Applications of Systems Engineering to the Research, Design, and Development of Wind Energy Systems

K. Dykes and R. Meadows

With contributions from: F. Felker, P. Graf, M. Hand, M. Lunacek, J. Michalakes, P. Moriarty, W. Musial, and P. Veers

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List of Acronyms

AAO	All-At-Once
AEP	annual energy production
BOS	balance of station
CAD	computer-aided design
CFD	computational fluid dynamics
CPS2	Control Performance Standard 2
CSCD	computer supported collaborative design
DAKOTA	Design Analysis Kit for Optimization and Terascale Applications
DOE	U.S. Department of Energy
DFMA	Design for Manufacturing and Assembly
DSM	design structure matrices
FAST	Fatigue, Aerodynamics, Structures, and Turbulence
FERC	Federal Energy Regulatory Commission
FESTIV	Flexible Energy Scheduling Tool for Integration of Variable Generation
FMEA	Failure Mode Effects Analysis
GIS	Geographic Information System
HPC	high performance computing
IDF	Individual Discipline Feasible
INCOSE	International Council on Systems Engineering
JEDI	Jobs and Economic Development Impact Model
LCOE	Levelized Cost of Energy
LIDAR	Light Detection and Ranging
MDO	multidisciplinary design optimization
MINLP	mixed integer nonlinear programming
MOO	multi-objective optimization
NAFnoise	Airfoil Noise
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
OEM	original equipment manufacturers
OFWIC	Offshore Wind Integrated Cost
O&M	operations and maintenance
QFD	Quality Functional Deployment
ReEDS	Regional Energy Deployment System
SAGE	Semi-Automatic Ground Environment
TSP	traveling salesman problem
TTS	time-to-solution
WAsP	Wind Atlas Analysis and Application Program
WESE	Wind Energy Systems Engineering
WindPACT	Wind Partnerships for Advanced Component Technologies
WinDS	Wind Deployment System
WILMAR	Wind Power Integration in Liberalized Electricity Markets
WRF	Weather Research and Forecasting Model

Executive Summary

Over the past 30 years, wind energy has evolved from a small industry active in a few countries to a large international industry involving major players in the manufacturing, development, and utility sectors. Coinciding with the industry growth, significant innovation in the technology has resulted in larger sized turbines with lower associated costs of energy and more complex designs in all subsystems—from the rotor to the drivetrain to the electronics and control systems. However, as the deployment of the technology grows and its role within the electricity sector has become more prominent, so have the expectations of the technology in terms of performance, reliability, and cost. For the industry to continue to succeed and become a sustainable source of electricity, innovation in wind energy technology must continue to improve performance and lower the cost of energy while supporting seamless integration of wind energy into the electric grid without creating significant negative impacts on local communities and environments. At the same time, the nature of the issues associated with wind energy design and development are noticeably more complex than in the past due to a variety of factors such as, for example, large turbines sizes, offshore deployment or complex terrains. Looking toward the future, the industry would benefit from an integrated approach that simultaneously addresses turbine design, plant design and development, grid interaction and operation, and mitigation of adverse community and environmental impacts. These activities must be integrated in order to meet this diverse set of goals while recognizing trade-offs that exist between them.

In order to address these challenges, National Renewable Energy Laboratory (NREL) has embarked on the Wind Energy Systems Engineering (WESE) initiative to evaluate how methods of systems engineering can be applied to the research, design, and development of wind energy systems. Systems engineering is a field within engineering that has a long history of application to complex technical systems such as aerospace. As such, the field holds much potential for addressing critical issues that face the wind industry today. This paper represents a first step for understanding this potential and lays out a conceptual design for the development of a WESE framework and tool. It reviews systems engineering methods as applied to related technical systems and illustrates how these methods can be combined in a WESE framework to meet the research, design, and development needs for the future of the industry. Subsequent efforts will focus on developing and implementing a framework based on the conceptual design illustrated in the last chapter of this report.

In general, systems engineering approaches have the following four characteristics: holistic, multidisciplinary, integrated/value-driven, and long-term/life-cycle oriented. The approach is holistic in that it considers the full technical system, including any number of performance criteria, as well as potentially non-technical concerns related to human factors or societal impacts. Systems engineering work is multidisciplinary, involving engineering, natural, computational, and even social sciences. It is also integrated and value-driven by considering the needs and interests of all customers and stakeholders. Finally, systems engineering is focused on the long-term or life cycle of the system and takes into account the cradle-to-grave life of the system. Beyond these four primary traits of the field, three common characteristics of the large-scale, complex technical systems are the focus of systems engineering work. These include complexity, uncertainty, and heterogeneity. The key characteristics of large-scale, complex technical systems also align with key attributes of wind energy systems, including the following:

- **Complexity:** Wind energy involves nearly every field of engineering and many of the natural and social sciences. The design of a wind turbine and plant interlinks these distinct disciplines for a holistic and multidisciplinary design that integrates the interests of a wide variety of stakeholders for operation over years and decades.

- **Uncertainty:** The science of wind and wind energy technology is still evolving. An incomplete understanding of both the physical processes and their interaction with the technology leads to an uncertain design environment. Even if a complete understanding of the system was obtained, there would still be uncertainty affecting system design, for example, with respect to the behavior of weather over time as it would impact a particular turbine or farm. Finally, there are external sources of uncertainty, such as political and economic developments, that can drastically affect the financial viability of wind energy projects.
- **Heterogeneity:** Wind turbines and plants must be designed for and operated in a wide array of environments—both from a physical standpoint and from an economic, social, and political standpoint. The U.S. Department of Energy (DOE) has separated factors that limit wind energy development into those that affect the cost of energy and those that impose market barriers such as social, environmental, and political factors.

The scope of wind energy design can be illustrated by a map of major design variables within a wind energy system as shown in Figure 1.

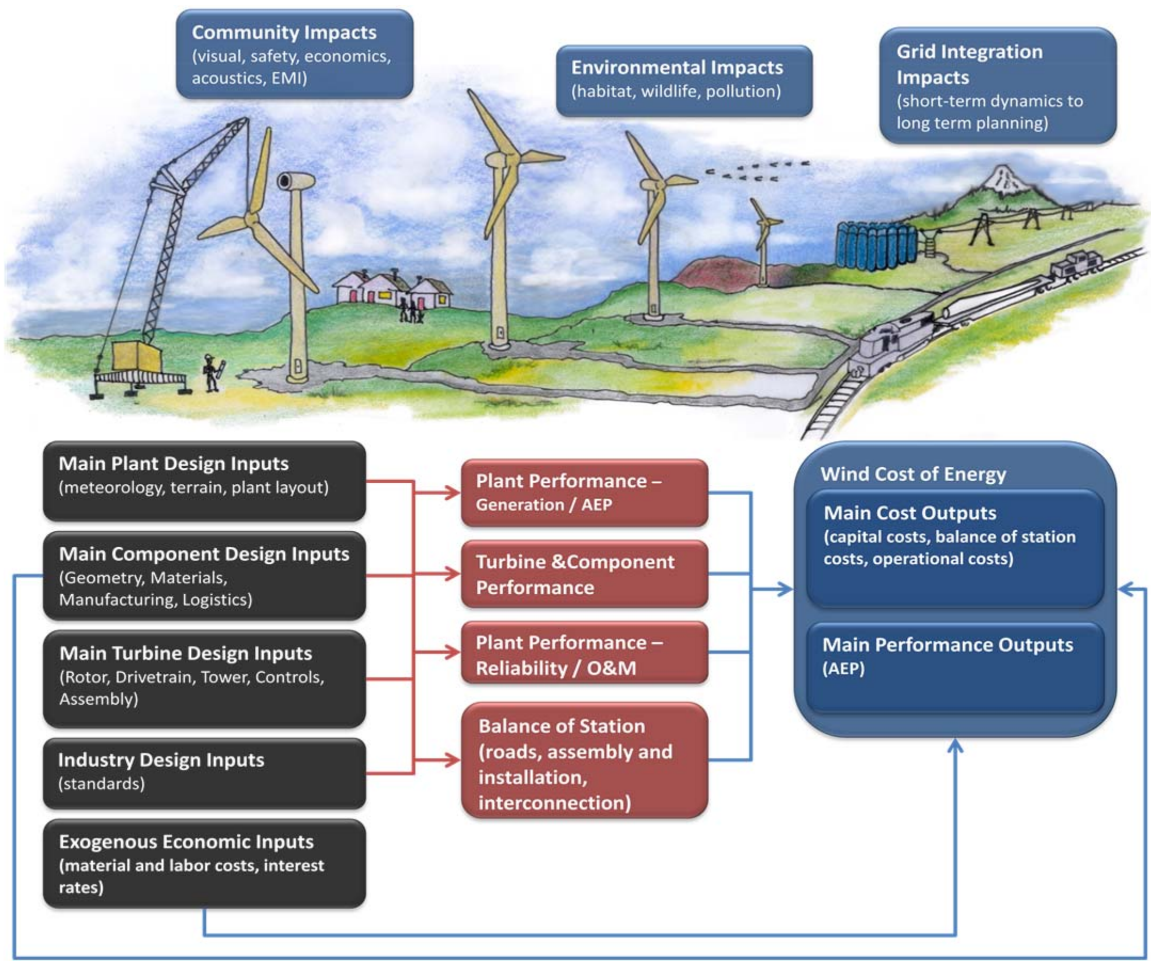

Figure 1. A systems view of wind energy systems development (artist: Rick Hinrichs)

The development and deployment of wind energy systems is affected by physical design drivers and impacts associated with various stakeholders from suppliers to original equipment manufacturers (OEM), developers, financiers, utilities, environments, and communities. A view of and an approach to wind energy research, design, and development must take all of these diverse factors into account. Design of these complex, uncertain, and heterogeneous large-scale technical systems is well suited to a systems engineering approach that is holistic, multidisciplinary, integrated, and life cycle oriented. This paper addresses a wind energy system that falls geographically within a wind plant. This includes all of the components, individual wind turbines, and the interactions between them as well as balance of station and operations and maintenance. In essence, the scope includes the traditional set of design drivers that are considered in looking at wind plant cost of energy. The methods reviewed in the paper reflect this scope, although the ultimate goal is to incorporate design objectives and methods that relate to the entire wind energy system, including grid interaction, community, and environmental impacts.

This paper surveys the landscape of systems engineering methods and catalogues the various existing modeling tools that relate to the design of wind energy systems from components to entire plants. It then provides an overview of how the existing set of design tools as well as future extensions may be coupled together within a systems engineering framework that will provide for a large variety of potential applications at the frontier of wind energy research, design and development. Examples of such applications that are relevant to future wind energy development may include:

- Optimization of the full wind plant system to achieve the lowest cost of energy and improve wind generated electricity costs relative to other generation technologies while maintaining or improving annual energy production. Use of systems engineering techniques such as multidisciplinary design optimization could yield plant designs that achieve significant system cost reduction by accumulating cost reduction across a number of components and consider long-term operation and maintenance impacts.
- Trade studies to evaluate different design concepts that are needed to prioritize R&D efforts to develop fixed-bottom and floating platform offshore wind plants. Use of systems engineering techniques such as multi-objective optimization and tradespace exploration could be valuable in assessing widely different concepts, including VAWTs.

As offshore wind technology infrastructure is developed in the US, supply chain analysis could be used to evaluate various port facilities along with technology options for installation and servicing wind projects. Combined with optimization of technology designs to accommodate port facility requirements, projects with the lowest cost of energy would be identified.

Many wind energy specific design tools and methods already exist to address aspects of the illustrated challenges listed above, but a systems approach is needed to tackle them with adequate rigor. Integrating these tools into a SE framework that (1) permits comprehensive analysis using well developed SE methods and (2) is designed to expand systematically to create an ability to address the issues above and will aid the wind industry in achieving the next generation of lower cost wind technology.

Methods in Systems Engineering

To address how a systems engineering approach might be used to design a wind turbine and/or plant, a survey was compiled of methods within systems engineering that may be applicable or that have already been tested for use in wind turbine and plant design. In general, these methods can be partitioned into three sets: design tools related to physical system design, methods related to supply chain and logistics, and other methods such as reliability and cost engineering. These methods will inform a WESE approach to the research, design, and development needs for the future of the industry.

Within the first set of tools related to physical system design, multidisciplinary design optimization (MDO) is featured because it has been used extensively in the design and research of aerospace and similarly complex technical systems. MDO allows the integration of different disciplinary design objectives into an overall system design optimization. It is a way to hierarchically decompose a complex design problem so that it maps better to existing partitions of disciplinary design efforts. MDO has been used already in a few research applications to wind energy that seek to optimize system cost of energy by integrating analysis across various disciplines including, for example, aerodynamics, structures and controls. In addition, the survey of methods for wind energy system design included a discussion of multi-objective optimization (MOO) that evaluates different design objectives either through a weighted technique or some sort of hierarchical ordering. Such methods are particularly appropriate when multiple stakeholders have conflicting interests for system design. MOO is also useful to evaluate a set of designs along various dimensions, such as wind energy system production, weights, reliability, etc. MOO techniques may result in a trade space of designs that can be compared using visual and statistical techniques. This may be used to evaluate trade-offs between different wind energy system designs or architectures rather than focusing on sensitivity to design parameters for a single detailed design.

In addition to turbine design, MDO methods can be extended to incorporate the entire wind plant and associated design objectives such as annual energy production, balance of station costs, and operations and maintenance costs. Looking at balance of station, supply chain considerations become important both in terms of initial plant design—including transportation, installation, and assembly logistics—but also to long-term O&M. Long-term development of a WESE framework may incorporate more advanced models for balance of station and O&M of wind plants that would integrate supply chain model techniques such as network analysis. With regard to plant operations and maintenance, reliability engineering and cost engineering are two methods that may also be applied to wind energy system design. Thus, a systems engineering approach to the research, design and development of wind energy systems may incorporate a variety of methods depending on system scope. The application of systems engineering methods at NREL will involve leveraging existing modeling tools within the development of a systems engineering specific tool.

NREL Research and Design Tools for Wind Energy Systems

The integration and optimization of overall system properties within the wind system design toolset used at NREL is already a near-term goal at the NWTC. Figure 2 shows the current state of NREL wind energy system design tools as they relate to the systems engineering methods discussed in the previous section. The right side of Figure 2 shows the expected and desired development of the program and reflects the goal of integrating and developing existing tools within an overarching systems engineering framework. NREL is a primary developer of many different tools for the research, design and development of wind energy systems, including a suite of aeroelastic design codes for detailed time-series analysis of various turbine loads as well as a cost of energy model that estimates how design changes may affect everything from specific component costs to annual energy production to balance of station costs. In addition, there are various models developed at NREL related to external impacts of turbine and plant design including noise analysis tools as well as dynamic models of wind turbines for grid interaction. Many of these tools incorporate aspects of systems engineering from multidisciplinary analysis in the aeroelastic codes to supply chain analysis in the cost of energy and balance of station models. These characteristics have led to the use of such tools within several systems engineering research projects focused on wind energy systems. However, the integration of the tools within an explicit systems engineering toolset and framework will allow for a wide range of new and higher fidelity analyses that will improve the overall performance of wind energy systems.

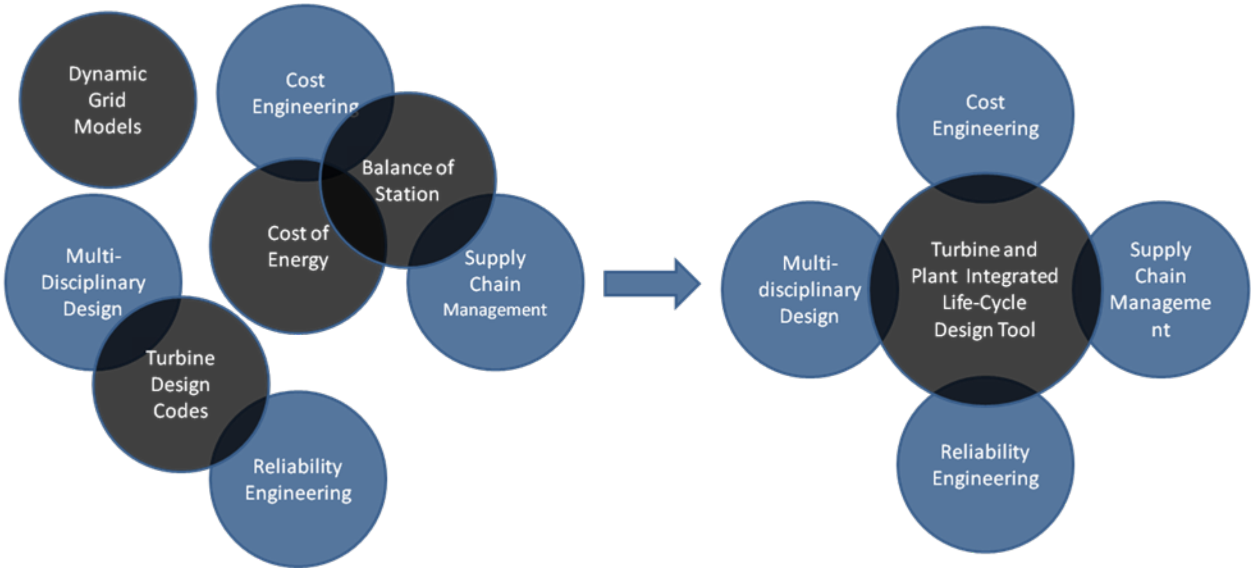

Figure 2. Systems engineering methods and NREL wind energy system design tools today (left); fully integrated WESE framework for the future (right)

Development of a WESE Tool

The overall vision for a systems engineering design approach is to develop a framework and corresponding toolset that will allow for the integration of a variety of models for different aspects of the overall wind energy system. At all times, a WESE framework will maintain the capability for representing the full wind energy system including individual turbines and components, wind plants and turbine to turbine interaction, and cost of energy modeling for the plant and balance of station. Later realizations of a WESE framework may extend into advanced supply chain representations as well as grid integration and analytical capabilities for community and environmental impacts. The full system representation will have varying levels of model fidelity for each aspect of the system. Depending on the application, different models for each sub-system or discipline may be used in an overall analysis.

As higher fidelity models and improved design tools are developed, they will be integrated for use in a WESE framework. This will allow for continual evolution of the overall tool and increased fidelity of different system sub-models. For instance, a tool may initially incorporate a few different models of the turbine itself including aeroelastic design codes such as the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) Code or the simplified WT_Perf or even parameterized metamodels. The tool might then be extended to interact with more detailed models for structural analysis of different turbine components that would interact with the full turbine model. Cost models might initially incorporate parameterized models such as the NREL model, other simplified models of turbine cost, or even an engineering-based cost model that is extended to capture detailed plant costs. Plant models might contain various levels of fidelity for modeling turbine interaction as well as site impact considerations on wind flows. The key aspect of development of a WESE tool is that it will allow for the integration of a range of models representing the different aspects of system design above and that these may be allowed to evolve over time. A high-level depiction of the models included in such a tool as well as the types of analyses to be performed is shown in the Figure 3.

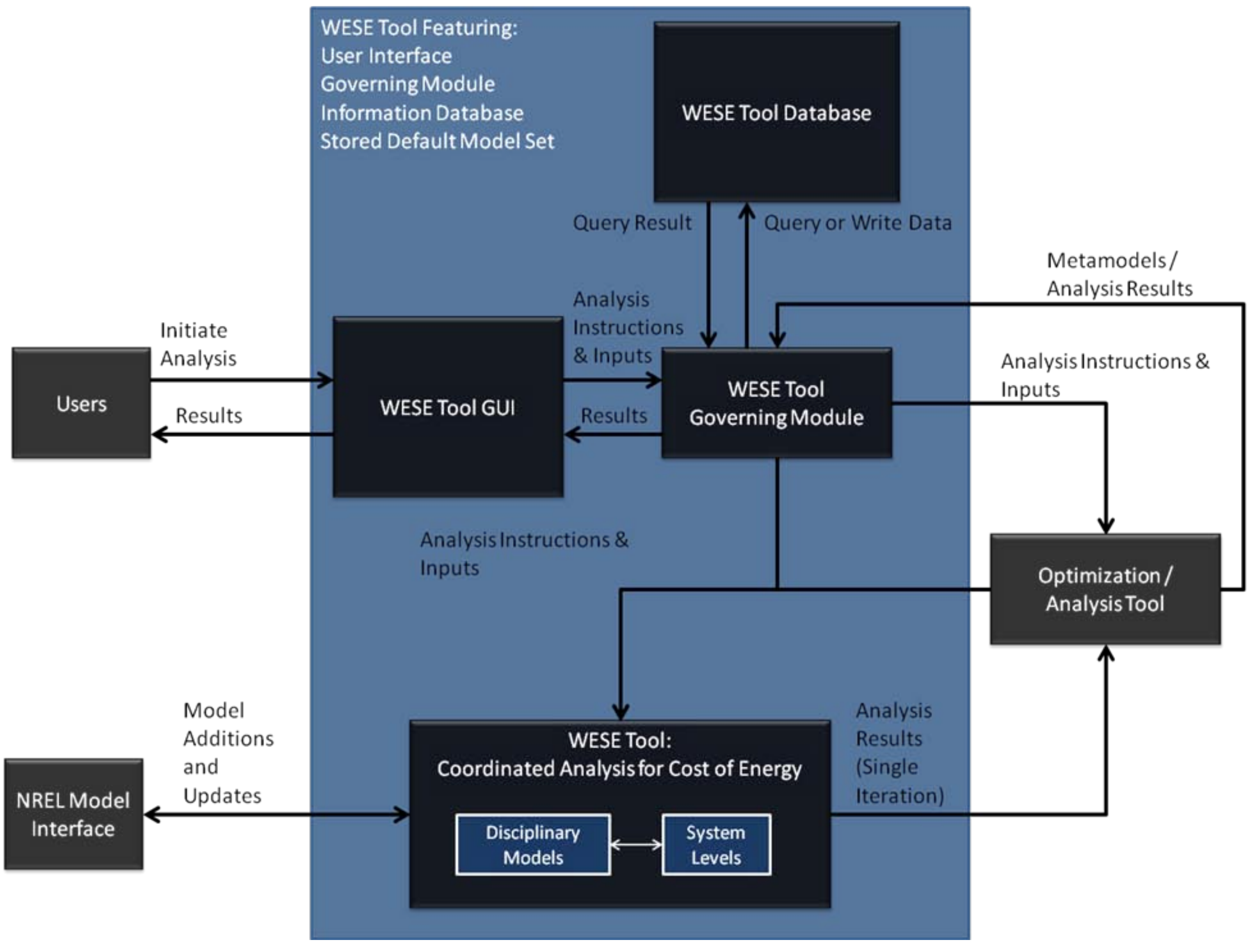

Figure 3. Overarching vision for long-term WESE framework development

A project of this scope could easily become intractable if not managed in a systematic way. Therefore, within the large space of development, it is important to consider particular applications that would constitute a progression in tool development that is feasible in the near term. Specific steps of integration will build out a tool's capabilities in terms of both model types and analytical methods. At the same time, a working toolset will be preserved at each step so that novel and useful analyses may be performed over the entire development of a tool. The potential steps to integration will reflect the current status of development of NREL wind energy analysis and design tools and also the needs associated with development of those tools. This will likely include four general phases:

1. Integration of physical turbine and cost of energy models for sensitivity analysis and optimization
2. Integration of detailed component design with physical turbine and cost of energy models for scenario analysis, trade studies and optimization
3. Integration of plant layout tools with the above set for full plant level analysis including for scenario analysis, trade studies and optimization
4. Integration of models for non-traditional design criteria such as utility, community, and environmental impacts.

A WESE tool could support a diverse set of applications and a variety of analyses such as multidisciplinary optimization (with different optimization algorithms and techniques), multi-objective optimization, and development of trade spaces. This would allow for both detailed design optimization as well as evaluation across diverse system architectures. For example, a MDO may be used to perform a detailed cost optimization of a particular point design, and MOO may be used to survey a wide variety of different wind turbine configurations. In addition, the tool would include a range of post-processing decision-support tools including sensitivity analysis, uncertainty quantification, and visualization methods. User inputs would include input parameters for system design (turbine, plant and exogenous factors), but also would include the specific analyses to be performed and the models to be used (selection of sub-models based on level of fidelity and type of representation desired or the incorporation of user-defined sub-models). Every analysis thus would include: (1) a connection of individual elements and sub-systems into a system design space for a full system representation and (2) varying levels of fidelity in terms of modeling different subsystems depending on the chosen application. The overall development of such a tool will be a complicated process that involves the integration of disparate codes, obtaining metamodels of adequate fidelity, coupling across software packages, and other challenges. Thus, careful planning and management of the overall process upfront and at each step along the way will be important to the overall success of the initiative.

In summary, NREL's wind energy systems engineering design initiative seeks to address a variety of issues that impact the current and future development of the wind energy sector. Wind electrical generation is a large-scale and complex technical system with various social impacts. As a result, a systems perspective and approach must be taken to the research, design, and development of these systems in order to meet the myriad of goals for future development of the technology. The inherent complexity of the physical system leads directly to a multidisciplinary approach to the design of the turbine itself, but also then to the plant level and beyond to the impacts that the plant will have on local utilities, communities, and environments. Systems engineering, which has a long history of development and application to a variety of industries, shows significant potential for addressing these system design challenges and will be a useful framework and tool for guiding and coordinating wind energy research, design and development activities among a variety of stakeholders including government, industry, national laboratories and academia.

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1 Introduction

Wind energy has evolved from a small industry in a few countries to a large international industry involving major organizations in the manufacturing, development, and utility sectors. Along with this growth, significant technology innovation has led to larger turbines with lower associated costs of energy and ever more complex designs for all major subsystems—from the rotor, hub, and tower to the drivetrain, electronics, and controls. However, as large-scale deployment of the technology continues and its contribution to electricity generation becomes more prominent, so have the expectations of the technology in terms of performance and cost. For the industry to become a sustainable source of electricity, innovation in wind energy technology must continue to improve performance and lower the cost of energy while supporting seamless integration of wind generation into the electric grid without significant negative impacts on local communities and environments. At the same time, issues associated with wind energy research, design, and development are noticeably increasing in complexity. The industry would benefit from an integrated approach that simultaneously addresses turbine design, plant design and development, grid interaction and operation, and mitigation of adverse community and environmental impacts. These activities must be integrated in order to meet this diverse set of goals while recognizing trade-offs that exist between them. While potential exists today to integrate across different domains within the wind energy system design process, organizational barriers such as different institutional objectives and the importance of proprietary information have previously limited a system level approach to wind energy research, design, and development.

To address these challenges, NREL has embarked on an initiative to evaluate how methods of systems engineering can be applied to the research, design and development of wind energy systems. Systems engineering is a field within engineering with a long history of research and application to complex technical systems in domains such as aerospace, automotive, and naval architecture. As such, the field holds potential for addressing critical issues that face the wind industry today.

