# Introduction

**Digital Twins** (DTs) are an emerging technology. By connecting wind farm operational data streams, such as SCADA and alarm/event data in combination with external data, DTs can optimise wind farm **performance monitoring and management**, ensuring maximum profitability.

**Key performance indicators** (KPIs), especially when contextualised by **benchmarking against performance baselines**, distil complex performance data into simple, actionable vocabulary understood by all wind farm stakeholders.

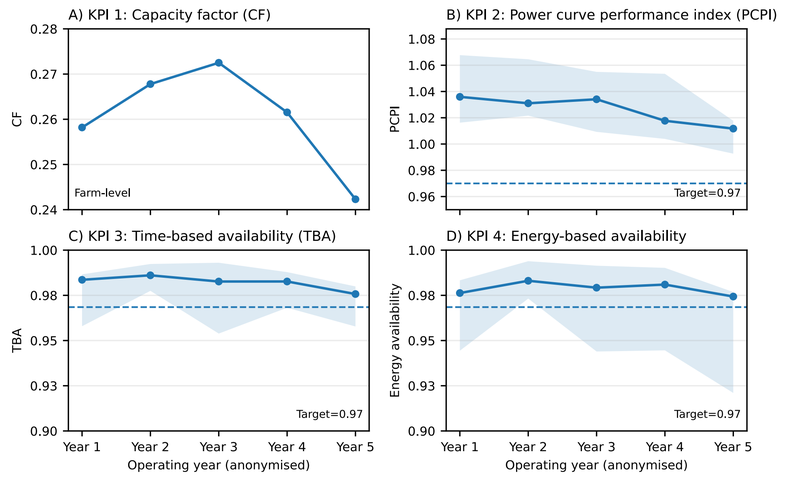
Basing a DT framework on the wind farm's data naturally leads to a **top-down** approach of viewing and breaking down the KPIs, while architecting the DT with bottom-up component models in mind can help wind engineers investigate deviations and under-performance of assets more quickly.

With current literature focusing either on DT capabilities, siloed subsystem demonstrators or IT implementation, there is a **gap** in the development of universal, comprehensive and open DTs, which remains a systems engineering and architecting problem.

# Method & Results

A systems engineering synthesis approach mapped aggregated stakeholder workflows and decision contexts onto **architectural design principles,** yielding the **modular top-down framework**.

The framework's feasibility was validated by a proof-of-concept instantiated offline on five years of industrial SCADA and alarm/event data, demonstrating end-to-end executability and producing the representative KPI outputs shown.




# Benefits

- A KPI-first, top-down workflow provides a consistent daily monitoring entry point across sites.
- A single operator-facing workflow scales across sites without re-implementation, allowing onboarding of new wind farms by configuration.
- Computationally-heavy, bottom-up physics-based models invoked on demand to help investigate deviation and underperformance.
- Shared intermediate data products are reusable across multiple KPIs, reducing inconsistency and improving traceability.

# Challenges

- Wind farm data onboarding remains one of the highest-effort tasks in DT implementation.
- Alarm/event logs are weakly standardised and OEM-specific, requiring manual mapping to a common taxonomy.
- No established DT-specific ontology or machine-readable interface schema exists for KPI governance and configuration at portfolio scale.

