Systems Engineering Methods

With Potential Applications to Wind Energy

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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?

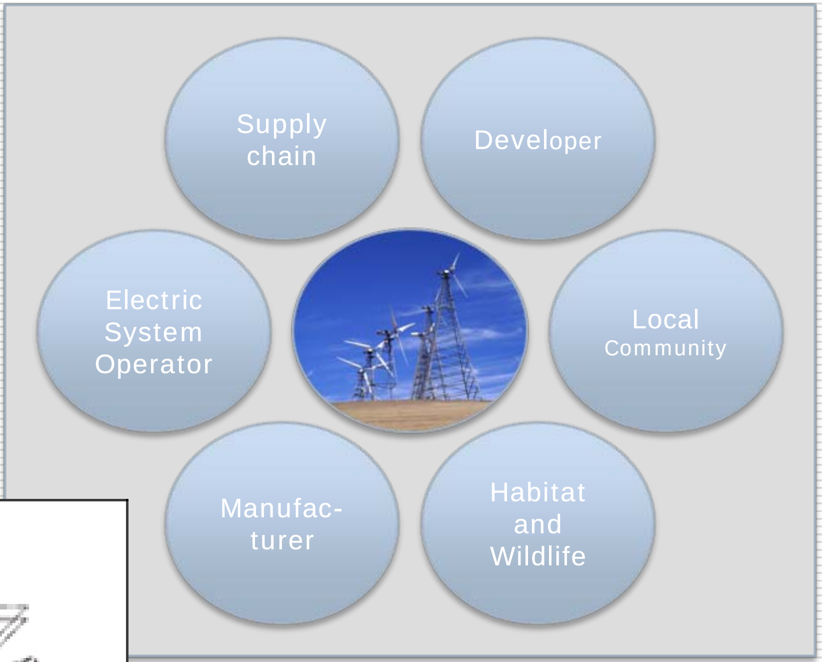
- International Council on Systems Engineering (INCOSE) Handbook Definition:
  - "Systems Engineering (SE) is an **interdisciplinary** approach and means to enable the realization of successful systems. It focuses on defining **customer needs** and required functionality early in the development cycle, 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)

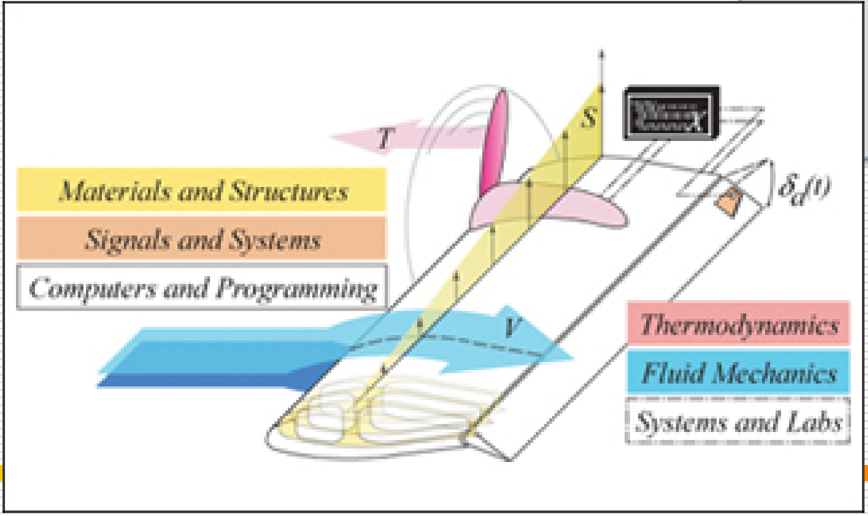
Systems Engineering: What is it?

