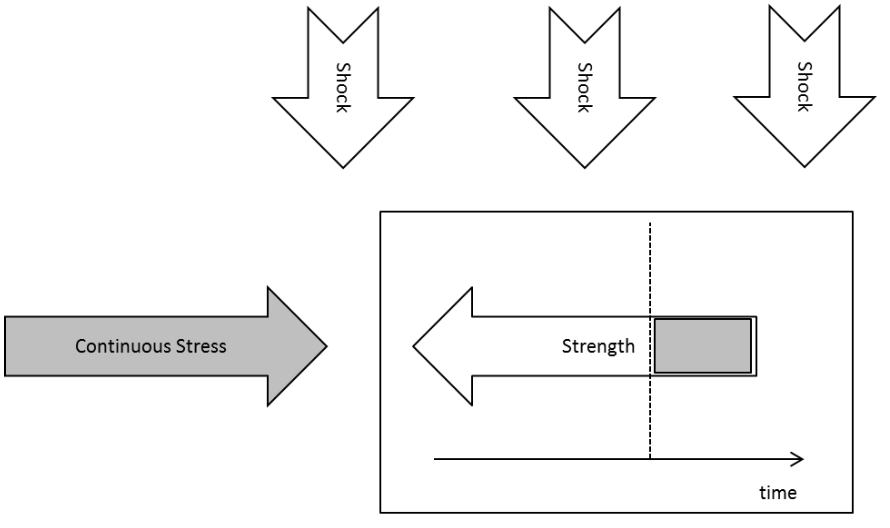


Fig. 3: Premature Serial Failure Elements of bathtub curve

Conceptual approach

- Medium to long term behaviour should be similar to existing (smaller scale) systems – modulo some uncertainty (on long term)
- Short term behaviour can be (much) worse due to design, manufacturing and operating errors
- Availability growth happens by recognizing and eliminating these errors

Offshore Wind Systems: Failure Mechanisms

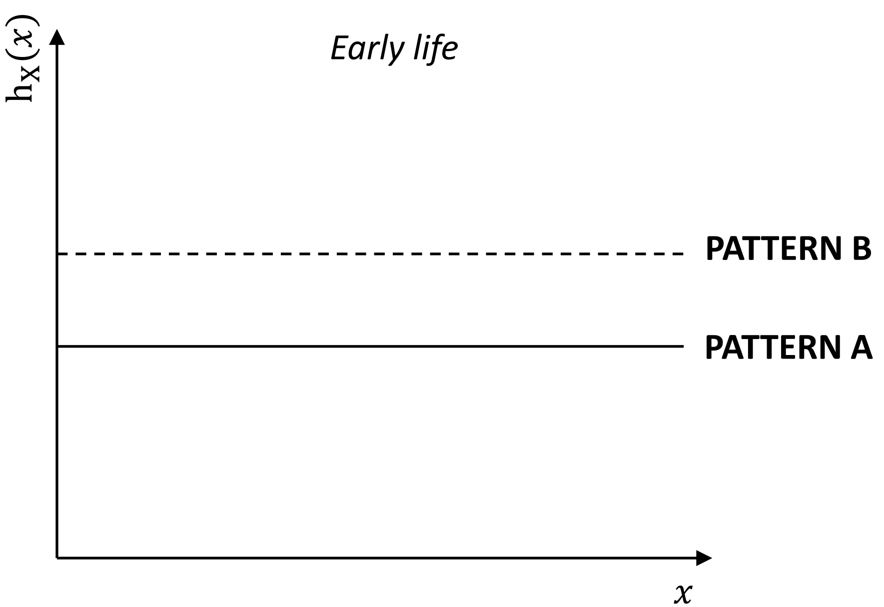


- Shock failures:
  - sudden failures
  - due to a single stress event that exceeds strength
  - random failures, constant FOM.
- Wear-out Failures
  - failures due to fatigue
  - accumulated damage exceeds some endurance threshold
  - monotonically increasing FOM

