Systems Engineering Methods

With Potential Applications to Wind Energy

Presentation to NREL Workshop
12/14/2010

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Outline

- Systems Engineering
  - Definitions and relationship to Wind Energy
  - Methods Overview: MDO, MATE

- Tradespace Exploration and Offshore Wind Energy
  - MATE Overview
  - MATE for Offshore Wind

- Summary
Systems Engineering: What is it?

- International Council on Systems Engineering (INCOSE) Handbook Definition:
  - “Systems Engineering (SE) is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.” (p. 6)
Systems Engineering: What is it?

- **Summary:**
  - Holistic – system behavior more than the sum of the parts / system level functionality
  - Interdisciplinary – engineering, natural sciences, (even social sciences)
  - Integrated - design process explicitly involves customers / stakeholders
  - Long-term / Life-Cycle Oriented – considers cradle to grave life-cycle for system

- **Key concepts:**
  - Complexity, Uncertainty, Heterogeneity
  - Socio-technical systems, economics and policy
Systems Engineering and Wind

- Holistic?
- Interdisciplinary?
- Integrated?
- Long-term?

Above: Wind Energy Stakeholders

Left: Different fields involved in blade design (MIT OCW)
Systems Engineering and Wind

- Current Status
  - Search for “wind” in *Systems Engineering Journal* returns 0 results
  - Search for “systems engineering” in *Wind Energy Journal* returns 0 results, handful of related results

- Tools for SE approach to wind
  - Turbine design (i.e. aeroelastic codes)
  - Wind farm layout (i.e. Windfarmer)
  - Cost models (i.e. Sunderland, WindPACT)
Systems Engineering and Wind

- Holistic: involves complete system from resource to grid
- Interdisciplinary: from civil to materials
- Integrated: perspectives of each stakeholder from manufacturers to communities
- Long-term: engage full life-cycle from design and manufacturing to disposal

Consulting and Engineering Firms / Research Institutions
Systems Engineering: Overview of Methods

- ESD Categorizes SE Fields:
  - Systems Analysis and Architecture (Conceptual Stage)
  - Systems Engineering (Conceptual through Disposal)
  - Systems and Project Management (Governing Processes)
Systems Engineering: Overview of Methods

System Architecture

Systems and Project Management

Overview of Systems Processes and Methods (Lagace)

Org Processes

Critical chain scheduling
PERT/CPM and product launch
Project management as a competitive tool
Product and process matching

SPM

Project planning
Project preparation

SysArch

the PDP

Systems Engineering

Overview of Systems Processes and Methods (Lagace)
Systems Engineering: Overview of Methods

- Some Systems Engineering Methods:
  - Multidisciplinary Design Optimization
  - Tradespace Exploration
  - Design structure matrices
  - System Dynamics

- Underlying these methods:
  - Physical and Empirical models
  - Analytic and simulated models
  - Probability and statistics
  - Optimization methods
  - Financial accounting and cost methods
  - Utility theory, cost-benefit, risk-benefit analysis
Systems Engineering: Overview of Methods

- Multidisciplinary (System) Design Optimization M(S)DO
  - Optimization performed across system rather than within discipline; system-level attributes determine design

- Concurrent Engineering (CE) or Integrated Concurrent Engineering (ICE)
  - Overall focus on quality of entire system across several three dimensions
    - manufacturing
    - supportability (operations and maintenance)
    - cost-estimation relationships (CER)
Systems Engineering: Overview of Methods (MSDO Steps)

(1) Define overall system requirements
(2) Define design vector \( x \), objective \( J \) and constraints
(3) System decomposition into modules
(4) Modeling of physics via governing equations at the module level - module execution in isolation
(5) Model integration into an overall system simulation
(6) Benchmarking of model with respect to a known system from past experience, if available
(7) Design space exploration (DoE) to find sensitive and important design variables \( x_i \)
(8) Formal optimization to find \( \min J(x) \)
(9) Post-optimality analysis to explore sensitivity and tradeoffs: sensitivity analysis, approximation methods, iso-performance, include uncertainty

Overview of MSDO (de Weck, MIT OCW)
Outline

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SE Approaches to Wind Energy: Example Application of SE

**OPTI-OWECS (Sunderland, TU Delft)**
- Designed for offshore (systems approach)
- Monopile structures only (shallow offshore)

Above and Left: systems approach leads to ultimate design (Kuhn et al. OPTI-OWECS Report)
SE Approaches to Wind Energy: Tradespace Exploration

- Tradespace Exploration
  - Subset of multidisciplinary design optimization methods
  - Focus on system architecture exploration (conceptual, considering many designs at high level)
  - Involves perspective of stakeholders and long-term focus
  - Potential for (offshore) wind energy as a design space
SE Approaches to Wind Energy: Offshore Wind