This paper represents a first step for understanding this potential through a review of systems engineering methods as applied to related technical systems. It illustrates how this might inform a Wind Energy Systems Engineering (WESE) approach to the research, design, and development needs for the future of the industry. Section 1 provides a brief overview of systems engineering and wind as a complex system. Section 2 describes these system engineering methods in detail. Section 3 provides an overview of different types of design tools for wind energy with emphasis on NREL tools. Finally, Section 4 provides an overview of the role and importance of software architecture and computing to the use of systems engineering methods and the future development of any WESE programs. Section 5 provides a roadmap of potential research integrating systems engineering research methodologies and wind energy design tools for a WESE framework.

1.1 Definition and History of Systems Engineering

Before addressing the potential for systems engineering applications to wind energy specifically, this paper will provide an overview of systems engineering and associated methods. The field of systems engineering has its roots in the engineering of large-scale complex technical systems in the mid-20th century. Beginning with the Manhattan project, several "super" projects for the engineering of completely new, large-scale and complex technical systems led to the founding of systems engineering as a distinct discipline (Hughes 1998). The Manhattan project laid the groundwork for systems engineering by combining frontier research with actual project development. It also coordinated a vast network of scientists and engineers across various disciplines necessary to the project. Following this, IBM's Semi-Automatic Ground Environment (SAGE) air defense system program incorporated a key aspect of systems engineering via the use of information processing and analysis by digital computers. Finally, the

Atlas Intercontinental Ballistic Missile Program resulted in the coined term "systems engineering," which then spread throughout defense and aerospace activities and institutions (Hughes 1998). These early projects involved the co-development of the technology and the scientific knowledge base that supported it. In addition, the development of these large-scale, complex technical systems demanded coordination across disciplines and organizations. Finally, these projects exploited the development of enabling technologies in digital computation for information acquisition, processing, and analysis. These early attributes are still important today to the field of systems engineering.

Several definitions of systems engineering can be found, but two prominent ones come from the National Aeronautics and Space Administration (NASA), a leading organization in the development and use of systems engineering techniques since its inception, and the International Council on Systems Engineering (INCOSE). The NASA Systems Engineering Handbook defines core ideas of systems engineering (bold lettering added):

> "Systems engineering is the art and science of developing an operable system capable of meeting requirements within often opposed constraints. Systems engineering is a **holistic, integrative discipline**, wherein the contributions of structural engineers, electrical engineers, mechanism designers, power engineers, human factors engineers, and many more disciplines are evaluated and balanced, one against another, to produce a **coherent whole** that is not dominated by the perspective of a single discipline… Systems engineering is a methodical, disciplined approach for the **design, realization, technical management, operations, and retirement of a system**. A 'system' is a construct or collection of different elements that together produce results not obtainable by the elements alone. **The elements, or parts, can include people, hardware, software, facilities, policies, and documents**; that is, all things required to produce system-level results." (NASA 2007, p. 3)

From this definition, critical components of a systems engineering approach can be isolated. Systems engineering approaches generally include the following four characteristics: they are (1) holistic, (2) multidisciplinary, (3) integrated and value-driven across stakeholders, and (4) long-term and life-cycle oriented. The approach is holistic in that it considers the full technical system including performance criteria as well as potentially non-technical concerns related to human factors or societal impacts. Systems engineering work is multidisciplinary, involving many disciplines in the engineering, natural, computational, and even social sciences. It is also integrated and value-driven by considering the needs and interests of all customers and stakeholders. Finally, systems engineering is focused on the long-term or life cycle of the system and takes into account the cradle-to-grave life of the system. While these attributes characterize general systems engineering methods, the degree to which they may be present for particular applications must be balanced in the interest of maintaining the tractability of a given research, design, and development problem. This tension between capturing all the important variables and interests associated with design of a technical system and maintaining tractability is a theme that will be revisited throughout this document—in particular, Section 5 addresses how systems engineering might be applied to wind energy research, design, and development.

In addition to the above four primary characteristics of systems engineering, three common characteristics of the actual large-scale complex technical systems themselves are complexity, uncertainty, and heterogeneity. The four systems engineering properties and large-scale technical system properties are depicted in Figure 4. In reviewing the literature on system design, these three parameters consistently surface and underlie a great deal of difficulty that engineers face in research, design, and development processes. Complexity expresses the idea that these systems have many interlinked components and subsystems—they may even involve systems of systems—and that there is significant non-linear behavior and coupling throughout the system. Secondly, such systems often involve a degree of heterogeneity with respect to the types of environments or users with which they interact—that is, they need to be agile in terms of adapting to a broad range of potential applications and external environments. Finally, uncertainty means it is difficult to understand exactly how these systems will interact with their environment or how they will behave in operation over long periods of time and under unknown conditions. Many unknowns will affect the system operation once put into use. These include aleatoric uncertainty due stochastic processes, such as turbulence and other meteorological phenomena. They also include the potentially more dangerous unknowns that are challenging to account for in system design (i.e., the epistemic or structural uncertainty), such as changing economics related to raw materials pricing or even limitations in understanding of the atmospheric physics that affect wind plant performance and costs. Each of complexity, heterogeneity, and uncertainty are addressed by systems engineering methods as will be discussed in Section 2. Particular methods may emphasize dealing with one or more of these critical system design issues.

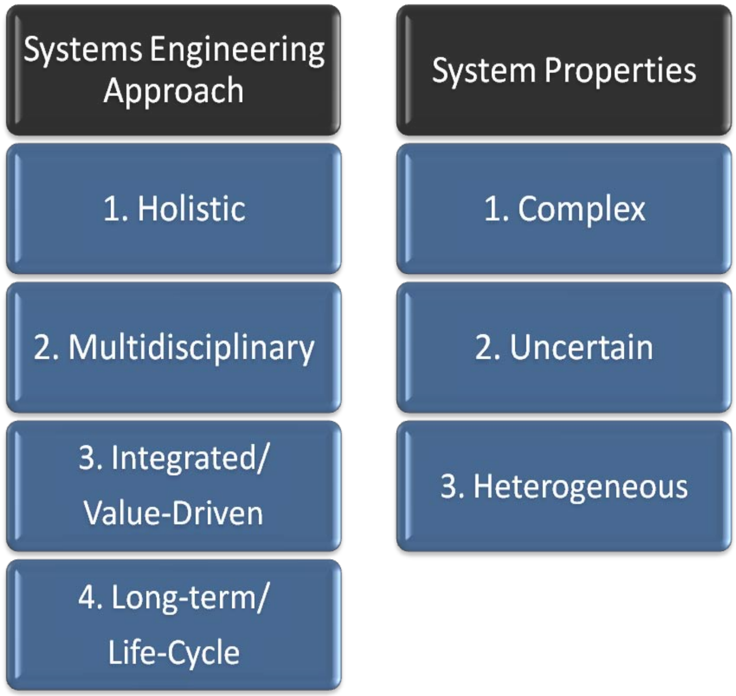

Figure 4. Key characteristics of systems engineering and associated large-scale complex technical systems

Today, methods from systems engineering are applied broadly to influence innovation and development of a wide range of technologies within a variety of industries. One major example of how the adoption of systems engineering techniques has led to successful system design and product commercialization is in the case of the Boeing 787. Systems engineering is used widely in military and aerospace applications where it was first developed. In addition, the automotive sector has widely adopted a systems engineering approach to vehicle design. Applications appear in other fields such as bio-medical technologies and naval architecture and even in healthcare systems. Wind energy systems, as we will discuss in the next section, are large-scale and complex technical systems that can benefit from a systems engineering approach to their research, design, and development.

The Boeing 787 Dreamliner Systems Engineering Project

The aerospace industry has been applying a systems engineering approach to their product development process for many years. A notable example of this is the Boeing 787 Dreamliner. The company used a system engineering approach to coordinate the many elements of this complex design. Their goal was to reduce overall operating costs by 20%, through a combination of increased fuel efficiency and reduction of operations and maintenance (O&M) costs. Boeing also wanted to improve passengers' in-flight experience by increasing cabin pressure, introducing larger windows, and using more advanced lighting. Even more ambitious, Boeing aimed to reduce research and development costs for the new plane to 40-60% of the costs for developing the 777 (Tompkins and Bruner 2004). Maximizing efficiency led to many design differences from past planes. The system architecture of past designs was maintained, but a primary difference from previous Boeing, Airbus, or McDonnell-Douglas planes was the extensive use of carbon composite materials. Composites allowed construction of the fuselage from significantly fewer pieces reducing the use of rivets, which in turn reduced obstruction of airflow over the main body of the plane. These changes led to increased fuel efficiency. The use of composites also allowed improvements in cabin comfort since the stronger composite materials allowed for larger windows and a higher cabin pressure. Boeing even found that using particular patterns, types, and colors of paint can reduce fuel consumption by as much as 20,000 gallons per plane per year. The program is a prominent example of the successful application of a systems engineering approach to the design of complex technical systems.

1.2 Wind Energy as a Complex System

The key characteristics of large-scale, complex technical systems also align with key attributes of wind energy systems, including:

- **Complexity:** Wind energy involves nearly every field of engineering and many of the natural and even social sciences. Within engineering, aerospace, mechanical, controls, electrical, materials, and civil engineering are all important to the design and development of wind turbines and plants. The natural sciences, mathematics, physics, chemistry, earth and atmospheric sciences, and even environmental sciences are important to understanding the science of wind energy systems. Within the social sciences, economics, policy, law, and sociology are important to understanding the larger interactions of wind energy technology with the markets and society. The design of a wind turbine and plant interlinks almost all of these distinct disciplines together for a holistic and multidisciplinary design that intrinsically integrates the interests of a wide variety of stakeholders for operation over long time periods.
- **Uncertainty:** The science of wind and wind energy technology is still evolving. Epistemic (or systematic) uncertainty is reflected by the incomplete understanding of both the physical processes and the interaction of the physics with the technology. This leads to an uncertain design environment. There are many sources of epistemic uncertainty affecting wind energy systems from the behavior of the turbulent winds to political and economic developments that can drastically affect the financial viability of wind energy projects. There are also aleatoric (or stochastic) sources of uncertainty such as which particular turbulence events will strike an individual rotor over its lifetime. This implies that some sort of treatment of uncertainty be built into the wind energy design process which may be accomplished either through proactive

attempts to quantify the uncertainty within the design process and through the use of design safety margins.

Heterogeneity: Wind turbines and plants must be designed for and operated in a wide array of environments—both from a physical standpoint and from an economic, social and political standpoint. Different wind regimes and terrains will affect wind turbine and plant performance while various factors related to the politics and social aspects of wind energy projects may affect their acceptance and deployment. DOE has separated those factors that limit wind energy development into those that affect the cost of energy and other market barriers that include social, environmental and political factors. Wind energy system design from the turbine to the overall plant must balance the issues involved with particular sites and the overall development of the industry, including the economic benefits of standardized technology and large scale production.

A view of and an approach to wind energy research, design, and development must take all of these diverse factors into account. Figure 5 illustrates a systems view of wind energy including design drivers and the impacts associated with various stakeholders.

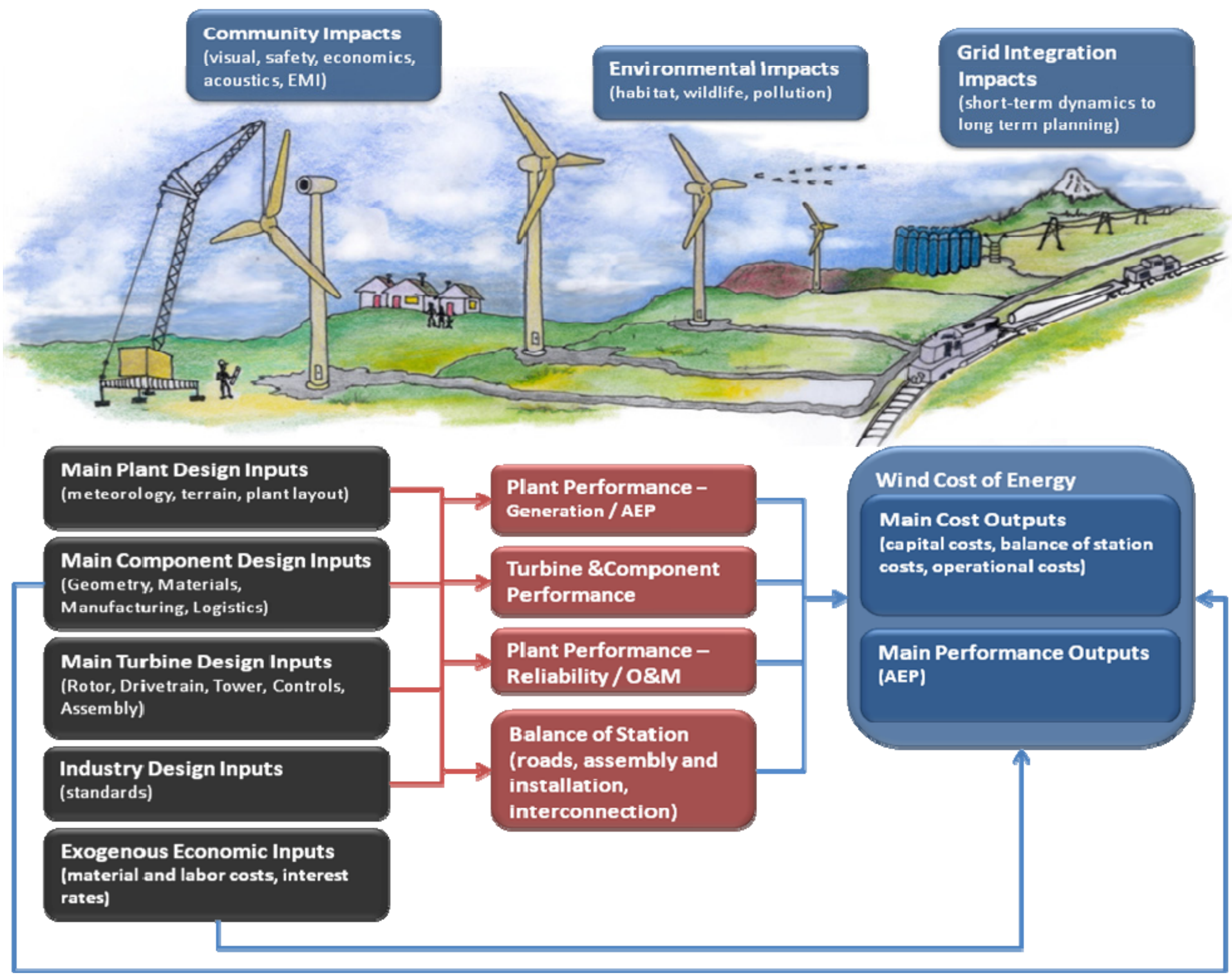

Figure 5. A systems view of wind energy systems including design drivers and impacts associated with various stakeholders from suppliers to OEMS, developers, financiers, utilities, environments, and communities (artist: Rick Hinrichs)

Visually, Figure 5 illustrates an overall view of a wind farm including individual turbines and overall plant design as well as its interconnections to the grid, the nearby communities and wildlife as well as the extended supply chain related to the transportation, installation and operations of a wind plant. Overlaid on the image is a simplified system map of wind energy which shows the key input design variables, intermediate design drivers, and overall cost of energy and external impacts of the system design. Brief descriptions of each of these design variables and impacts are described below. The subsections on each group of design variables (Section 1.2.1) and impacts (Section 1.2.2) are not comprehensive since adequate treatment of each set would require several pages of discussion. The following subsection on wind energy system level design issues (Section 1.2.3) uses a couple of specific examples to illustrate the complex relationships between wind energy design variables and system level impacts on both cost of energy as well as external impacts to the grid, community and environment.

1.2.1 Input Design Variables for Wind Energy Systems

1.2.1.1 Component and Turbine System Design

On the input side, wind energy system design variables can be classified by which entity has direct control over their specification. Component suppliers and manufacturers have direct influence over the main component design inputs, which include primarily the configuration, geometries, materials, assembly, and auxiliary features such as sensor instrumentation and actuators. At the turbine level, manufacturers can design the main configuration for each subsystem including the rotor, drivetrain, and tower but also secondary systems for pitch, yaw, power electronics, braking, and cooling. Within each primary subsystem there exist a number of design choices. The rotor configuration includes rotor diameter, tilt, and coning. For the particular blades, key airfoil design variables include the design tip-speed ratio, rotor solidity, and maximum chord, taper, trailing edge configuration, and tip design. The overall structure of the blade is another important design feature as it relates to manufacturing and transport. For the drivetrain, a myriad of different configurations are possible depending on whether the system is direct drive or has a gearbox, has one or multiple generators, and all the aspects of a particular design within a configuration such as the gear ratio, type of generator, and machine rating and speed. Towers are either lattice or more commonly monopole. The hub height is a key design consideration for modern towers as it relates to other aspects including the tower wall thickness, diameter, materials, taper, and sectioning. Finally, secondary systems each have a range of options resulting in an enormous overall number of potential configurations for wind turbine designs.

1.2.1.2 Wind Plant Layout and Site Design

Beyond the turbine, there are many other design choices that are primarily the domain of the developer who buys a particular manufacturer's turbines for a specific wind plant. Decisions to be made around plant siting include the site characteristics in terms of wind resource class and seasonal/diurnal profiles, terrain, and other meteorological characteristics. Beyond this, siting is influenced by many issues, including transmission and physical site access, land value, interconnection options, and environmental and community sensitivity. Once a site is selected, additional options remain including the type of turbine, the layout of the plant, the interconnection process to the electric grid, as well as plant installation and long-term operation. Outside of the individual company design decisions, other factors influence system design at an industry level including design standards, grid codes and integration rules, and other standards related to plant operation and safety. Finally, external to the industry are all the exogenous inputs related to overall economic variables in terms of material and labor costs, as well as financing effects from economic cycles and political activity.

1.2.2 Design drivers, Cost of Energy and Other Impacts of Wind Energy System Design

1.2.2.1 System Design drivers for Turbines and Plants

Design choices from different stakeholders combine to drive key system output variables and impacts. Related to these end-state variables of interest are a set of intermediate variables related to plant performance and balance of station costs. From the plant performance side, the industry rules, component, turbine and plant design choices all link together to influence the annual energy production from a wind energy plant. Annual energy production is affected by the plant rated capacity, aerodynamic, mechanical and electrical efficiency, losses due to transmission, blade soiling, blade erosion, and turbine array interactions, curtailment of the plant, and availability. In addition, balance-of-station costs are affected by various decisions related to turbine and plant siting and design both in terms of plant transportation, assembly and construction costs, as well as longer term O&M costs related to system reliability and replacements. The Levelized Cost of Energy (LCOE) for the system is composed of the total capital costs for a project (including turbine capital costs and balance of station costs associated with engineering and construction of an entire wind plant), as well as the annual operating expenses (including operation and maintenance costs, component replacement costs, and any other annual expenses), annual energy production for the plant, and project financing.

1.2.2.2 Cost of Energy and Other Impacts of Wind Energy System Design

The LCOE is the key variable of interest in much of wind energy research, design, and development. However, several other variables are also of interest related to the impact that wind energy has on grid operation, on local communities, and on the local environment. Wind energy has begun to affect grid operation and planning on every time scale from short-term power quality and regulation to day-to-day commitment of generation resources and reserves to longer term planning for system reliability and capacity procurement. For the environment, key concerns focus on the habitat impacts related to species displacement and fragmentation as well as direct wildlife impacts related largely to bird and bat fatalities. However, there are also the positive environmental impacts that may be present in terms of reduction in pollution on a local, regional, or even global level. Finally, local communities may be impacted by wind energy projects via several paths, including the visual profile including aesthetics and turbine induced visual flicker as well as noise impacts and even potentially safety concerns or electromagnetic interference. There are also economic impacts to the local community, which may surface both in job creation or land lease rents. Just as with LCOE, these external impacts of wind energy plants are affected by the combination of design decisions at every level of the system from the component to the turbine to the plant.

1.2.3 Examples of System Level Design Issues in Wind Energy

Adequate discussion of all the aspects of a wind energy system is beyond the scope of this paper. However, it is important to illustrate the complex, uncertain and heterogeneous aspects of a wind energy system and this is done via three concrete examples: wind energy system noise, controls, and ice-loading concerns for site-specific offshore wind applications.

1.2.3.1 System Noise

One classic example of a system property that crosses disciplines as well as stakeholder interests has to do with the acoustics produced by the operation of a wind turbine and plant. Noise from turbines is one of several important constraints affecting the social acceptance of wind energy system deployment (Huber 2010). Issues associated with the noise were detected in the early days of wind turbine development during the 1970s and 1980s, such as with the early downwind turbines of the federal wind energy program, and this one of the major reasons why almost all turbines built today have the rotor operate upwind of the tower, avoiding tower wake interaction noise. Figure 6 depicts how the successive generations of wind turbines have fared in terms of noise impacts. Turbines designed and built in the 1980s produced significantly more noise than turbines built in the 1990s. In Figure 6, sound power levels in dB(A) are expressed in log-form, as is typical practice, and this means that a decrease of 10 dB in noise power level is actually a 10-fold decrease in sound intensity at the turbine source [W/m^2]. Thus, reductions in sound power levels from the 1980s to the 1990s were quite impressive, especially for larger turbines with rotor diameters of 25 meters or more (van Dam 2005).

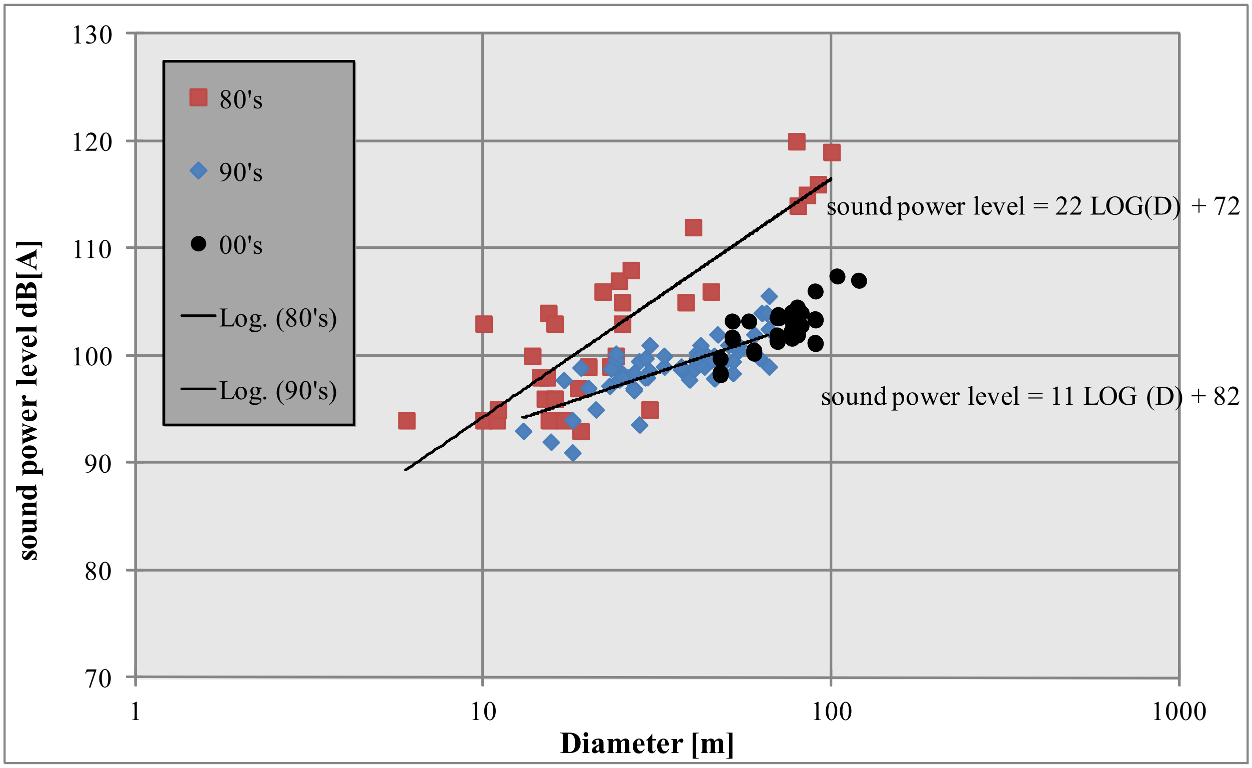

Figure 6. Noise contributions from turbines grouped by year of manufacture for the 1980s, 1990s, and 2000s through 2005 (based on van Dam 2005)

However, despite the improvements noted above, noise is still a significant concern in wind energy system design. This turbine noise has a variety of sources, each of which have a particular frequency (Hz) and intensity (dB(A)) profile in the infrasonic and audible hearing range and can potentially affect humans depending on a combination of factors as will be discussed below. The noise level (in dB(A)) is propagated through the terrain as a function of the number of turbines, wind gradients, surrounding terrain, and distance from the source. Humans, in turn, perceive this relative to ambient noise in the area. Thus, overall sensitivity is a function of hearing ability of an individual, indoor versus outdoor location, the ambient noise in the surrounding area, vibration frequencies of nearby structures, and the dB(A) level of various frequency levels at the point of reception (Wagner et al. 1996). The noise power levels illustrated in Figure 6 are those emitted at the source (i.e., at the turbine site) and will trail off as one moves away from the source as a function of square of the distance. Therefore, by the time the turbine noise reaches a nearby community, the sound power level will be significantly reduced (approximately 6 dB(A) for every doubling of the distance from the turbine) (Wagner et al. 1996). Local noise limits are typically 50 to 60 dB(A) but can drop to 45 dB(A) and below in residential areas (Wagner et al. 1996). Thus, there is an implicit tradeoff in the design of a turbine and the siting of a turbine in terms the noise impacts on nearby communities.

Bringing the discussion back to system properties of complexity, uncertainty, and heterogeneity, each is important with respect to design of wind turbines for noise impact mitigation. Complexity is involved since noise stems from many different sources in the system, and there is coupling between these systems as well as impacts of those decisions on overall system performance and cost. Figure 7 traces design variables through the wind system that ultimately have an impact on noise impacts from a wind plant. However, even the representation in Figure 7 isn't complex enough to capture all of the nuances of the wind plant design process that ultimately impact system noise, and, as can be seen, there is an implicit trade-off between system noise impacts and the overall cost of energy for the wind plant. There is also significant uncertainty involved since the science of the production of noise from a particular turbine and plant as well as the science of how noise impacts individuals and communities is continuously evolving. There are also a variety of potential innovations in wind turbine designs that have uncertain impacts on noise as well as system performance and cost. Finally, heterogeneity is also present in the design of wind energy systems for noise mitigation since every site will have different characteristics in terms of how particular turbine selection and placement will interact with the local terrain and climate to produce noise and how the local community will react to the noise produced.