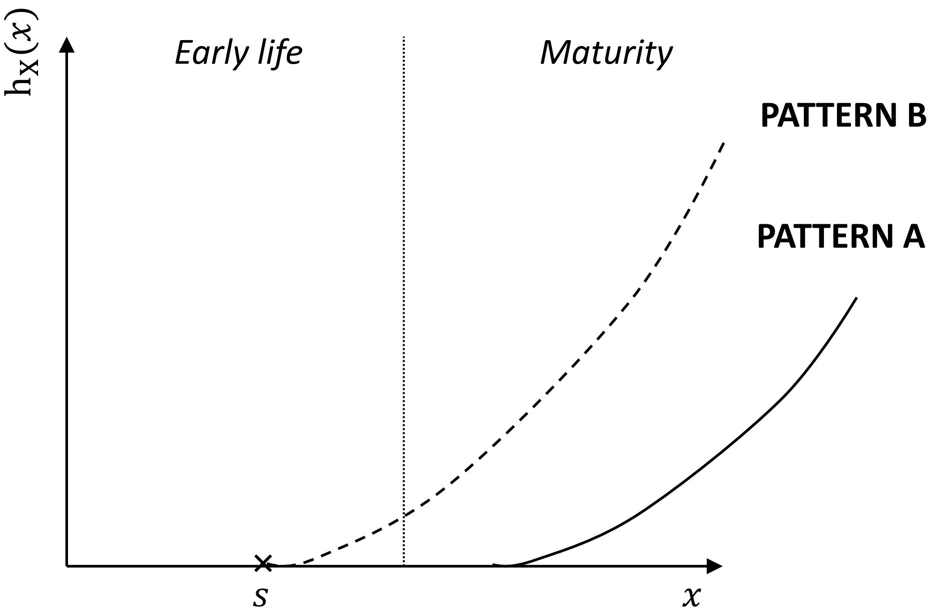
Considered separate independent effects

Target vs. Actual Reliability: Failure Mechanisms

Shock Failures

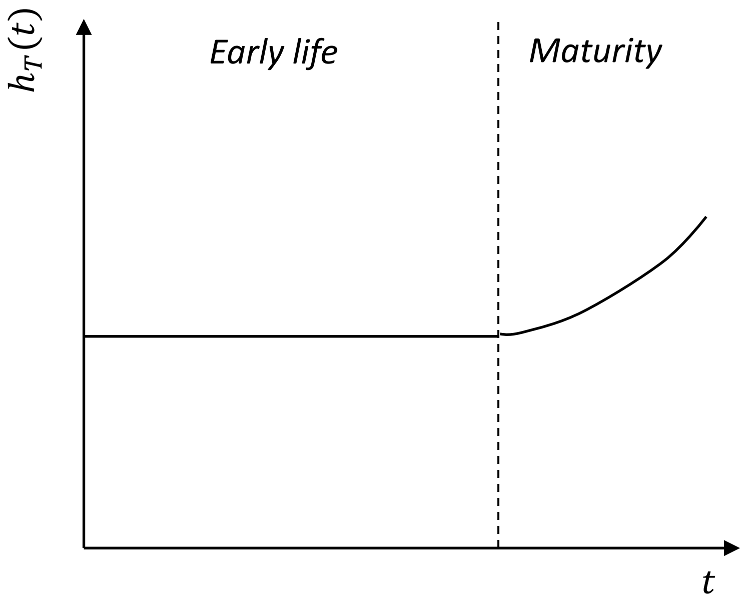


Wear-out

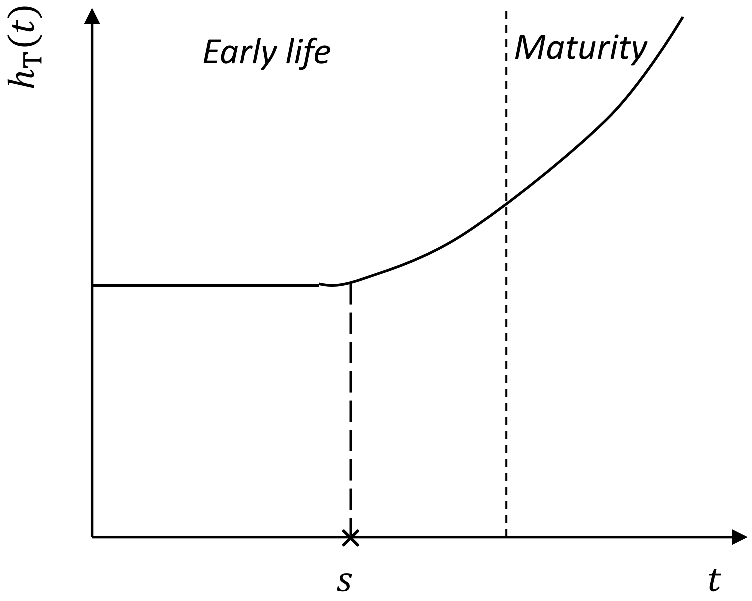


Target vs. Actual Reliability

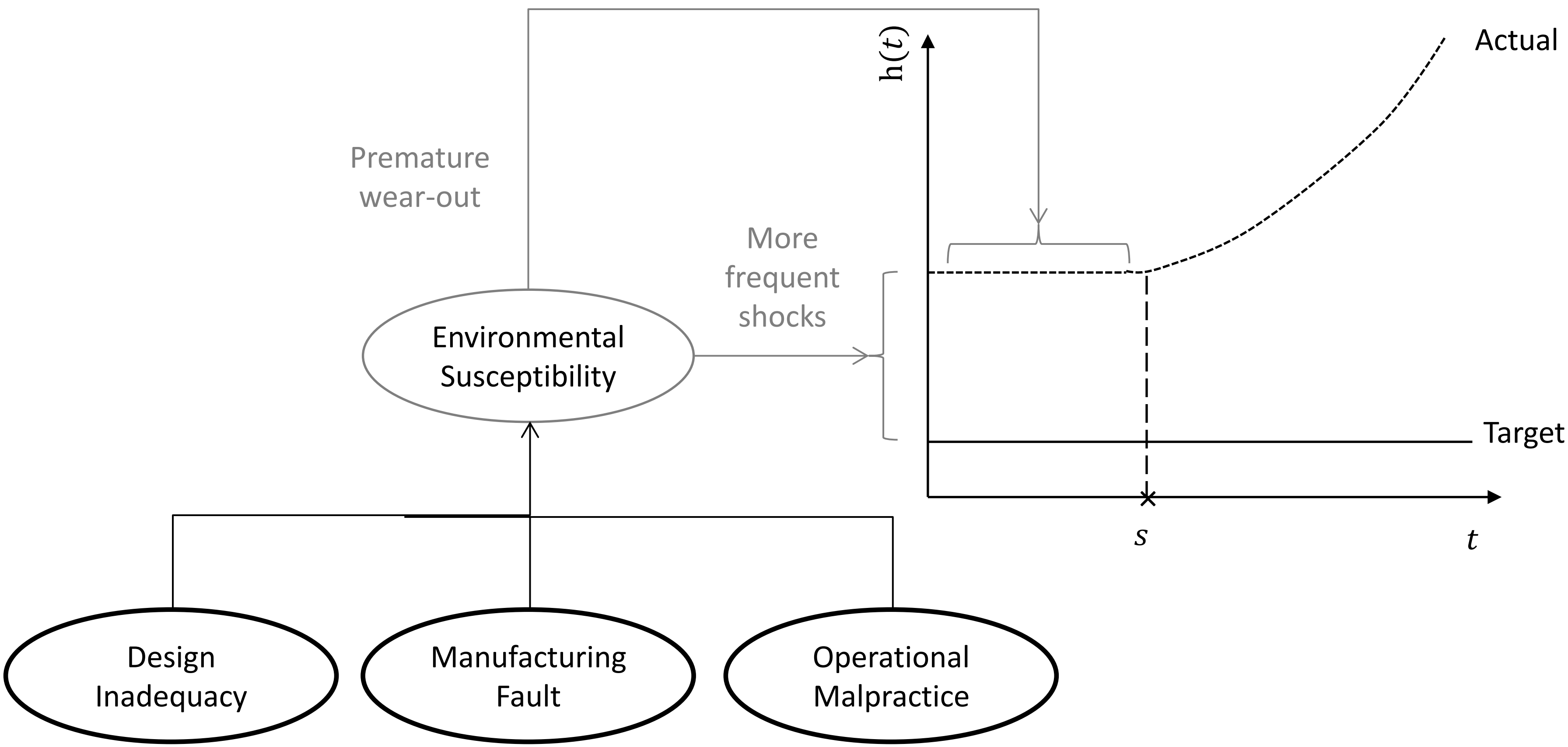
