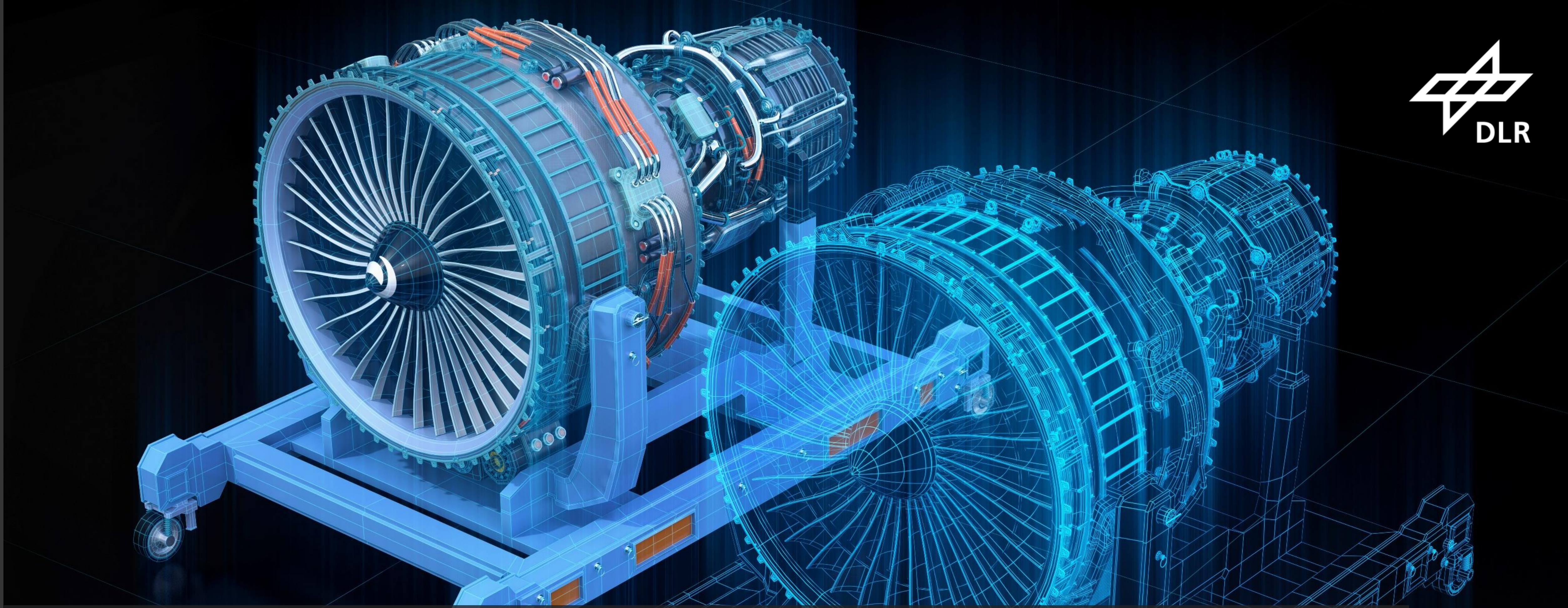

INSIGHTS INTO INTEGRATED ENGINE MAINTENANCE MODELLING

MRO Monday 2026

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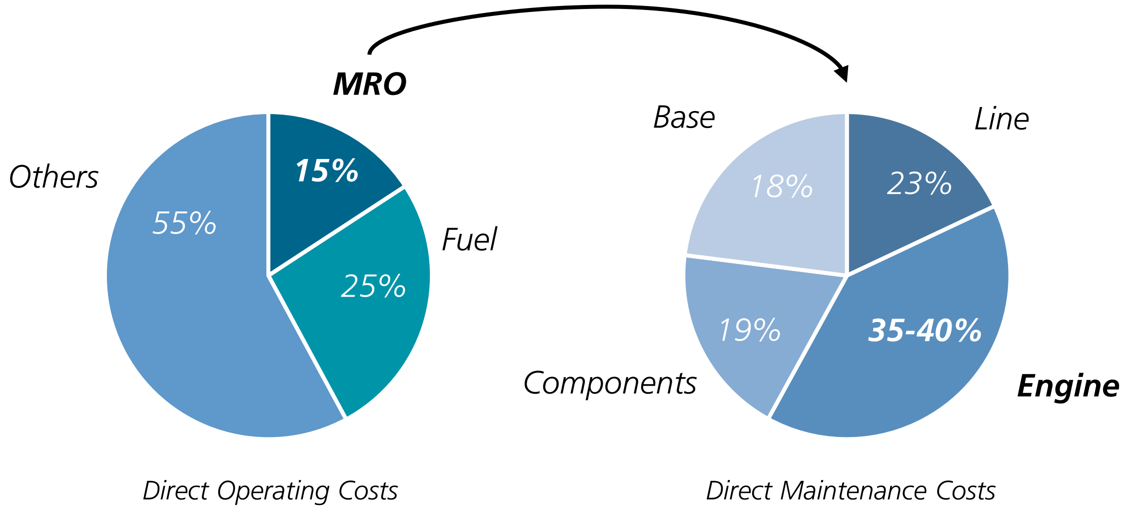
Institute of Maintenance, Repair and Overhaul | Product Lifecycle Management | Lifecycle Modelling and Optimization