Figure 7 exhibits some of the heterogeneity, in particular on the plant design choices and exogenous influences. More importantly, the complexity and interactions across the system in terms of noise impacts and performance and cost trade-offs are illustrated. The following discussion traces these relationships and provides discussion about how different design choices to mitigate noise will also likely have significant impact on system performance and cost. Turbines provide both mechanical and aerodynamic sources of noise. From the mechanical side, machinery within the nacelle—including the gearbox, generator, hydraulic actuators, cooling fans, and auxiliary equipment—may all serve as sources of noise (Wagner et al. 1996). The predominant and more difficult to mitigate sources of noise stem from the aerodynamic operation of the turbine, including the unsteady loading noise from the blades passing through tower wakes (for down-wind rotors); inflow turbulence noise due to blade interaction with atmospheric turbulence; and airfoil self-noise from a variety of sources, including the blade trailing edge flow, separation noise, tips, and manufacturing imperfections (Wagner et al. 1996). One well-known empirical formulation of noise impacts from wind turbines depend on the tip speed and the size of the turbine (Wagner et al. 1996) is as follows:

$$L_{NoiseLevel} = \log_{10}\left(\frac{V_{tip}^{50} D^{10}}{4}\right) \propto V_{tip}^{5} D \qquad (1)$$

Higher-fidelity models have been developed to account for the various sources of noise impacts on turbine design (Wagner et al. 1996, Moriarty 2005), but the above formula presents a reasonable rule-of-thumb for wind turbine noise production.

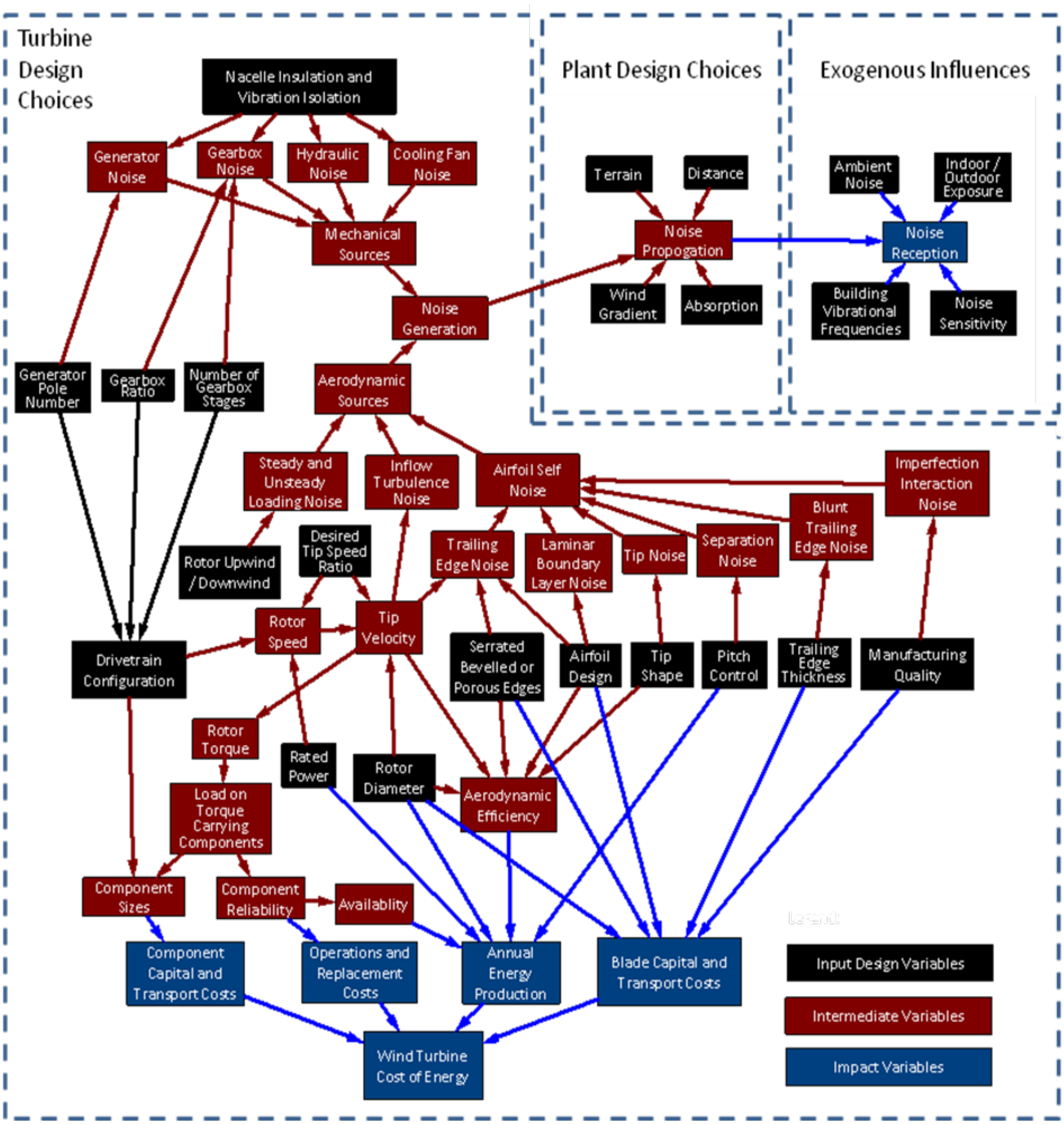

Figure 7. System map of noise influences and impacts throughout the wind energy system design process

Adjustments to the tip speed will affect noise output and noise level constraints will affect the design tip speed for a wind turbine. These noise design criteria do not stop with the tip speed. The design of the tip speed is closely related to the design of the blade planform and, in particular, the maximum chord length (Manwell et al. 2002, Malcolm and Hansen 2006). In addition, the torque needed from the rotor to transmit a given power level to the drive train is an inverse function of the tip speed since power output is equal to the torque multiplied by the rotational speed. Thus, noise limits that reduce the allowable tip speed for a turbine implicitly increase the loads transferred through the torque carrying components, which then translate to structural designs that require more material, larger dimensions, and therefore higher weights and costs.

The tip speed and more specifically the rotor speed are related directly to the operation of the drivetrain such that the design of rated rotor speed will impact design choices on gearbox ratios and drivetrain configurations. For instance, a direct drive machine could have a smaller design with fewer poles if the rotational speed were increased ($NumberofPoles = \frac{60 * Frequency}{SynchronousSpeed * 2}$) and thus a lower tip speed for noise consideration affects the size and weight of a potential direct drive generator. A similar relationship exists for the design of the gearbox in terms of the ratio needed to step up from the low-speed at the rotor to the high-speed at the generator. Other solutions that reduce noise through the application of trailing edge serrations or modified tip shapes may affect aerodynamic efficiency or impact system costs if they result, for example, in higher costs to manufacturing of the blades. Thus, there are a myriad of potential design choices that may affect noise in the system and each has a subtle and complex impact on the rest of the key design impact variables related to cost of energy.

In order to improve wind energy system designs to both mitigate noise impacts while maintaining or improving overall cost of energy, a systems engineering approach would capture all of these interrelated impacts. This would ultimately improve the understanding of relationships between noise related design variables, impacts and cost of energy and the ability to evaluate designs with respect to these criteria. Systems engineering approaches are well-suited to research and design where multiple objectives and stakeholder perspectives are important to the design of a complex system.

1.2.3.2 Wind Turbine Controls

The Wind Partnerships for Advanced Component Technologies (WindPACT) Turbine Rotor Design Study (Malcolm and Hansen 2006) reported several interesting findings related to system design improvements that spanned various disciplines. The study found that an increased tip-speed ratio combined with a reduced maximum chord length would have significant cost savings for the overall system (Malcolm and Hansen 2006). However, careful consideration of the noise impacts plays a role in the feasibility of such design solutions. Moving from noise to controls, the combination of passive controls in flap-twist coupling for the blades, a higher tip-speed ratio combined with a reduced maximum chord length, and tower feedback to the active system controls could together result in significant reductions in system loads and thus lead to a lower overall cost of energy.

Controls have the potential for reducing system design loads as well as improving overall system performance and cost metrics. Controls naturally require system-level evaluation since they necessarily cross sub-system boundaries (particularly between the aerodynamics and structures but also with electrical and even external impacts, such as noise). A specific example of how control strategies can be used to significantly influence overall system design comes from Europe's UpWind project. Those studies found that the incorporation of control strategy considerations early in the design process would result in much lighter and structurally efficient component design allowing a 20-MW turbine to become a potentially feasible size for offshore wind energy applications (UpWind 2011). In particular, they found that the use of advanced techniques in distributed aerodynamic blade controls and individual pitch control could lower fatigue loads considerably allowing for development of longer and lighter blades necessary for a 20-MW turbine. In addition, the incorporation of advanced measurement technologies such as Nacelle mounted Light Detection And Ranging (LIDAR) were found to improve wind estimation accuracy to enhance smart control strategies for reducing overall system loads, again allowing for lighter structures (UpWind 2011).

Controls are also critical for wind plant operation in terms of overseeing all aspects of the turbine and plant operation from individual components to the point of wind plant interconnection to the grid. Traditional control strategies for wind turbines include supervisory controls for start-up, shut-down and safety, operational controls related to variable speed drivetrains for optimized power capture, and operational controls related pitching for steady power production and load shedding. Additional control strategies have been developed for drivetrain damping and tower fatigue reduction. Finally, research is being pursued on novel control techniques including plant level controls to mitigate array losses as well as active power controls, which will allow wind turbines to provide ancillary services to the electric grid (Laks 2009). All of these various control schemes involve tradeoffs when considering the full system design. For instance, pitching blades to maintain generator output at rated levels may introduce tower vibration and motion that contributes to shorter lives for drive train components or may introduce more frequent extreme torque loading on servo-motors which also shortens the life of those components. This would in turn increase replacement costs for components over the life of a wind project and impact the overall cost of energy. Thus, a systems-level approach to governing these different goals in the control of wind energy systems is necessary and should reflect the long-term operation of the turbine and plant.

Current research in controls uses a systems engineering approach by incorporating systems engineering attributes of uncertainty and complexity into the controls design. Research into multi-input, multi-output control systems accommodates coupling between loops, various levels of system uncertainty, and potentially even adaptive and non-linear strategies (Laks 2009). Such strategies, as in the case of the UpWind project, may have significant effects for the potential overall design systems which again emphasize the need for a holistic and multidisciplinary approach to the research, design, and development of wind energy systems that is central to systems engineering approaches.

1.2.3.3 Ice Loading on Offshore Wind Turbines

For a last example of the integrated and complex nature of wind energy system design, we turn to the offshore environment where the number of complicated dynamics expands from those involved with land-based applications. In some ways, offshore wind energy may be considered a favorable environment for wind energy applications if sites have less atmospheric turbulence and higher wind speeds at lower hub heights. However, many aspects of offshore wind environments, as illustrated in Figure 8 introduce design challenges that are not present for onshore wind energy systems. Inclusion of wind, waves, ice, currents, scour, and other factors lead to ever more complex dynamic system behavior that can lead to more frequent component or system failures. In addition, difficulties associated with access can compound the costs associated with any given system failure. One particular offshore wind energy design issue

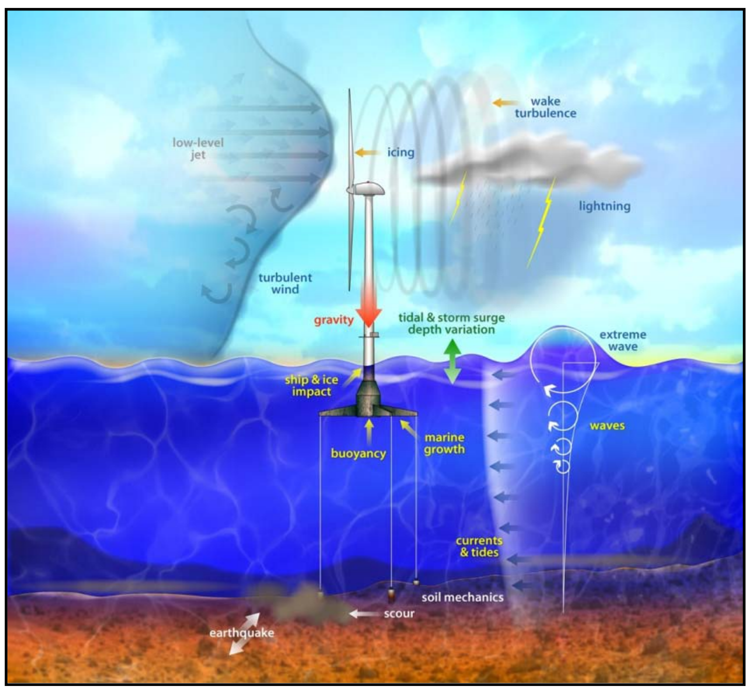

Figure 8. Dynamics associated with the design of advanced offshore wind energy systems with floating platforms (Musial 2010)

associated with select sites is ice-loading of the turbine support structure. In the Great Lakes, which is one of the top offshore wind regions in the United States (Musial 2010), ice loading of the tower and foundations will be a primary design driver since ice conditions can be severe with ice thickness of up to 1 meter. Here, the extents of ice cover and ice thicknesses (and therefore maximum ice force predictions) are highly variable.

Interaction between ice and a wind turbine results from the contact between a moving or expanding ice sheet and a structure (Figure 9). The load imparted on the structure from ice can be the largest load experienced by the structure, and therefore has the potential to dictate the structural design parameters of offshore wind turbine systems in ice-prone regions. Ice loading can result in significant horizontal and vertical loading to the structure during movement of impinging ice floes and during expansion cycles. The magnitude of the load depends on the failure mode of the ice as it fractures against the structure, which falls into two primary categories:

- **Static:** significant horizontal and vertical loading to the structure during movement of impinging ice floes and during expansion cycles.
- **Dynamic:** under certain conditions, the frequency of ice fracture events can match the natural frequency of the turbine structure, resulting in a potentially damaging resonance (a lock-in resonance). Ice can also build up around the base at the water surface and change the dynamic characteristics of the turbine/tower system by altering the stiffness and mass properties of the structure.

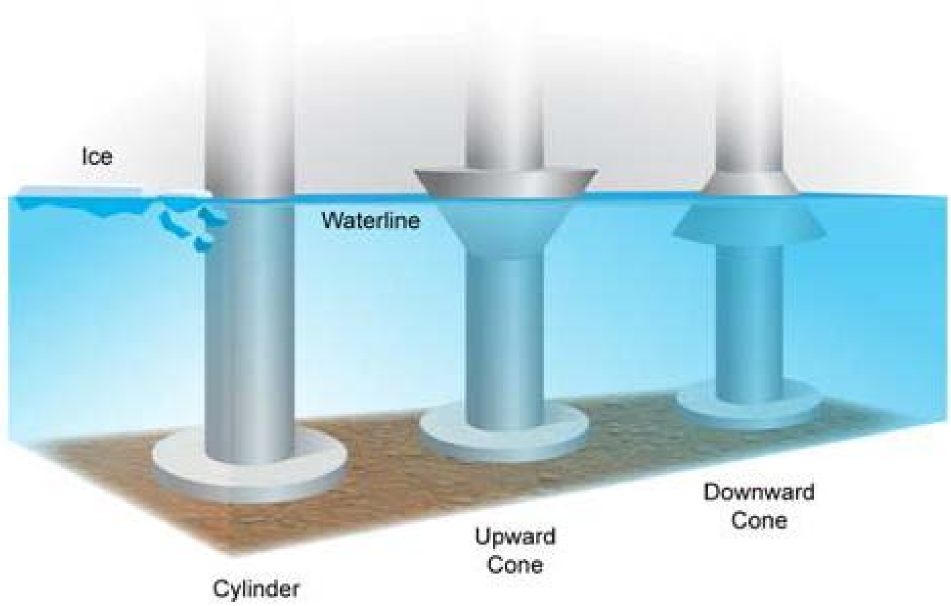

Figure 9. Different waterline geometries have been proposed to mitigate the ice loading impacts on offshore wind turbine structures

The structure geometry at the waterline has a large effect on the ice forces. There are many studies on forces generated from different types of ice on a variety of structure geometries. In 2003, the National Research Council of Canada completed a series of scaled laboratory tests to investigate key ice engineering issues for offshore wind farms in Denmark. The results identified different failure modes and their magnitude, the likelihood of lock-in vibrations, and optimum cone angles/design for load mitigation (Barker et al. 2005).

At the turbine level, ice loading can affect the turbine control strategy. Advanced control strategies can be developed that use active sensing to assess the excitation of a fundamental frequency in the system from ice. Fundamental modes of the wind turbine system change with operating status. Depending on the mode of the excitation, active controls can be used to shut down the wind turbine, altering the system properties and alleviating the effect of the excitation.

At the wind plant level, the presence of ice affects the O&M strategy including not only when the plant is accessible for maintenance, but the type of vessel used to access the plant for maintaining the plant during extremely cold winters. Ice will also factor into array optimization. Ice flows will break up as they move through a wind plant, with the first row of turbines encountering the largest forces. Adversely, due to wake effects, the last row of turbines from the incident wind direction will encounter increased mechanical loading from more turbulent winds. The combination of ice loading and wake effects will change the optimized layout of the wind plant when compared to the consideration of wake effects alone.

Thus, the impacts of ice loading crisscross through the entire wind energy system affecting nearly every aspect of plant design—from individual components including the tower and foundation in particular, but also the entire plant and related O&M strategies. This again illustrates the complexity of designing a wind energy system where addressing one design issue impacts and is impacted by various other system design variables and issues. Heterogeneity is again present since ice conditions will vary significantly from site to site. Only a multidisciplinary and holistic approach to wind energy research and design can appropriately address all of the system impacts from ice-loading and identify design innovations and changes that can improve system level performance from consideration of ice effects. Whether looking at external impacts such as noise, site-specific design conditions such as ice-loading, or system-level design choices such as those involving turbine and plant controls, issues of complexity, heterogeneity and uncertainty surface in a number of ways. There are many other system design considerations that also feature these attributes and thus illustrate how wind energy systems are inherently suited to a systems engineering research, design, and development approach.

1.2.4 Wind and Systems Engineering

Given all the factors involved, wind energy is one of the most complex large-scale, technical systems currently deployed worldwide. Wind energy systems affect a large and diverse set of stakeholders; involve a range of disciplines; have a scope that is extremely broad, ranging from individual components to entire plants and their interaction with the grid; and is designed for operation over a long time-scale that is on the order of decades. The resulting complexity, uncertainty, and heterogeneity associated with wind energy systems presents significant challenges to system design. Compartmentalized research, design, and development of wind energy turbines and plants are likely to miss all the nuances and interconnections throughout the system that could lead to a lower cost of wind-generated electricity. Systems engineering provides both a framework and set of tools that can assist with wind energy system research, design, and development from a holistic and integrated perspective. Such an approach will be designed to cross the boundaries between manufacturers focused on turbine design, developers focused on plant design and operation, and other communities interacting with the technology in order resolve issues with which a single perspective and level of analysis would not be able to deal. The next section will address methods within systems engineering that may be applied to wind energy research, design, and development.

2 Methods in Systems Engineering

Numerous methods from the field of systems engineering can potentially be applied to wind energy research, design, and development. Figure 10 shows the absurdity of allowing any one of these to dominate the design process.

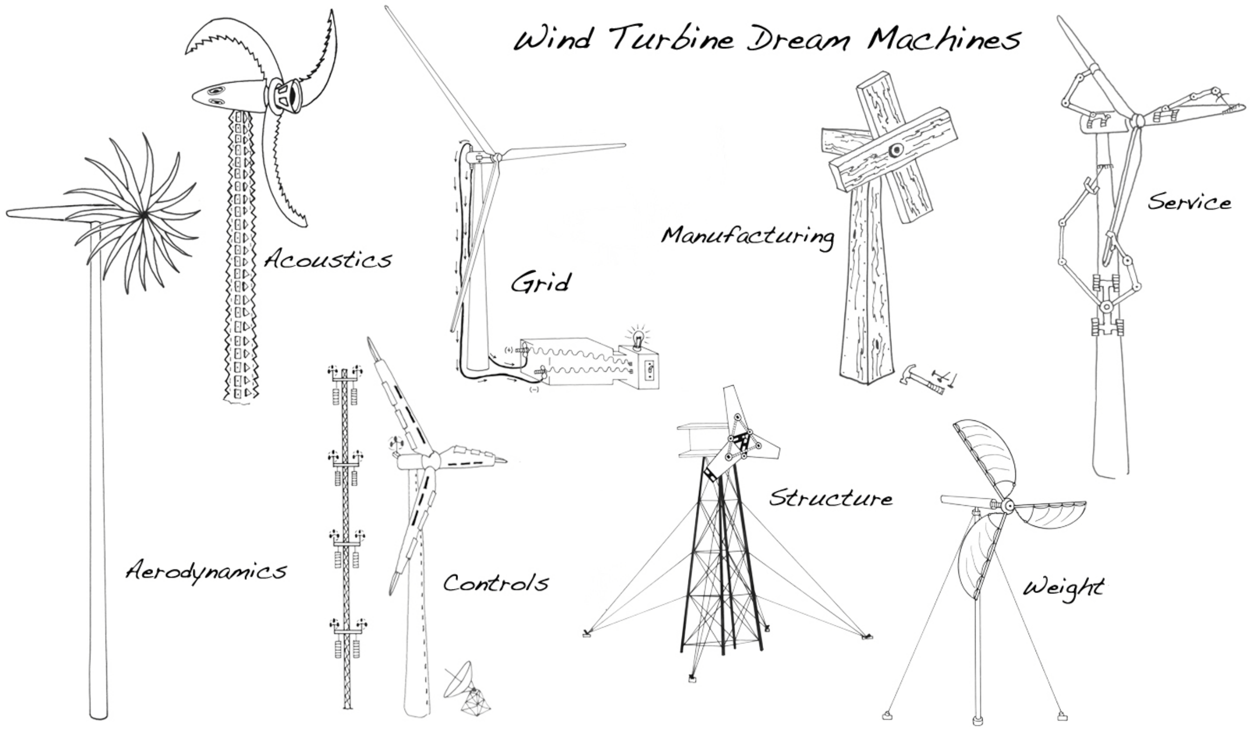

Figure 10. Dream Turbines: A Multidisciplinary View of Wind Turbine Design. A cartoon by Vega aircraft engineer C. W. Miller has become a popular representation of what would happen if one discipline dominated the design of an airplane. Here, a cartoon was created to represent wind turbines resulting if only one discipline dominated the design process. The humorous results illustrate the need for a systems perspective. (artist: Rick Hinrichs)

Here, we focus on those methods that can address research and design issues from the component level all the way to plant operation. The first set of methods focus on turbine and component design and borrow heavily from the aerospace sector. These include the systems engineering sub-fields related to multidisciplinary design optimization and multi-objective optimization. The extension of these methods to analysis at the plant level and to turbine/plant interaction is also discussed. Next, concurrent engineering is reviewed as it applies to those aspects related to the overall organization of the design process for a holistic and life cycle approach that includes design tool selection, communication mechanisms across design teams and organizational processes that support the overall design development. Supply chain management is then briefly discussed as it relates to transportation and logistics issues associated with turbine and plant design. Finally, a section on other methods touches on reliability engineering and safety engineering that may affect initial design as well as long-term operation of a system. A brief overview of methods in risk and cost engineering is presented.

2.1 System Design and Optimization

A few important and related methods within system design and optimization include MDO and MOO. MDO focuses on optimization of a single, key "system-level" attribute (such as cost), though it also may allow for optimizations at the "subsystem" or disciplinary level for key disciplinary parameters (i.e., multiple levels of optimization for different design drivers such as aerodynamics and structures). On the other hand, MOO as well as multi-criteria design optimization, focuses on trade-offs among different global system objectives and may use aggregation techniques across objectives of interest or some sort of ordering of system-level objectives. For instance, for a wind energy application, MOO might look at simultaneously optimizing for system cost (from industry perspective) and system capacity factor (from the utility perspective); whereas an MDO approach would optimize for one of the two variables (cost) while the second would exist as a constraint or a sub-level optimization objective. Thus it can be seen that from an MDO perspective, there is typically a single key stakeholder or decision maker whose interests are dominant in the system design process while for MOO, multiple interests from a single or multiple stakeholder(s) may be relevant. MOO addresses system heterogeneity (though MDO may address this somewhat as well through multi-level approaches), while MDO focuses on bringing together the complexity associated with designing technology across disciplines. Uncertainty impacts the system in a number of ways and can be incorporated into MDO and MOO methods via the use of stochastic optimization. These methods are not mutually exclusive and may be used together for a comprehensive system analysis. However, the choice between MDO, MOO or the use of both methods should depend largely on the application and questions of interest in order to produce results that maintain adequate validity.

2.1.1 Multidisciplinary Design Optimization

2.1.1.1 Overview of MDO Methods

This section provides an overview of the history and basic components of MDO methods. For more detailed discussion of MDO, please see *Appendix A: Detailed Overview on State-of-the-Art in MDO Methods and Associated Optimization Algorithms*.

The precursor to MDO involved nonlinear programming for optimization of structures beginning with a seminal piece of work looking at structural optimization of a three bar truss (Schmit 1971, Agate et al. 2010). The general formulation of a structural design optimization problem is based on this original formulation from Schmit's work (Agate et al. 2010):

$$\begin{aligned} \min_x \quad & f(x,p) \\ \textit{such that} \quad & x_{LB} < x < x_{UB} \\ & g(x,p) \le 0 \qquad h(x,p) = 0 \end{aligned} \tag{2}$$

In this general formulation, $f(x,p)$ is an objective function depending on a vector of decision variables x and fixed parameters p that influence the objective (i.e., cost minimization). There are different constraints in the system that may include upper and lower bounds (x_{UB} and x_{LB}) on the decision variables as well as both inequality constraints represented by $g(x,p)$ and equality constraints $h(x,p)$ where both g and h are vectors of constraint functions that depend on x and p . Such analyses were used for a variety of structures and eventually began to incorporate data from other disciplines as inputs into the optimization process. Eventually, the use of data from other disciplines (such as aerodynamics) led to the recognition that some combined analysis across those disciplines within the system optimization would be important. The challenge of this however, is that design variables as well as output variables are not confined to single and distinct discipline but are instead “coupled” throughout the entire complex system.

This led to the establishment of the first generation of MDO tools, which focused on analysis across disciplines incorporating coupled variables across boundaries all within a system-level analysis and optimization process. Thus, the original non-linear optimization problem of Schmit (1971) has to be modified to account for this coupling:

$$\begin{array}{llll} \min_x & f(x,y,z,p) & & \\ \textit{such that} & x_{LB} < x < x_{UB} & y_{LB} < y < y_{UB} & z_{LB} < z < z_{UB} \\ & g(x,y,z,p) \le 0 & h(x,y,z,p) = 0 & \end{array} \quad (3)$$

The new formulation separates the overall set of design variables into those that are global, x, those that are local to a specific discipline, z, and those that are coupled across disciplines, y. The coupled variables can be expressed as a function of the global design variables, the local discipline specific design variables, and the coupling variables of other disciplines: $y_i = y_i(x, y_{j,j\neq i}, z_i)$. Such a representation is equivalent to the simplest and most basic MDO technique Multidisciplinary Feasibility MDO (Depince et al. 2007). This can be seen in Figure 11, adapted from Alexandrov and Lewis 2002.