PATTERN A



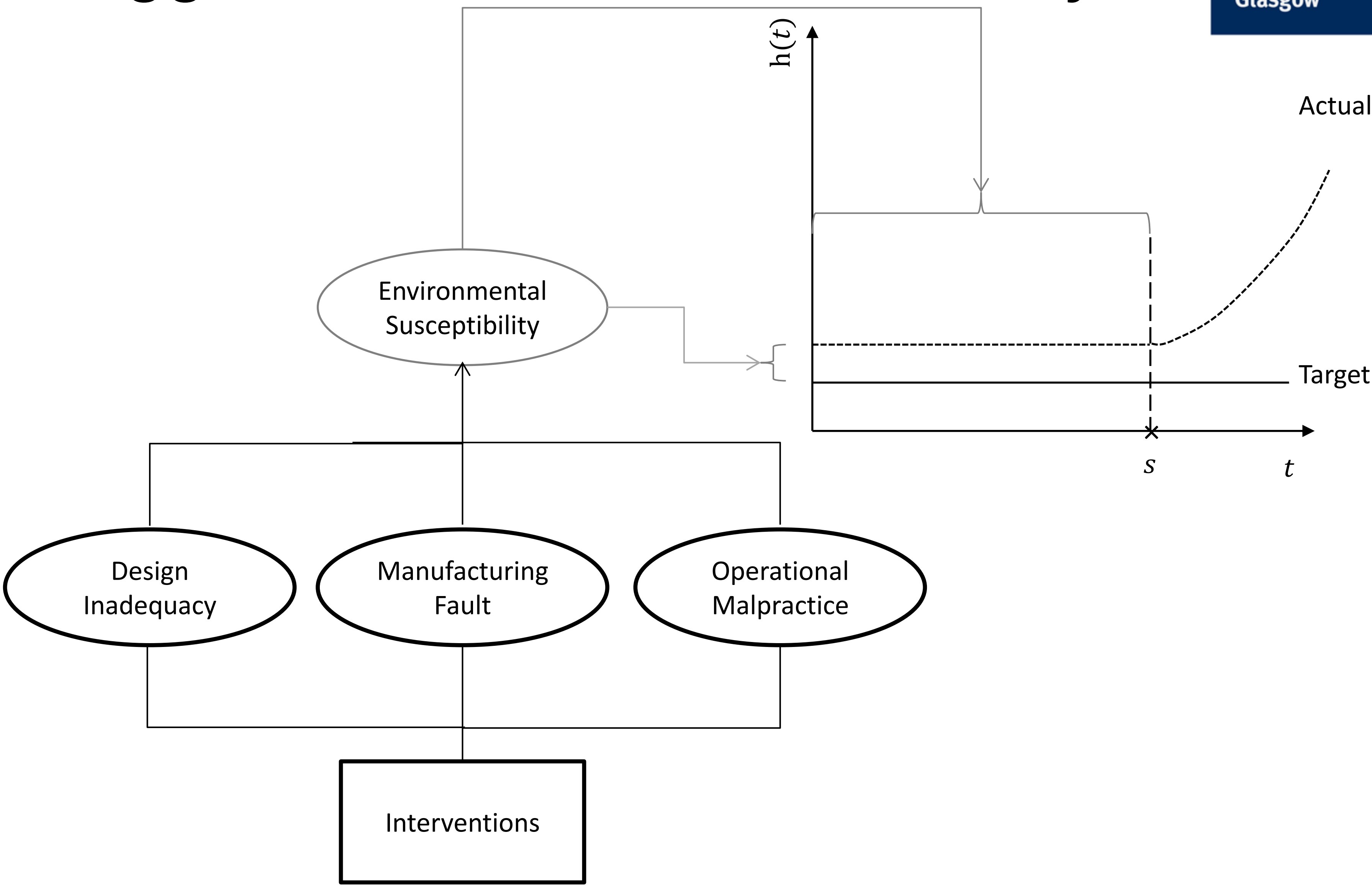
PATTERN B



Triggers and Reduced Reliability

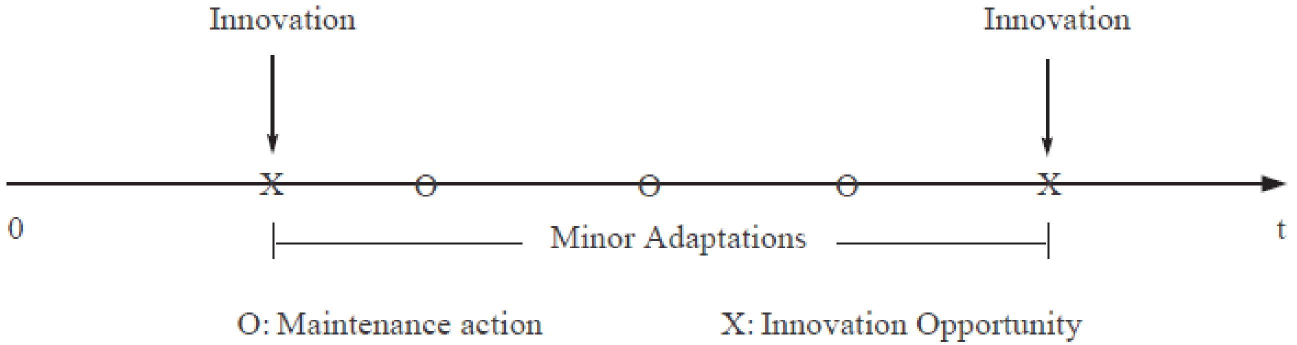


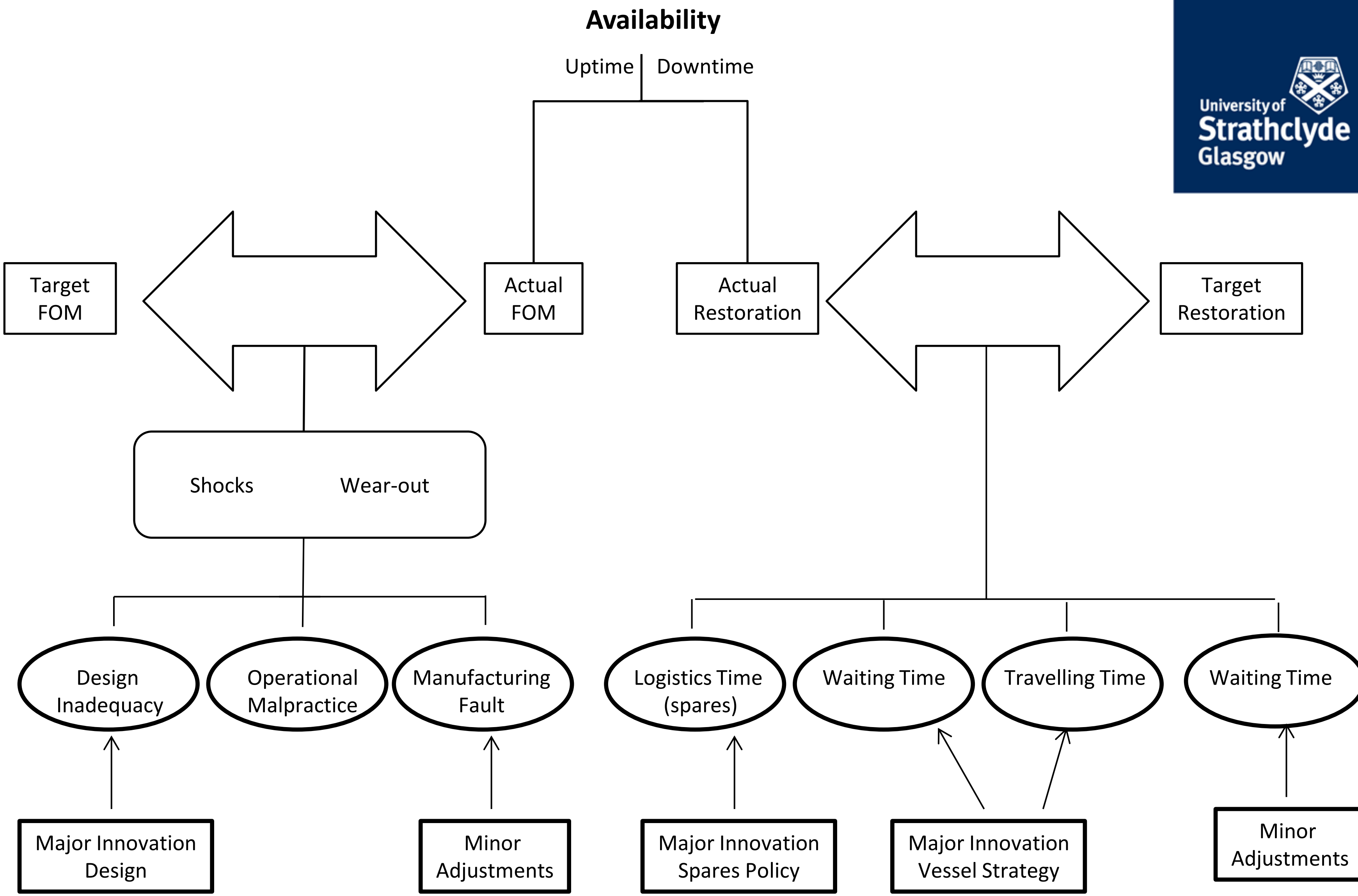
Triggers and Reduced Reliability



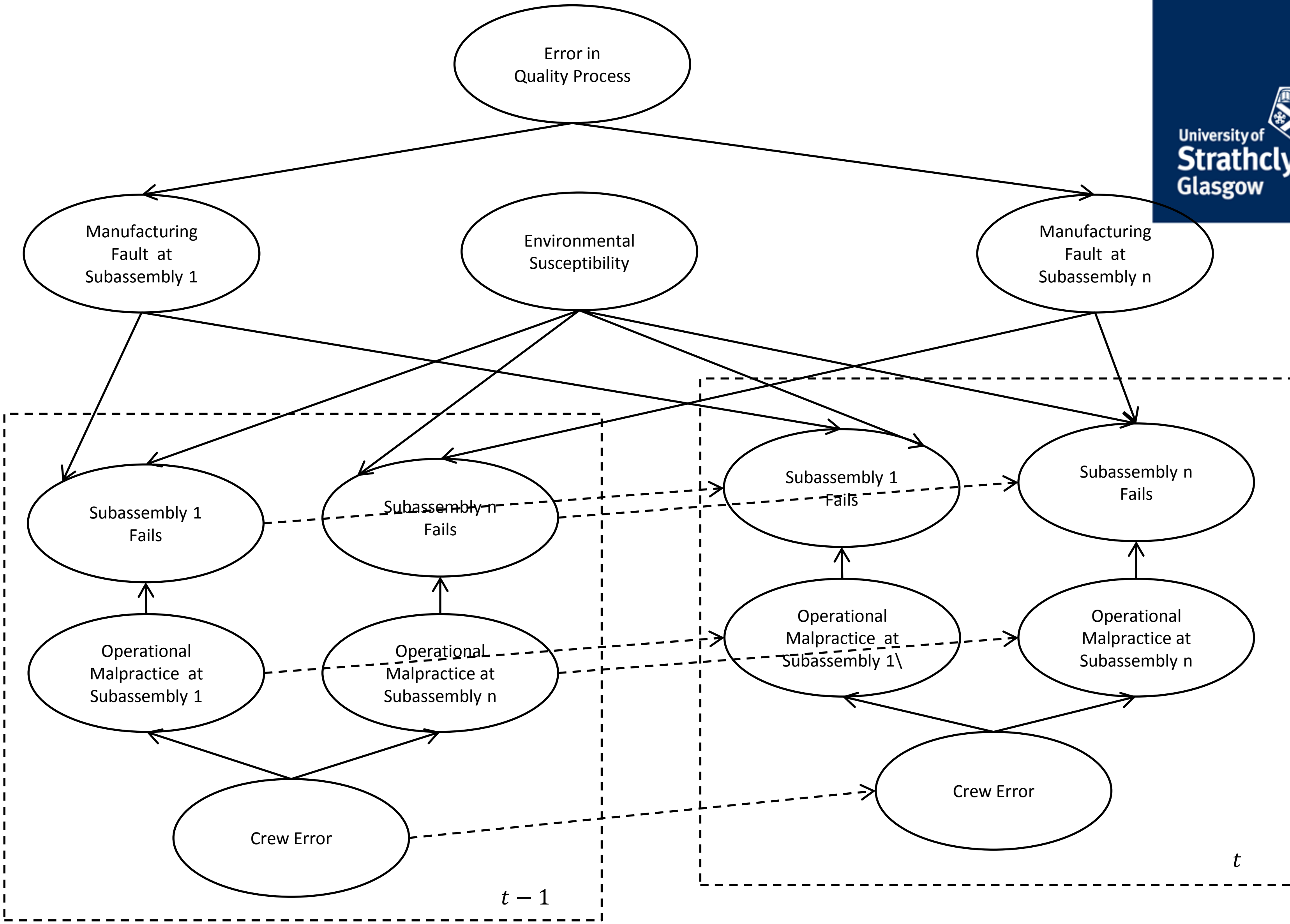
Availability growth drivers

- Innovations
  - Radical design modifications that impact underlying behaviour; requiring a discrete model
- Minor Adaptations
  - Planned and opportunistic adjustments during operation that impact the underlying behaviour; captured through model pattern
- Maintenance Actions
  - Control degradation that impact 'virtual age'





