NREL
Transforming ENERGY

Wind Plant Operations and Maintenance Challenges and Research Opportunities

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Photo by Dennis Schroeder, NREL 55200

Outline

- Major advances in wind energy
- Main operations and maintenance (O&M) challenges
- Related R&D activities at NREL
- Opportunities for operations research and management sciences community.

U.S. Department of Energy (DOE) 1.5-MW turbine. *Photo by Lee Jay Fingersh, NREL 17245*

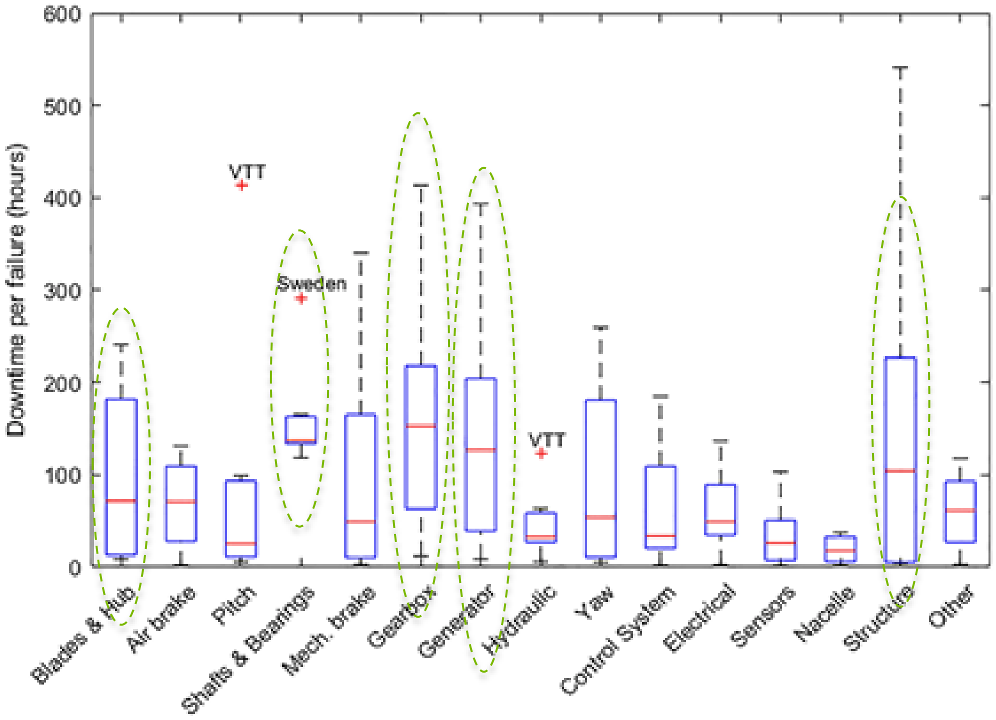
Major Advances in Wind Energy

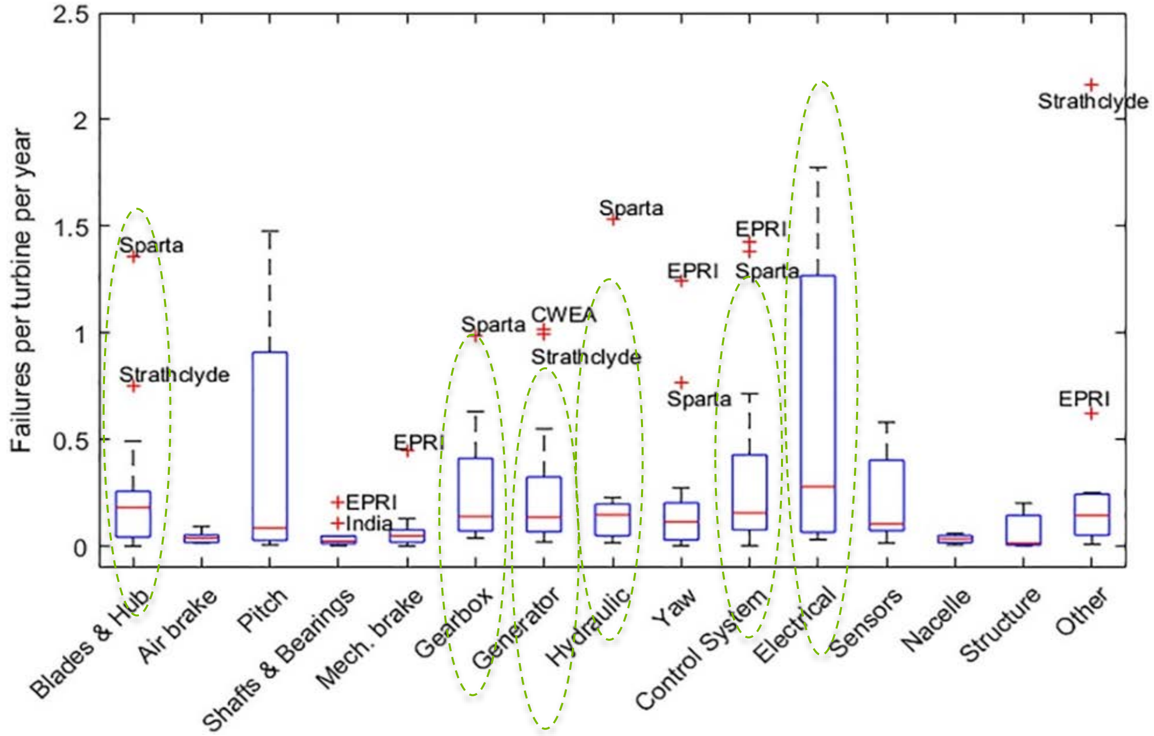
- Global cumulative installed capacity during the past 10 years:
  - Land-based: more than tripled (234 gigawatts [GW] in 2012 to 780 GW in 2021)
  - Offshore: increased by about 13 times (4 GW in 2012 to 57 GW in 2021)
- Within 1−2 years:
  - Blade length increased by 195% : ~40 meters (m) to ~118 m
  - Tower height increased by 230%: ~80 m to ~264 m
  - Turbine rating increased by 967%: ~1.5 megawatts (MW) to ~16 MW
- More sensors (e.g., dedicated condition monitoring packages by default)
- More automation (e.g., drone-based blade inspection)