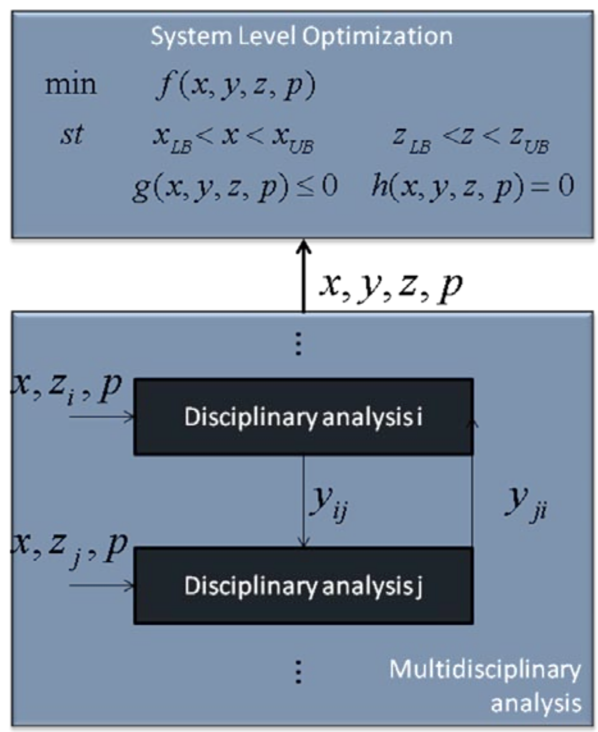

Figure 11. MDO using single-level optimization and underlying multidisciplinary analyses (adapted from Alexandrov and Lewis 2002)

However, developments in the last few decades have recognized the importance of both optimization at the system level and at the disciplinary level since with increasing system complexity and model fidelity, whole-system at-once optimization becomes computationally prohibitive (Agate et al. 2010). This has led to a decomposition of the optimization process and to the introduction of “multi-level” MDO where there are optimization routines both at the system level and at disciplinary levels as shown in Figure 12 (Depince et al. 2007, Allison et al. 2005, and Tosserams et al. 2008). For example, from the perspective of wind turbine design, a single-level MDO might focus only on cost of energy whereas a multi-level MDO may have sub-optimizations related to specific component weights, drivetrain efficiency, etc.

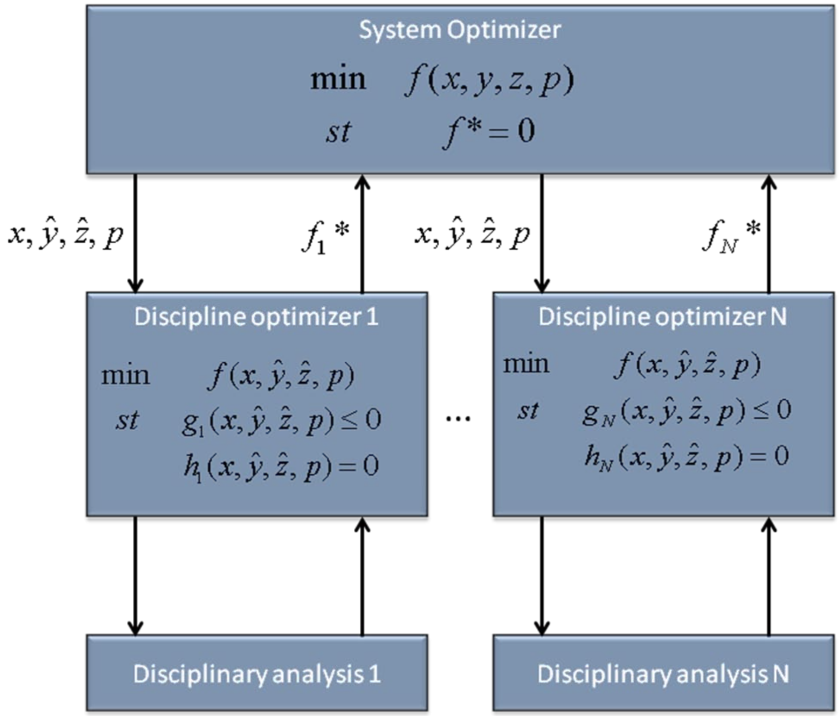

Figure 12. MDO for multi-level optimization using the Collaborative Optimization technique (adapted from Allison et al. 2005)

Many potential ways exist to mathematically formalize and categorize these multi-level MDO models. Early MDO efforts were segregated into two types: optimizations involving medium fidelity models with a few disciplines or optimization of many disciplines at a higher conceptual level using lower fidelity models and many design variables (Agate et al. 2010). With better modeling tools and increased computational power, there has been a movement towards merging these two spheres such that models of high fidelity can now run optimizations with many variables and many disciplines. Still, there is a need for analysis at various levels for both overall system architecture as well as specific detailed designs.

Historically, applications of MDO have been seen mainly in the aerospace and automotive sectors though there has been a growing interest in the use of MDO for other sectors such as in naval architecture (Hart 2010). Interestingly, the emphasis within aerospace is more on multidisciplinary design (aero, structure, servo) whereas in the automotive sector the emphasis is more on multi-attribute design (noise/vibration/harshness, drivability, crashworthiness) (Agate et al. 2010). This illustrates how the type of system (technical/social components and stakeholder interests) can heavily influence the high-level design processes. Wind energy appears most similar to aerospace and thus most appropriate to approach from a multidisciplinary focus. At the same time, certain attribute characteristics related to human and environmental interaction with the system such as noise, flicker, safety, and wildlife impacts are of increasing importance in affecting the overall acceptance of wind energy technology deployment. Thus, parallels to both the aerospace and automotive traditions within MDO are potentially relevant.

Table 1. Example attributes and disciplines in the design of aerospace, automotive, and wind energy systems (adapted from Agate et al. 2010 to include wind energy)

Aerospace	Automotive	Wind Energy
Structures	Style	Structures
Aerodynamics	Crashworthiness	Aerodynamics
Mission Performance	Noise – Vibration – Harshness	Electricity Generation – total energy output
Propulsion	Performance – propulsion	Electricity Generation – capacity factor
Controls	Performance – stability	Controls
Manufacturing	Performance – drivability/ ergonomics	Manufacturing
Noise	Performance – durability	Noise

Even for the traditional MDO areas of aerospace and automotive, a number of new research directions have been proposed including the integration of manufacturing concerns, adaptation of the methods for evaluation of new and innovative configurations, and further needs for model validation and verification (Agate et al. 2010). On top of this, a few novel research directions involve both horizontal development (i.e., dealing with long-term uncertainty, full life cycle economics, and manufacturing) and vertical development (i.e., involving product families and systems of systems) of the field. For a more detailed discussion of MDO methods and associated optimization techniques, please see *Appendix A: Detailed Overview on State-of-the-Art in MDO Methods and Associated Optimization Algorithms*. Applications of these methods to wind energy could potentially take on some of these research challenges such as the integration of manufacturing considerations and full life cycle economics as well as the perspective of systems MDO considering both individual turbine design as well as entire wind plant design and operations.

An important component of MDO work is the post-processing analysis of modeling results helps to provide insight into various aspects of optimized designs or a set/space of designs. To this end, metamodels, discussed in more detail in *Appendix A*, are useful in aiding uncertainty analysis and quantification methods. Such analysis can be performed globally, across the entire design space, or locally, around point designs (Simpson et al. 2008). Various commercial and public software packages have been developed to support this type of analysis including Sandia's DAKOTA software as discussed in Section 4.

The twin themes of *sensitivity analysis* and *uncertainty quantification* go hand-in-hand with the construction and use of metamodels. In both, the object is to understand the dependence of output values on input parameters (including initial conditions) (Saltelli et al. 2000). Sensitivity analysis and uncertainty quantification allow the metamodel user to take into account how they depend on, at best, imprecisely known parameters. Sensitivity analysis, in its concrete local form, is simply the calculation of derivatives of output quantities with respect to input parameters. As such, it forms the core of any gradient-based algorithm to optimize properties as functions of parameters. In addition, applying various sampling methods (from classical experimental designs [Box et al. 2005] to carefully chosen sparse grids [Smolyak 1963]) in conjunction with sensitivity analysis provides a global view over a design space of interest regarding how robust the system is to changes in important parameters, and therefore how precisely parameters have to be chosen, which becomes important feedback in the overall multi-level MDO process.

Similarly, uncertainty quantification allows us to understand how knowledge (at least, hypotheses) about the distribution of input values affects the distribution of output values in a simulation. There are two classes of uncertainty, corresponding roughly to whether we at least know the *distribution* of input parameter values (aleatoric uncertainty) of whether we do not (epistemic uncertainty). In simple form, the former case is studied via the various parameter sampling strategies, while the latter relies on propagation of raw bounds of input parameters. More advanced forms allow the propagation of distributions themselves (not just samples of them), known generally as *stochastic expansion* (Eldred et al. 2011), and the propagation of probability values themselves (not just samples of them), as developed in *evidence theory* (Yager and Liu 2008). In general, probabilistic techniques are important to wind energy research, design and development.

While the above discussion focused in particular on the complexity aspects of wind energy design that involves many linkages through the system, uncertainty is another key feature of these systems. It is possible that designs discovered through the MDO process will be unacceptable from an engineering perspective because the uncertainty in the inputs will render such designs less than optimal when accounting for model uncertainty. This is where it may be necessary to consider uncertainty while performing MDO. There are several approaches to optimization under uncertainty (Giunta 2004). The goal in any case is to identify optimal design choices while accepting the parts of the process that are uncertain. Thus, probabilistic techniques, uncertainty quantification, and stochastic simulations are important to the design process. For example, the dissertation work of Veldkamp focused on the probabilistic analysis of wind turbine fatigue (Veldkamp 2006).

2.1.1.2 Applications of MDO to Wind Energy Systems

In the last several years, a variety of attempts have been made to apply MDO methods to wind energy system design. The natural parallels between wind energy and aerospace have led to efforts by systems engineers and researchers to apply their expertise in MDO to wind energy (Crawford and Haines 2004, Bottasso et al. 2010, Vlahopoulos et al. 2011). A summary of these wind energy MDO efforts is shown in Table 2, and a more detailed discussion each of the three individual bodies of work follows.

Crawford's work focuses on the integration of CAD as an organizing platform for storing the geometry related to system design in an MDO approach to the design of wind turbines (Crawford 2003, Crawford and Haines 2004). The work incorporates the suite of NREL aeroelastic design codes for the disciplinary analysis of interest and a cost-scaling model based on linear, quadratic, and cubic functions of the rotor diameter, influencing cost changes in respective subsystems. An overarching software management tool, CAPRI-wind, was built that performs the optimization and interfaces with the NREL codes and CAD software. The work involved a sequential optimization approach with system-level analysis of the cost of energy. Interestingly, CAD tools are used commonly to store information relevant to determining manufacturing costs such that the approach has the potential for addressing overall capital costs for components including both materials and manufacturing costs.

Bottasso, Campagnolo, and Croce's work, in contrast, focused on an MDO approach to the design of a wind turbine blade specifically by looking at the structural and aerodynamic trade-offs in blade design while accounting for the full aero-servo-elastic effects on the blade structure as well as noise constraints (Bottasso et al. 2010). The objective function used optimization of the annual energy production (AEP)-to-weight ratio as a proxy for system cost, noting the significant impact both variables have on wind turbine cost of energy. The work involved a comprehensive aero-servo-elastic, non-linear, finite-element-method-based, multi-body dynamics solver at a first level with a second level using a finite element, cross-sectional model of the blade to do section-wise load calculations to determine the blade weight and then a third level using macro parameters to optimize the overall objective of the AEP-to-weight ratio minimization. The work, as in Crawford's work, used a sequential formulation for optimization. The analytical tools used in this model involved a much higher degree of fidelity while the system scope of analysis and design was smaller than in Crawford's work.

Finally, Vlahopoulos, Kim, Maki, and Sbragio's work, focused on full-scale wind turbine design (Vlahopoulos et al. 2011). In this case, however, the authors applied a multi-level MDO approach to the system design using two disciplines (one maximizing AEP, the other minimizing blade root moment) under a system level analysis and optimization (minimizing cost of energy). Again, similar to Crawford, the work borrowed extensively from the NREL design tool suite including both aeroelastic design codes and cost models. In addition to the distinct multi-level approach, the work also incorporated the use of Kriging-based metamodels to replace the higher fidelity models of HARP_Opt and WT_Perf, thus expediting the overall optimization process with.

Table 2. MDO Applications to Wind Energy Research

Study	MDO Approach	Design Variables	System Optimization Outputs
Crawford and Haines 2004	Sequential optimization of full turbine using NREL aeroelastic design codes, custom cost of energy algorithm, and CAD software interface	Rated Power Maximum RPM Rotor Diameter Blade Chord Lengths Blade Twist Angles Blade Thicknesses	Cost of Energy Annual Energy Production System Design System Weights
Bottasso et al. 2010	Sequential optimization of turbine blade energy/weight ratio using two disciplines (aerodynamics and structures) and interfacing to detailed aerodynamic and structural models	Aerodynamics (detailed airfoil design) Structures (detailed blade design)	AEP Blade Design Blade Weight Airfoil Design
Vlahopoulos et al. 2011	Multi-level optimization of full turbine using NREL aeroelastic design codes, cost of energy model and metamodel for aerodynamics discipline	Aerodynamics (Rated Power Rotor Diameter Hub Height Maximum RPM) Structures (Rated Power Rotor Diameter Hub Height Maximum RPM Shell Thicknesses Web Thicknesses)	Cost of Energy Annual Energy Production Shell Thickness Twist Angle Chord Blade Loads and Masses Tower Mass

In addition, research efforts focused on turbine subsystem and component design optimization have been prevalent for blades and rotors (Hjort et al. 2009, Zhiquan et al. 2002, and Benini and Toffolo 2002); generators (Li and Chen 2008); control systems (Scholbrock 2011, Kusiak and Song 2010); and even towers (Yoshida 2006). Each optimization study result claims a system-wide reduction in the cost of energy, anywhere from 2–15%, based on the particular sub-system optimization. Finally, other efforts at national labs, such as FOCUS6 from the Energy Research Center of the Netherlands – Wind Turbine Materials and Constructions (ECN-WMC), provide capabilities for optimized design of a wind turbine. The program integrates different modules for the turbine subsystem and overall design (see Section 3.3, Turbine Design Tools) but allows for different levels of analysis and optimization, including sensitivity analysis through variation of a few specific parameters or a fully automated optimization with user-defined objective functions, constraints, and output parameters (de Winkel 2011). While there is no cost model included in the FOCUS6, the objective function specification is flexible, and a simplified functional representation of cost could be defined as an input to the model (de Winkel 2011).

2.1.1.3 Wind Plant Layout Optimization

Beyond the optimization of turbine and component design, the next layer of wind energy system design is the plant. This includes everything from selection of a site, selection of a turbine model and number, placement of those turbines on the site, and even operation of the plant through various control strategies. Within the large space of wind plant layout optimization, a myriad of approaches have been taken both within the research and commercial space. Traditionally, developers followed several rules of thumb in the spacing of wind turbines within a wind plant resulting in the traditional "rows and columns" array of wind turbines: turbines spaced 8–12 rotor diameters apart in the windward direction and 3 rotor diameters apart in the crosswind direction (Manwell et al. 2002). However, effects of complex terrain and atmospheric effects as well as the multi-directional nature of wind flows propagating through the plant have identified a need to take a more active and scientific approach to the layout optimization problem.

From the research side, the approach has typically been to take the following:

1. A certain type or set of terrain and wind conditions
2. A specific type or range of wake models for turbine interaction
3. A specific turbine model or a few model types
4. A specific number of turbines and layout grid size
5. One or several optimization methods in to find an optimized wind plant layout under semi-idealized conditions.

Scholbrock presents a thorough overview of the different types of wake models and optimization methods that have been used by researchers to study the wind plant system layout problem (Scholbrock 2011). In terms of algorithms as surveyed in Réthoré 2010, the majority of studies to date make use of a genetic algorithm to find the optimum turbine layout (Mosetti et al. 1994; Elkinton et al. 2006; Grady et al. 2005; Kusiak and Song 2010; Rasuo and Bengin 2010; Wan et al. 2009; Wang et al. 2009). Several other algorithms have been used including a vertex tracking algorithm (Donovan 2005); heuristic methods; gradient descent algorithms (Lackner and Elkinton 2007); Simulated Annealing; Monte Carlo methods (Marmidis et al. 2008); particle swarm optimization (Wan et al. 2009); pattern search methods (Du Pont and Cagan 2010); and combinatorial optimization (Mustakerov and Borissova 2010). These studies focused primarily on optimization using a single turbine type across the entire wind plant. In addition, most of the studies assumed regular terrain with no major features, in a regular shape, such as a square or a circle. However, even under these simple scenarios, increases in AEP compared to the "rule of thumb" were as much as 150% (Grady et al. 2005). One study went a step further to optimize both the wind turbine layout and the wind turbine type to minimize the cost of energy for the wind plant, though the study did not allow for multiple turbine types in a single wind plant (Mustakerov and Borissova 2010). All of these optimizations use relatively abstract and involve simplified models of the turbine wake interaction effects in the wind plant. These wake models can be separated into distributed roughness element, kinematic, field, and CFD models (Scholbrock 2011). Distributed roughness models adjust the surface roughness parameter as wind turbines are added to a domain, while kinematic models, the most common in the above studies, are based on conservation of momentum in turbine wake by wake spreading (Scholbrock 2011). The latter began with work by Jensen in 1983 and was extended to the "PARK model," which has become the most common wake model for use in turbine layout optimization studies, although current research efforts are leaning towards more advanced wake representation, including full CFD models.

Field models provide a more detailed description of the flow by using two dimensions and take into account a larger set of factors that can affect the flow including atmospheric effects such as stratification, turbulence, and Coriolis forces (Scholbrock 2011). The last and most computationally intense wake model types include CFD-based models such as Reynolds averaged Navier-Stokes, Large Eddy Simulation, and Direct Numerical Simulation (Scholbrock 2011). Recent work at RISØ has looked at using these high-fidelity models within a layout optimization tool (Larsen 2011). The resulting tool, TOPPFARM, has an optimization platform that takes into account site-specific characteristics and turbine models and combines these together in order to perform an optimization of the layout that considers energy production, turbine degradation, O&M costs, and variable installation costs (Larsen et al. 2011). The different analysis tools include a model of the wind plant wind field, turbine aero-elastic codes, control strategies, and an overarching cost model. In particular, modeling of the wind plant field involved various levels of fidelity and the use of metamodels in the form of an engineering look-up table with interpolation that could be used within the optimization process for faster computation (Larsen et al. 2011). However, the optimization process for the projects focused solely on the wind plant and took the wind turbine design as a given input prior to the optimization process.

2.1.1.4 Integrated Wind Turbine and Plant Design/Optimization

As demonstrated in the previous section, a large body of work exists that looks at various levels of optimization and designs for wind energy systems including individual components, wind turbine subsystems, entire wind turbines, and wind plant layout. However, there is a lot of potential development for enhancements to design both within different system levels (horizontally) and across different system levels (vertically). Firstly, as was shown, very few explicit applications of MDO have been made to wind turbine and subsystem design. The potential incorporation of a variety of high-fidelity models; the expanded use of metamodels; and expansion of the number of subsystems, disciplines, and design variables presents a huge space for potential research. Across system levels, from components to subsystems to turbines to wind plants, the feedback of design variables between any one of these different levels of design are present only in a few works to date, such as in Kühn et al. 1997a, Fuglsang et al. 2002, and Ozkan and Duffey 2011. The closest approach from the wind energy community to a large-scale MDO looking at integrated wind turbine and plant design was developed at RISØ to look at site-specific turbine design (Fuglsang et al. 2002). In this paper, the authors used aeroelastic models for two different turbine types in order to optimize both isolated wind turbines and turbines in wind plants for a variety of different terrains. Five different optimization scenarios were considered, with options for modifying an existing turbine on site and for completely replacing the turbine. Using these methods, Fuglsang et al. 2002 found a reduction in the cost of energy in each of six different wind scenarios, with the maximum benefits at low wind speed, low turbulence sites. The study did not, however, include plant layout optimization as a component of the analysis.

Comprehensive work done in collaboration between Delft University of Technology in the Netherlands, the University of Sunderland in the United Kingdom, and several industrial partners took an explicit "systems approach" to looking at Structural and Economic Optimization of Bottom-Mounted Offshore Wind Energy Converters (Opti-OWECS) (Kühn et al. 1997a). The study involved the development of cost models for offshore turbines, including their foundations as well as balance of station and O&M. It also involved extensive physical modeling of the structural response of turbine designs to extreme conditions using finite element analysis and involved dynamic modeling of long-term behavior of turbines using combined wind-wave models (Kühn et al. 1997a). Finally, site-specific design was developed by the integration of Geographic Information System (GIS) tools with a cost-of-energy model based on the prior work in order to evaluate cost of energy for offshore wind in shallow waters across Europe (Kühn et al. 1997a). The work resulted in an integrated tool for turbine and plant design that considered cost of energy and represented a thorough systems approach for the development of a final two-bladed downwind design on a soft-soft monopole for shallow offshore applications (Kühn et al. 1997a). However, explicit use of MDO techniques was not involved and each step was a sequential progression from the last where a set of concepts were evaluated for feasibility at different sites. The set of sites and concepts were then evaluated for performance at a conceptual design level; component concepts were evaluated; then structural evaluation of those concepts evaluated the costs, aerodynamics, structures, and reliability of selected sub-system concepts (Kühn et al. 1997b). The approach in general captured many of the aspects for wind energy system design but did not encompass the flexibility for a wide variety of applications since each task in the project built upon the last.

The final work to be discussed also links wind turbine design to overall plant design, including environmental and financing aspects of the system design. The Offshore Wind Integrated Cost (OFWIC) model incorporates models for wind, wave, turbine, balance of station, O&M, environmental pollution impacts, financing, scheduling, and network integration to do detailed optimization for a specific site while also including various sources of uncertainty in the design variable set (Ozkan and Duffey 2011). This approach represents a holistic approach to designing an entire wind energy system, while the fidelity of representation of different components and disciplines in the system was therefore simpler than some of the earlier MDO studies discussed in Table 2. This again illustrates the trade-offs that exist in problem scope and fidelity of representation that must be considered in any particular system engineering application. The research in the overall field of MDO as applied to wind turbines and plants is still evolving, and there are plenty of opportunities for developing and leveraging these methods for wind energy research, design, and development. Huge opportunities for research activity exist focused on multidisciplinary design of wind energy systems that consider multiple levels of system design from the components to the turbines to the plants and even beyond, incorporating transportation, logistics, grid integration, and environmental/community concerns.

2.1.2 Multi-Objective / Multi-Criteria / Multi-Attribute Optimization

An important subset of MDO methods are MOO methods, also known as multi-criteria optimization and multi-attribute optimization. The key difference, as noted before, between traditional MDO and MOO is the optimization of a collection of objectives at the system level rather than a single, specific objective. The resulting optimizations can either contain a single design (if some sort of aggregation function or hierarchy is used to create a composite function across the different objectives) or they can contain a "space" of designs that can be compared against each other during post-processing analysis.

Another key difference between MDO and MOO concerns their respective disciplinary origins. While MDO was developed primarily within the aerospace and system engineering design disciplines, MOO has a much longer and more diverse history that originated within the field of economics nearly a century earlier, and then into mathematics before ultimately reaching engineering in the late 1970s (de Weck 2004). Vilfredo Pareto's name is most famously associated with the concept of a *Pareto frontier* or *Pareto optimum*, which is used throughout the optimization literature and in a myriad of disciplines from economics to operations research. The general idea is that point designs along a Pareto frontier are "Pareto equivalent" and selecting between them involves a trade-off between two system design criteria such as performance along some dimension (wind energy production, for example) and cost (wind energy plant LCOE, for example). For instance, ignoring cost for a moment, if there is some way to value the combined effect of different levels of machine rating and capacity factors for a wind turbine design, then this would potentially result in a Pareto frontier that maximizes some combined utility arising from collective optimization of both parameters. This is illustrated in Figure 13.

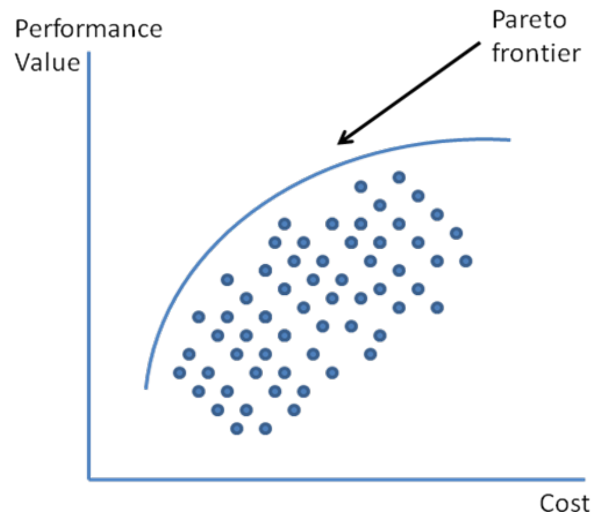

Figure 13. Graphical example of a Pareto frontier—points at the outermost edges near the line are "Pareto-equal" in terms of value and cost trade-offs

Since the mid-1980s, a wealth of research activity in MOO has been developed in the systems engineering design space among other disciplines. Broadly, MOO methods can be classified into two categories based on whether the method collapses the multiple objectives into a single objective (i.e., scalarization methods) or whether the multiplicity of objectives is preserved in the optimization process (i.e., Pareto methods) (de Weck 2004). In the first case, scalarization methods apply some functional transformation to the multiple objectives in order to combine them. These may include an aggregate function using a weighted sum or even the incorporation of multi-attribute utility analysis. In particular, multi-attribute utility theory seeks to elicit the value preferences that stakeholders have for different system objectives in order to combine them into a single utility function as one would do in standard microeconomic theory (de Weck 2004, Ross 2006).

On the other hand, Pareto methods allow for increased autonomy of the decision-maker in evaluating the trade-offs between key system design attributes. In order to reduce the design space to a manageable number of designs for decision analysis, different techniques are used, such as Pareto filtering, which identifies designs that are “dominated” by other designs and are filtered out, thus building a Pareto frontier as seen in Figure 13. Such techniques are particularly useful if the types of systems being compared are not detailed variations of a single design concept but instead represent a broad range of system configuration possibilities (Ross 2006). In this sense, the concept of a design “trade space” becomes important where there are many potentially adequate designs along the Pareto front, and careful consideration of different designs along the front is important to assess the key trade-offs between different designs for further consideration (Ross 2006). The notion of trade studies, used to evaluate system configuration trade-offs early in the design process, is a key aspect of systems engineering identified by various systems engineering organizations (NASA 2003, Haskins et al. 2010).

2.1.3 Concurrent Engineering / Project Management

Concurrent engineering and integrated design have to do with managing the human element of the systems engineering of large-scale complex technical systems. There are many synonyms for concurrent engineering, including concurrent design, computer supported collaborative design (CSCD) or cooperative design, and integrated product and process development (IPPD) (Shen et al. 2008, Haskins et al. 2010). According to the NASA Systems Engineering Handbook, concurrent engineering involves all elements related to design of complex technical systems including people and tools as well as organizational processes and facilities (NASA 2007). It involves designing a product through collaboration among multidisciplinary product developers from the entire product life cycle, including preliminary design, detailed design, manufacturing, assembly, testing, quality control, and product services (Shen et al. 2008). While in the previous sections MDO was described as a single analysis tool for holistic design that could perform optimization at the push of a button, concurrent engineering recognizes that there is a natural partition of responsibilities in the design of commercial products. Often, these segmentations fall along traditional disciplinary lines and "systems integration" must be performed across the relatively independent disciplinary design groups. This is especially important as industry sectors become increasingly global and geographically distributed. At the same time, the development of increasingly advanced and sophisticated models, computational tools, and communications technologies allows for an increased level of integration activity throughout the entire design process. Therefore, from both sides—industry needs and enabling technologies—there is a push toward a systems engineering approach to the product design that is embodied in concurrent engineering.