Availability
Uptime
Downtime
Target FOM
Actual FOM
Actual Restoration
Target Restoration
Shocks
Wear-out
Design Inadequacy
Operational Malpractice
Manufacturing Fault
Logistics Time (spares)
Waiting Time
Travelling Time
Waiting Time
Major Innovation Design
Minor Adjustments
Major Innovation Spares Policy
Major Innovation Vessel Strategy
Minor Adjustments


Error in
Quality Process
Manufacturing
Fault at
Subassembly 1
Environmental
Susceptibility
Manufacturing
Fault at
Subassembly n
Subassembly 1
Fails
Subassembly n
Fails
Operational
Malpractice at
Subassembly 1
Operational
Malpractice at
Subassembly n
Crew Error
$t-1$
Subassembly 1
Fails
Subassembly n
Fails
Operational
Malpractice at
Subassembly 1\
Operational
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Subassembly n
Crew Error
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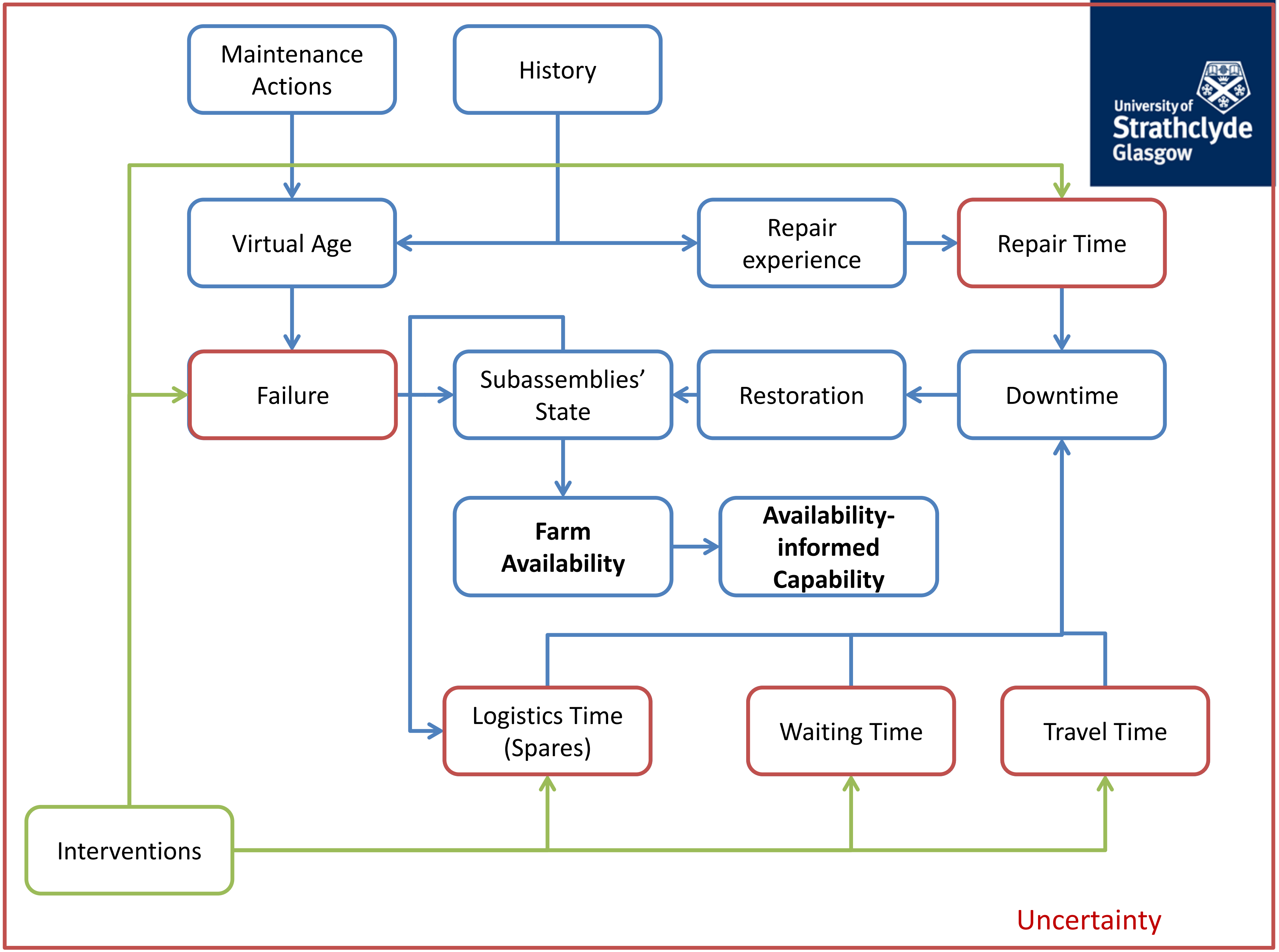
Maintenance Actions
History
Virtual Age
Repair experience
Repair Time
Failure
Subassemblies' State
Restoration
Downtime
Farm Availability
Availability-informed Capability
Logistics Time (Spares)
Waiting Time
Travel Time
Interventions
Uncertainty
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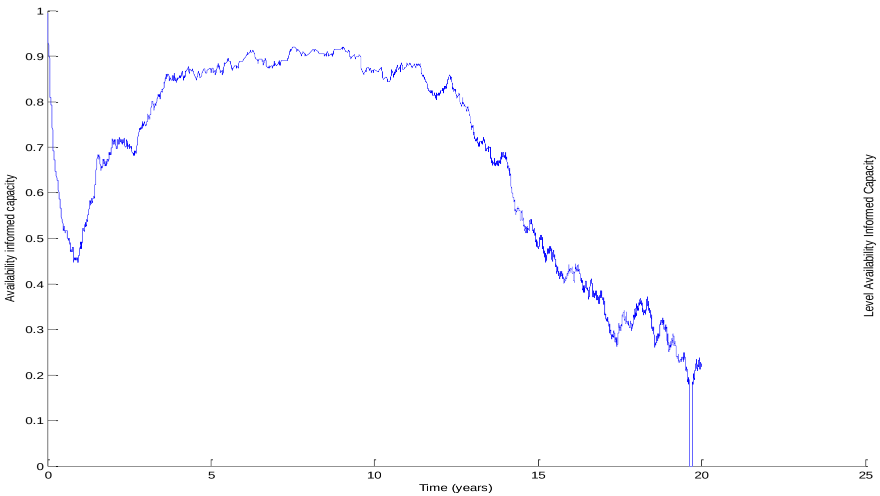
Illustrative example