- More digitalization (e.g., advanced modeling and analysis for performance, reliability assessment; portable digital devices with advanced software for technicians)
- Increased performance, reliability, and reduced levelized cost of energy
- Hybrid plant development by integrating wind with other power generation technologies (e.g., solar, battery storage, and hydrogen).

Sources:

- Global Wind Energy Council. *Global Wind Report 2022*. https://gwec.net/global-wind-report-2022/
- https://www.asme.org/topics-resources/content/6-advances-in-wind-energy
- https://www.nesfircroft.com/blog/2021/12/the-biggest-wind-turbines-in-the-world?source=google.com

Premature Component Failures

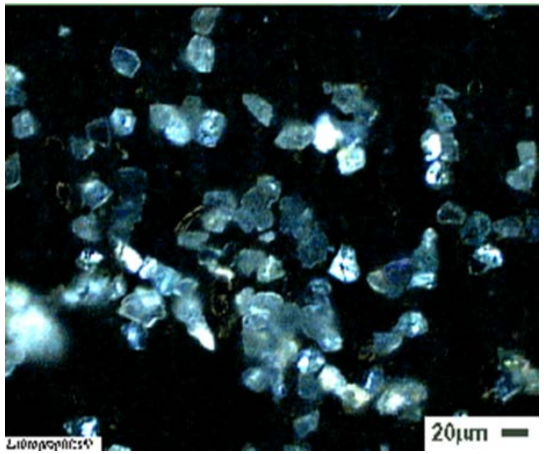




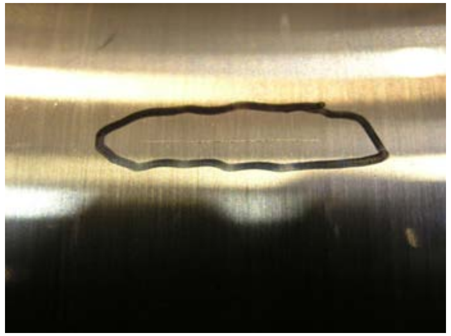
- (Left) Median values of downtime per failure (hours) caused by different subassemblies; top drivers: gearbox, generator, shaft and bearings, structure, blades and hub
  - Structure may be due to the surveyed data including offshore wind plants
- (Right) Median values of failures per turbine per year by different subassemblies; top drivers: electrical, blades and hub, control system or hydraulic, gearbox, generator.