Aero-engine maintenance drives aircraft maintenance costs

Economic relevance of engine maintenance

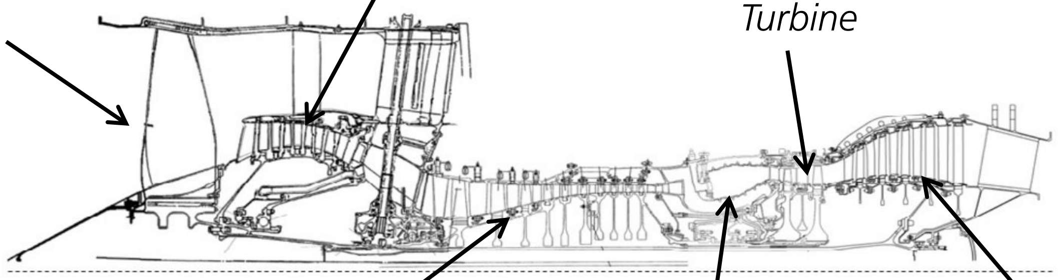
- Direct maintenance costs account for about 10-15% of the direct operating costs
- Up to 40% of these expenses can be attributed to engine maintenance activities (trend increasing)
- High-cost shop visits and life limited parts make engines a major economic risk factor
- Improved planning of engine maintenance can reduce cost exposure and increase fleet availability



Source: Aircraft Monitor

Even incremental improvements in the planning and execution of engine maintenance activities can substantially enhance economic and operational efficiency.

Higher efficiency increases maintenance demand



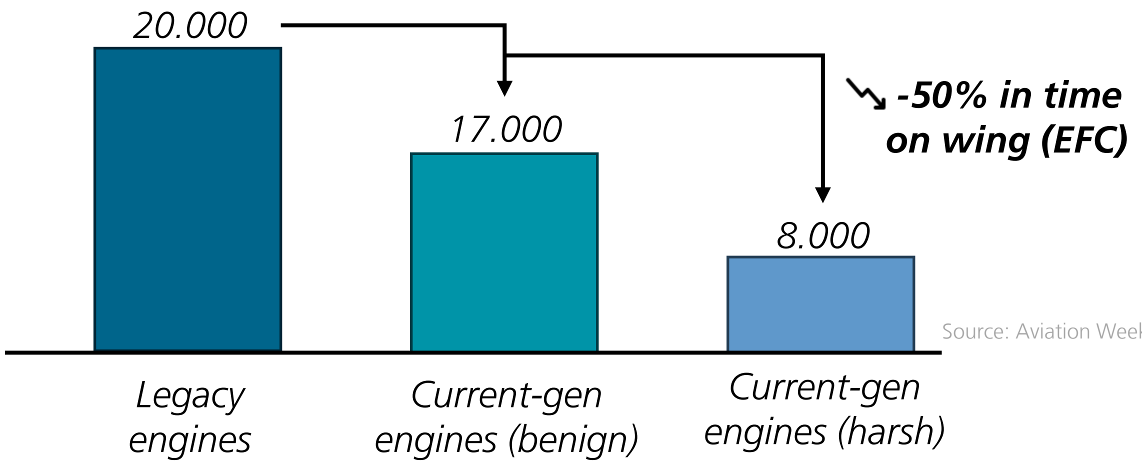
Source: International Aero Engines, V2500 General Familiarization (2000)

Propulsion efficiency

- High mass flow with reduced jet velocity (RR UltraFan, CFM RISE)
- Steadily increasing bypass ratio (>12:1)
- Allowed through geared fan concepts and composite fan blades