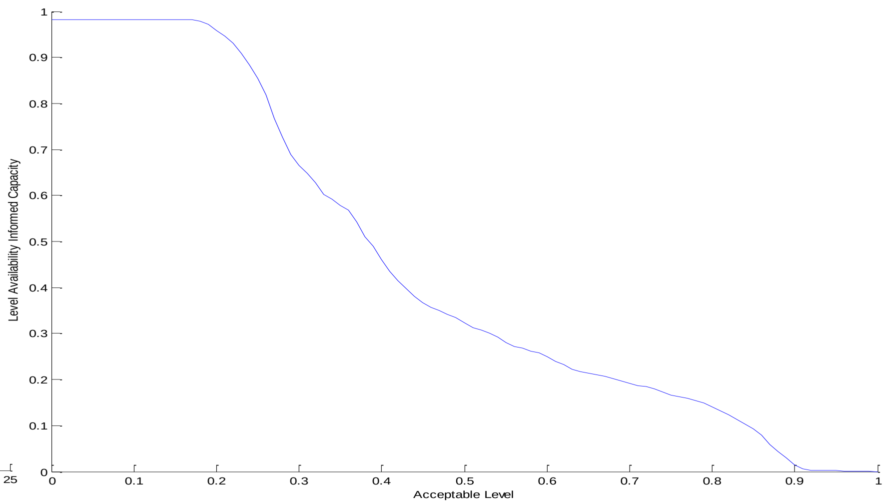
- We simulate an offshore wind farm with 200 turbines, each of which has 18 sub-assemblies.
- We assume minor adaptions are made on each sub-assembly continuously.
- Innovations are made on each sub-assembly a single time in the summer for each of the first 4 years of the life of the farm.
- The simulation is run for the first 20 years of operation of the wind farm.

Single simulation results

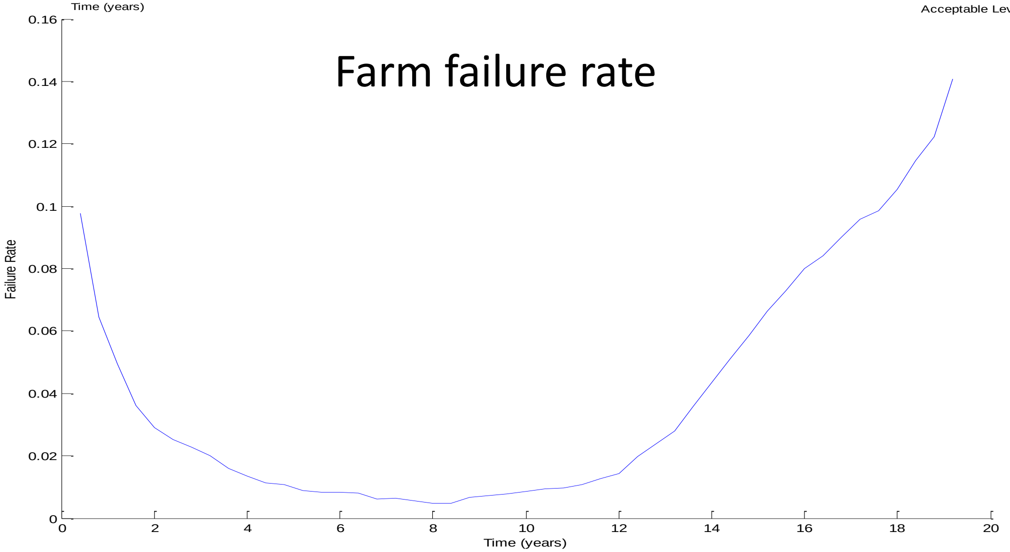
Farm availability informed capability



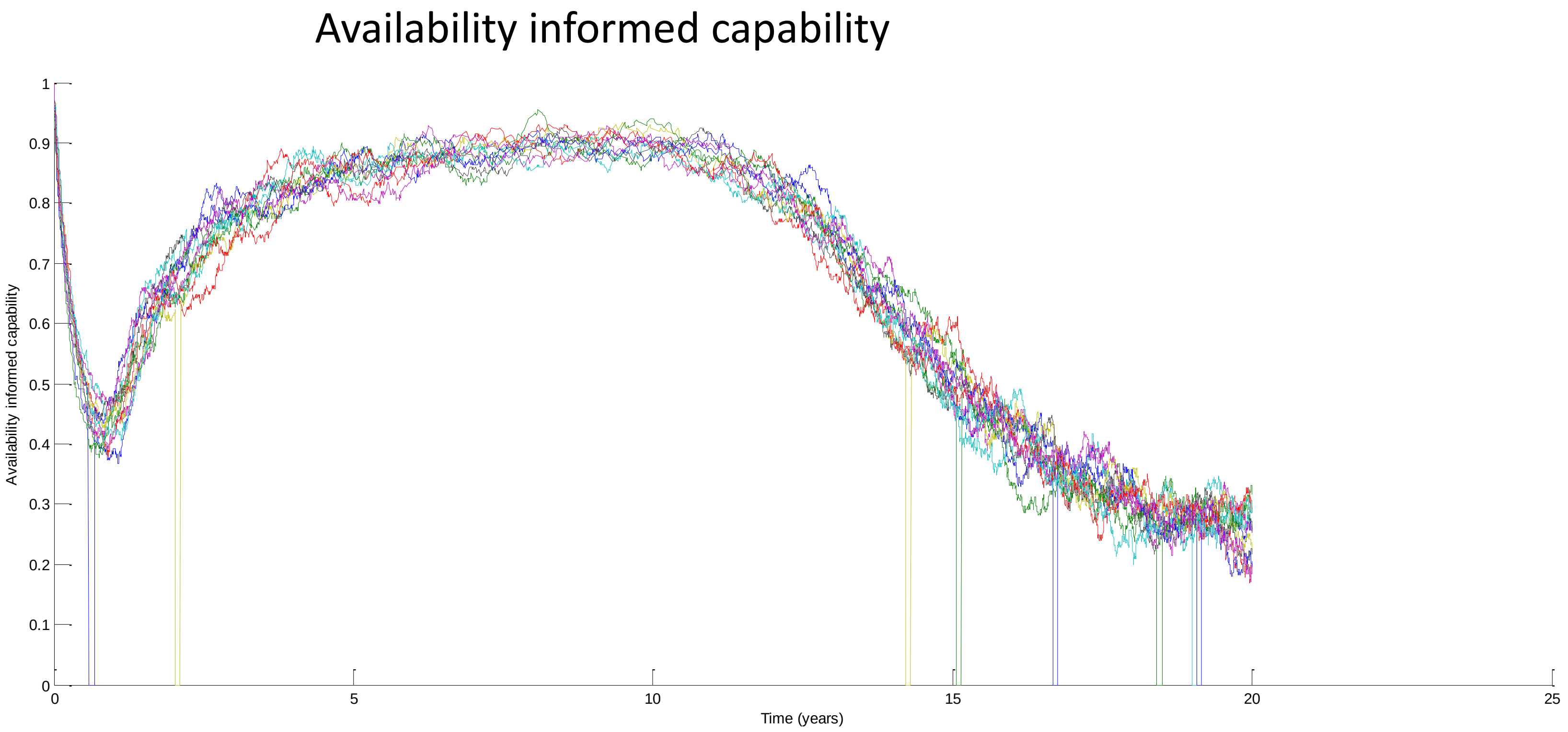
Farm level-availability informed capability