- Different potential approaches to the design of offshore wind turbines
  - Marinization of onshore turbine
  - Extension of fundamental design concept to offshore conditions
  - “Blank sheet” approach for offshore design environment – (tradespace studies here)

- Trade-off in technology learning versus design environment optimization

Collection of turbine prototype images: Areva Multibrid, Sway, Hywind and NOVA
SE Approaches to Wind Energy: MATE for Offshore Wind

Steps for MATE Analysis:

1. Understand design problem and establish mission statement
2. Elicit system design attributes based on mission statement and stakeholder interests
3. Identify potential design variables and corresponding values
4. Develop system model and mapping between attributes and variables
5. Identify preference sets for stakeholders
6. Establish an architecture Tradespace based on system costs and utilities

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MATE for Offshore Wind: Step 1 – Design Objective and Scope

Stakeholders

- Key decision makers include manufacturers, developers / operators
- Particular interest in non-traditional stakeholders such as community, system operators

Stakeholder Concerns Potentially Influencing Design

- Turbine Manufacturers
- Component Suppliers / Contractors
- Wind Farm Developers
- Wind Farm Operators
- System Operators
- Rate Payers
- Supporting Workforce
- Environmentalists
- Community Groups
- Financiers
- Government Officials
- Government Agencies

Direct contact with technology
Indirect contact with technology
No direct contact with technology
MATE for Offshore Wind: Step 1 – Design Objective and Scope

- Scoping System: two (coupled) levels

<table>
<thead>
<tr>
<th>Single Turbine</th>
<th>Wind Farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsystem Variation: Rotor, Tower, Foundation, Drivetrain, Controls</td>
<td>Single Turbine, Layout, Interconnection, Substation, Installation and Maintenance Vessels</td>
</tr>
<tr>
<td>Environmental Conditions: Wind, Waves, Water/Ice and Seabed</td>
<td>Environmental Conditions: Wind, Waves, Water/Ice and Seabed, Distance to Shore</td>
</tr>
</tbody>
</table>
MATE for Offshore Wind: Step 1 – Design Objective and Scope

- Bounding System: What can be modeled?
  - Single turbines
    - Conventional designs
      - 3-blade horizontal-axis with fixed bottom foundations
    - Non-conventional designs
      - 2-blade horizontal-axis
      - Floating foundations
      - Vertical-axis of various types
      - Radical concepts (i.e. AWECS)
      - Others...

MATE for Offshore Wind: Step 1 – Design Objective and Scope

- Preliminary selection
  - Stakeholders: operators / developers, manufacturers / designers
  - Scoping:
    - Single turbine
    - Subsystem and environmental condition variation
  - Bounding
    - Conventional designs
      - 3-blade horizontal-axis with fixed bottom foundations
      - 2-blade horizontal-axis
      - Floating foundations
      - Vertical-axis
### MATE for Offshore Wind: Step 2 – Design Attributes

- **Design attributes onshore and offshore:**

<table>
<thead>
<tr>
<th>Performance</th>
<th>Cost</th>
<th>Reliability / Availability</th>
<th>Environmental footprint</th>
<th>Community impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>Components/subsystems</td>
<td>Component lifetimes</td>
<td>Wildlife (direct impacts)</td>
<td>Acoustics</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>Assembly</td>
<td>Maintenance cycle times</td>
<td>Habitat (indirect impacts)</td>
<td>Visual impacts - flicker</td>
</tr>
<tr>
<td>Efficiency (aero, mechanical, electrical)</td>
<td>construction</td>
<td>Component modularity / serviceability</td>
<td></td>
<td>Visual impacts - aesthetics</td>
</tr>
<tr>
<td>Farm layout effects on performance</td>
<td>Operations and maintenance</td>
<td>O&amp;M equipment performance and cost</td>
<td></td>
<td>Historic preservation</td>
</tr>
<tr>
<td></td>
<td>Disposal</td>
<td></td>
<td></td>
<td>Electricity rates</td>
</tr>
</tbody>
</table>
MATE for Offshore Wind

Step 3: Design Variables

- **Design Variables for Offshore Wind**
  - **Rotor characteristics:**
    - Configuration – horizontal-axis / vertical-axis, upwind / downwind, number of blades
    - Blade and hub design
  - **Drivetrain**
    - (Gearbox) - Generator combined configuration
  - **Tower**
    - Height and type (Lattice, monopole)
  - **Foundation**
    - Fixed-bottom (monopile, jacket and monopole, full-jacket, tripod, gravity-base)
    - Floating platform (barge, spar buoy, tension-leg, semi-submersible)
  - **Farm**
    - Turbine layout
    - Electrical interconnection layout and substation

Images from AWEA / National Renewable Energy Laboratory
## MATE for Offshore Wind:
### Step 4 – Development of Model