Source: Dao, C., B. Kazemtabrizi, and C. Crabtree. 2019. “Wind Turbine Reliability Data Review and Impacts on Levelised Cost of Energy.” Wind Energy 22(12): 1848–1871.

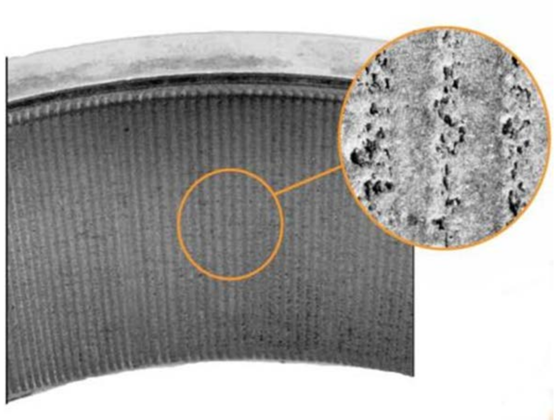
Complex Failure Modes: Gearboxes As an Example



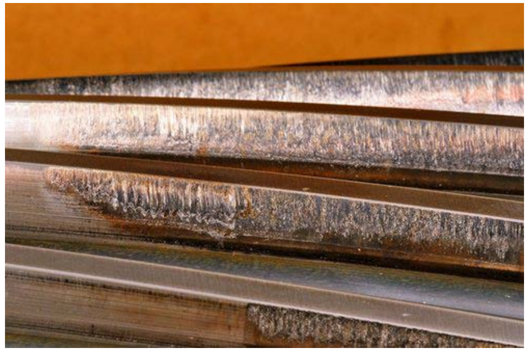
Lubricant contaminants



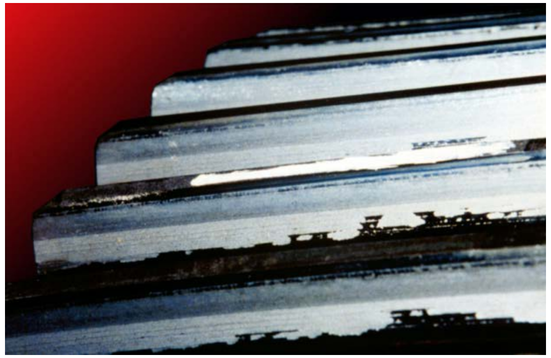
Axial cracks (gearbox bearings)



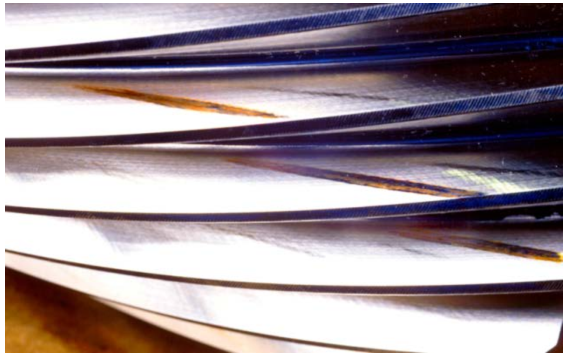
Fluting (generator bearings)



Scuffing (high-speed stage pinion)



Micropitting



Fretting corrosion

Photo sources: (top left) Bill Herguth, Herguth Laboratories; (top middle) Gary Doll, University of Akron; (top right) Ryan Evans, Timken; (bottom three) Bob Errichello, GEARTECH

Variable and Harsh Operational Conditions

- Changing wind speeds and directions
- Intermittent operation with many starts and stops
- Transient and sometimes high loads from wind, the grid, braking, and misaligned shafts.

- High torque and low-speed input
- Remote locations (difficult for maintenance)
- Harsh environmental conditions
  - Contamination from dust and wear debris
  - Wide temperature range (−30 °C to +100 °C)
  - High humidity and water ingress
  - Icing events
  - Lightning strikes.