The development of concurrent engineering and CSCD began in the 1980s with the coining of the term *computer supported cooperative work* by Grief and Cashman in 1984 (Shen et al. 2008). Shortly thereafter, the concept of concurrent engineering was developed and defined as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support" (Turino 1992, Shen et al. 2008). One of the key early contributions of the field was to bring the downstream considerations of manufacturing and product services upstream into the preliminary design consideration process. Recognizing that the flexibility to make major design changes is much larger at the beginning of the design process as opposed to later on closer to production, companies were motivated to create integrated product teams that would cover the entire life cycle for product design (Haskins et al. 2010). Therefore, concurrent engineering primarily emphasizes two traits: (1) a multidisciplinary approach to the overall design process as seen in MDO, and (2) the use of technologies and processes that build communication across organizational teams involved in the design process. Research in concurrent engineering focuses on developing these multidisciplinary design tools, communication technologies, and management processes. Design of complex engineering systems may then be coordinated across disciplines, both inside single companies or across a complex network of companies that includes suppliers, for instance, of individual components; manufacturers of turbine systems; and developers of entire wind plants.

The multidisciplinary design tools of MDO and MOO were highlighted in the previous section. There are many other design tools used in concurrent engineering such as Quality Functional Deployment (QFD), Taguchi Methods, Design for Manufacturing and Assembly (DFMA) and Failure Mode Effects Analysis (FMEA) (Loureiro et al. 2004). These design tools are complemented by communication tools in the overall concurrent engineering approach.

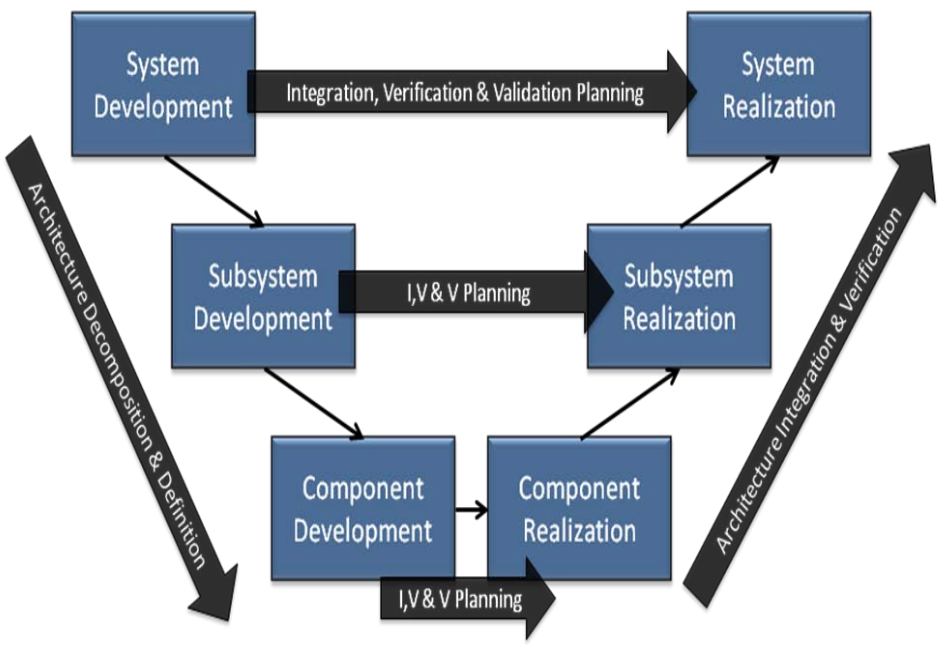

Figure 14. Design "Vee" model adapted from the INCOSE Systems Engineering Handbook (Haskins et al. 2010)

Communication tools involve standard technologies such as the Internet as well as design-specific tools, such as computer-aided design (CAD), that allow various agents in the design network to share and access the same sets of information. In terms of management processes, there are various methods within concurrent engineering to guide the design life cycle, including the waterfall, spiral, and Agile models (Haskins et al. 2010). Probably the most well known of all such design life cycle management processes is the design "Vee" model, which represents the different phases in design and the coordination activities that should occur across them at each step, as illustrated in Figure 14 (Haskins et al. 2010). Beyond design life cycle models, there are various processes and associated tools within concurrent engineering to support the design of large-scale complex systems including team management (organizational structure); product structure management (use of Bill of Materials, object-based design structure matrices [DSM]); workflow and process management (use of task-based DSM and other tools); design change management; visualization-based collaborative workspace (emphasizing visualization decision-support tools); and integration interface management (layout of information flows across design agent groups) (Shen et al. 2008).

Each of these areas of concurrent engineering—models, communication tools, and organizational processes—are important in the overall design process and are intimately connected to the organization of overall software architecture that supports the concurrent design process. The section on software architecture and computation will emphasize the role of each of these areas in development of a systems engineering approach to design of complex technical systems. Indeed there are many overlapping considerations between developing a concurrent engineering approach to the design process and the software that supports the process. While concurrent engineering relates more to system design from a commercial standpoint, the integration of design, communication, and organizational processes is equally important to research and development programs associated with large-scale complex systems. The ability to integrate across design tools and to improve communication between research tasks *during* the research and development process would lead to improved overall research methodologies, enhanced validity of analysis and results, and improved overall impact on the understanding of design of wind energy systems.

2.2 Supply Chain Management: Transportation and Logistics

In general, supply chain management focuses on flows. These flows can be of materials, information, or even finances among the entire network of organizations associated with a given product—from suppliers of raw materials, to manufacturers of components, to manufacturers of assembled products, to distributors of those products, and the customers who ultimately own and use and operate those products (Lummus and Alber 1997). The Association for Operations Management defines the *supply chain* as the processes involved to take initial raw materials through to the ultimate consumption of the finished product that links across supplier-user companies (Cox et al. 1995). From a wind energy perspective, as shown in Figure 15, the supply chain may include a large number of entities, such as: (1) mining companies that supply rare-earth metals, which are then supplied to (2) manufacturers of different types of generators, which are then delivered to (3) an OEM that assembles that generator along with the rest of the nacelle components and then delivers the turbine via (4) some transportation firm a developer contracts with to a site where (5) a construction firm assembles the entire turbine that is part of a larger plant, which is then owned and maintained over the long term.

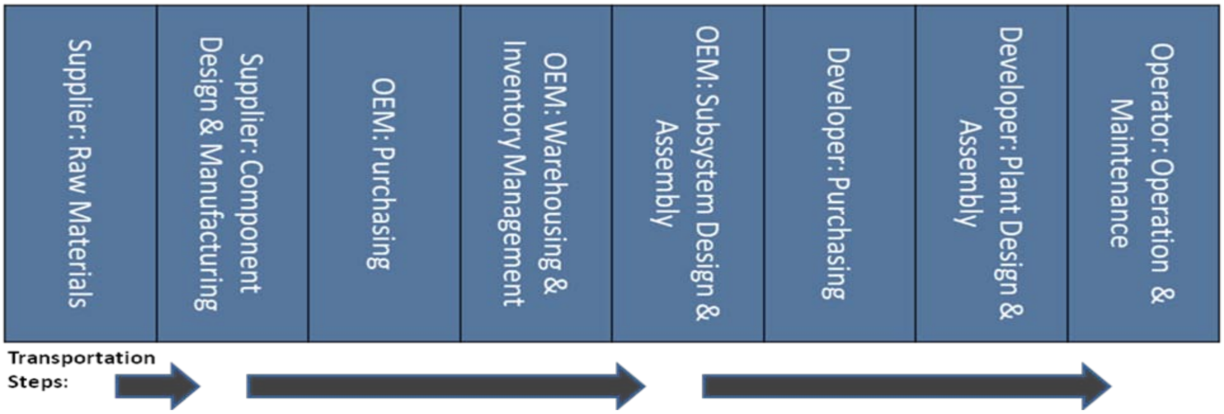

Figure 15. Supply chain view of the wind turbine industry

The supply chain accounts for everything that relates to transfer of materials and products that ultimately impacts system cost. Interest in supply chains and supply chain management has grown steadily since the 1990s due to many factors, including the shift away from traditionally vertically-integrated firms, increased national and international competition, and the desire for a holistic approach to firm performance across departments and functions (Lummus and Vokurka 1999). Since the mid-1980s, firms in several industries have begun to take supply chain design and management seriously, beginning with the textile industry and moving to the computer industry (e.g., Hewlett-Packard) to the retail industry (e.g., Walmart) to the building products industry (e.g., Georgia-Pacific Corporation), and interest in the topic from an academic standpoint has grown steadily as well (Lummus and Vokurka 1999). The approach to supply chain management includes the core principles of systems engineering, such as a holistic approach to system analysis and management integrated with customer value and focused on the cradle-to-grave life cycle of the product, as well as crossing intra-firm and inter-firm boundaries (Mentzer et al. 2001). The field of supply chain management is immense and includes broad topics associated with demand, inventory, logistics, and transportation from both a planning and management perspective. The scope discussed in this report is limited to transportation and assembly logistics that relates to the balance of station and operations associated with a wind energy system. Issues associated with manufacturing and supply of materials are also extremely important but will be deferred in the interest of scope.

Similar to the field of system design, there is also a heavy emphasis in transportation planning on optimization. However, instead of a single physical system such as a wind turbine, the optimization of interest for transportation planning involves a network. Therefore, network analysis and optimization methods underlie much of transportation planning and management research. In general, the problem involves minimization of transport costs for a set of products between a set of suppliers and a set of customers. There may be intermediate points of aggregation as well so that the product is transformed as it is moved through the network (i.e., in conversion from raw materials, to components, to sub-system assemblies, to a fully assembled product). Methods used to support this analysis stem from graph theory and computer science in particular where extensive algorithm development has focused on analyzing and optimizing network performance. The analysis typically starts with the representation of the network and includes all of the various nodes/vertices, connecting edges (both directed and undirected), and the attributes of both network vertices and edges (which may be heterogeneous along different dimensions). Algorithms have then been designed to solve problems related to various network types, such as the classic "shortest path problem" for network flows (Daganzo 2005). This problem and related sub-problems, such as the "traveling salesman problem (TSP)," involve different mathematical programming algorithms to find, for instance, the shortest weighted-path between two vertices in a network or, in the case of TSP, the shortest path that goes through every vertex exactly once and ends at its origin.

There are many such "archetype" problems in network analysis, and a few of these are relevant to supply chain management such as the "transport problem" and the "transshipment problem" (Daganzo 2005). In transport, one is concerned only with the flow of fixed denominations of goods from a set of origins to a set of destinations while in transshipment, goods can be aggregated and partitioned off at different points (i.e., goods from multiple suppliers can be aggregated together in a warehouse and then shipped in bulk, or vice versa: goods at a warehouse can be separated into groups for smaller shipments to different destinations). Transshipment is defined as the act of taking an item out of a vehicle and loading it onto another and does not typically include the transformation of that item that may occur through manufacture or assembly (Daganzo 2005). These analyses are very complex and involve multiple types of costs, including holding costs in rent for facilities and costs for holding inventory; transportation costs in terms of distance and headways and size effects for permitting and multiple modes of transport; and finally, handling costs associated with loading and unloading products. In addition, many aspects of the transportation variables and costs are uncertain, resulting in a number of stochastic effects in the system (Daganzo 2005). Including the transformation of goods via manufacture and assembly, the ability to look at product-family or multi-product supply chain considerations, as well as the flexibility in decisions regarding facility location all add another layer of intricacy resulting in a highly complex optimization problem that pushes the boundaries of algorithm design and computation. Finally, there may be the dynamics associated with different logistics needs at different times for the system, such as the different needs associated with initial installation for a large-scale construction project and long-term O&M.

2.2.1 Applications of Supply Chain Management in Wind Energy

Returning to wind energy systems, the scope of research questions that may be addressed via supply chain theory and methods is extensive. Supply chain questions may even be integrated with other system design issues from the individual turbines to the plant. The WindPACT studies coordinated by NREL in the early 2000s represented one specific study that aimed to capture the complexity of integrating turbine design with plant design as well as supply chain considerations.[1] The report *WindPACT Turbine Design Scaling Studies Technical Area 2: Turbine, Rotor and Blade Logistics* focused on the logistics associated with the transportation and on-site assembly of the entire turbine, including the tower, nacelle, and rotor (Smith 2001). The study involved a hypothetical wind plant of 50 MW in South Dakota combined with a set of different sourcing plants, transportation modes, and assembly options as well as multiple turbine sizes in order to develop detailed industry cost estimates for transportation, assembly, and installation (Smith 2001). The number of source options for different components was limited to existing facilities in a few places in order to reduce the dimensionality of the overall problem. Using these significant simplifications, estimates for the particular project for particular turbine sizes and designs were obtained in order to assess the overall cost of energy for respective turbine sizes and the key cost challenges facing each type, such as transport of the nacelle, tower, and blades for larger turbines with higher hub heights (Smith 2001). The study's strengths included: (1) the thorough and extensive data collection on transport costs by mode and component as well as the integrated transport/assembly costs for different logistics strategies, and (2) the integration of turbine system design issues with transport/assembly cost considerations for a holistic approach to evaluation of the cost of energy. However, much more could be asked of integrated turbine, plant, and supply chain design for wind energy. For instance, continued scaling of land-based wind turbine technology will require new designs that overcome transportation size/weight restrictions such that a design process must be integrated with logistics in order to improve the overall cost of energy. Similarly, for offshore wind technology, the complex nature of logistics

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[1] Detailed WindPACT reports can be found at http://www.nrel.gov/wind/windpact.html (last accessed 08/10/2011)

associated with the installation and operations and maintenance of a wind plant can be a significant aspect of the overall cost of energy which again alludes to the need for design processes that integrate with supply chain analysis.

2.3 Other Important Systems Engineering Sub-Fields Related to Wind Energy Development

While there are many other methods in the area of systems engineering, the above methods discussed were chosen for their particular relationship to the cost of energy for wind systems, including turbine, plant design, and transportation concerns. Other methods also have a significant impact on cost of energy, such as reliability engineering and the closely related areas of robust design and safety engineering. In addition, the sub-fields of decision and risk analysis, as well as risk management, are closely related to some of the multidisciplinary design work discussed earlier. Finally, cost engineering is often treated as a unique academic niche that merits a short discussion. Beyond this, there are a number of methods that would aid in the analysis of a more broadly defined system scope for wind energy that extends into the grid integration space as well as the impacts on the environment and local communities. In the interest of scope, discussion of these methods has been deferred to subsequent work.

One key area of interest with respect to turbine designs and plant operation has to do with turbine reliability. Turbine reliability affects turbine availability and therefore annual energy production as well as maintenance and replacement costs to the system. Therefore, reliability has a dual effect on wind energy system cost of energy. Reliability engineering is a sub-field of systems engineering that attempts to understand the life cycle reliability for a given system. Methods within the space emphasize probability and statistics that inform models that affect the design, testing, and operation of a technical system. It is very difficult, if not impossible, to simulate the environmental conditions to which a system will be exposed given both uncertainty of environmental conditions and the long-lived exposure the system will have to that environment. Thus, within the wind energy industry, as with many other industries, design and testing standards are used in order to ensure that systems can maintain certain levels of reliability throughout their expected life. These standards are sometimes derived from probabilistic analysis and involve a variety of assumptions or they may be based on design experience that has accumulated over time. Either way, reliability issues are still a significant concern for the industry and use of reliability engineering tools can aid in understanding and managing these concerns. Two complementary tools in this space are hazard analysis, to identify potential threats to system reliability, and failure mode and effects analysis (FMEA), to analyze the failure modes within a system and the associated severity for different potential failure modes. Such analysis can be combined with reliability analysis methods using probabilistic techniques (Probabilistic Risk Assessment) to understand the mean time between failures and expected lifetimes for different components and subsystems within the system (Tavner et al. 2007).

These methods are also important to safety engineering which is critical for influencing design for human interaction with a system. Humans interact with technical systems both during their operation as well as for installation and maintenance, and safety engineering borrows from reliability engineering in order to ensure worker safety is met at all such points of interaction.

In addition to understanding the effects of design on downstream reliability performance of the system, the above methods can be used to support the operation of the system for reliability. More recently, interest in condition monitoring and prognostics and health management has received attention as a way to provide a more proactive approach to management of reliability throughout the entire life cycle of the system (Jazouli and Sandborn 2011). These methods extend the analysis techniques to active management of the system that evaluates the trade-offs in costs from upfront design choices with predictive maintenance of the system during its operation and the downstream costs of lost availability as well as unscheduled maintenance and replacement of system components.

This decision trade-off between upfront design choices and downstream impacts on reliability is one regarding issues associated with decision and risk analysis / risk management of a complex technical system such as a wind turbine and plant. Decision analysis is a relatively old field focused on formalizing decision processes with a set of methods and tools to introduce as much systematic rationality as possible (Howard 1966). The main tool associated with decision analysis is the decision tree that maps single or multiple decisions to their potential outcomes in a structured way in order to assess the relative value of different options. The outcomes may also have a degree of uncertainty such that the selection of one decision may lead to multiple potential outcomes with different probabilities of occurrence. Different methods can then be used to evaluate different end states, such as expected value theory, avoidance of extremes, or other outcome-weighting schemes. Decision analysis is therefore tied closely to risk analysis and the associated methods in reliability engineering.

Finally, cost engineering is another sub-field of systems engineering important to large-scale complex technical systems that focuses in particular on the costs associated with a project rather than the technical system itself. The discipline integrates project management and engineering to understand how scheduling and engineering for large-scale projects influences overall cost. For a wind energy plant, this can be most closely associated with the balance of station, financing, and scheduling costs associated with the installation of a particular plant, which is similar to other large civil engineering or construction projects. In particular, such cost estimates take into account the time value of money and the effect of delays and schedule on the cost of energy. For a wind energy plant, these costs can surface from the time initial feasibility studies of a plant are performed, to the time it takes to permit a project, to the time it takes to construct and commission a project for operation.

The above mentioned topics of reliability engineering and cost engineering are important to overall wind energy system design and deserve as much discussion as supply chain management and even multidisciplinary design. Future work and planning will look more closely at these methods due to their importance to wind energy system design, performance and costs. In summary, there are a wide variety of methods in systems engineering and arguably, all of them hold potential applications to wind energy systems due to the large-scale and complex nature of the technology and its interaction with its environment. While the numbers of instances in which systems engineering methods have been explicitly applied to wind energy are few, there are a number of places for which tools developed to analyze and design wind energy systems have an implicit systems engineering approach or could be easily adapted for use in a larger systems engineering framework.

3 Modeling of Wind Energy Systems with Emphasis on Tools Developed at NREL

Tools to model wind energy systems have been under development since the large federally funded wind energy research programs began in the 1970s. These tools model every aspect of a wind energy system from the individual components to full turbines operating over long time periods to interaction of individual turbines in wind plants and even to the interaction of wind energy turbines and plants with the electric grid. The below survey highlights the role of modeling tools at these various levels of system design with particular emphasis on tools used at the NWTC that may be integrated into a WESE tool and framework. Such tools are an important building block within the creation of a systems engineering approach to wind energy research, design and development.

3.1 Overview of NREL Wind System Design Tools

The integration and optimization of overall system properties within the wind system design toolset is a near future goal for NREL. The left side of Figure 16 shows the current state of wind energy system design tools used at NREL as they relate to the systems engineering methods discussed in the previous section. On the right, the expected and desired development of the program reflects the goal of integrating and developing existing tools within an overarching systems engineering framework. The blue circles indicate the types of system engineering methods that are applicable to wind energy research design and development, as discussed in Section 2. The gray circles represent the existing tools that might be integrated together into a full system analysis tool within a WESE framework. Such a potential path for integration of wind energy modeling tools into a WESE framework will be discussed in Section 5.

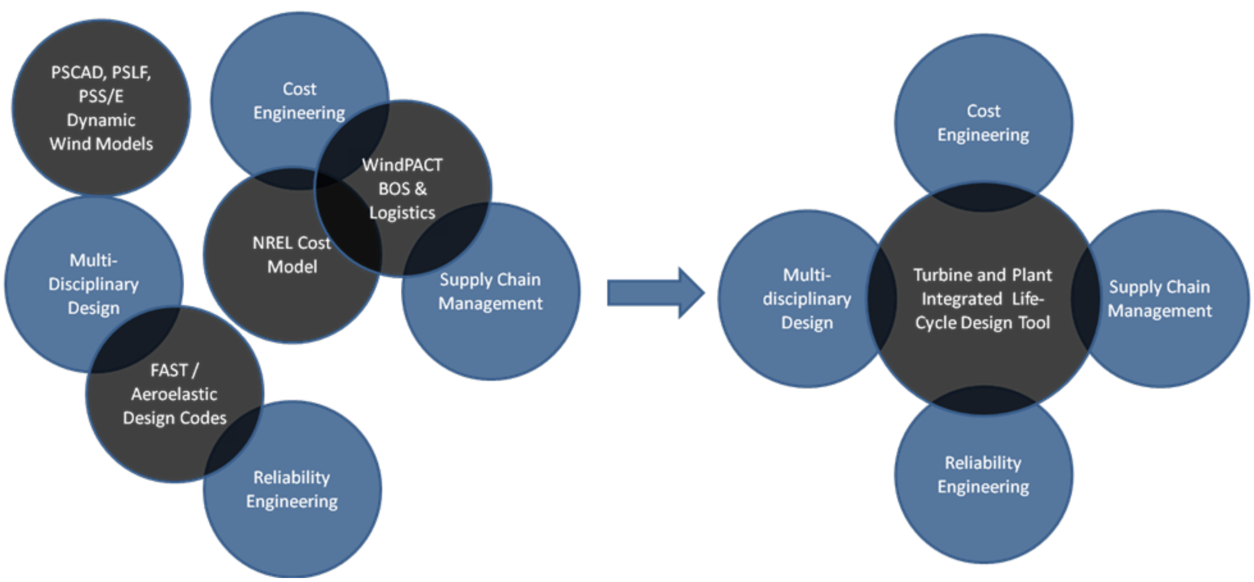
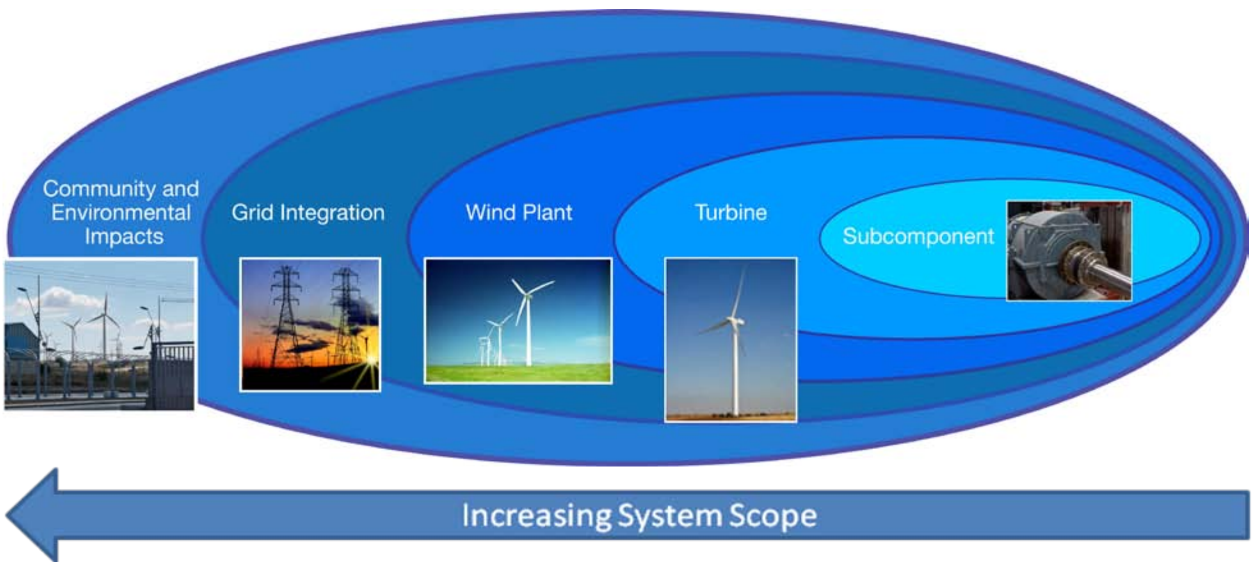


Figure 16. Overlap of systems engineering methods and NREL wind energy system design tools today (left) and direction of fully integrated model for the future (right)

As illustrated in Figure 17, design tools used at NREL apply to different scales of the project from sub-component to wind farm scale and beyond. In the existing NREL toolset, the finest level of detailed modeling occurs at the subcomponent level. At the turbine design level, turbine subcomponent properties are simplified. For example, at the subcomponent level, modeling can focus on a complex geometric representation of all materials in the substructure, down to the blade resins and coatings. However, at the turbine design level, the blade is typically represented in a more simplified manner—for example, as a beam with much fewer degrees of freedom than the subcomponent model.

As spatial boundaries expand to include wind plant optimization and grid integration, the modeling of wind turbine subcomponents simplify further. For example, when modeling a rotor for turbine-to-turbine interaction in a CFD model, historically the representation of the turbines were such that the individual beams and actions of rotation disappear and are instead replaced by an actuator disk, which was a disk structure within the model with a pressure drop across it to represent the power extracted by individual turbines. Or, in the case of plant optimization, a simplified wake model can be used to represent turbine interactions without any physical representation of the rotor. Current research is moving past such simplifications, but in practice many simplifications are necessary depending on the scale of the model and the desired research analysis. In contrast, as you drill down to the subcomponent level, models of specific substructures become more refined and have greater degrees of freedom. For example, turbine design tools can be used to develop inputs to subcomponent models in order to create load cases for critical subcomponents, such as the gearbox.



Images Left to Right: NREL/PIX 19709, NREL/PIX 19498, NREL/PIX 16541, NREL/PIX 17118, NREL/PIX 08566

Figure 17. Design tools used at NREL apply to all scales of a wind farm project

Although a systems engineering approach to wind energy system design has not been an explicit program goal for NREL in the past, many of the in-house tools have been developed for research and analysis of wind turbines, components, and plants and therefore include some elements of systems engineering methods. In particular, NREL's aeroelastic design codes are inherently multidisciplinary by necessity in order to represent the complex dynamics of long-term wind turbine operation.

The NREL team is already working on some elements for modular assembly of coupled models with varying fidelity that are important to a systems engineering approach to wind energy system research, design, and development. This modular approach allows a hierarchy of interchangeable models for each component of the system. For example, a developer interested in offshore wind plant optimization needs the ability to run a large number of relatively inexpensive simulations over a range of parameters and therefore would specify relatively simpler, but computationally more efficient, models for most components. On the other hand, a researcher investigating gearbox fatigue under different atmospheric stability conditions will require fewer simulations but with more sophisticated and computationally expensive models. Accurate model coupling that is both robust and flexible requires careful consideration from a numerical methods/algorithms and software/computing perspective, which is a significant component an overall systems engineering approach.