- 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

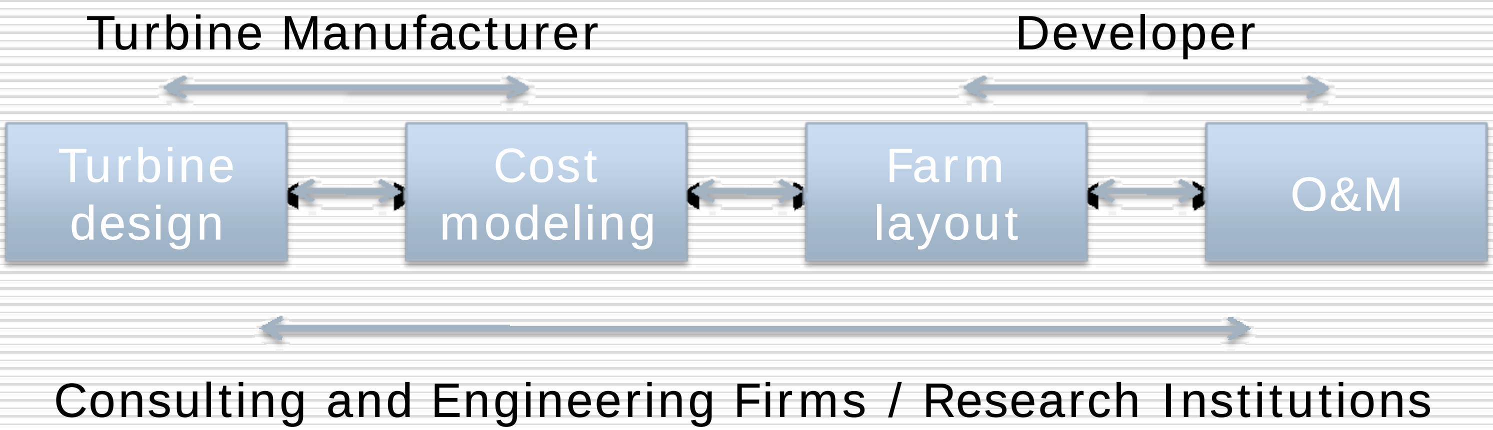
Left: Different fields involved in blade design (MIT OCW)

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



Systems Engineering: Overview of Methods

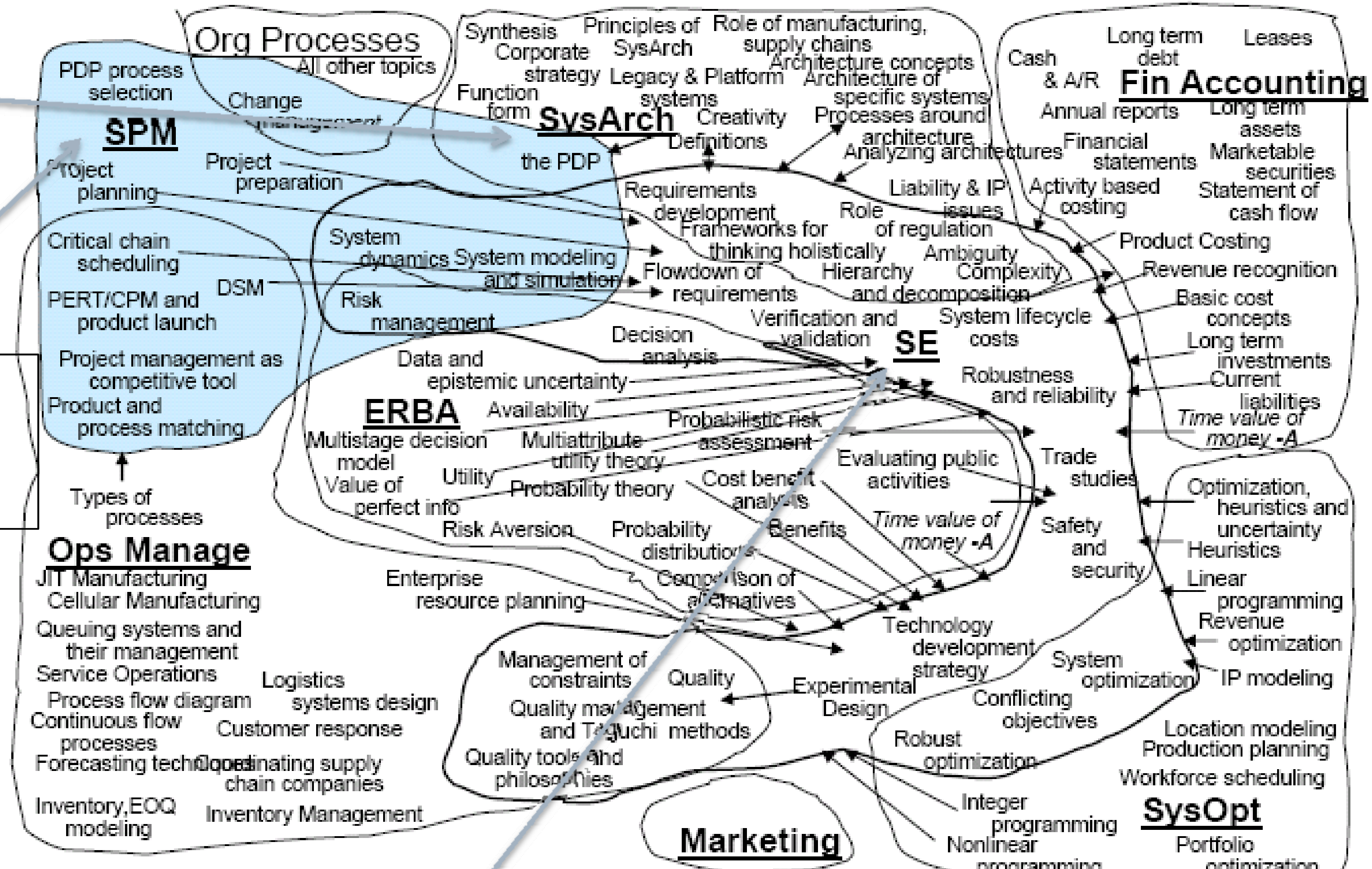
- ESD Categorizes SE Fields:
  - Systems Analysis and Architecture (Conceptual Stage)
  - Systems Engineering (Conceptual through Disposal)
  - Systems and Project Management (Governing Processes)