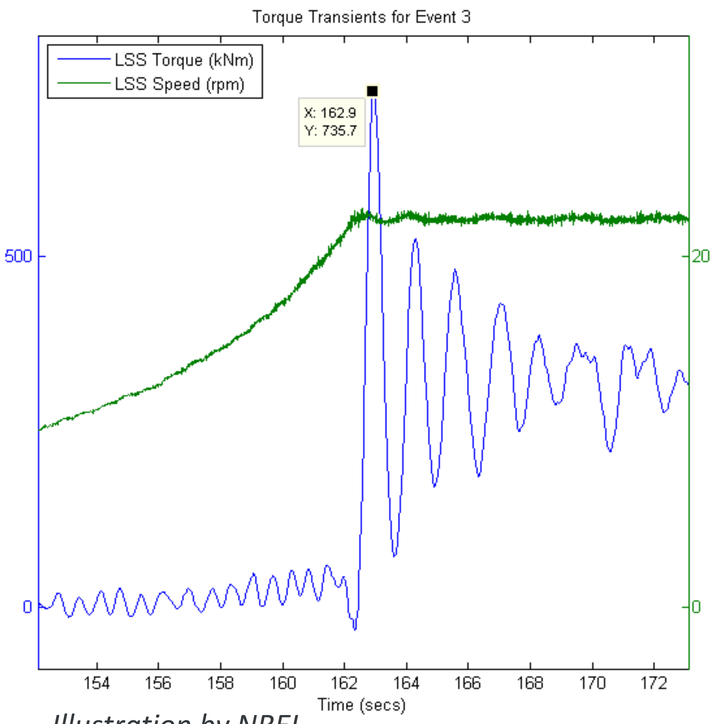


Illustration by NREL

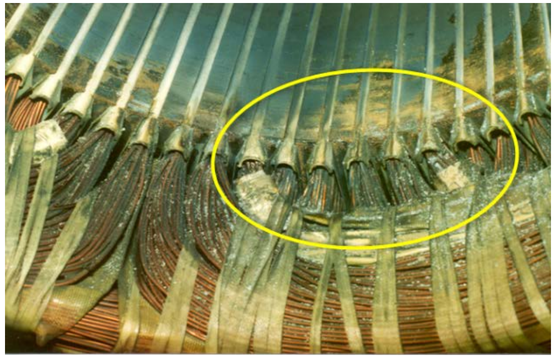


Photo source: Kevin Alewine, Shermco Industries

Uniqueness with Offshore

- Accessibility could be dramatically reduced due to:
  - Complex wind and wave conditions
  - Further away from shore
  - Frozen seawater.
- With reference to land-based plants:
  - Extensive marine logistics
  - Higher safety risks during personnel transfer from service vessels to turbines or floating platforms, or failed mooring lines for floating foundations
  - Undersea cables much harder to monitor and maintain
  - Scour needs to be monitored and assessed for unprotected foundations.

Offshore wind turbine anchor comparison. *Illustration by Joshua Bauer, NREL 49055*

Wind Plant O&M Research Opportunities

- Operation and maintenance (O&M) research needs:
  - According to Global Wind Energy Council, wind installed capacity around the world reached 837 GW by the end of 2021
  - A 1% performance improvement: ~$2.7 billion additional revenue (assumed: 30% capacity factor, $120/megawatt-hour [MWh] electricity rate)
  - Extremely high replacement costs for most subsystems.
- O&M cost reduction and business opportunities:
  - O&M costs account for up to 35% of levelized cost of energy for land-based wind plants in the United States[1]
  - Further O&M cost reductions achievable by improved practices
  - Global O&M market likely to reach $53 billion by 2030[2]
- Actions to improve performance, reliability, and availability are more critical for offshore wind.

