Optimal Maintenance Strategy for Wind Turbines with Markov Decision Processes

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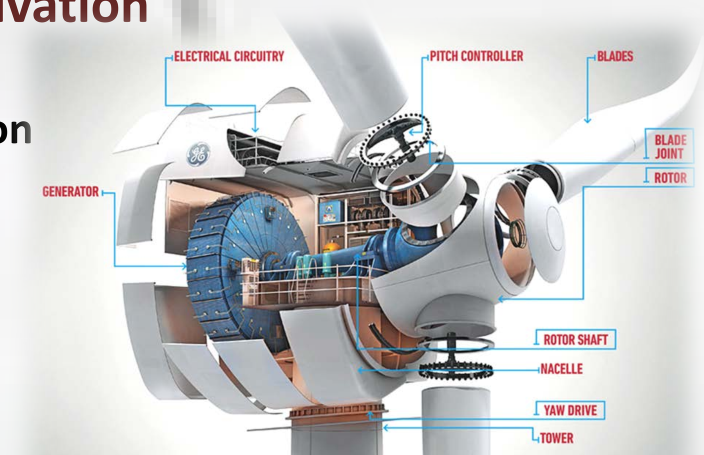
Motivation

- **Fast-growing wind energy installation**
  - Nearly 7GW of new wind energy capacity in 2011 according to AWEA
  - 31% increase compared with the installation in 2010