Thermal efficiency

- Increase in overall pressure ratio (~50:1)
- Turbine inlet temperatures above metal melting points (internal cooling)
- Enabled by superalloys, thermal barrier coatings, additive manufacturing

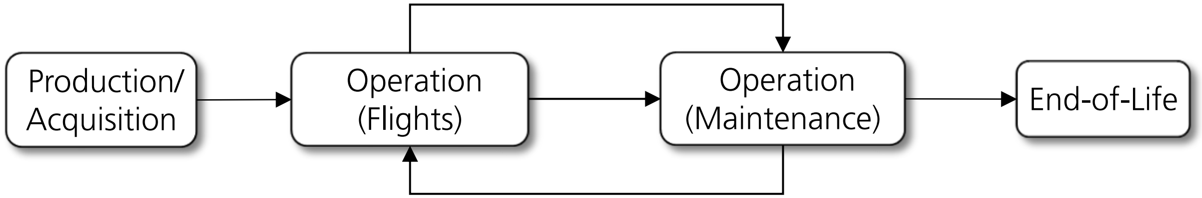


Source: Aviation Week

Physical limits of engine development lead to significantly lower times on wing

Lifecycle system behaviour shapes maintenance activities

Lifecycle simulation considering economic and ecological assessment factors

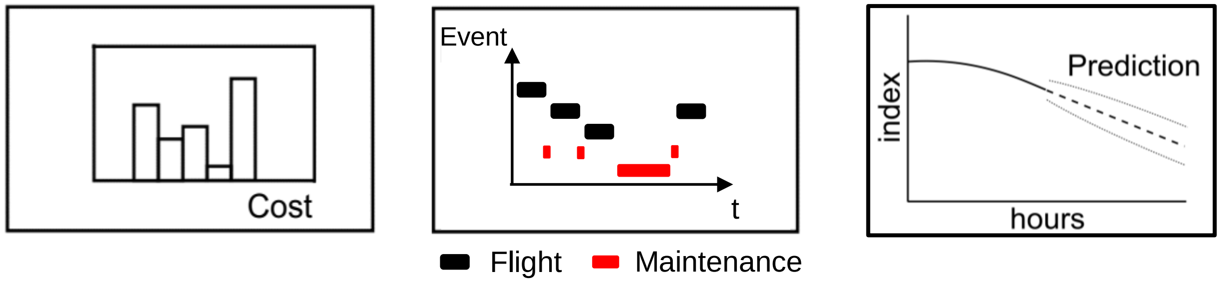


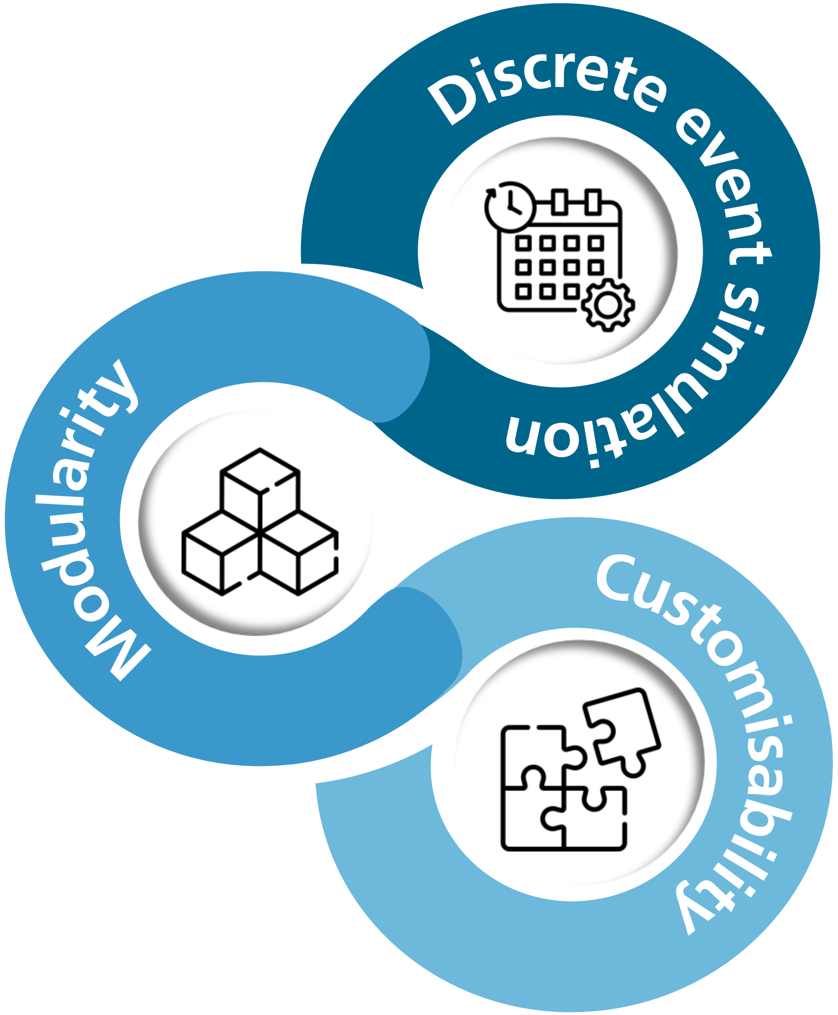
Modular discrete event simulation framework