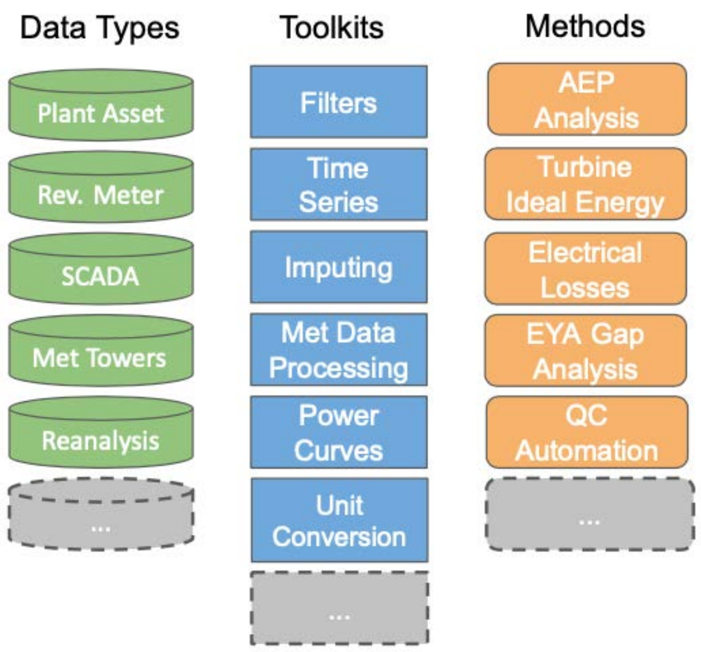
[1] Keller, J., S. Sheng, Y. Guo, B. Gould, and A. Greco. 2021. *Wind Turbine Drivetrain Reliability and Wind Plant Operations and Maintenance Research and Development Opportunities*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-80195. https://www.nrel.gov/docs/fy21osti/80195.pdf.
[2] Fine, A. 2022. "Wind Turbine O&M Market Expected To Reach $53 Billion by 2030." North American Windpower. https://nawindpower.com/wind-turbine-om-market-expected-to-reach-53-billion-by-2030.

An Open-Source Framework for Operational Analysis of Wind Plants (OpenOA)

https://github.com/NREL/OpenOA

OpenOA Features

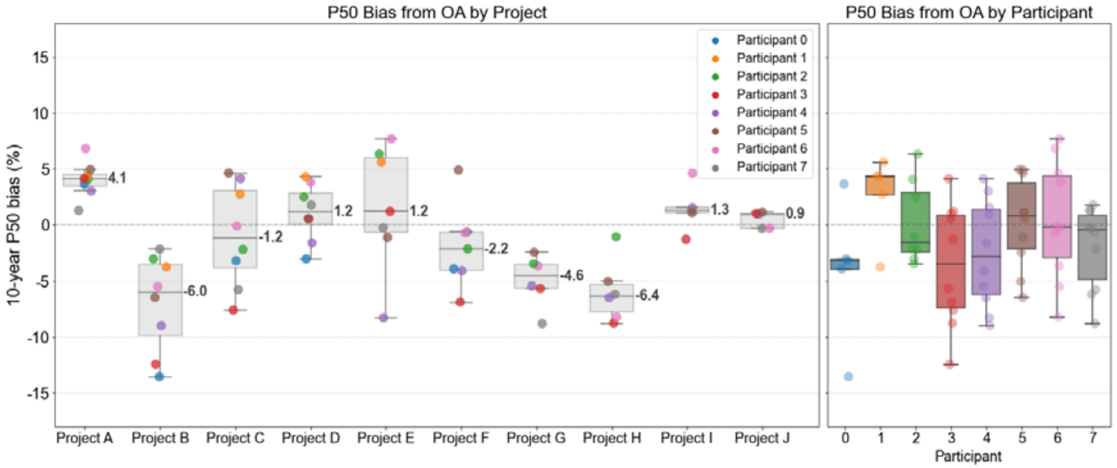
- Modular code design
  - **Data types** for organizing input data
  - **Toolkits** for performing low-level operations
  - **Methods** for performing specific operational analyses
  - New modules can be added when ready.
- Documented examples
  - Example **Jupyter Notebooks** illustrating methods and core low-level toolkits
  - Examples use a data set based on publicly available SCADA data from ENGIE's *La Haute Borne* wind plant (https://opendata-renewables.engie.com).