Systems Engineering: Overview of Methods

System Architecture

Systems and Project Management

Overview of Systems Processes and Methods (Lagace)



Systems Engineering

Systems Engineering: Overview of Methods

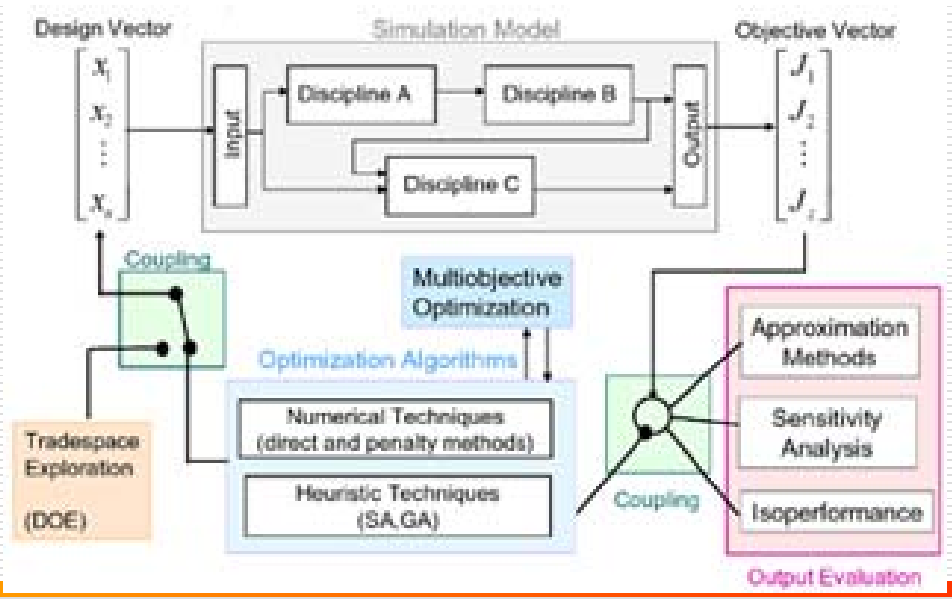
- Some Systems Engineering Methods:
  - Multidisciplinary Design Optimization
  - Tradespace Exploration
  - Design structure matrices
  - System Dynamics
- Underlying these methods:
  - Physical and Empirical models
  - Analytic and simulated models
  - Probability and statistics
  - Optimization methods
  - 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 xi
(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)