The following sections provide an overview of the types of tools used for wind turbine design research, including subcomponent models, turbine design tools, wind plant layout and optimization tools, cost models, and wind plant integration. The emphasis of the discussion is on tools used and/or developed at NREL as a building block for the final chapter, which focuses specifically on how NREL may move towards developing an in-house systems engineering framework for wind energy research.

3.2 Subcomponent Models

At the subcomponent level, many generic models exist that can be applied to the wind turbine design. For example, SIMPACK is a multi-body simulation model used at NREL for drive train analysis. Multi-body simulation tools model the internal components of the drivetrain as rigid bodies and define their interaction with other components. Therefore, when combined with aeroelastic wind turbine design tools, the drivetrain can be modeled in more detail. Load cases for individual drive train components can be developed and combined with the standard set of IEC 61400 load cases to improve the overall design process (Oyague et al. 2009). This is particularly valuable in studying multiple design criteria, such as turbine capital costs and long-term reliability. More comprehensive subcomponent models, such as finite element analysis tools, can also be used to evaluate more detailed design issues such as gear contact stress, torsion and bending behavior of the gear shafts, and generator housing deflections (Oyague et al. 2009). There is similar scale and complexity for each subcomponent in the wind turbine system (Figure 18), and associated detailed subcomponent models are capable of modeling each one.

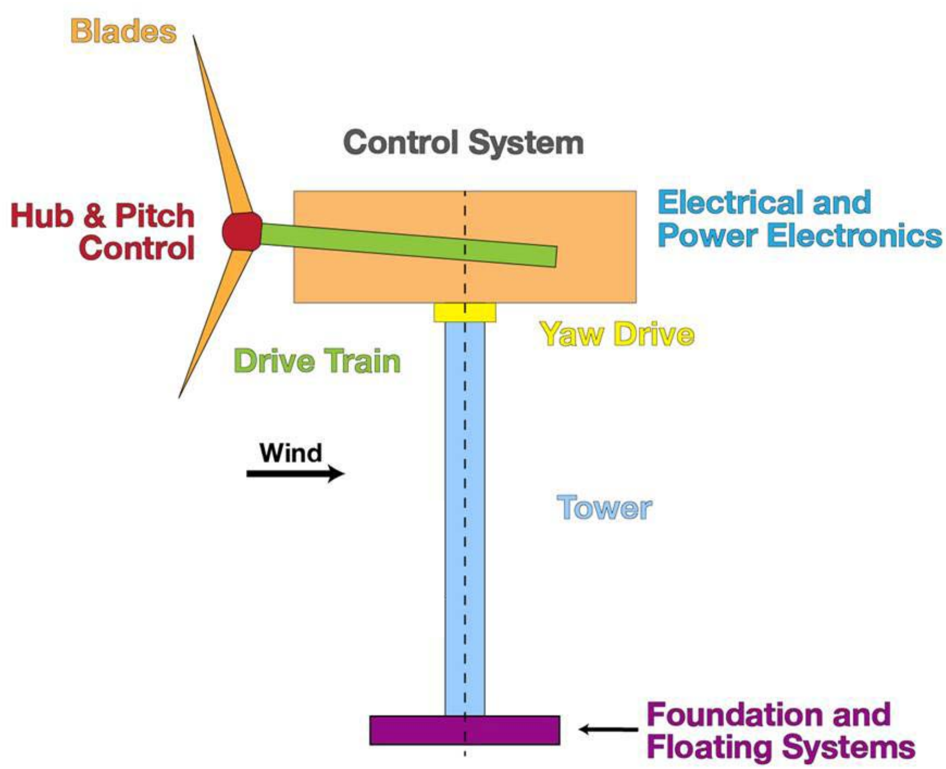


Figure 18. Accurate modeling of the wind turbine system depends on the interfaces with all critical subcomponents

3.3 Turbine Design Tools

The analysis of wind energy structures requires advanced design tools that model the important physical phenomena and system couplings, including the environmental excitation (wind, waves, and current) and full-system dynamic response (rotor, drivetrain, nacelle, support structure, and controller). The wind industry relies extensively on advanced design software tools for the analysis of wind turbine performance, loads, structural integrity, fatigue life, and cost. The fundamental design tools are comprehensive "aero-hydro-servo-elastic" models that simulate the coupled dynamic response of a complete wind turbine system (from the rotor, through the drivetrain, nacelle, and tower, to the substructure and foundation). This means that they incorporate integrated models for the wind loading (aerodynamics); wave loading (hydrodynamics); control and electrical system (servo) dynamics; and structural (elastic) dynamics (gravitational, inertial, centrifugal, gyroscopic loads, etc). The integrated modeling of these physical phenomena is important for capturing the coupled effects that dictate the global response of a wind turbine and for system-wide design optimization. There are a variety of tools in this space, including tools developed at national labs as well as commercial tools maintained by wind energy consulting firms. Table 3 gives an overview of different aeroelastic design tools available today.

Table 3. Common commercial and research aero-hydro-servo-elastic design codes for wind turbines (for more detail on available codes and capabilities see Jonkman and Musial 2010)

Code	HAWC2	FAST	GH BLADED	Flex5	PHATAS
Source	RISØ (Denmark)	NREL (US)	Garrad Hassan (UK)	Dong, Vestas A/S (Denmark)	ECN (Netherlands)
Licenses	Academic or Commercial license	Open Source	Commercial	Commercial (but Source Code Included)	Commercial

The models above may include modal, multi-body, or combined modal and multi-body, or even finite-element method representations of the wind turbine structural dynamics. They all generally use blade-element/momentum theory for the aerodynamics with dynamic stall but may also use a generalized dynamic wake model in addition to dynamic stall. The inclusion of offshore structural and hydrodynamic capabilities varies significantly across the tools, and there are ongoing development and code comparison efforts to evaluate different codes applied to offshore wind turbine design analysis (Jonkman and Musial 2010). Of the above models, only NREL's FAST tool is freely available and open source. Various international efforts have worked over the years to evaluate and compare these codes for wind turbine design. Reports of these efforts are available from the International Energy Agency, which coordinated those efforts through IEA Wind Tasks 23 and 30 (Jonkman and Musial 2010).

3.3.1 NREL Aeroelastic Design Tools

NREL has developed and maintained wind turbine aeroelastic design tools since the 1980s. This involves a set of preprocessors that create input files for wind and structural data, simulators that run time-domain simulations of wind turbine operation, and post-processors that analyze the simulation results. FAST and associated models developed at the NWTC are featured in Figure 19.

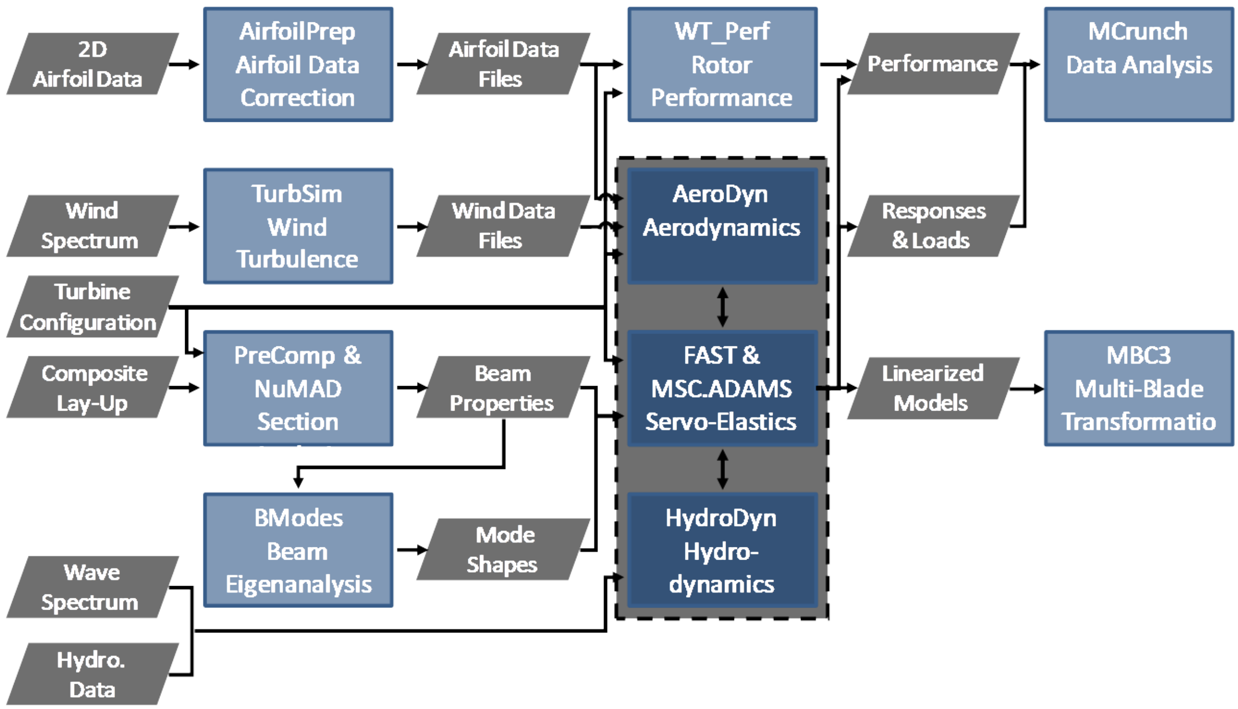


Figure 19. Key NREL codes in the turbine design process

The NREL suite for horizontal-axis turbines includes aeroelastic simulators of varying levels of complexity in the form of preprocessors, simulators, and postprocessors. NREL has developed several programs to create input files for aeroelastic and performance simulators. These codes are used to establish wind turbine component properties, including mechanical properties of flexible components, such as blades and towers, as well as the aerodynamic properties of the airfoils. Tools like BModes, which is a finite element code that provides dynamically coupled modes for a beam and airfoil preparation, help users generate the airfoil data files needed by other modules. Preprocessors are also used to define external conditions. For example, TurbSim is used to generate stochastic, full-field or hub-height turbulence files that can be used by simulator codes like Garrad Hassan's BLADED and all of NREL's AeroDyn-based aerodynamic codes. As shown in Figure 20, NREL's core computer-aided engineering tool, FAST, joins a rotor aerodynamics module (AeroDyn); a platform hydrodynamics module (HydroDyn); a control and electrical system dynamics module (various); and a structural dynamics module (internal) to enable coupled, nonlinear, aero-hydro-servo-elastic

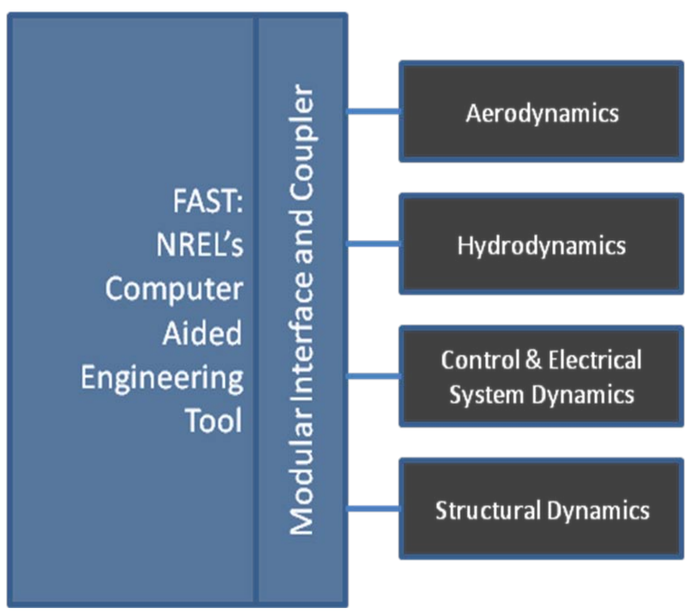


Figure 20. NREL's modular computer-aided engineering tool, FAST

analysis in the time domain. The FAST tool enables the analysis of a range of wind turbine configurations, including two- or three-blade horizontal-axis rotor, pitch or stall regulation, rigid or teetering hub, upwind or downwind rotor, and lattice or tubular tower. The wind turbine can be modeled on land or offshore on fixed-bottom or floating substructures.

The modules are distinct, allowing them to interface with other computer-aided engineering tools and allowing them to be exchanged for other modules. The ability to exchange modules is important for benchmarking, research, and industrial applications. Increasing wind-system complexity requires coupled analyses, for which the required fidelity is dictated by the application. This modularization framework enables one to select modules. For example, FAST's structural fidelity is limited by its DOFs. However, the AeroDyn and HydroDyn modules have also been interfaced to the nearly unlimited DOF multi-body dynamics tool MSC.ADAMS (Laino and Hansen 2001), a commercially available and general purpose tool from MSC Software Corporation. Coupling of commercial ADAMS with NREL's AeroDyn and HydroDyn enables higher fidelity structural analysis of wind systems with aerodynamic and hydrodynamic loading. Such integration is also a feature that is important to and would be incorporated into a systems engineering approach to wind energy research, design, and development.

In addition to FAST, NREL has developed other codes that simulate wind turbine performance, such as WT_Perf, which uses blade-element/momentum theory to model the steady, rotor performance of horizontal-axis wind turbines. WT_Perf can generate performance data for all combinations of parametrically varied wind speed (or tip-speed ratio), blade pitch, and rotor speed. It is a simple performance code that is fast and relatively easy to use for applications where all that is needed is a general estimate of power production and root-flap bending moments. From a systems engineering perspective, the choice between FAST or WT_Perf reflects the need for models of multiple levels of fidelity, depending on the particular research or design application. As reflected in the MDO wind energy applications discussed in Section 2, users of higher-fidelity models are more commonly associated with detailed component optimization (Bottasso et. al. 2010), while optimization of overall system configuration might involve a lower-fidelity representation such as FAST or even WT_Perf (Vlahopoulos et al. 2011, Crawford and Haines 2004).

Finally, there exist complementary simulation codes to FAST that target acoustic impacts of wind turbine design. Models that calculate the acoustic impacts of a wind plant are the most sophisticated of the set of tools to estimate community impacts. Detailed noise models of turbine and wind plant operation exist such as the NREL Airfoil Noise (NAFnoise). NAFnoise uses semi-empirical routines to predict the noise output of any airfoil from a turbine modeled using FAST (Moriarty 2005). A systems engineering approach that looks at noise mitigation in wind turbine and plant design, such as illustrated in Section 1, would depend on the ability to integrate models for wind turbine and plant noise with the aero-hydro-servo-elastic models.

3.3.2 Future Work and Needs

Work on verification and validation of the codes is ongoing, as is the coupling of FAST to other modeling tools, such as OpenFOAM for array modeling. Future work will focus on validating codes for modeling of offshore systems with field test data from demonstration projects and adding the capability to model multi-pile support structures (tripods, jackets) in HydroDyn, which are proposed for use in transitional depth waters. Many of these developments are compatible to the development of a systems engineering approach for wind energy research, design, and development. Section 5 will further highlight these potential synergies.

3.4 Wind Plant Layout and Optimization Tools

The principal objective of any wind plant developer is to achieve a balance between upfront investment costs and downstream operations costs for the lowest overall possible LCOE for the project while avoiding adverse community impacts that would impede either upfront project permitting or lead to problems once the plant is operating. From a LCOE perspective, both the individual design of turbines as well as the impact that those designs may have on annual energy output, balance of station (BOS), and operations costs are important. The technical and economical aspects of onshore wind plants have been incorporated into specialized optimization tools used by developers today (see Table 4).

3.4.1 Wind Farm Interaction (wake) Models and Mesoscale Weather Models

Turbine wake losses are significant in affecting both onshore and offshore wind plants. In particular for offshore applications, state-of-the-art modeling tools routinely underestimate the plant losses from wake and other effects to be 10% or more (Moriarty et al. 2011). Wake effects can also contribute to higher-than-expected maintenance costs for wind plants. At the microscale, local fluid dynamics are modeled using CFD software packages. NREL is using one such CFD software package, OpenFOAM, which is an open-source CFD tool. NREL has developed a solver in OpenFOAM that models the atmospheric boundary layer and a basic turbine model to create an inflow and a fully turbulent wake field. OpenFOAM is a research-grade simulation tool. For developers, other publicly available tools exist with simplified wake models, such as the Wind Atlas Analysis and Application Program (WAsP). WAsP from RISØ in Denmark is a software tool that calculates wakes based on semi-empirical information and is therefore faster to run. At the macroscale, models such as the Weather Research and Forecasting Model (WRF), a numerical weather prediction model, simulate large, mesoscale phenomena. This model was developed under the leadership of the National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration (the National Centers for Environmental Prediction and the Forecast Systems Laboratory), the Air Force Weather Agency, the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration. WRF models weather patterns over wide regions of the United States and gives the variation of wind speed over time. Bridging macroscale models like WRF with microscale models, such as OpenFOAM, enable the analysis of how global and regional weather effects interact with local terrain to affect the operation of wind turbines and plants. The next intuitive step is to couple such models back to individual turbine models to build a holistic understanding of long-term performance of wind plants to aid in the design process. An initial interface between FAST and OpenFOAM has also been developed (Lee et al. 2011) and simulations of offshore wind plants have been performed. In addition, NREL team members have demonstrated initial coupling of WRF and OpenFOAM and validation. Such coupling of both detailed and simplified models again represents a central tenet of a systems engineering approach to wind energy research and design.

3.4.2 Layout Design and Optimization Tools

A number of key factors need to be considered when determining a wind farm's layout—these include the number and types of wind turbines, construction and maintenance operations, reliability, and electrical loss minimization, among other factors. Additionally, offshore wind farms must consider factors such as distance to the shore, water depths, and seabed geology when optimizing the plant's layout. However, the most crucial factor that determines the wind farm size for any given capacity, onshore or offshore, is the spacing between the turbines. If distance between individual wind turbines is too close, there is a significant risk of reduced overall wind farm performance due to wake effects. On the other hand, increasing distance between individual wind turbines will increase the infrastructure costs of the project. In addition to power production and infrastructure costs, future maintenance related operations must be considered when deciding on the final layout. In particular, various system loads and their impacts on long term reliability must be addressed.

There exists a number of public and commercial tools available to assist in the wind turbine layout design process. These tools combine GIS information to get site-specific resource and terrain characteristics, along with various types of wake models and optimization techniques to assist in real-world wind farm layout design processes. Tools may begin with some modified form of a PARK wake model for faster optimization and then use a more refined model, such as the Eddy-Viscosity model, for final placement. Other tools may import results of wind flow models that are simplified or full CFD simulations. WAsP, based on a linearized potential flow wake model, is imported into several of the software packages. However, many of the software packages now also include the option of interfacing with CFD model output files that characterize wind flow in more complex terrain. A list of commercial and research wind turbine layout tools is provided in Table 4.

Table 4. Common public and commercial wind plant analysis and optimization tools

Tool	Company/Organization
Meteodyn WT	Meteodyn
WindSim	WindSim
WindFarm	ReSoft Ltd.
openWind	AWS Truepower
WindFarmer	GL Garrad Hassan
WindPro	EMD International A/S
WindLAYOUT	GE Energy
Ventos	Natural Power
Raptor NL	WindLab
OpenFOAM	Silicon Graphics International

Most commercially available tools optimize on AEP, although many may offer some way of optimizing for the cost of energy. The University Of Massachusetts Amherst, Massachusetts Institute of Technology, and Woods Hole Oceanographic Institute collaborated to create a publicly available tool, the Offshore Wind Farm Layout Optimization project. The project linked micrositing criteria with cost optimization algorithms in order to minimize the cost of energy while maximizing energy production (Elkinton et al. 2006). The software tool quantifies the cost difference for projects in varying distances from shore and in different water depths. Cost scaling relationships in the model were developed using European studies. The project has many similarities to the work of Ozkan and Duffy 2010, as discussed in Section 2, since it also integrates the design of wind turbines with farm layout optimization.

3.4.3 Future Work and Needs

Work is needed both for modeling wind turbine interactions on and offshore as well as for optimized plant design and long-term operations. A combination of wake models and mesoscale models, coupled to turbine structural dynamic models, are needed for a computational simulation of a full wind-turbine power plant, along with its interaction with regional weather. Additionally, wind farm layout design and optimization models are needed that analyze the trade-off between turbine performance losses and wind plant layout cost savings. For wind plant design optimization, there is a need to integrate the turbine design with the overall plant design as is being addressed through the OpenFOAM-FAST coupling but without the added layer of optimization for looking at overall optimized system design. Such developments are important to a systems engineering design approach. In particular for offshore applications, significant work is needed in the plant layout and operations design space. At present, no validated, fully coupled, open-source tool can simulate the full range of systems and physical scales required for accurate prediction of wind plant behavior.

3.5 Wind Cost Models

Models for the cost and financing of wind energy may involve just the turbine capital costs or they may be extended to include a number of other important considerations such as: balance of station and operations costs, energy production, or even detailed project finance. NREL has developed wind cost models for these different applications with varying levels of fidelity in terms of representation of different aspects of overall wind energy system cost depending on the particular model.

3.5.1 Cash Flow Models

Cash flow models reflect the streams of income and expenses anticipated over the life of a project. Financial analysis typically assumes a 20-year period. Investment decisions may be based on returns of individual partners, subsidy revenue, etc that are independent of the plant and turbine design. A simplification often used to compare projects is LCOE. The LCOE is the cost of energy produced over the life of the project, generally considered to be 20 years. LCOE calculations are more uncertain than capital cost estimates because they include future projections of energy production, operational costs, decommissioning costs, and long-term reliability, in addition to the initial capital cost (Musial 2010). LCOE can be calculated with a number of different methods or approaches to represent several differing perspectives.

Two LCOE models developed at NREL are the System Advisor Model and the Cost of Renewable Energy Spreadsheet Tool. The System Advisor Model is a performance and economic model designed to facilitate decision-making for people involved in the renewable energy industry, ranging from project managers and engineers to incentive program designers, technology developers, and researchers. The model calculates the cost of generating electricity based on information the user provides about a project's location, installation and operating costs, type of financing, applicable tax credits and incentives, and system specifications. The Cost of Renewable Energy Spreadsheet Tool is an economic cash flow model designed to enable the renewable energy community to assess projects and design cost-based incentives (e.g., feed-in tariffs), and to evaluate the impact of tax incentives or other support structures.

3.5.2 Capital Cost, Balance of Station, and Operations Cost Models

This category of model includes greater fidelity in terms of representation of the technology at the expense of less detail from the financing and cash flow perspective. Many institutions have developed publically available wind turbine and plant cost models over the last two decades. NREL's Cost and Scaling model has gone under several stages of development since the early 2000s. Other such models have also been developed primarily within research institutions such as the University of Sunderland (Harrison 1993, Kühn 1997a). Empirical models have also been developed that are highly simplified scaling models of cost with turbine size based on historical data (Manwell et al. 2002). All of these cost models focus in particular on horizontal-axis turbines and most for a small set of configurations with respect to rotor, drivetrain, and tower. NREL's model shown in simplified relational form in Figure 21 captures design variations for different rotor, drivetrain, and tower designs. The detailed set of studies that made up WindPACT were used to develop this comprehensive cost of energy model for a hypothetical wind plant that includes (1) turbine capital costs and plant energy output, (2) BOS costs, and (3) the long-term costs associated with continued operation of the plant. Several sub-studies were done on rotor design and manufacturing, turbine logistics, alternative drivetrain configurations, and BOS costs.[2]

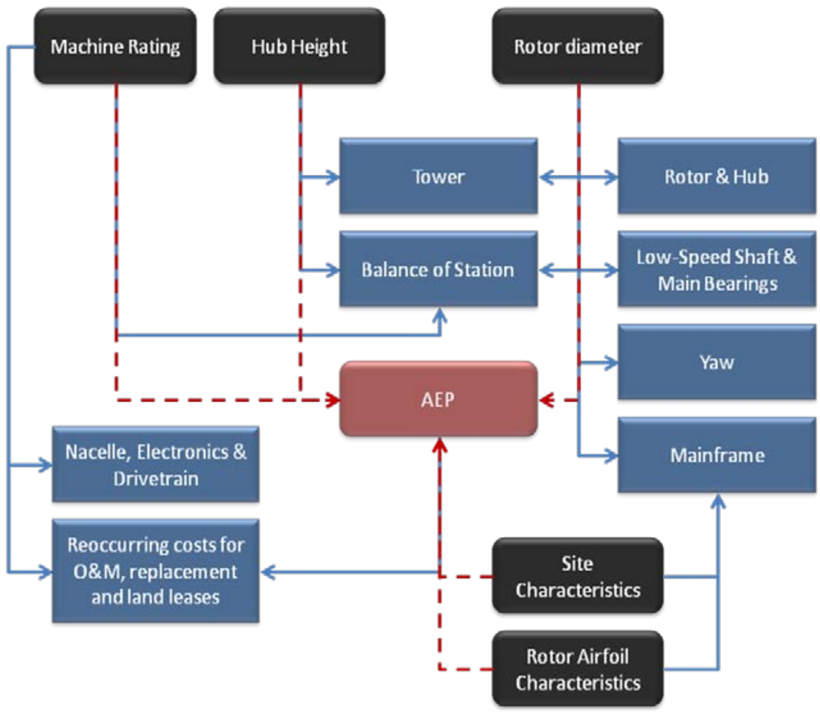


Figure 21. Cost model relationships (based on Fingersh et al. 2006)

3.5.3 Future Work and Needs

Cost modeling involves moving targets: technologies are constantly changing, material prices shift as various supply- and demand-side forces adjust, and general economic and political conditions may change. For instance, shifting prices in materials relating to impacts on drivetrain technology costs (i.e., permanent-magnet generators) is one current area of interest to industry. Incorporating uncertainty into models is one important goal that needs to be addressed in future model development and is well suited to systems engineering approaches and methods.

Ongoing research focuses on strengthening model estimates and algorithms to meet customer needs in all areas of wind project techno-economic analysis. NREL is expanding its Wind Turbine Design Cost and Scaling Model (Fingersh et al. 2006) to better represent the initial capital investment of offshore wind projects in particular. In addition to balance of station costs for offshore, improved modeling of overall long-term system costs for O&M are important to cost modeling for both onshore and offshore wind plant applications. This links back to the overall plant design and analysis tools discussed above but also implies novel areas of research related to controls development for reliability as well as condition monitoring. The cost model is where all of these design efforts will come together for overall system design and evaluation.

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[2] Detailed WindPACT reports can be found at http://www.nrel.gov/wind/windpact.html (last accessed 08/10/2011)

In addition, future work will focus on the ability to assess novel turbine configurations for both onshore and offshore applications. The WindPACT studies were developed largely during the early 2000s and represented the state of the art at that time. For today's research, it is important to develop cost models that extend the cost-modeling base for evaluation of novel component designs within the overall system. It is also important to include project costs for major system design changes and to assess the impact of variation of individual design parameters on overall system costs. Many of these overlap with systems engineering research objectives and will be discussed in the next chapter.