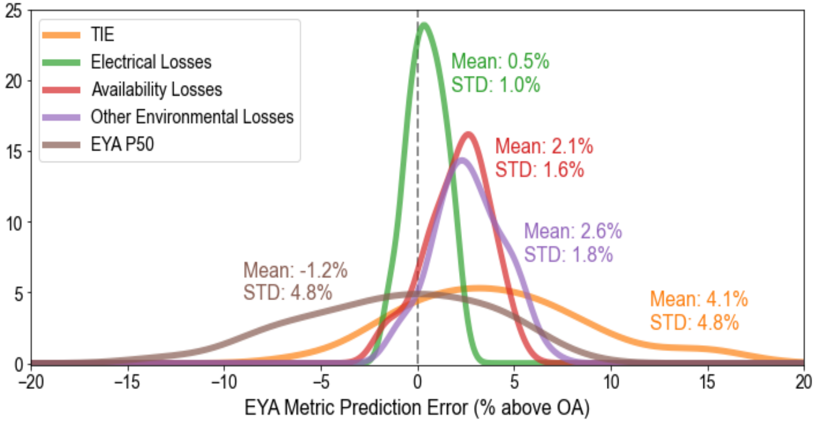
Applications of OpenOA

- Data quality control and preprocessing
- Plotting of time series and maps
- Performance analysis
  - Annual energy production (AEP)
  - Loss calculation
  - Gap analysis.

- Phase 1 of **WP3 Benchmarking Project**
  - Provides long-term AEP benchmark to compare with EYA estimates for 10 commercial projects.



- **Gap analysis** to determine sources of EYA prediction error.



Acronyms
WP3: wind plant performance prediction
EYA: energy yield assessment
TIE: turbine ideal energy

Drivetrain Reliability Condition Monitoring and Prognostics Research

Drivetrain Reliability Research

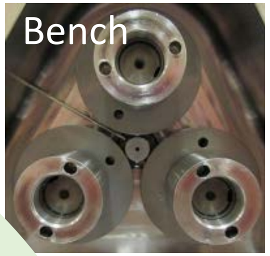
Pitch, Main, and Generator Bearings and Gearboxes

- Identify failure modes
  - Prevalent, costly, and uncharacterized

START

Characterize failures

cracking, wear, micropitting, fretting, …



Quantify damage contributors

load, stress, cycles, slip, friction, current, …

Develop rating or life model

fatigue, friction energy, …

Verify life model

predictions (hindcast) vs. actual failures (forecast)

- Cooperative R&D Agreements
- Technology Commercialization Funds
- Funding Opportunity Announcements

FINISH

- Improve designs
  - Components, controls, materials, coatings, lubricants…
- Predict Remaining Useful life
- Optimize O&M
- Improve standards
  - AWEA Recommended Practices
  - IEC 61400-4 and AGMA 6006

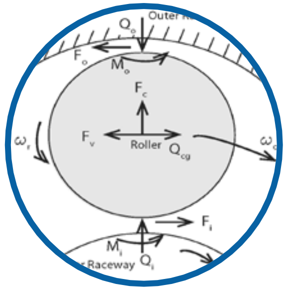
Frictional Energy-Based Reliability Assessment and Prognosis

4 SCADA

5 Failure Records

1

Roller Sliding,
$\Delta V, \mu$



2

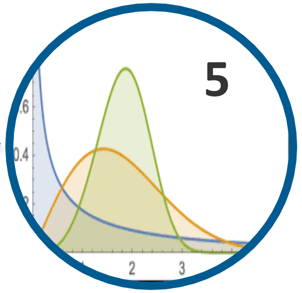
Roller Load,
N

3

Frictional Energy,
E

Model validated by experiments on a commercial turbine

Wind Plant,
E



Probability of Failure, *PoF*

Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT)