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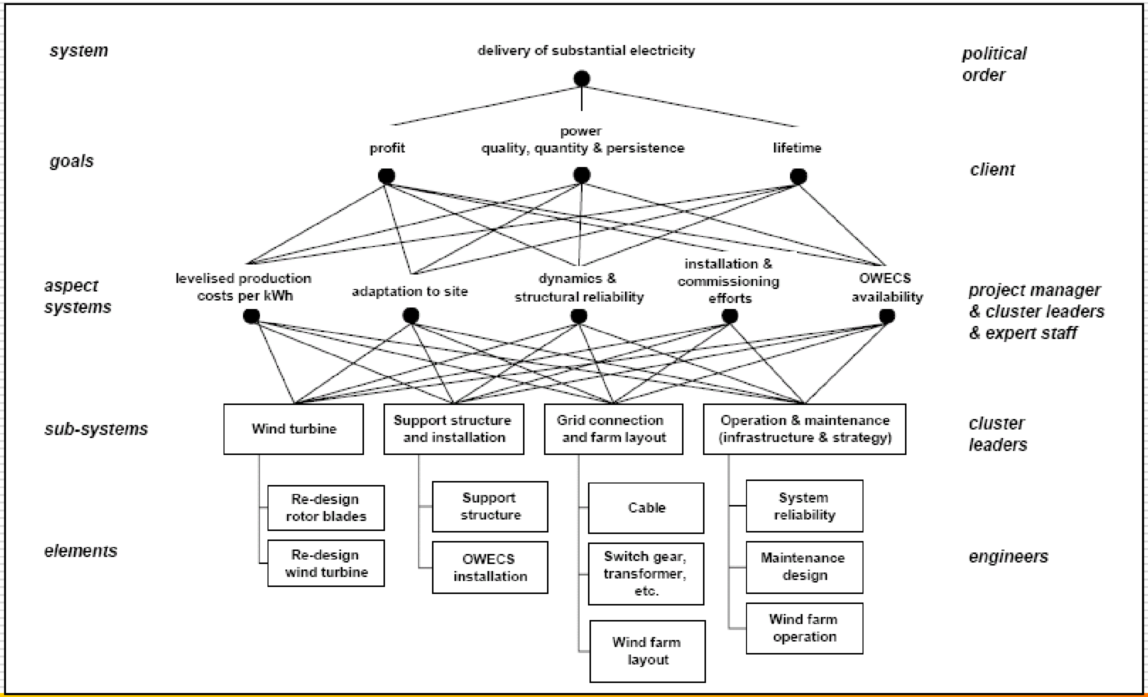
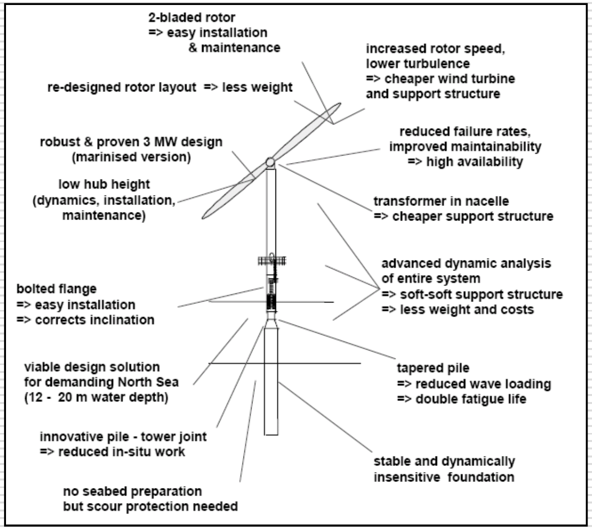
SE Approaches to Wind Energy: Example Application of SE