- Preliminary Mapping Attributes to Subsystem Choices

<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Foundation (monopile, gravity-based, tripods, jacket, spar, TLP, barge)</td>
<td>3</td>
<td>3</td>
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<td>9</td>
<td>3</td>
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<td>Rotor configuration (upwind versus downwind)</td>
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<td>9</td>
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<td>Hub Configuration (fixed, teetered, hinged)</td>
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<td>Individual Blades (Number)</td>
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<tr>
<td>Gearbox (none, parallel shaft, planetary)</td>
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<td>9</td>
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<td>9</td>
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<tr>
<td>Generator (synchronous, induction, DFIG)</td>
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<td>9</td>
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<td>1</td>
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<tr>
<td>Electronic Control System</td>
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<td>Yaw Control System (passive vs active)</td>
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<tr>
<td>Pitch Control System (passive vs active)</td>
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<td>1</td>
<td>0</td>
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<td>46</td>
</tr>
<tr>
<td>Braking / Safety Control System (disk break, stall-regulated, pitch-regulated)</td>
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<td><strong>Total</strong></td>
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<td><strong>43</strong></td>
<td><strong>28</strong></td>
<td><strong>24</strong></td>
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<td><strong>19</strong></td>
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<td><strong>15</strong></td>
<td><strong>396</strong></td>
</tr>
</tbody>
</table>
## MATE for Offshore Wind: Step 4 – Development of Model

### Summary of cost model approaches

<table>
<thead>
<tr>
<th>Model</th>
<th>Sunderland / Opti-OWECs</th>
<th>Burton</th>
<th>NREL / WindPACT</th>
<th>OWECOP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td>Physical parameters, subsystem variants</td>
<td>Rotor diameter, subsystem variants</td>
<td>Physical parameters, subsystem variants</td>
<td>Machine performance characteristics</td>
</tr>
<tr>
<td><strong>Analysis Method</strong></td>
<td>Inputs + First principles + empirics -&gt; loads -&gt; weights -&gt; costs</td>
<td>Relative subsystem values + empirics -&gt; costs</td>
<td>Inputs + First principle-based equations + empirics -&gt; weights -&gt; costs</td>
<td>Inputs + Empirics + Site characteristics -&gt; costs</td>
</tr>
<tr>
<td><strong>Offshore Adaptation</strong></td>
<td>Monopile foundations</td>
<td>None</td>
<td>Monopile foundations</td>
<td>Monopile foundations</td>
</tr>
<tr>
<td><strong>Main advantage / Drawback</strong></td>
<td>First principle basis and offshore detail / complexity</td>
<td>Simplicity / empirical basis and no offshore</td>
<td>Input empirical data / offshore detail limited</td>
<td>Site characteristics and offshore detail / use of non-traditional input and analysis</td>
</tr>
</tbody>
</table>
MATE for Offshore Wind: Step 4 – Development of Model

Potential model methods
- Application of first principles (similar to OWECOP, etc)
- Use software design package (frequency or time-domain)

Challenges
- Computational resources
- Non-conventional technologies beyond state-of-the-art
- Coupling of long-term operational impacts within farm / for site with turbine design
MATE for Offshore Wind: Step 5 – Stakeholder utilities

- Broad stakeholder set identified
- Initially focus on traditional stakeholders of manufacturers, developers and operators
- Traditional metrics of cost, performance and reliability
  - Long-term cost of energy (COE) metric
MATE for Offshore Wind
Step 6 – Tradespace Creation

- Tradespace Creation: Toy Model
  - Based on NREL WindPACT cost model and underlying physical assumptions
  - Variation of parameters
    - Site characteristics – average wind speed
    - Gearbox/generator - Three-Stage planet/helical, Single-stage with medium-speed gen, multi-path drive with multiple gen, or direct drive
    - Offshore or onshore location
  - Attributes of annual energy production and capacity factor
Mate for Offshore Wind: Step 6 – Tradespace Creation

- Toy Model Result: Single Attribute pareto response to input variation

![Graph showing the cost of turbines per MW vs. turbine capacity in MW. The graph displays a Pareto frontier, indicating the boundary between the feasible and infeasible options for turbine capacity and cost.](image-url)
Mate for Offshore Wind: Step 6 – Tradespace Creation

- Variation for stakeholder: say utility has slight preference for capacity factor over energy production and vice versa for developer
MATE for Offshore Wind

- Development interests:
  - Scope of model – turbine versus farm
  - Detail of physical model – tractability versus enough resolution into system behavior
  - Dealing with uncertainty – costs, complex offshore environment, new technologies
  - Incorporation of environmental and community (more qualitative phenomena)
  - Comparison across various stakeholder groups and potential a distribution of preferences within stakeholder groups
Summary

- Strong tradition in systems engineering, strong tradition in design of wind energy systems
- Various models in wind energy to consider performance and costs
- Recent attempts to bring them together under a systems framework (TU Delft)
- Tradespace exploration was presented as one systems tool with potential applications to novel offshore wind energy system design
Q&A