Farm failure rate

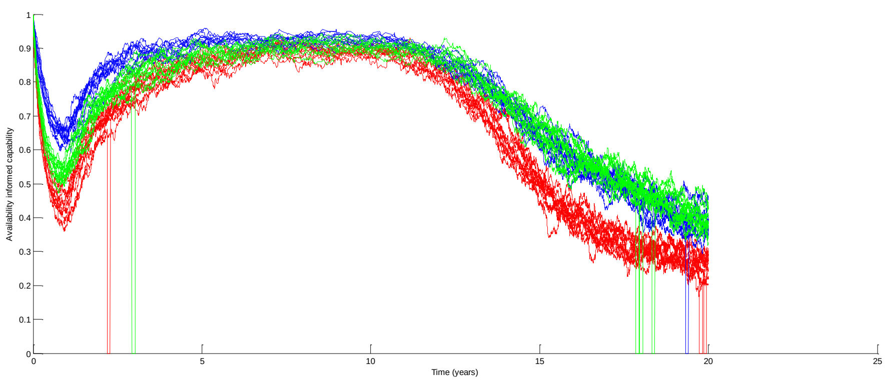


Aleatory uncertainty from multiple simulations

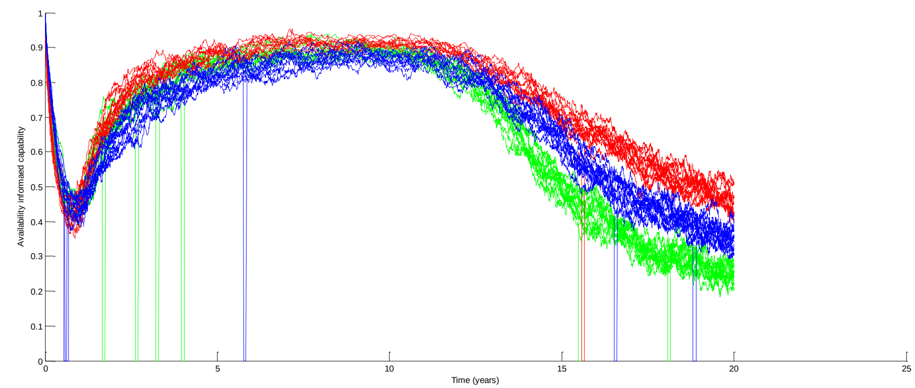


12 simulations, each run with the same parameter values

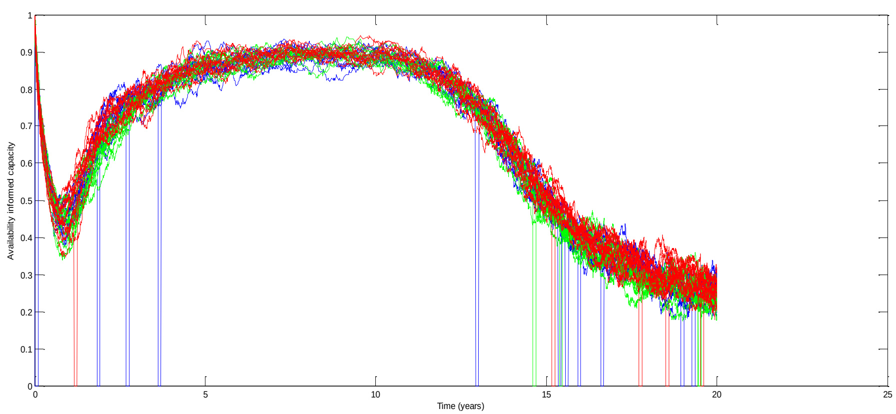
Epistemic uncertainty from multiple parameter values



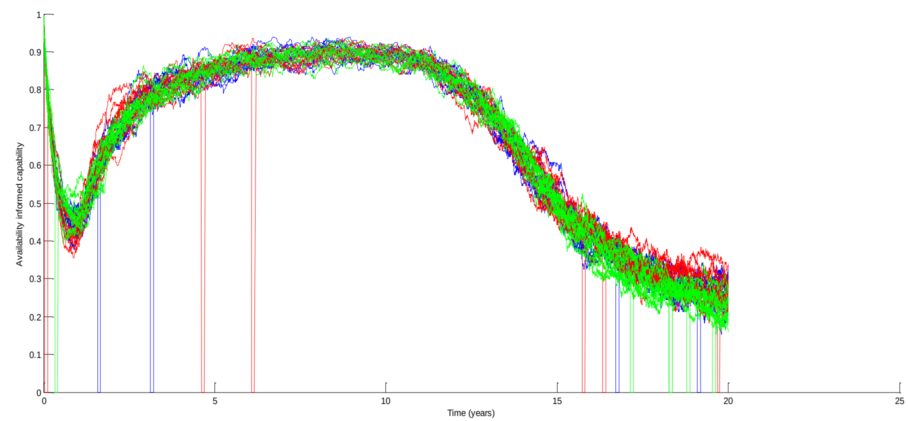
Setting a_0=0.05,0.075,0.1 (r,g,b) in failure intensities.



Setting b_0=0.7,0.8,0.9 (g,b,r) in failure intensities.



Setting a_0=5,6,7 (g,b,r) in restoration intensities.



Setting b_0=3,4,5 (g,b,r) in restoration intensities.

Estimation of Uncertainty

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- Running the simulation multiple times gives an estimate of the aleatory uncertainty.
- Running the simulation on multiple parameter values gives an estimate of the epistemic uncertainty.
- How do we choose the range of parameter values to run the simulation at?

Whose uncertainty?