Unified maintenance approach for fixed checks and condition monitoring

Existing monitored parameters to forecast maintenance before they occur

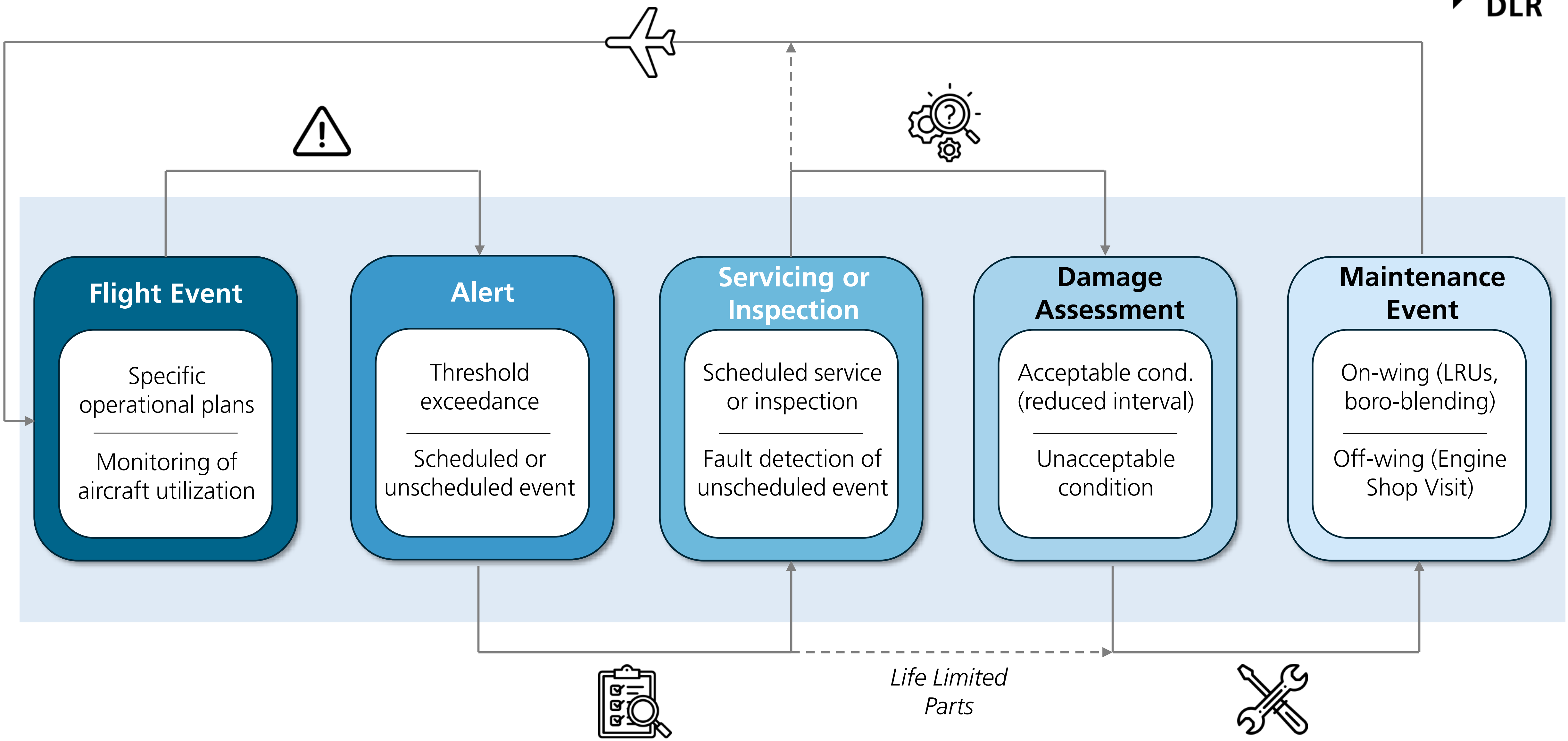
Results (output)