# Digital Twin Framework for Wind Farm Performance Monitoring and Management: A KPI-first Top-down Approach

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# Modular Framework

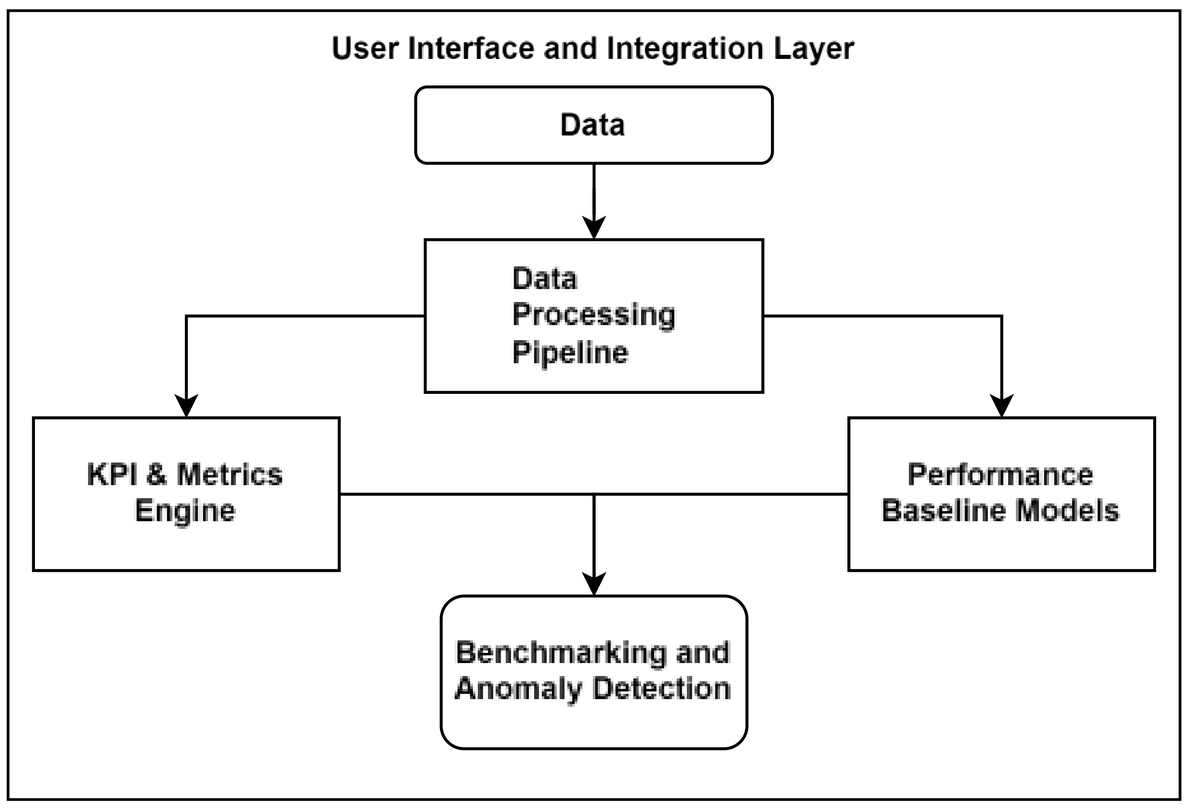
**Data Processing Pipeline**
Transforms SCADA, alarm/event and external data into analysis-ready time series, masks, and operating-state labels.

**KPI & Metrics Engine**
Computes stakeholder-facing indicators for wind farm and turbine performance.

**Performance Baseline Providers**
Provides contextual expectations (physics-based, historical/statistical, or hybrid).

**Benchmarking & Anomaly Detection**
Quantifies deviations between observed performance and expectations (performance baselines).

**User Interface & Integration Layer**
Exposes KPI overviews in a dashboard, drill-down pathways, and reporting materials.




# Design Principles

**Modularity and loose coupling**
Enable independent development, testing and replacement of DT capabilities without cascading changes.

**Separation of concerns and layering**
Improve maintainability and deployability by decoupling data handling, analytics and presentation

**Extensibility by configuration**
Enable configuration and addition of more KPIs based on stakeholder requirements and data availability.

**Interoperability by explicit interfaces**
Allow integration of external definitions, tools and baseline models while keeping the top-down workflow stable.

**Traceability and auditability**
Operational decisions require transparency on how indicators were computed and contextualised.

**Confidentiality-aware reporting**
External benchmarking, evaluation and reporting must avoid disclosing sensitive proprietary information.

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