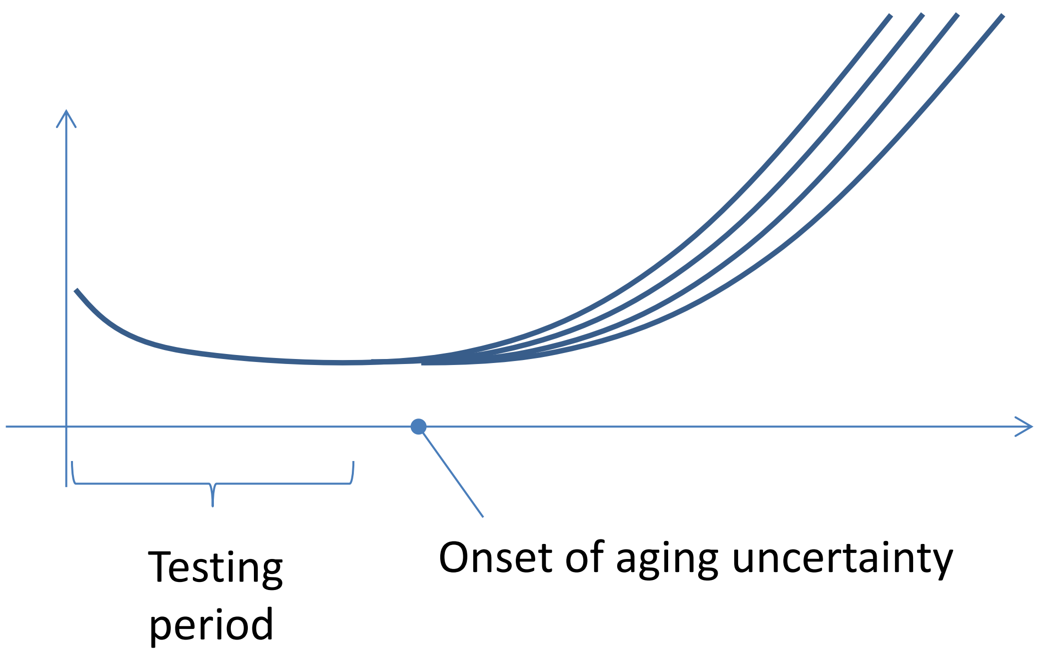
- Different viewpoints of OEM, generator, OFTO, maintenance provider, financial markets etc
- Cost/benefit cases for testing and instrumentation
- Need to create robust system that manages risks through life – so control perspective rather than static risk view

Bayesian/subjective approaches to “similar but not identical data”

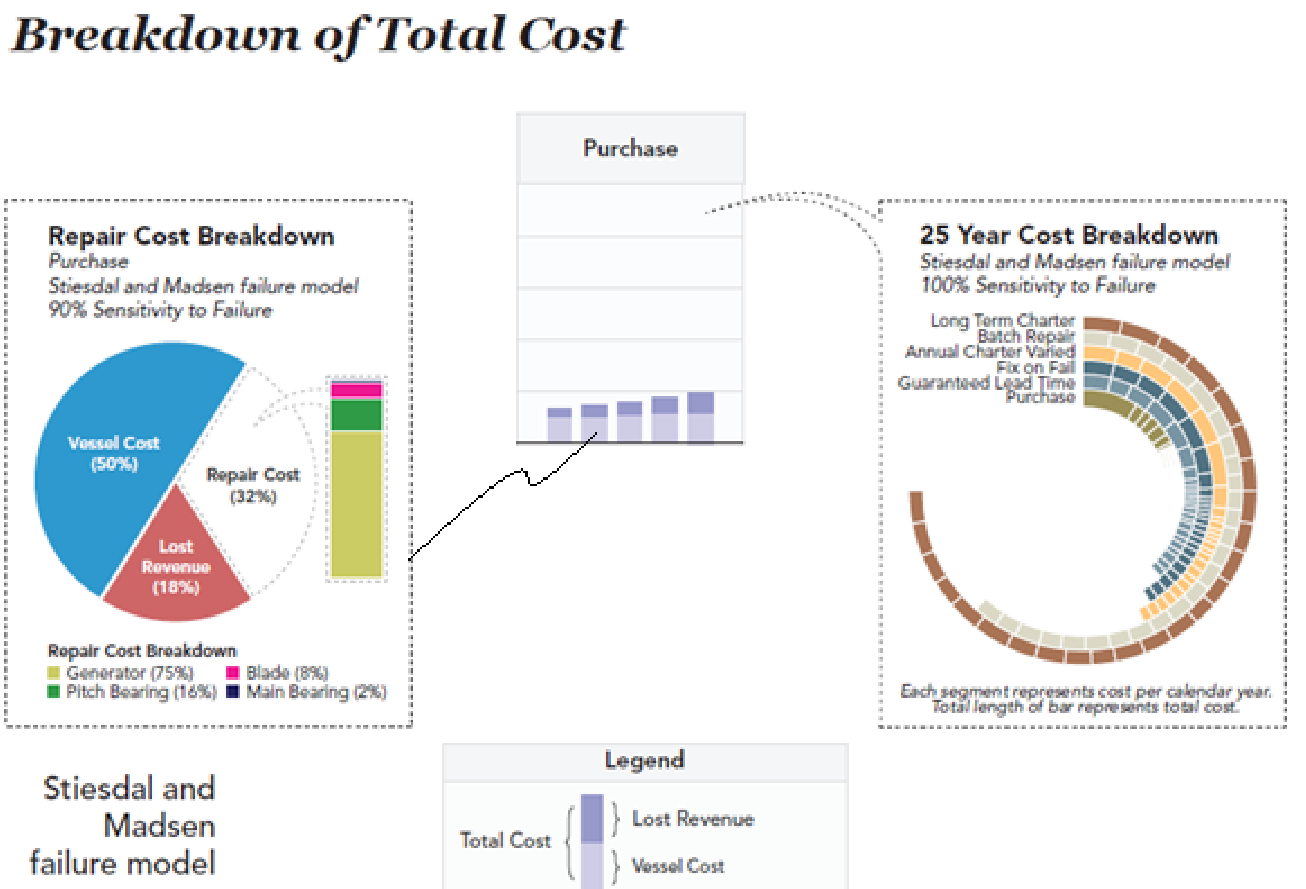
- 2 stage Bayesian model – each baseline failure rate drawn from common Gamma
- Expert Judgement – absolute
- Expert Judgement – relative
- Tolerance uncertainty – recognizes impact of environment on similar systems
- Bayesian networks/proportional hazard etc
- REMM approach using FMEA identifying concerns at design stage

Parameterizing appropriately

- Onset of aging…uncertainty



Heavy Lift Project



Stiesdal and Madsen failure model

Summary

- Availability growth is an important concept.
- Capability definition allows for partial performance states, without compounding impact of wind.
- Getting a handle on the different uncertainties affecting early life availability of an offshore wind farm is crucial to decision making.
- Potentially big difference between “steady state” system behaviour and early life behaviour
- Model allows us to test impact of uncertainties at subsystem level on the overall performance.