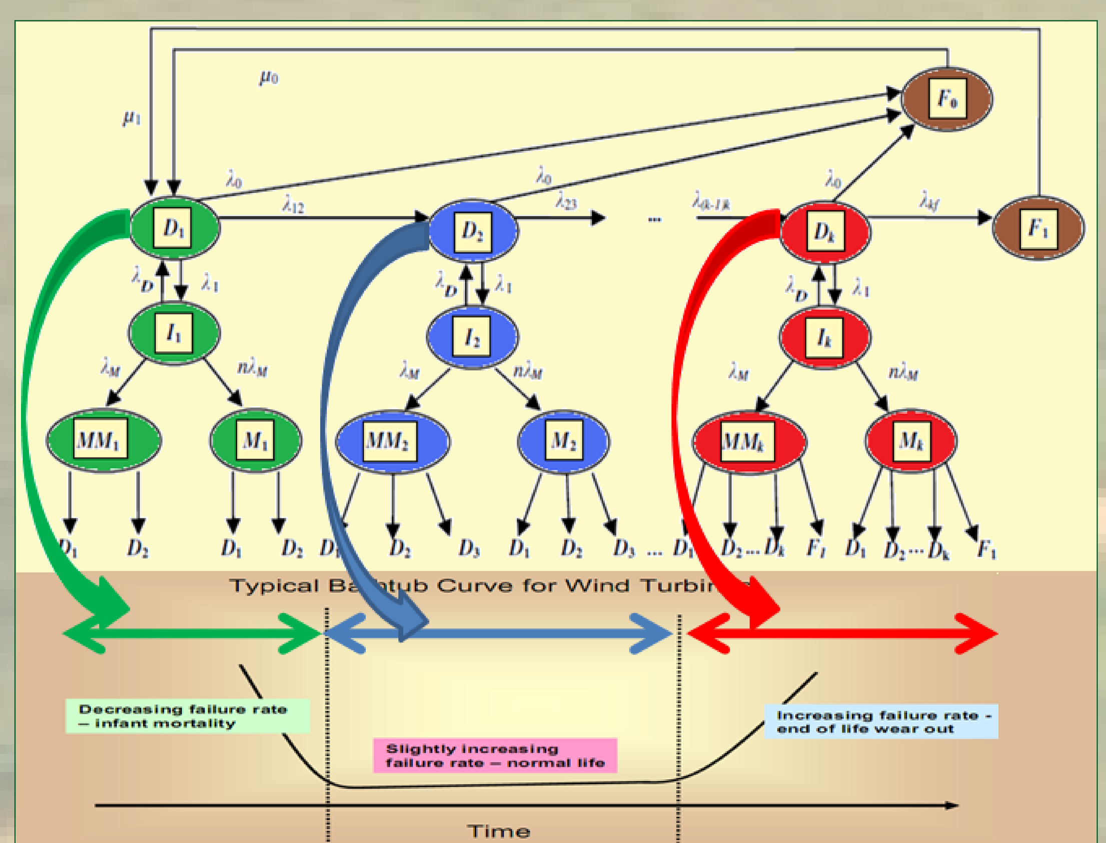


The GE 4.1-113 wind turbine

- **Concerns with regard to efficiency, and availability of wind turbines due to higher stress compared with the conventional generation**
  - Many moving and rotating subassemblies installed at high elevation
  - Parts exposed to the weather changes including variable wind speed and temperature
- **Requirement for an effective strategy to preserve the health and improve the reliability of wind turbines**
  - Practicing a variety of techniques such as Inspection, corrective maintenance, preventive maintenance, condition monitoring, and replacement
- **Significance of a trade-off between the dollar amount spent on the maintenance activities and the resulting benefits**
  - Estimated cost of selected maintenance strategies
  - Penalties and rewards for having an equipment with different health condition
  - Aiming at maximizing the benefit or the availability of the wind turbine

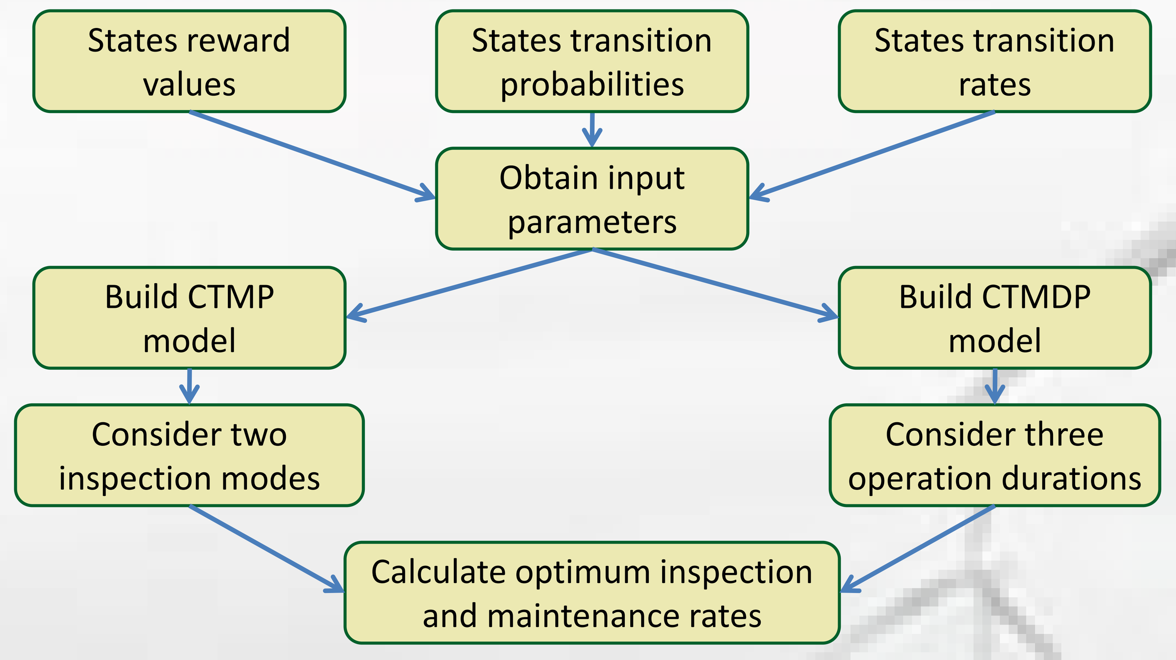
Model

- **Develop a model for the operation of wind turbine and obtain the optimum maintenance strategy**
- **Apply continuous-time Markov process (CTMP) and Markov Decision Process (CTMDP)**
  - A stochastic process illustrating a graph between states of the system
  - Transitioning to other states with specific transition rates
  - A real valued reward function associated with each state-action pair



States:		Transition rates:
D: Deterioration I: Inspection F: Failure	MM: Major maintenance M: Minor maintenance	λ: Failure rate µ: Repair rate

Method



Case Study

- **3MW direct-drive wind turbine**

Main Parameters	Typical values
Random failure rate	1.5 times a year
Repair duration due to random failure	3.5 days
Repair duration due to deterioration	14 days
Major maintenance duration	5 days
Minor maintenance duration	1 days
Inspection duration	1 hour
Critical inspection rate	once a year
Levelized net income from wind turbine operation	2 cents per kWh
Ratio of minor to major maintenance rate	2
Capacity Factors	0.3, 0.35, 0.25 for D1, D2 ,D3 respectively