- 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

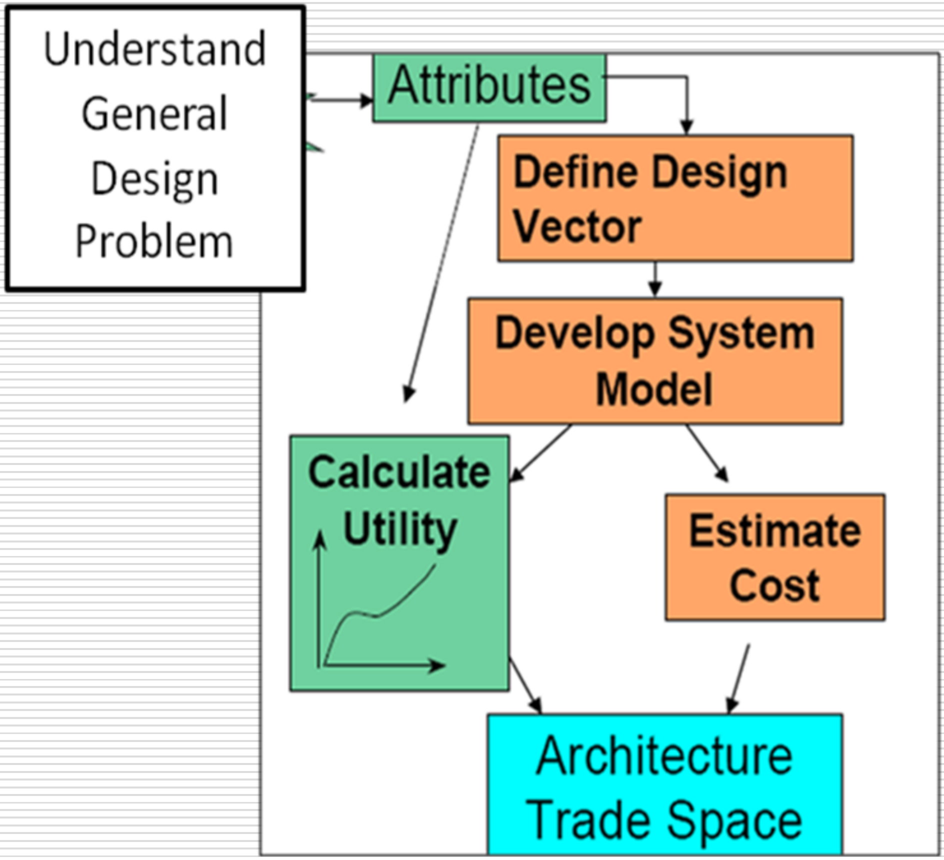
- Different potential approaches to the design of offshore wind turbines
  - Marinization of onshore turbine
  - Extension of fundamental design concept to offshore conditions
  - “Blank sheet” approach for offshore design environment – (tradespace studies here)
- Trade-off in technology learning versus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



[1]Ross, A (2006) *Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration*. PhD Thesis, MIT.

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

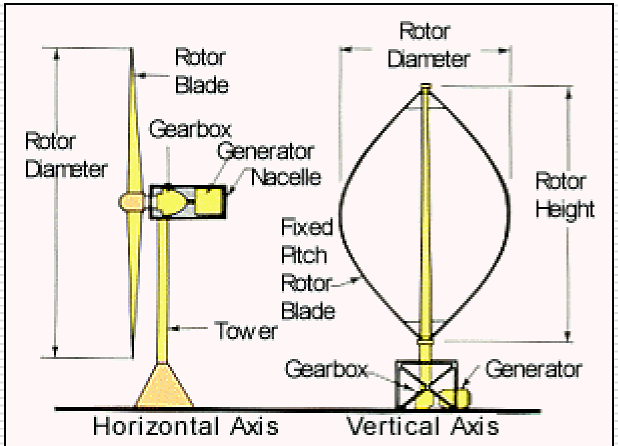
MATE for Offshore Wind:
Step 1 – Design Objective and Scope

- Scoping System: two (coupled) levels

Single Turbine	Wind Farm
Subsystem Variation: Rotor, Tower, Foundation, Drivetrain, Controls	Single Turbine, Layout, Interconnection, Substation, Installation and Maintenance Vessels
Environmental Conditions: Wind, Waves, Water/Ice and Seabed	Environmental Conditions: Wind, Waves, Water/Ice and Seabed, Distance to Shore

