Introduction

Motivation
- Wind is often regarded as “energy for free”
- Not true: O&M contributes ~20% to the final price of energy
- Investors’ expectations are high on turbine availability
- Failures must be detected and fixed as quickly and efficiently as possible

Objectives
- Integrated system for monitoring, diagnosis and maintenance
- The focus of the talk is on maintenance scheduling
Workflow covered

**Failure Detection** & **Prognosis**
- Failure detection and maintenance scheduling for wind farms
- Automated mapping of SCADA alarms & signals
- Decision support to human experts by diagrams & reports

**Alarm**
- Wind speed
- Produced energy
- Alarm (failure)
- Alarm (technicians present)
- Turbine restarts
Failure detection & prognosis

- Failure detection
  - Identify an existing failure
  - Measured signal falls out of operational limits
  - SCADA issues a warning, may stop the turbine

- Failure prognosis
  - Recognize failures before they actually occur
  - By physical measurements (e.g., vibration) or life data analysis
  - Current precision sufficient for controlling spare part logistics

Failure and maintenance mapping

- Selection of the best maintenance action for each failure
  - Recommendations from Failure Mode and Effects Analysis (FMEA)
  - Historical success rates
  - Interdependencies with other maintenance tasks
  - Cost analysis

- Software provides
  - Decision support to experts
  - Automated task generation
    - Weighted set covering problem
Maintenance scheduling

- Schedule of a team
- Selected task
- Availability of technicians, parts, etc.
- Wind speed

Maintenance execution

- Execution tracking by feedback from technicians
  - Actual failure mode
  - Failed component
  - Task execution, duration, spares, etc.

- Refinement of the applied models
  - Failure detection
  - Failure & maintenance mapping
  - Task definitions
  - Turbine design
The maintenance scheduling problem

- The model covers all types of field maintenance
  - Corrective (detected failure)
  - Predictive (prognosed failure)
  - Preventive (planned maintenance)
  - Retrofitting, etc.

- One instance of the scheduling problem involves
  - One zone: set of farms maintained using common resources
  - Short-term horizon: 3-7 days
  - The set of tasks defined in the input

Maintenance scheduling: tasks

- Tasks
  - Non-preemptive, with known deterministic duration
  - All requirements are assumed to be known a priori

- Requirements of the tasks
  - Skilled technicians
  - Spare parts
  - Hired services (cranes, special trucks)
  - Weather conditions

- Further constraints
  - Travel times between farms
  - Incompatibility of tasks, etc.
Maintenance scheduling: objectives

- Production of turbine depends on
  - Wind speed (external)
  - Turbine condition (depends on maintenance schedule – internal)

- Production loss due to
  - Failures
  - Maintenance

- Optimization criterion
  - Minimizing total production loss
  - Irregular criterion (potentially worth postponing the tasks)

Solution approach

- Combination of mixed-integer programming (MIP) and custom heuristics
  - MIP solves the core optimization problem
  - Heuristics reduce the complexity of the MIP and handle some special situations

- The MIP
  - Time-indexed formulation
  - Solved by a commercial MIP solver (ILOG Cplex 11.2)
  - Solved to optimality (unless time limit is hit)
Solution approach: the MIP

Minimize

\[ \sum_{j=1}^{J} \sum_{t=1}^{T} z_{j,t} + \sum_{i=1}^{N} \phi_i y_i \] (1)

subject to

\[ \sum_{k=1}^{K} \sum_{r=1}^{R} x_{i,k,r} + y_i = 1 \quad \forall i \] (2)

\[ x_{i,k,r} = 0 \quad \forall i, j, k : \epsilon \in j \] (3)

\[ \sum_{i=1}^{N} \sum_{k=1}^{K} x_{i,k,r} \leq 1 \quad \forall k, t \] (4)

\[ \sum_{r \in \mathcal{R} : f(t) = f} \sum_{t \in \mathcal{T} : t' < t + p_t} x_{i,k,r} \leq \delta_{i,f,t} \quad \forall i, f, t \] (5)

Min. production loss

Task executed in some way or postponed

Infeasible assignments excluded

Capacity constraints (technicians, services)

Solution approach: the MIP (contd.)

Production loss

Technicians must travel

Task compatibility

Variables’ domains
Solution approach: the heuristics

- Heuristics for pre-processing
  - Decomposition according to nearby sets of farms
  - In massively oversubscribed problems, omit the least important tasks
  - Segmentation of extremely long tasks

- Heuristics for post-processing
  - Iterative improvement by re-partitioning and re-positioning the segments (necessary due to the segmented long tasks)

Computational evaluation

- Evaluation of the MIP approach to the core problem
  - Heuristics switched off
  - Random instances generated based on real historical records
  - Up to 50 tasks at 7 wind farms
  - Time limit set to 10 minutes

- Results
  - 95% of the instances solved to proven optimality
  - Average optimality gap of ~0.01% for the remaining instances

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Evaluation on real-life problems

- Experimental setup
  - 105 turbines at 6 farms, maintained by 12 teams
  - Scheduler was run every morning during 3 weeks
  - Larger problems than expected, with 200-250 tasks

- Results
  - Overwhelmingly positive feedback
  - Optimality gap around ~1%
  - Some additional features requested, e.g.,
    - Certain tasks require multiple teams
    - Preempted tasks must be continued by the same team

Conclusions

- Integrated system for monitoring, diagnosis and maintenance of wind farms
  - Maps available engineering knowledge in failure detection
  - New models and algorithms for maintenance scheduling
  - Optimizes wind farm operation by minimizing production loss
  - Validated on real-life data
  - Potential industrial exploitation
Thank you for your attention!