https://github.com/WISDEM/WOMBAT

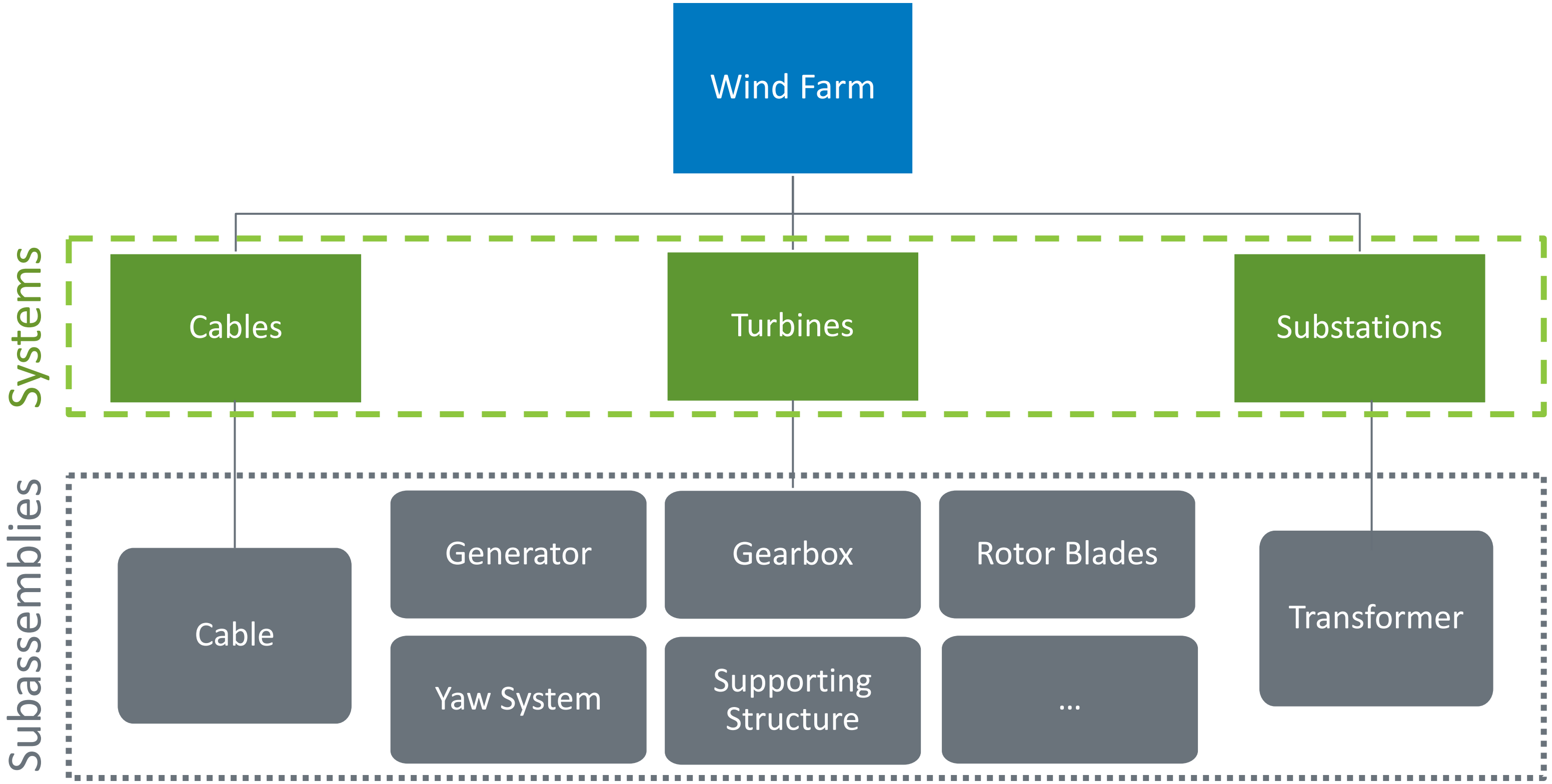
Approach

- Prescriptive modeling via discrete event simulation:
  - Enables weather and site-specific variability
  - Robust strategy and technology definition
  - Focuses on comparing scenarios rather than optimization.

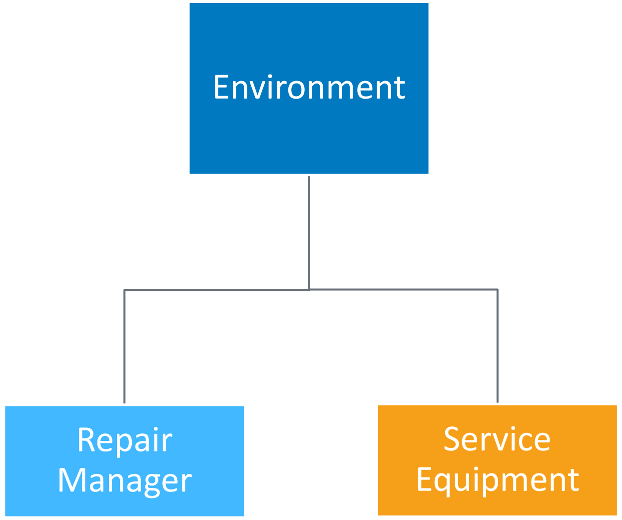
- Modular and flexible code base:
  - Allows for new methodologies and technologies to be tested with ease
  - Provides a tool to analyze both offshore and land-based wind farm O&M costs.