Pohya et al.: A Modular Framework for the Life Cycle Based Evaluation of Aircraft Technologies, Maintenance Strategies, and Operational Decision Making Using Discrete Event Simulation (2021)

System monitoring enables condition-based maintenance



Utilization and LRU failures drive engine line maintenance

Line Maintenance Events

Service Events

Fixed intervals driven by utilization (FH, FC, MO)

Service tasks include oil refills, hydraulic fluids, filter discards, etc.

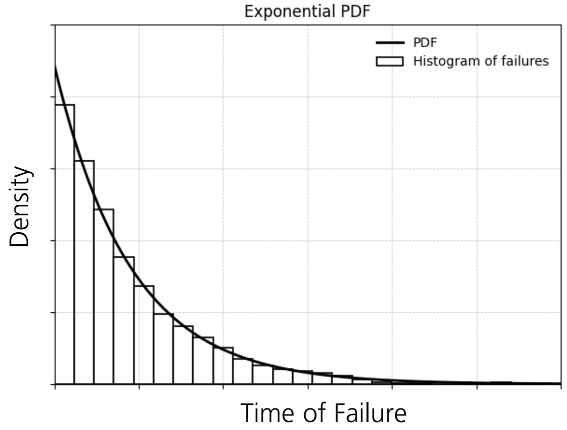
Inspection Events

Fixed intervals driven by utilization (FH, FC, MO)

Inspection tasks are, among others, characterized by GVIs, DVIs, and SDIs

Line Replaceable Units

$$t = -\frac{1}{\lambda}\ln(1-u), \qquad u \in [0,1]$$



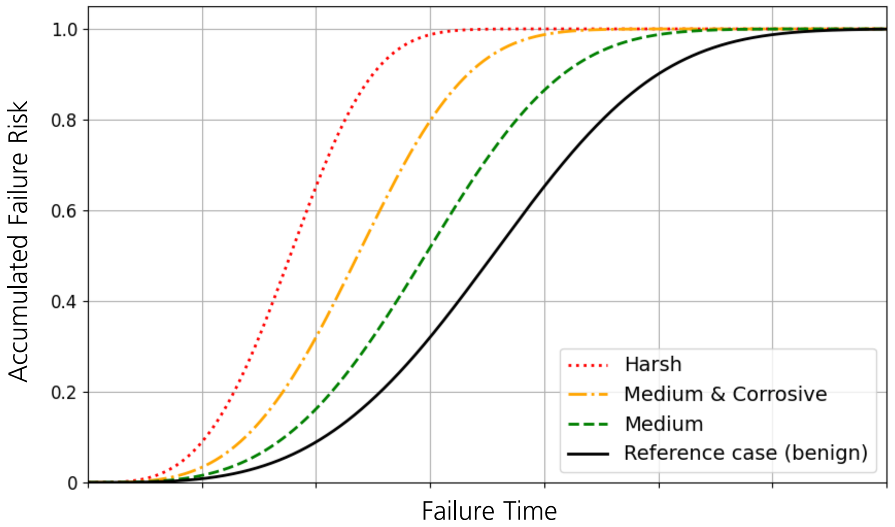
Service and inspection tasks are initiated once predefined fixed thresholds are exceeded while the failure time of line replaceable units is determined by their MTBFs applied to an exponential distribution.