3.6 Wind Plant Integration to the Electric Grid System

Though this paper is not focused on models of wind interaction with the electric grid, they are critical to wind energy development and analysis as an entire system. Wind energy interacts with the grid in the entire spectrum of frequencies. The interactions are influenced by the dynamic of the wind resource (turbulence, diurnal, seasonal, etc.), the turbine dynamics (mechanical and electrical), and the power system dynamics. At one end, there are power system stability and dynamics from microseconds up to sub-minute interactions. From minutes to hours and days, the operation of the grid in steady state is a concern for reserve adequacy and system balancing, system dispatch as well as system unit commitment. Beyond this, wind energy affects grid operational planning in the midterm for seasonal hydrothermal coordination and maintenance scheduling. Finally, over the long term, increasing levels of wind energy as a percentage of generation capacity in a system will have an impact on security of supply in capacity and transmission expansion planning. NREL's research efforts and ongoing model development cover the entire set of areas as described above and illustrated in Figure 22.

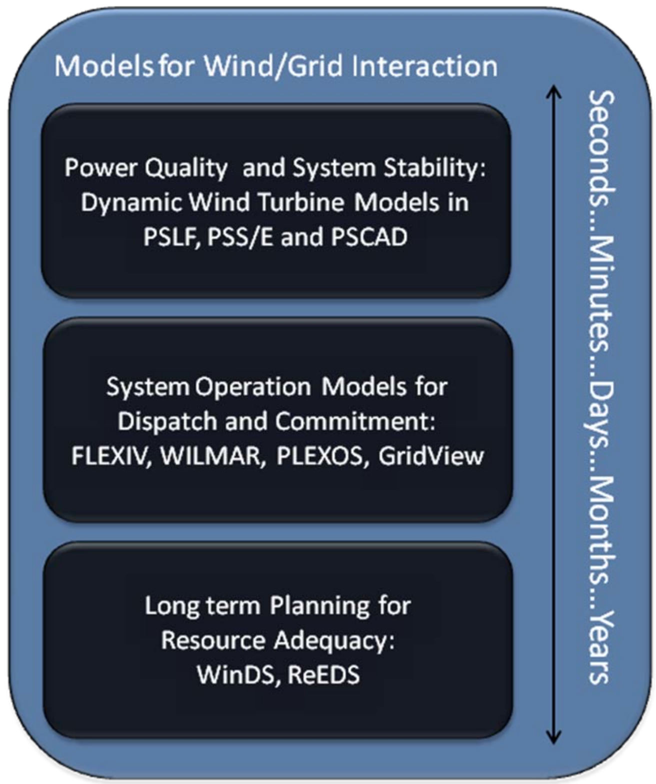

Figure 22. Wind-grid interaction models used and/or developed at NREL

3.6.1 Power System Dynamics and Steady-State Power Flow

Understanding the interactions of single or multiple wind turbine generators with the grid is of interest to system operators, wind turbine manufacturers, and wind farm developers. NREL has developed a series of dynamic wind turbine models that represent the four dominant wind turbine types available in the market: fixed-speed induction generator; variable-slip induction generator with variable rotor resistance; variable-speed, doubly-fed asynchronous generator with rotor-side converter; and variable-speed generator with full converter interface (Muljadi 2010, Singh 2011). Models of these turbines have been developed on several power system software platforms commonly used in utility planning. These dynamic models are available for deployment in several commercial software packages such as PSS/E, PSLF, and PSCAD that can then be used to examine the impact of the dynamics of grid operation on wind turbine generators or the impact of wind turbine generators on the dynamics of power systems. For PSS/E and PSLF, these turbine models can be tuned to represent turbines for different manufacturers, types, and control strategies. For dynamic models developed on PSCAD platforms, a generic model of each configuration has been developed to capture the dynamic interactions between the aerodynamics, structures, and electrical system (Muljadi 2010, Singh 2011).

Beyond dynamics, the models above can be used for steady-state power flow analysis in both PSS/E and PSLF. These models include an equivalent representation of a full wind power plant as a single generator in the system (Muljadi 2010). This single generator aggregates across fluctuations that may be present for individual wind turbines in the farm and is validated through comparison to extensive data sets from real-world wind farm operation (Muljadi 2010).

3.6.2 Power System Operations and Planning Models

Power system operations and planning models are important to understanding how wind energy will affect bulk system reliability, costs, and emissions. Models have been developed by NREL to look at day-to-day grid operations (Ela et al. 2011, Meibom et al. 2011) as well as for long-term planning for the grid with different levels of wind energy in the system (Short et al. 2009). In the first case, models have been developed that can be used for a particular system. The models show the effects of wind energy system production costs, fuel use, and system reliability criteria such as a balancing area control error and Federal Energy Regulatory Commission (FERC) Control Performance Standard 2 (CPS2) (Ela et al. 2011). This Flexible Energy Scheduling Tool for Integration of Variable Generation (FESTIV) model takes into account the existing generation mix and operational constraints in the system, the transmission network configuration and constraints, forecasted and actual demand profiles, and wind forecasted and actual generation. With this information it can perform automatic generation control (actual movement of generation up and down by unit), security constrained economic dispatch, and security constrained unit commitment (Ela et al. 2011). Stochastic aspects of the wind energy are explicitly taken into the account in the Wind Power Integration in Liberalized Electricity Markets (WILMAR) model which has been adapted for U.S. markets via collaboration between NREL and RISØ National Laboratory of Denmark. Simulations with the model show that taking the stochastic effects into account in the system operation improves overall system production costs and reliability (Meibom et al. 2011).

Two other commercial models have been used by NREL for short-term grid operation on the order of hours to days—these include the PLEXOS analysis tool from PLEXOS Solutions, LLC and GridView energy market simulation and analysis tool from ABB Control, Inc. Both of these tools are security constrained economic dispatch and commitment models using DC optimal power flow. Finally, efforts to look at the long-term viability of generation capacity and transmission infrastructure led to the development of the NREL Wind Deployment System (WinDS) (now Regional Energy Deployment System [ReEDS]) model that uses a linear program to perform capacity expansion with wind as an endogenous component of that process for the entire United States (Short et al. 2009). Such a model is used to evaluate both how high-level policy decisions affect wind development into the future and how high-levels of wind energy in the system may impact system costs and reliability.

3.6.3 Future Work and Needs

Presently, NREL has several research efforts in the wind-grid integration that parallel and complement industry activity and needs. Various enhancements to current models are underway from the short term dynamic modeling to system operational models as well as long term planning models. From the operations side, FESTIV and WILMAR represent very recently developed tools that are undergoing constant development and evaluation through application to various real-world scenarios. On the planning side, enhancements to ReEDS are on-going. The model is being applied to evaluate the effects of wind development on system reliability across the United States. It is also being used to assess capacity and transmission expansion needs for increased wind deployment.

Modeling efforts are also underway that bridge the current divide between modeling efforts on the structures and aerodynamics side of wind turbine design with those from the electrical engineering side. Active power control represents a key area for future development that unites the areas of aerodynamics and structural dynamics with short-term dynamics of grid interaction related to active power and frequency control.[3] Generally, there are three ways in which wind turbines can respond in the short term to assist in grid stability: (1) inertial response to mimic the inertia of large synchronous generators, (2) primary response to mimic conventional governors, and (3) secondary response to provide automatic generation control for power scheduling (Miller and Clark 2010, Miller et al. 2010). However, the use of controls to affect the grid interaction of a turbine will also have effects on the energy output of the turbine as well as the loads induced on the turbine (Fleming 2011). Balancing the role of active power control for grid stability with conventional objectives of power capture maximization and structural load minimization presents a challenging new paradigm that bridges disciplines. Care must be taken when considering the introduction of additional control objectives so that there is no reduction in the performance of conventional control activities such as speed regulation, power capture, and load minimization. Thus, active power control brings together dynamic models of wind turbine design with those for turbine-grid interaction and again exhibits a potential application of wind energy research and design suited to a systems engineering approach.

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[3] NREL held a workshop in 2011 on the topic of active power control that reflects state-of-the-art initiatives in the area: www.nrel.gov/wind/systemsintegration/active_power_control_workshop.html (accessed 08/23/2011).

4 Software Design and Computation: Overview and State of the Art

Before moving to a discussion of how systems engineering methods might be applied in specific ways to the research, design, and development of wind energy systems, a discussion is needed of the important role that software design and computing will play in that development process. Whereas the previous two sections described the state of the art both in wind energy modeling and in systems engineering methods, this section has a prescriptive tone towards describing important software design principles within the context of a potential WESE framework. Key to success of such a tool will be a requirements-based architecture and implementation that fulfills the needs of users. These users have varying backgrounds, levels of experience, desired outcomes, and roles in the planning, development, deployment, and use of large wind energy systems. The software must be efficient and fast enough for the range of component applications that will be coupled under a WESE framework. The components will range from simple parameterized formulations to high-fidelity numerical simulations running on platforms from single workstations to large supercomputers. The design should facilitate efficient development, maintenance, and support of the resulting software. In short, a detailed requirements gathering and analysis effort is necessary to define what the WESE approach should be, what it will do, for whom, and with what level of resources. The intent here is to provide a framework and a set of high-level directions for thinking about software and computational considerations for designing and implementing successive versions of a WESE toolkit.

4.1 Software Design

The design and implementation of a WESE framework will begin with the formulation of a software architecture that describes the structure or structures of the system. This structure comprises software elements, the externally visible properties of those elements, and the relationships among them. A well-designed architecture embodies the earliest, highest-level set of design decisions—those difficult to get right and the hardest to change afterwards. It creates a skeletal system on which future incremental design and development will take place. It also provides a basis for forming team structures and a vehicle for subsequent communication and interaction on refining and implementing the design (Bass et al. 2003).

In the case of a WESE framework, the software should be designed to perform optimization over other preexisting components, and some of these components are computationally expensive. WESE software should couple to the component models through abstract application program interfaces, allowing interchange of components with varying cost and complexity and providing flexibility over a range applications and users. WESE software should also be efficient and suitable for high-performance parallel computers when needed. To the extent possible, WESE software should facilitate the use of existing open-source software, both in its core optimization capabilities and with respect to component models.

The objective is to develop software architecture that is scalable both in terms of functionality and computational performance. Functionality of WESE optimization framework should scale from the initial set of subsystems varying from an initial prototype to components representing a full wind plant. Computationally, the framework should interoperate within high-performance computing environments as more sophisticated and computationally intensive components are adapted to WESE software environment. A detailed set of requirements and their rationale are described here.

Flexibility and Extensibility: WESE architecture and software framework should facilitate interchange of different instances of the same type of simulation component (e.g., gearbox models of varying fidelity) as well as incremental and evolutionary growth of capability and functionality using new types of simulation components as needed. This would provide new capability and functionality without major revision or refactoring of a WESE framework or component software. Flexibility is currently a requirement of other NREL efforts that will be components of WESE such as the Gearbox Reliability Collaborative project at NREL (Link et al. 2011).

Component compatibility: WESE architecture should support the integration and use of legacy components with minimal reengineering to accommodate computing platform, operating system, programming language, or other environmental inconsistencies. This may involve wrapping the component within a WESE-compatible interface or remote procedure calls to other systems. Alternatively, automatic conversion utilities that map incompatible interfaces (i.e., from an Excel spreadsheet to a conventional programming language implementation) may also help mitigate costly reengineering.

Composability: WESE architecture should support optimizing over large-scale wind energy system components, each of which may itself be a finer-scale optimization over subcomponents. For example, WESE may optimize over an array of turbines, each of which is an optimization over rotors, gearboxes, tower structures, etc. Recursive optimization or "nesting" over such hierarchies should be natural and straightforward.

Community/Open Source: In order to best provide a service to the community of stake holders in wind energy, access to and use of the framework and publicly released components of the WESE software should be as open and public as possible, both for developers and users of the software.

Intellectual Property Secure: At the same time, the architecture, interfaces, and governing policies should facilitate protection of investments in proprietary enhancements to WESE software by individual or select groups of stakeholders unless and until, at these stakeholders discretion, these are contributed back to the publicly maintained and distributed system.

Portability: Ultimately, WESE software and its components should be supported on the full range of platforms in use by the stakeholder community. This requirement may be met incrementally, beginning with a subset of platforms that will be gradually expanded. It should be possible to swap in more computationally intensive components with the assumption that these are ported to provide good use of high performance computing (HPC) resources.

Maintainability: The design and implementation of WESE should be modular, readable, and well documented to facilitate maintenance and support. This requires establishment of resources and policies governing maintenance and support of ongoing development, user support, bug tracking and repair, version control, public releases of new versions of the WESE software, and maintaining repositories of contributed software.

Performance and scaling (computational): WESE software should provide acceptable performance in terms of time-to-solution (TTS) for its intended set of applications. WESE software should be scalable in the sense that meeting TTS requirements for a given user and application should be a matter of increasing available computational resources (e.g., more processors) within the strong-scaling limits imposed by the problem size and WESE configuration.

Usability: WESE software should be reasonably simple for a user with domain expertise (but with limited software and computing expertise) to install, use, and understand. For example, the mechanics of using available computational resources to run the WESE system, including HPC systems, application servers, and/or cloud computing, should be incorporated within user interfaces and technical reference documentation.

Verification and Validation: WESE software should be verified and validated at each step in its development. A formal set of verification and validation methods should be applied to both the overarching WESE tool as well as individual sub-models used within the WESE framework. Good practices for verification and validation will be taken from existing efforts and guidelines (Oberkampf and Roy 2010).

4.2 Data Architecture

The WESE system will become an integration tool and repository for a large and increasing number of product models representing attributes such as function, form, and behavior as well as the object's relationships to other objects in a wind energy installation. Product model data is concisely and abstractly represent-able using the Core Product Model (CPM), developed at the National Institutes of Standards and Technology (Fenves 2005), and which consists of two types of classes called object and relationship classes in the entity-relationship model (Chen 1976).

An example of a large-scale systems engineering project using CPM is the Leading Edge Architecture for Prototyping Systems (LEAPS) (Hurwitz 2001) project for rapid-design and virtual prototyping of naval vessels within the U.S. Department of Defense Modernization Program. LEAPS is the product model repository used by the Naval Sea Systems Command (NAVSEA). LEAPS enables engineering analysis of a product's design, verifies capabilities, and determines manufacturability. It supports conceptual and preliminary ship design and analysis integration. LEAPS has programmer interfaces for different kinds of analysis tools, its own internal product metamodel, and indexing mechanisms. The LEAPS metamodel is formally defined and documented using the Unified Modeling Language (UML) (Lubell et al. 2008).

Patterning after LEAPS and other related projects, the WESE data architecture may be based on a class structure and ontology that includes the requirements of each product model being designed, its characteristics, systems, components, and behaviors and provides an interface to the user for creating, modifying, and composing product models into larger and larger systems in a way that is automatable and scalable to large HPC systems.

4.3 Advanced Computational Techniques

Satisfying computational performance requirements of the WESE system will require HPC, especially for components that involve numerical simulation of flows and structural responses. At the same time, performance and scaling requirements must be managed within the constraints of other requirements for usability, portability, extensibility, and maintainability.

HPC takes the form of large-scale, parallel supercomputing clusters hosted by DOE, the U. S. Department of Defense, NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), universities, and industry. As was previously mentioned in Section 3, there are a variety of models for wind energy systems involving various levels of fidelity. Integrating several models of high orders of fidelity together may involve a need for HPC. HPC applications must be designed to run on clusters of thousands of individual computers networked together to provide aggregate computational power in hundreds of trillions of operations per second. The individual components envisioned for WESE that will require this level of computing power must have already been designed to run on these systems using techniques such as parallel domain-decomposition, message-passing, and multi-threading. Consideration of future HPC systems (for example Peta- and exa-scale computers) may impose additional challenges on a WESE tool and efforts must be implemented to ensure that scaling to these levels is feasible. From the standpoint of an overarching optimization framework, the issue is more one of organizing and scheduling the execution of the multiple applications making up the multidisciplinary optimization problem. However, issues associated with organizing and scheduling can be complex particularly for modeling large technical systems such as wind energy turbines and plants. Automation of optimization processes may not be straightforward and careful planning and management of the use of HPC resources must be adhered to for WESE development. It must be done across these systems in a way that is efficient as well as accessible and manageable for end users.

Cloud and **grid computing** are conceptually related technologies that assemble arbitrarily sized, on-demand collections of network-connected computers, possibly geographically distributed and from multiple domains, for application to scientific, technical, or business tasks. Collections of servers can be instantiated and destroyed in response to fluctuating loads. Grid computing, which preceded cloud computing, formed around the needs of scientific computing data management in research and academic computing (Foster and Kesselman 2004). Cloud computing is grid computing adapted to commercial information technology. Both imply virtualization—the ability to present multiple system images (e.g., UNIX, Windows), configurations, and capabilities—and allocation of physical resources without action or knowledge by the end user. The end-user view is similar to the view customers have of a utility: customers pay for the computing that they use without the need to invest in, maintain, or be bound to a particular system or physical infrastructure (Ferreira et al. 2005).

With regard to the specific requirements of the WESE optimization framework, the virtualization provided by cloud-based computing would provide an on-demand mix of hardware and system environments to allow grid-enabled components of WESE to run in their native environments without reengineering. A cloud computing infrastructure would support scaling over a wide range of WESE applications and performance requirements, from light-weight to massive. Users would require only client software and Internet access to use WESE, even from remote locations.

HPC and cloud computing are not mutually exclusive. Commercial cloud computing services such as EC2 (Amazon 2011) and Azure (Microsoft 2011) include or plan to include cloud-based high-performance computing resources. Research and academic clouds are capable of hosting WESE. Employing HPC-enabled cloud computing would involve engineering a WESE framework and component applications to conform to grid middleware and cloud application program interfaces.

4.4 Optimization and the DAKOTA Project

A major effort at Sandia National Laboratories has led to the development of an overarching optimization software that may be similar to or used by a WESE tool developed at NREL. The Design Analysis Kit for Optimization and Terascale Applications (DAKOTA) toolkit utilizes object-oriented design with C++3 to achieve a flexible, extensible interface between analysis codes and system-level iteration methods. This interface is intended to be very general, encompassing broad classes of numerical methods that have in common the need for repeated execution of simulation codes (Eldred et al. 1996, Adams et al. 2009).

Accomplishing the interface between analysis codes and iteration methods in a sufficiently general manner poses a difficult software design problem. These conceptual design issues are being resolved through the use of object-oriented programming techniques. In mating an iterator with an analysis code, generic interfaces have been built such that the specifics of each iterator and each analysis code are hidden. In this way, different iterator methods may be easily interchanged and different simulator programs may be quickly substituted without affecting the internal operation of the software. This isolation of complexity through the development of generic interfaces is a cornerstone of object-oriented design, and it is required for the desired generality and flexibility of advanced strategies (e.g., hybrid algorithms and sequential approximate optimization). The application interface isolates application specifics from an iterator method by providing a generic interface for the mapping of a set of American Institute of Aeronautics and Astronautics input parameters (e.g., a vector of design variables) into a set of responses (e.g., objective function values). Iteration methods available in the DAKOTA system currently include a variety of optimization, nondeterministic simulation, and parameter study methods. During the development of a WESE tool, every effort should be made to leverage existing software packages and initiatives, such as DAKOTA, as they represent important contributions to the development of a WESE tool that are pre-date the tool development.

4.5 Related Systems Engineering Software

The previous discussion, in conjunction with the information presented in Section 2 and Section 3, highlight the enormous complexity of the task and the potential for failure if this complexity is not recognized and properly planned for—including the use of a phased approach for development, prioritization of model integration and application selection, and careful upfront planning. The following discussion highlights similar efforts that have been successfully implemented. The commercial systems engineering software that has been developed in other domains can be used as a reference for the development of the WESE tool. Understanding the strengths and weaknesses of different software products may lead to a better understanding of the features that should be included in the WESE software project. At the same time, they will also inform an understanding of the difficulty of the overall process so that a manageable tool of tractable scope and size can be developed or even borrowed from existing applications. Several software packages were surveyed to identify the kinds of features that are used in other commercial systems engineering software.

Process Integration: A workflow specifies how the models within a particular systems engineering domain are integrated together. All the software surveyed included a graphical user interface to facilitate coupling models into a process workflow. Some software packages offered additional workflow tools that include verifying the correctness of the workflows, graphs for viewing the workflow in different ways, and version control systems for managing multiple users that all contribute to a single workflow (Core 2011, Genesys 2011, and Cradle 2011). Support for multiple levels of model fidelity within the workflow is another possible feature (Halbach et al., 2010). Including support for designing model relationships within a process workflow is an important feature necessary in the WESE tool.

Design Exploration: Some of the systems engineering software emphasized the analysis of the workflows by including built-in tools for exploring the design space specified in the process workflow. For example, both the Model Center (ModelCenter, 2011) and the iSight software (Van der Celden et al., 2010) included capabilities that performing parameter scans, sensitivity analysis, and optimization. Other tools offered an interface for user-specified analysis procedures (Halbach et al., 2010). As mentioned previously, the WESE tool will include a flexible analysis component interface that facilitates leveraging existing analysis software such as DAKOTA.

Visualization and Parallel Computing: Other features relevant to the WESE project include visualization of workflow simulation analysis (ModelCenter 2011, iSight 2011), and the ability to execute concurrent workflows in parallel on an HPC system (Simulia 2011). It is likely that the WESE project will also include these features and extend the degree to which analysis can be done in parallel by allowing for a degree of parallelism within a workflow.

5 Potential Directions for Application of Systems Engineering to Wind Energy

This chapter brings together systems engineering methods, software architecture and computing, and NREL tools for a discussion of potential directions for research at NREL that would combine these topics. It describes a framework for wind energy research that integrates and builds upon NREL's existing set of tools within a well-defined software architecture that allows for efficient and advanced computing techniques. Figure 23 represents the comprehensive systems engineering approach to tool integration for supporting a variety of analytical needs.

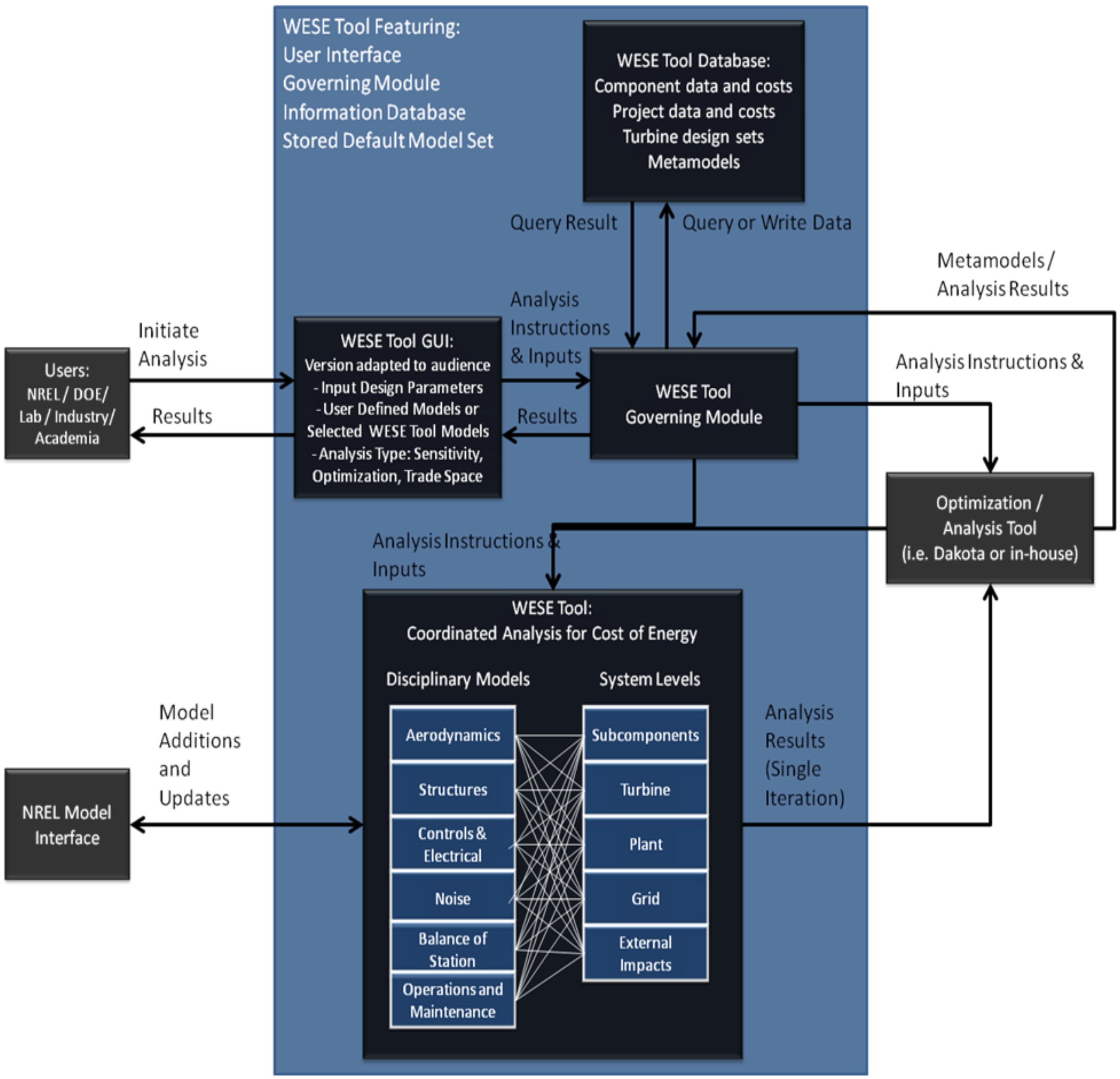

Figure 23. Overarching vision for long-term WESE tool development

The goal should be to leverage existing capabilities as much as possible and coordinate them through the development of an overarching WESE framework and tool. The tool itself will encompass the governing software and associated architecture and will likely contain a default set of models that are coordinated across the different wind energy system levels for analysis. There should be a flexible interface to allow for the interaction of a variety of users and flexible to accommodate collaboration across potential user groups. The overall vision for wind energy systems engineering is to develop a framework and corresponding toolset that will permit the integration of a variety of models that address different aspects of the overall wind energy system. At all times, a tool will maintain the capability for representing the full wind energy system including individual turbines and components, wind plants and turbine interactions from wake effects, and cost of energy modeling for the wind plant and BOS. Later realizations of a tool may extend into advanced supply chain representations as well as grid integration and analytical capabilities for community and environmental impacts. The full system representation will have varying and interchangeable levels of model fidelity for each aspect of the system. Depending on the application, different models for each sub-system or discipline may be used in an overall analysis.

As research continues in different sub-model or disciplinary areas, resulting model advancements will be integrated for use in a WESE tool allowing for continual evolution of the overall tool and increasing fidelity of different system sub-models. For instance, a tool may initially incorporate a few models of the turbine itself including aeroelastic design codes such as FAST or the simplified WT_Perf or even parameterized metamodels. A tool might then be extended to interact with higher fidelity models for structural analysis of different turbine components that would interact with the full turbine model (i.e., similar to the work of Crawford 2003 and Bottasso et al. 2010). Cost models might initially incorporate parameterized models such as the NREL model (Fingersh et al. 2006), other simplified models of turbine cost (Burton 2006), or an engineering-based cost model (Harrison 1993) that is extended to capture detailed plant costs (Ozkan and Duffey 2011). Plant models might contain various levels of fidelity for modeling turbine interaction as well as site impact considerations on wind flows. The systems engineering tool will allow for the integration of a range of models representing the different aspects of system design and these be allowed to evolve over time.