- Well-documented and tested code base:
  - Enable easy modification for analysis of new scenarios
  - Enhances the accuracy and consistency of results.

High-Level Software Architecture



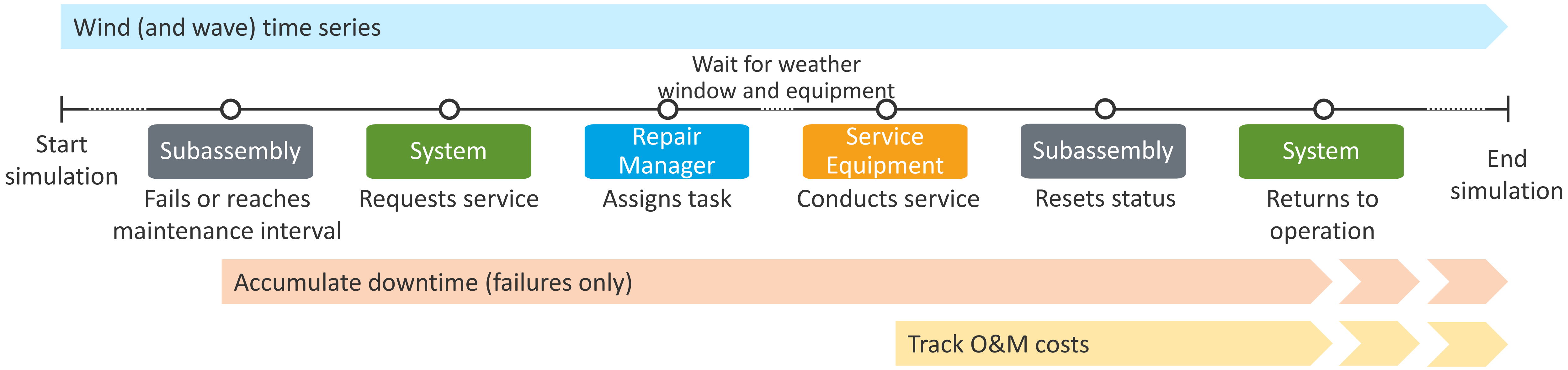
- User API for easy setup and running
- Data classes for inputs and validation
- Composable wind farm stores maintenance and repair frequencies and costs.



- *SimPy* environment handles weather and timing
- Service equipment tracks repair capabilities and costs
- Repair manager schedules equipment operations.

Repair Event Simulation

- WOMBAT evaluates O&M costs using discrete event simulation (series of events in sequential order where no changes occur between events).
- Each subassembly has user-defined repair and maintenance tasks with their own timing.



Opportunities for Operations Research and Management Sciences Community

Future Opportunities

- OpenOA
  - Wake losses quantification methods
  - Individual turbine performance assessment
  - Evaluate performance improvements (e.g., aerodynamic upgrades, controls).
- Drivetrain condition monitoring and prognosis research
  - Improve accuracy and reliability of diagnostic decisions, including level of severity evaluation
  - Develop reliable, accurate, and practical prognostic techniques to enable remaining useful life estimation of turbine components/subsystems.
- WOMBAT
  - Identify areas with high potential for innovations to reduce O&M costs
  - Continue to validate and build additional modeling capabilities to support new O&M innovations
  - Standardize approach to quantifying trade-offs between availability and operational expenditures.

Future Opportunities (Cont.)

- Open data standards and reference software implementations that facilitate better analytics at scale through industry working groups (e.g., ENTR, OSDU)
- Fusion of various data streams to optimize O&M practices, reduce loads, and extend life of turbine subsystems/components
- Grid impacts modeling and analysis considering market prices, curtailments, etc.
- Inventory planning by considering estimated component life and supply chain constraints
- Maximize digitalization benefits from sensing to O&M decision making
- Uncertainty representation and interpretation, quantification, propagation, and management
- How can we optimize hybrid plants in terms of dispatching of different power generation technologies and O&M?
- **What fundamental changes are needed in terms of O&M to face much higher renewable penetration at global scale?**

Thank you!

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The Block Island Wind Farm—the first offshore wind farm in the United States. *Photo by Dennis Schroeder, NREL 40389*

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