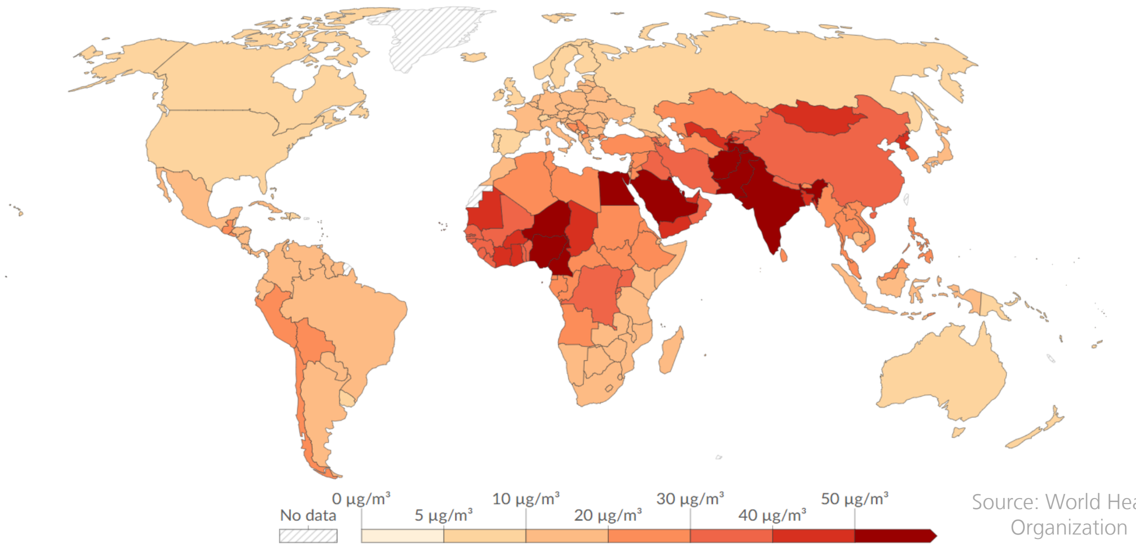
Turbomachinery faces degradation and environmental stressors

The Weibull distribution

- Capability to model multiple failure characteristics
- Weibull distribution defined by scale (η) and shape (β) parameters
- Degradation depends strongly on environmental conditions
- Time-to-failure distributions adjusted using an effective severity factor s_{eff}
- Conditional reliability accounts for restoration and reduced lifetime

$$t = \frac{\eta}{s_{\mathrm{eff}}}\left(\left(\frac{T}{\eta/s_{\mathrm{eff}}}\right)^{\beta} - \ln(u)\right)^{\frac{1}{\beta}} - T, \quad u \in [0,1]$$