Proposed Educational Course for Fall 2012

Title:

Reliability Assessment of Engineering Systems

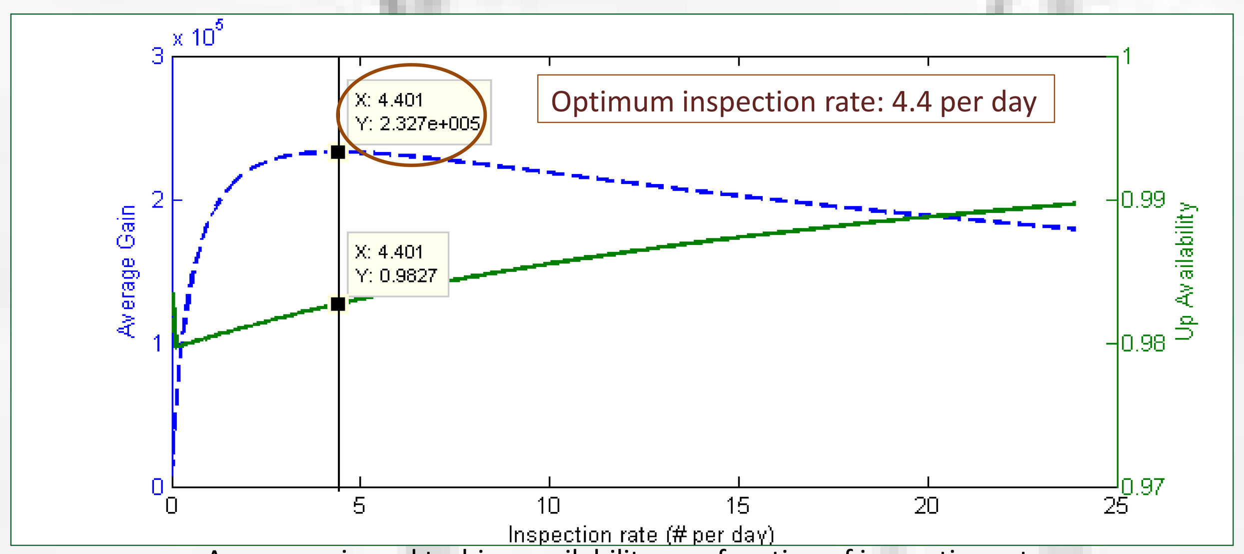
Course objectives:

- To learn the definition of a component and a system from a reliability perspective
- To develop and solve mathematical models for the failure, repair, and related processes of systems with particular applications to wind turbines and wind farms
- To identify, collect, and analyze data as well as to estimate the parameters of the models
- To evaluate the reliability indices of components and complex systems using appropriate models and parameters

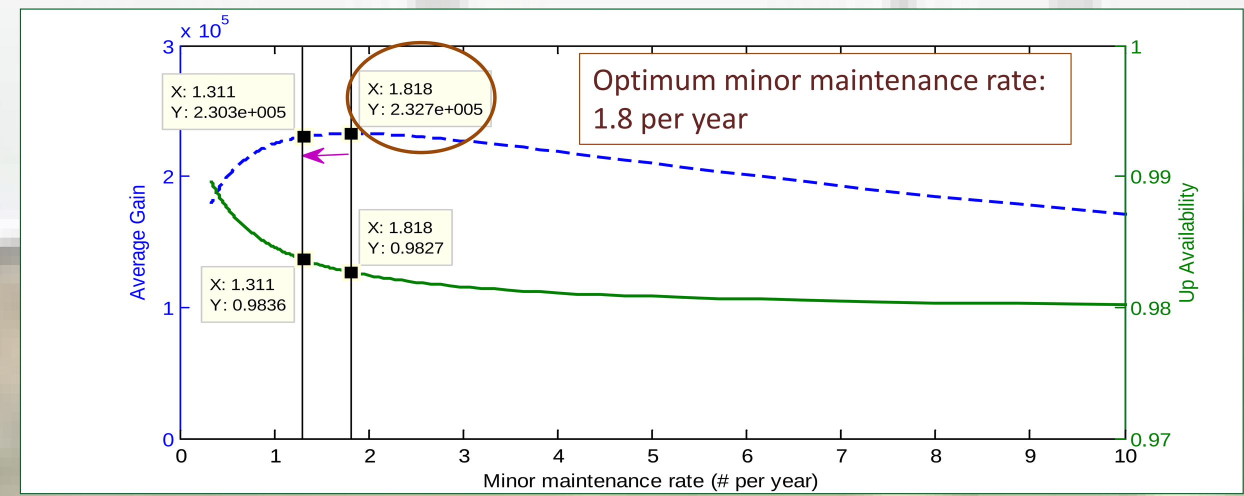
Course outline:

- Review of Probability and Statistics
- Data Analysis/Estimation of Parameters
- System Reliability
- Series/Parallel/Complex Systems
- Cut Set, Tie Set, Fault Tree, and Event Tree
- Approximate System Reliability Evaluation
- Repairable Systems
- Failure Mode, Effect, and Criticality Analysis
- Markov Processes
- Monte Carlo Simulation

Case 1: Optimum inspection and maintenance rates (wind turbine is available during inspection)

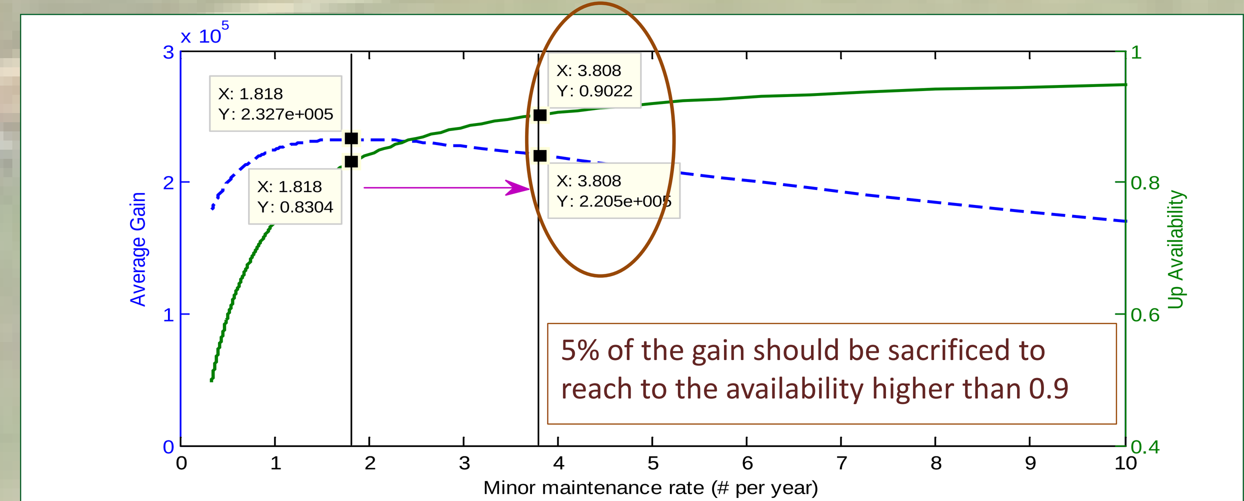


Average gain and turbine availability as a function of inspection rate



Average gain and turbine availability as a function of maintenance rate

Case 2: Optimum inspection and maintenance rates (wind turbine is unavailable during inspection)



Average gain and turbine availability as a function of maintenance rate

Case 3: Optimum decisions based on CTMDP

Inspection rate	First operation duration (first 3 years)	Middle operation duration (year 3 to 12)	Last operation duration (year 12 to 20)	Availability
4.4 times a day	do nothing	do nothing	do nothing	0.8304
Every 47 days	minor maintenance	do nothing	major maintenance	0.9787

Results and Conclusions

- The results of CTMP show that the optimum inspection rate is 4.4 times per day. This is equivalent to the minor maintenance rate of about twice a year, and major maintenance of once a year according to problem assumptions.
- The results of CTMDP are dependent on visited inspection states. By decreasing the inspection rate, the change in maintenance decisions appears at the rate of once per 47 days. Optimum decisions change at different operation periods.
- When wind turbine is available during inspection, more frequent inspections provides higher availability and reduced number of maintenances.