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…



Wind Turbine Configurations

Graphic from AWEA Wind Energy Basics: http://www.awea.org/faq/wwt_basics.html

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

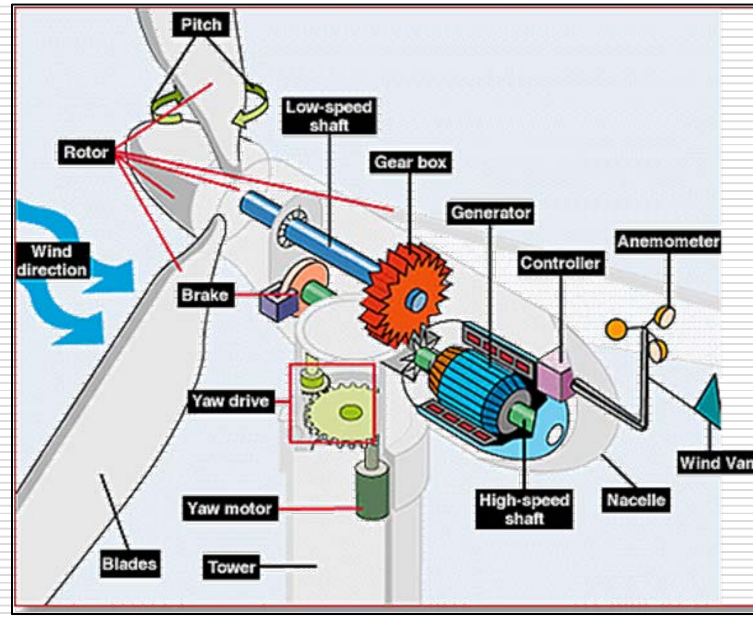
MATE for Offshore Wind: Step 2 – Design Attributes

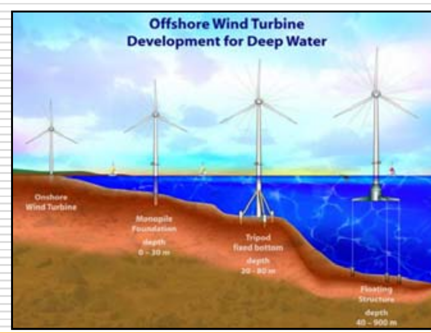
- Design attributes onshore and offshore:

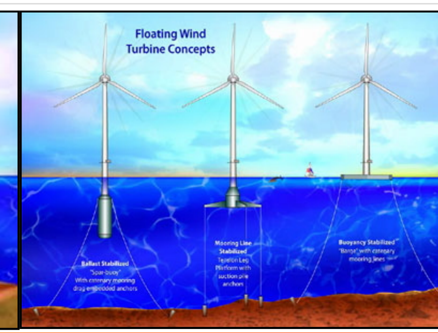
Performance	Cost	Reliability / Availability	Environmental footprint	Community impact
Rated capacity	Components/subsystems	Component lifetimes	Wildlife (direct impacts)	Acoustics
Capacity factor	Assembly	Maintenance cycle times	Habitat (indirect impacts)	Visual impacts - flicker
Efficiency (aero, mechanical,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

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

Design Subsystem Areas	Design Attributes: Rated Capacity	Capacity Factor	Efficiency - Aerodynamic	Efficiency - Mechanical	Efficiency - Electrical	System Lifetime	Component Lifetime	Availability	Maintenance Cycle Time	Component Serviceability	Visual Impact	Acoustic Impact	Environmental Impact	Total
Foundation (monopile, gravity-based, tripods, jacket, spar, TLP, barge)	3	3	0	0	0	9	9	3	3	9	9	3	3	54
Rotor configuration (upwind versus downwind)	0	3	9	3	3	9	9	9	9	9	1	9	3	76
Hub Configuration (fixed, teetered, hinged)	1	3	1	9	1	9	9	9	9	9	0	9	0	69
Individual Blades (Number)	9	9	9	1	1	9	9	9	9	9	9	9	9	101
Gearbox (none, parallel shaft, planetary)	9	9	1	9	1	9	9	9	9	9	0	9	0	83
Generator (synchronous, induction, DFIG)	9	9	1	1	9	9	9	9	9	9	0	9	0	83
Electronic Control System	1	1	1	1	9	9	9	9	9	9	0	0	0	58
Yaw Control System (passive vs active)	0	3	3	0	0	9	9	9	9	1	0	3	0	46
Pitch Control System (passive vs active)	0	3	3	0	0	9	9	9	9	1	0	3	0	46
Braking / Safety Control System (disk break, stall-regulated, pitch-regulated)	0	0	0	0	0	9	9	9	9	1	0	0	0	37
Total	32	43	28	24	24	90	90	84	84	66	19	54	15	