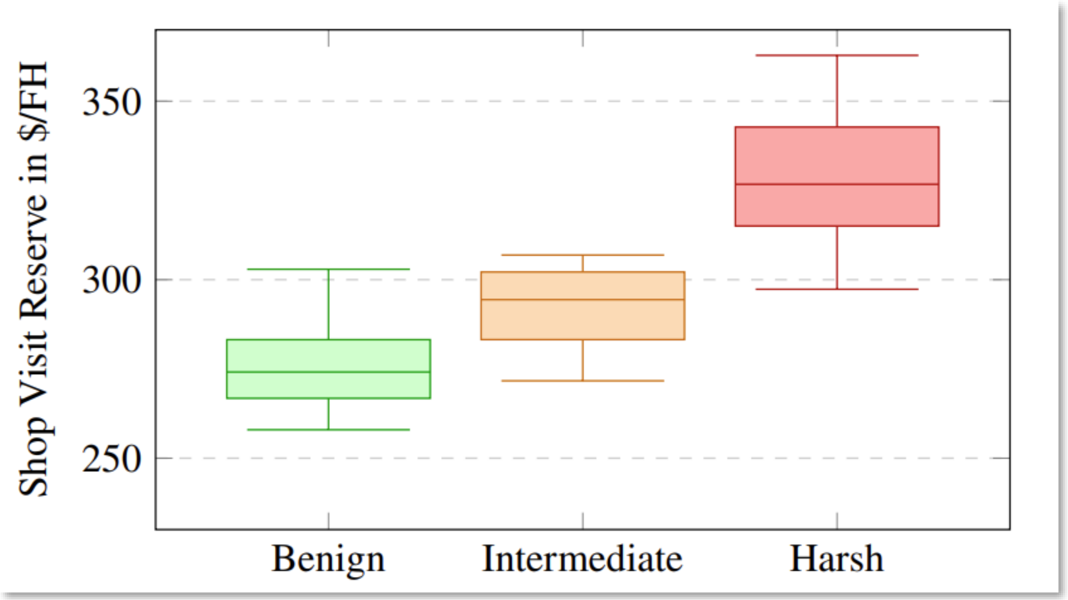




Source: World Health Organization

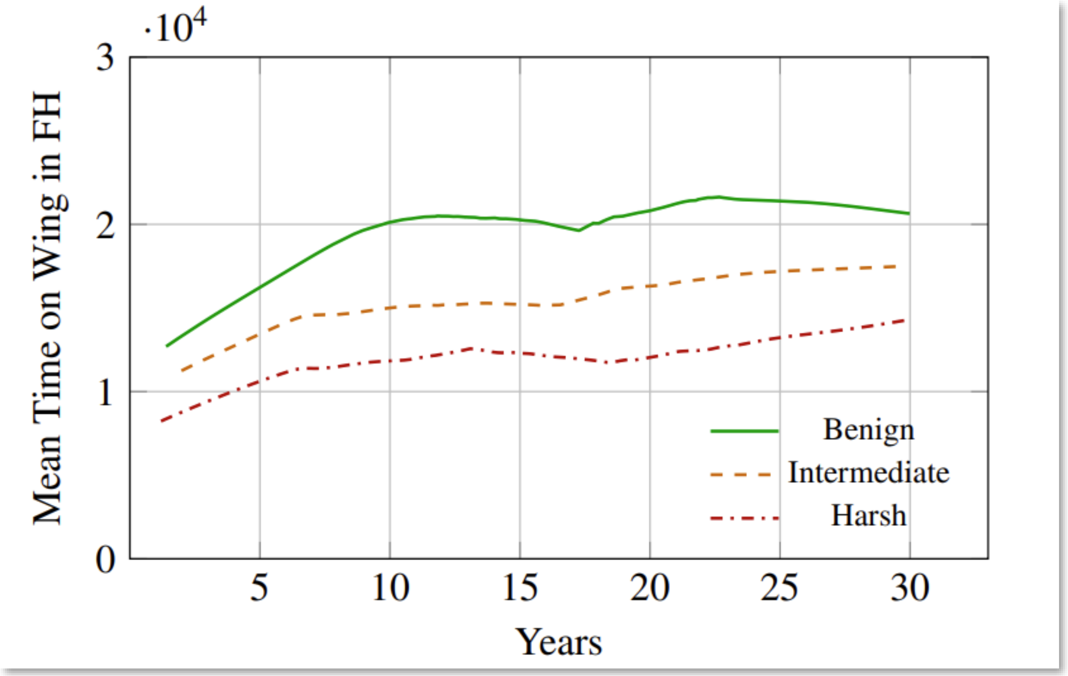
Industry seeks cost and planning certainty

Engine related maintenance cost



Clear upwards trend of shop visit reserves for harsh operated engine fleets

Availability and reliability



Noticeable decrease in engine availability due to lower reliability of components in harsh operated engines

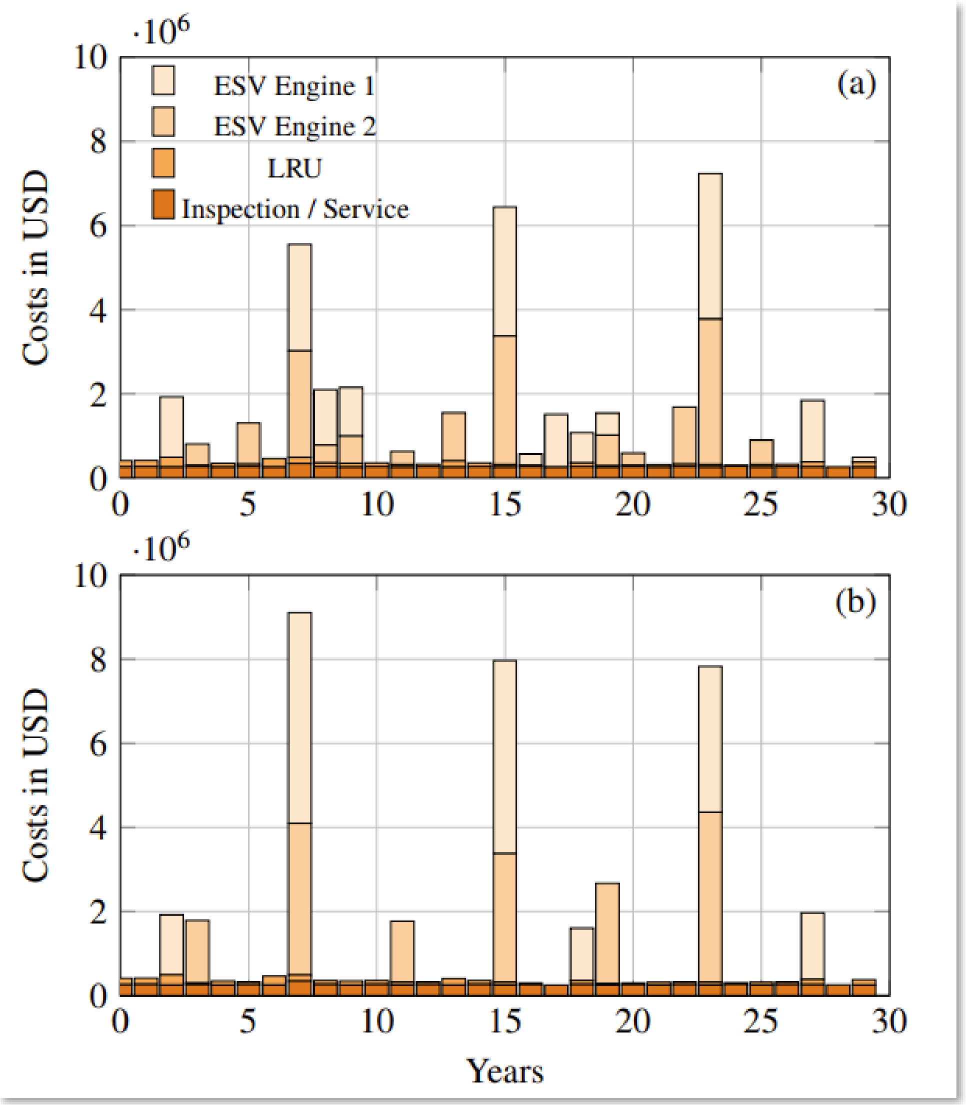
Lehmann et al.: A Probabilistic Approach to Engine Maintenance Modelling Using Discrete-Event Simulation (2026)