MATE for Offshore Wind: Step 4 – Development of Model

- Summary of cost model approaches

Model	Sunderland / Opti-OWECS	Burton	NREL / WindPACT	OWECOP
Inputs	Physical parameters, subsystem variants	Rotor diameter, subsystem variants	Physical parameters, subsystem variants	Machine performance characteristics
Analysis Method	Inputs + First principles + empirics -> loads -> weights -> costs	Relative subsystem values + empirics -> costs	Inputs + First principle-based equations + empirics -> weights -> costs	Inputs + Empirics + Site characteristics -> costs
Offshore Adaptation	Monopile foundations	None	Monopile foundations	Monopile foundations
Main advantage / Drawback	First principle basis and offshore detail / complexity	Simplicity / empirical basis and no offshore	Input empirical data / offshore detail limited	Site characteristics and offshore detail / use of non-traditional input and analysis

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

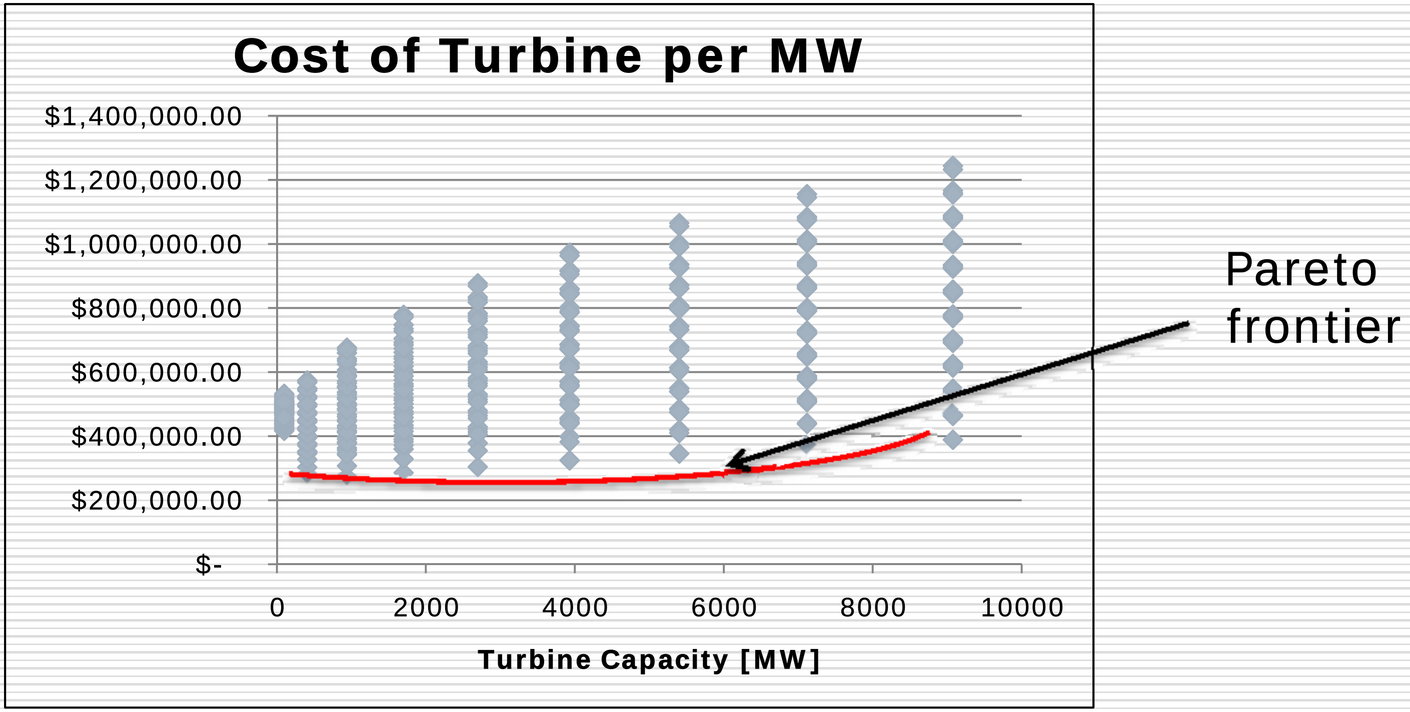
- Broad stakeholder set identified
- Initially focus on traditional stakeholders of manufacturers, developers and operators
- Traditional metrics of cost, performance and reliability
  - Long-term cost of energy (COE) metric