Tailored strategies improve cost, reliability, and availability

Effects of maintenance strategy

- Opportunistic maintenance reduces shop visits through task consolidation
- Usage of component condition and remaining useful life during shop visits
- Improvement of operational efficiency and avoidance of subsequent shop visits
- Engine health modelling enables such considerations and paves the way for predicitive maintenance strategies

Task consolidation can lead to a significant decrease in engine shop visits over an engine's lifecycle

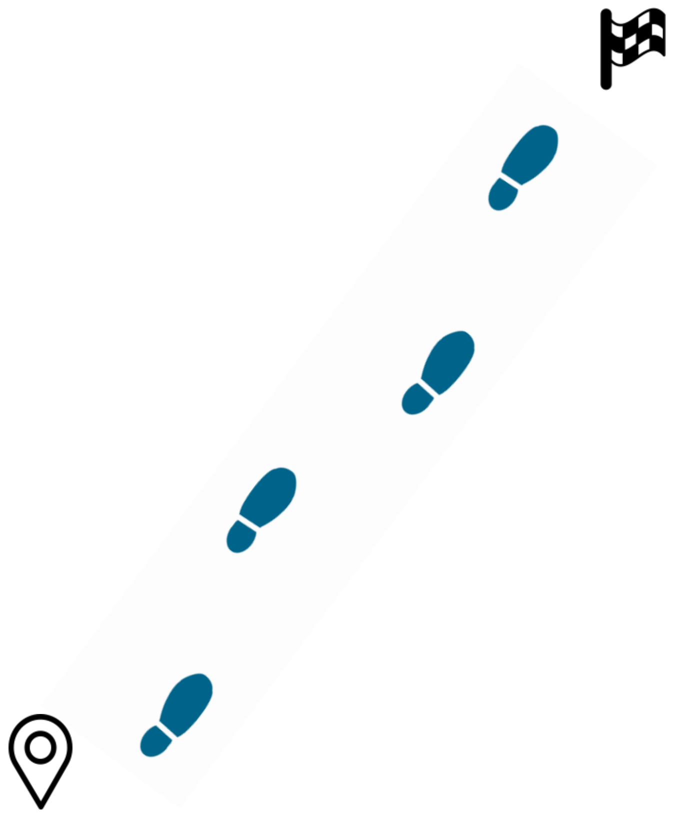


Lehmann et al.: A Probabilistic Approach to Engine Maintenance Modelling Using Discrete-Event Simulation (2026)

Probabilistic modelling supports fleet-level assessment but limits physical insight

What’s next?

- Proposed framework is able to reproduce expected behaviours, values, and maintenance effects
- Further validation of baseline probabilistic approach across multiple engine types
- Development of high-fidelity degradation models based on physical deterioration mechanisms (e.g. physics-informed machine learning)
- Implementation of degradation models or surrogates into lifecycle modelling framework *LYFE*^{2}
- Assessment of economic potential of predictive maintenance through integrated engine health modelling



“Predictions are difficult, especially when they concern the future” – Niels Bohr

Thank you!

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Feel free to connect!

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