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

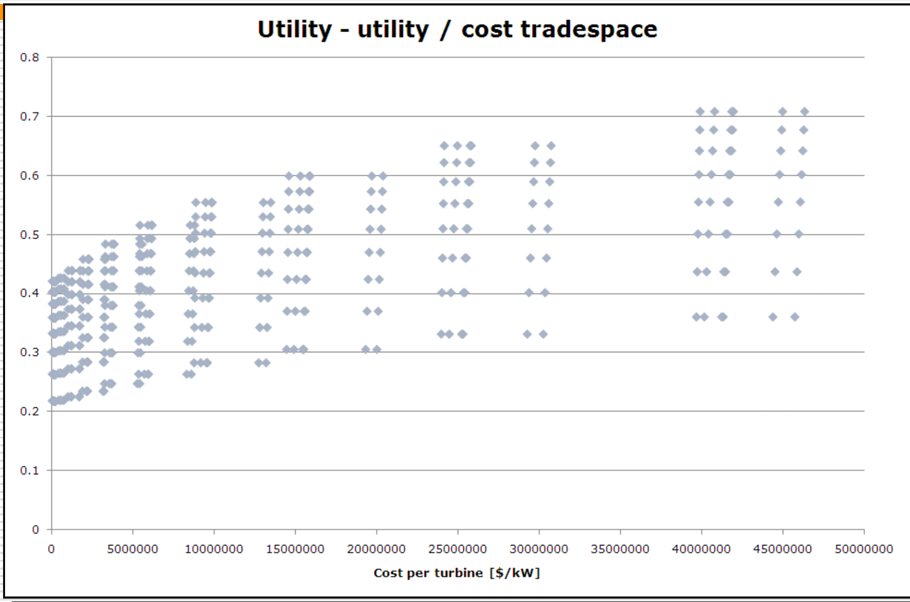
Mate for Offshore Wind: Step 6 – Tradespace Creation

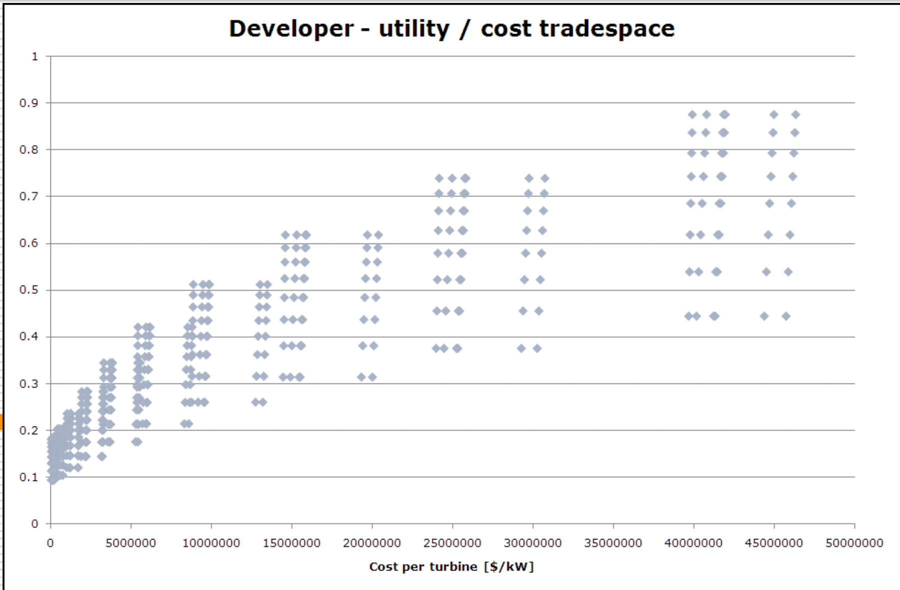
- Toy Model Result: Single Attribute pareto response to input variation



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