Individual components of the WESE system will interoperate as parts of an overarching software framework that provides interfaces between the model components and a core optimization capability such as is provided under the DAKOTA framework and architecture. Component models should be interchangeable through common application program interfaces within a WESE framework and tool. Thus, it will be possible for a user to select from multiple instances of a type of component to provide varying degrees of fidelity (in exchange for varying computational cost). A WESE framework will be able to interface to legacy model component software without modifying the framework itself and with minimal reengineering of the components. However, cross-platform operability for that component will be limited to the computers that that module runs on. Nevertheless, a WESE framework itself may be insulated from these restrictions through remote procedure calls, virtualization, and (computational) grid-enablement. A WESE framework should be maintained and supported across the range of systems and operating system environments. These include high-performance computing resources where necessary and available as was discussed in the previous section. Workflows for different users and applications will be supported through appropriate graphical or other user interface modalities.

In addition to allowing for integration of diverse sub-system models, a WESE tool will support a variety of analyses depending on the need and the audience. Development of the tool may allow for high-level coordination of research activities between academic institutions, NREL, other laboratories. Facilitation of collaboration is a key feature of the overall initiative, such as that demonstrated by Argonne National Laboratory's "Autonomie" for vehicle system research, design, and development applications (Halbach et al., 2010). Different groups may need such a tool for specific applications including those from DOE and government, NREL, industry, and from academia. A WESE tool will support analysis needs from the different stakeholders, including the following:

- DOE in evaluating technology to set research and development priorities as well as helping a larger government audience evaluate policies related to wind energy technology and system development—simplified versions of the tool are expected to provide rapid analysis to aid in decision making for both groups
- NREL and other research laboratories in cutting across different research initiatives, allowing better understanding of the role of particular research activities within the larger system context
- Industry in evaluating component design within a larger system model, as well as evaluating turbine and plant integrated design impacts on cost of energy and other key variables, and even analyzing supply chain issues that cut across traditional industry boundaries between OEM and developers
- Academia both in research activities as well as in education—academia will benefit from and contribute to the tool development; simplified versions of the tool may also assist in educational activities such as classes on wind turbine design or wind energy system planning

The diverse set of applications and users for a WESE tool mean that a variety of analyses will be feasible. A tool will support optimization including MDO and MOO but also potentially a variety of analyses that might be supported, for instance, by Sandia's DAKOTA software analysis tool. This will allow for both detailed design optimization as well as evaluation across diverse system architectures. For example, an MDO may be used to perform a detailed cost optimization of a particular point design, and MOO may be used to survey a wide variety of different wind turbine configurations. In addition, a tool should include a range of post-processing decision-support tools including sensitivity analysis, uncertainty quantification, and visualization methods. User inputs will include input parameters for system design (turbine, plant and exogenous factors), but also will include the specific analyses to be performed and the models to be used (selection of sub-models based on level of fidelity and type of representation desired or the incorporation of user-defined sub-models). Every analysis thus will include: (1) a connection of individual elements and sub-systems into a system design space for a full system representation and (2) varying levels of fidelity in terms of modeling different subsystems depending on the chosen application.

Depending on the type of user, the WESE software architecture will support a wide range of workflows. It will support very high-level, prepackaged configurations of pre-processing, models, optimization, and analysis as well as mechanisms for expert users or system developers to compose and customize systems from WESE building blocks. Other intermediate modes of use will also be supported. The scope of potential development for such a tool is recognizably enormous. Within the large space of development, it is important to consider particular applications that would constitute a progression in tool development that is *feasible in the near-term*. A more detailed discussion of potential applications of a tool will follow in the next sections. Each area reflects the integration within a WESE tool of systems engineering methodologies with existing and evolving NREL analytical tools.

5.1 Evaluate Innovative Technologies for Effects on LCOE

As illustrated in the introduction, wind energy systems are complex; small changes in one part of the system may have significant repercussions on the operation and cost of distant elements in the system. The example illustrated how different controls strategies could affect system loads and thus component sizes, and ultimately system costs including initial component costs, BOS costs, and even long-term O&M costs. The implementation of a WESE tool will allow users to evaluate how novel control strategies may affect overall system design loads, energy production, and overall cost of energy. Initially, this will involve the integration of NREL aeroelastic design codes and cost models to allow for multidisciplinary design of a wind turbine including traditional fields of aerodynamics and structures as well as controls and system level impacts on cost of energy.

A specific example of the benefits of integrating design tools within a WESE framework would be the evaluation of how combining active control methods with system design choices may affect overall long-term system behavior and costs. The European Union UpWind project concluded that using passive and active controls in the turbine blades would lead to the feasible development of very large (10-MW+) turbines for offshore wind energy applications (Upwind 2011). Other aspects related to offshore wind energy development and controls include the study of how integrating active controls, passive controls, and overall turbine design may lead to a much lower cost of energy. This may include using existing and novel control sensors and actuators and evaluating how their use affects turbine loading. Control sensors and actuators may impact overall design and component costs as well as downstream O&M costs.

In addition to evaluation of novel control strategies, the integration of design tools in WESE will allow for evaluation of the impact of turbine scaling or configuration changes on cost of energy. Similar to the WindPACT efforts, such analyses will serve to help evaluate research and development initiatives for their potential impacts on wind energy system costs. The integrated WESE tool can be used to extend that work by looking at new applications, larger turbines, and the limitations of the WindPACT results, including the integration of cost and physical models. Key design drivers can be better understood, and the sensitivity of cost of energy at the *system* level can be related to changes in particular design variables or a combination of design variables. For example, users of WESE could assess the sensitivity of cost of energy to changes in drivetrain mass per power rating, rotor mass per swept area, and tower mass per unit height. WESE will allow assessment of how changes in any one of those parameters may affect overall system cost of energy via secondary impacts on other system component designs and reliability. The current NREL cost model does not involve a physical linking of sub-structures in the cost of energy calculations such that secondary effects of changing single design variables will not feedback to the entire system. This limitation will be eliminated through the first phase coupling of the NREL cost models explicitly to the NREL design codes within a WESE tool framework as is illustrated in Figure 24.

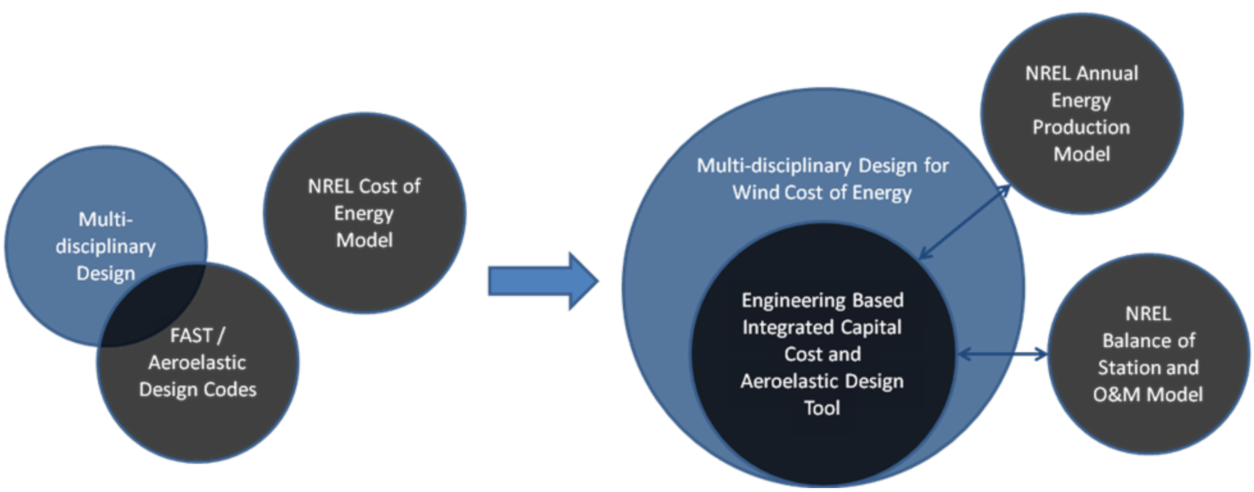

Figure 24. Initial integration of NREL aeroelastic design codes with cost modeling tools within a WESE framework

5.2 Evaluate Specific Component Designs

The integration of physical turbine models and cost models in a WESE tool will allow for modular selection of sub-models within the larger multidisciplinary design tool. Thus, detailed models of specific sub-systems or disciplines may be integrated with the large system design tool to determine the impact of specific component design on overall system behavior in terms of energy production, cost, and other impacts. The key aspect of a WESE tool design for this objective is the modularity of a tool to accommodate models of different fidelity levels within a single design analysis and optimization.

An example of component design selection would be the evaluation of a new type of generator or drivetrain and their potential impact on the rest of the system in terms of loads, sizing, and cost of energy. Specifically, a WESE tool will have the ability to model different types of generator configurations within a full offshore floating wind turbine design to determine the impacts of lighter weight and more reliable designs on system costs. This type of analysis will also serve to provide designers with the detailed load cases needed to build reliable, cost-effective generators.

Another example of component design activity would be the evaluation of foundations for both transitional depth and deep-water applications. A detailed component model from a particular industry or research partner can be integrated directly with the aeroelastic design codes and cost models. Alternatively, a metamodel of that component could be produced and used within the system analysis and optimization. Overall impacts on energy production, design loads, and cost of energy would allow for some insight into how the specific component design might improve the overall performance of a wind turbine. Applications of these activities from evaluation of component design to system optimization around new component innovations are illustrated in Figure 25.

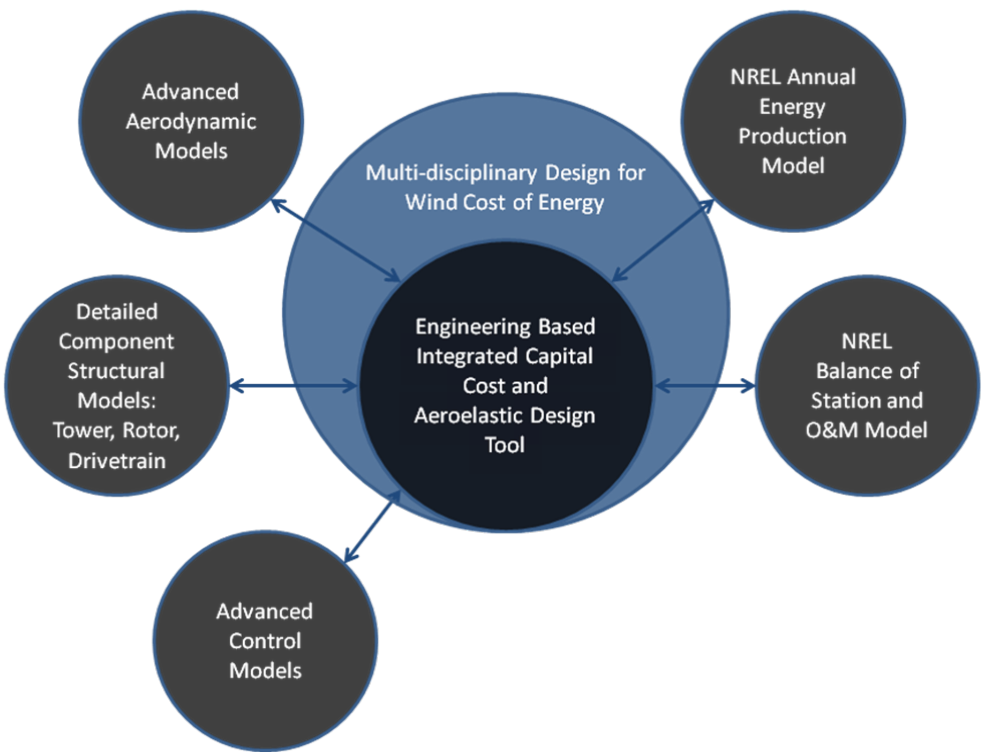

Figure 25. Enhancement of WESE tool for more detailed component models and disciplinary models

5.3 Site Optimization and Integrated Evaluation of Turbine and Site Design with Overarching Cost Drivers

Eventually, the development of a WESE tool will involve not just the integration of single turbine and cost models but also the overall wind plant including turbine-to-turbine interaction and a more detailed representation of BOS and O&M. Figure 26 illustrates how these layers will be added to a WESE tool to complement the existing models for improved analysis of turbine and plant design.

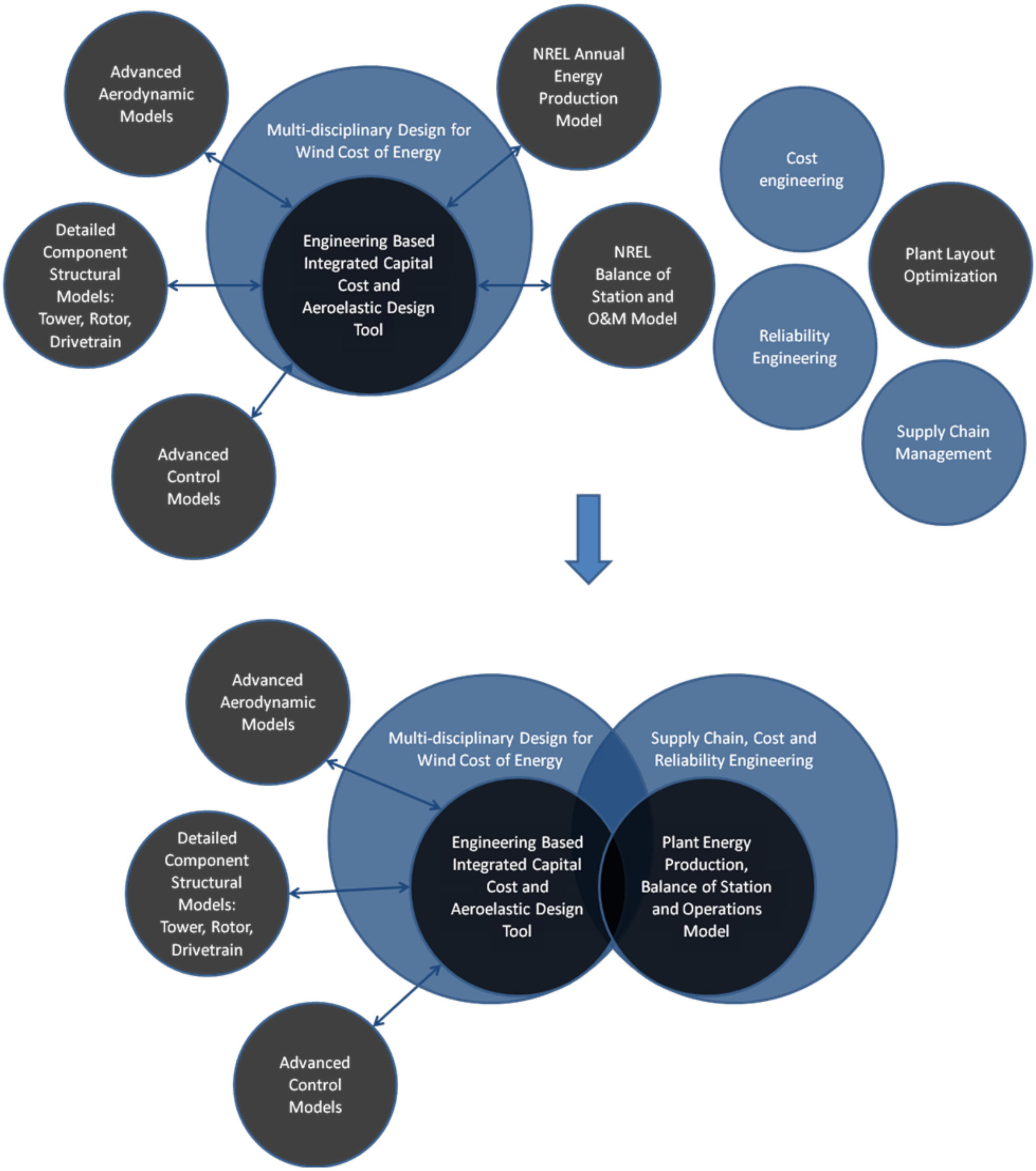

Figure 26. Extension of turbine, component, and cost model integration to include other system engineering methods and representation of the full wind plant

This effort will capitalize on existing efforts at NREL to develop enhanced turbine interaction models, such as those that interface between the CFD software OpenFOAM, the mesoscale weather model WRF, and the aeroelastic design code FAST (Moriarty et al. 2011). However, this will extend that effort by allowing such tools to integrate with NREL's evolving models for turbine capital costs, BOS costs, and O&M costs. Such efforts will also be integrated with layout optimization efforts developed both in-house and potentially from academia and other research institutions such as RISØ. The integration of turbine, plant, and cost modeling tools will drastically improve the ability to analyze how changes to system design will impact both individual turbines as well as the entire plant in terms of energy production, capital costs, BOS, long-term reliability, and O&M costs. Addressing plant level effects, developers will build on the work of Fuglsang et al. 2002, Kühn et al. 1997a, and Ozkan and Duffey 2011. A WESE tool will incorporate plant models for turbine wake effects and O&M as well as overall BOS to allow for integrated evaluation of turbine and plant. One type of analysis that would result from this study includes the integrated design of turbine and plant when faced with ice-loading concerns as discussed in the Introduction. A WESE framework would allow for optimization that takes into account the foundation type (optimized for ice loads), array optimization from wake effects and ice regime, and wind turbine array layout to minimize BOS costs and O&M costs. The ability to synthesize these types of analyses and optimize around cost could lead to drastically different foundation and wind layout designs than previously developed based on independent analyses.

Other potential extensions of WESE modeling are related to grid interactions or larger supply chain modeling considerations. For example, supply chain models that take into account the types of vessels needed for installation and operation of an offshore wind plant might be added to a plant-level model. For onshore applications, models might be added that look at transportation, installation, and assembly logistics associated with wind plant design. Such studies would extend the work of WindPACT to potentially include network models for transportation for overall plant design that includes GIS information for modeling of plant operation, grid interconnection, and logistics. A detailed micro-siting design of a wind plant might be performed that integrates a flexible turbine model (or a selection across a set of turbine types), with a wind plant model that captures turbine-to-turbine interactions for impacts on energy production and reliability as well as BOS impacts of turbine and plant layout design.

5.4 System Design, Evaluation, and Optimization for Non-Conventional Design Drivers Including Community and Environmental Interests

Consideration of non-technical system attributes will be integrated into a WESE tool. Grid integration, community, and environmental impacts will be modeled to achieve a full system model that incorporates the entire design and impact variable space. For example, noise was considered in detail in the introduction in order to represent how consideration of a single design criterion may have impacts throughout the entire wind energy system design process. Integrating various noise models into a WESE tool—from highly simplified empirical representations to state-of-the-art, physics-based models—will allow for new analysis on how noise considerations may impact overall system design.

It is also important to assess the impacts of system design on integration of wind into the electric grid. As was discussed earlier, this may be done at a variety of time scales, but in particular, the short-term interaction of wind energy with the grid is highly interlinked to individual turbine design and therefore system cost of energy. The integration of dynamic models for grid interaction of wind turbines—such as those developed for Power System CAD, Power System Simulation for Engineering, Positive Sequence Load Flow, or eventually Simulink in Matlab—into a WESE tool will allow for new types of analyses and work, such as that related to the interaction of active power control techniques with other turbine control strategies related to power production and load minimization.

Environmental considerations must also be taken into account in the overall WESE tool. While impacts of wind system design on wildlife and habitat are arguably the most difficult to model analytically, there is some opportunity for incorporating factors on how certain system design factors may affect wildlife and habitats, including control strategies in turbine operation related to curtailment and cut-in speed, use of lighting, types of support structure, turbine height, rotor swept area, and speed. Quantification and analysis of impacts will be a challenge, but it may be possible to evaluate, for instance, how the change in one of these given variables may impact overall system performance and cost of energy—thus, it would help to evaluate how an environmental impact mitigation strategy would impact key system performance and cost metrics.

The emphasis of this environmental area of model development, in general, is on the various interests that different stakeholders may have with respect to wind energy system design. Ultimately, these objectives are difficult to compare explicitly to system cost objectives without abstracting away their value (i.e., willingness to pay/accept). Therefore, it is possible to approach these varied stakeholder interests either as constraints in the design process, as particular scenarios for considering the impact of their implementation on system design, or finally as important and separate objectives that might be evaluated in parallel with traditional metrics of system energy production and cost. The full WESE tool, incorporating models across the entire wind energy system, is shown in Figure 27. It reflects an abstract representation of how the different models may fit together within a WESE tool or framework.

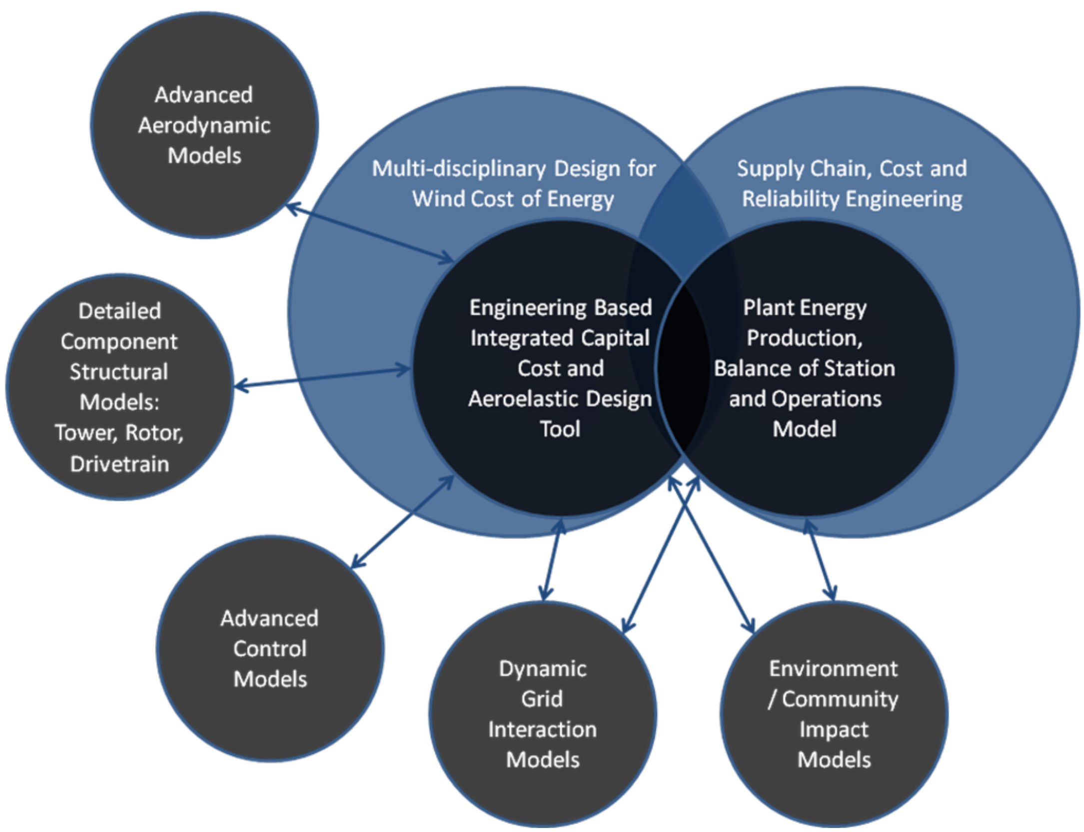

Figure 27. Full WESE tool incorporating detailed component designs; aeroelastic design codes; cost models; plant models; and utility, environment, and community impact models with various levels of fidelity available to represent each system sub-model

Figure 20 in this section represents how the overarching flow of information throughout a WESE tool may develop. Thus, each of the models above would interface with tool while the systems engineering methods would be built into the overall WESE tool governing module which would oversee and coordinate the use of appropriate models depending on the analysis of interest. Eventually, all of these modular models will be incorporated into a tool such that a large variety of analyses looking at all aspects of the system may be accomplished while always preserving a full system view to some degree.

There is a natural progression of WESE tool development from initial coupling of turbine and cost models, to the modularization of those models allowing for a wide variety of analyses related to component design interacting with turbine design, to the coupling of turbine and cost models with an overall wind plant model that can take into account turbine interactions and many plant design considerations such as balance of station and O&M, and finally to the integration of various stakeholder interests that impact system design including utility, community, and environmental interests. The overall tool can be partitioned using high levels of details for certain sub-system representations and highly abstracted representations for others. The overall system-level representation, however, is preserved in all of the analyses and will continue to evolve and develop along with each respective research areas. Thus, a WESE tool is not just a tool but also a research framework that will enable long-term objectives and analyses for multiple audiences.

This last section has emphasized one particular sequence of development for a systems engineering approach to wind energy research, design, and development. It highlights some of the target users and users that might be envisioned both in the short term and the long term. It emphasizes optimization and MDO in particular, but it is meant to also capture other systems engineering methods that may be specifically useful for analysis that incorporates a larger system boundary than the wind turbine and plant (i.e., grid, community, and environmental impacts). Actual development of such a framework or tool will need a more thorough examination of user needs, an understanding of the challenges faced with integrating existing software tools, and an overall management of the development that allows for meeting short-term analysis objectives while preserving scalability for later extension of the tool for longer-term objectives. Future work should focus on these challenges in order to build a WESE tool that will provide the potential benefits that may be achieved via a holistic, multidisciplinary, integrated, and life-cycle-oriented approach to wind energy research, design, and development.

6 Summary and Conclusions

This paper represents an effort to survey the landscape of potential research development in wind energy through the use of a systems engineering tool and framework. The history of systems engineering is a relatively long one (beginning in the mid-20th century), but it is only relatively recently that explicit systems engineering efforts, MDO in particular, have been tied to wind energy research (Crawford and Haines 2004, Bottasso et al. 2010, and Vlahopoulos et al. 2011). While the use of systems engineering for wind energy applications has been limited in research, the use of such methods has had a strong presence in the related fields of aerospace and automotive engineering. The ties to aerospace are obvious—it is another large and complex technical system that deals with integration of multiple disciplines including aerodynamics, structures, controls, and others. Vehicles, on the other hand, have important parallels to wind energy from the perspective of large-scale manufacturing and extensive supply chain considerations. Therefore, it seems appropriate that systems engineering techniques be evaluated for their potential application to wind energy.

The field of systems engineering has several key aspects regarding the approach to design of large-scale complex technical systems. These include a holistic perspective of the system, multidisciplinary design across the entire system, integration of multiple stakeholder interests into the design process, and a life cycle approach to system design. These correspond to attributes of complexity, heterogeneity, and uncertainty that make design of such systems more challenging and therefore qualify them for a systems engineering approach to research, design, and development. Wind energy maintains all of these characteristics. There are multiple stakeholders in the field, such as component suppliers, turbine manufacturers, developers, operators, utilities, and communities. The design of wind energy systems crosses various disciplinary boundaries from civil to materials engineering and from physics to the social sciences. The system is large and must be addressed holistically as components within a wind turbine and a plant are linked together such that a design change in one key design variable may impact the entire system. Wind energy systems must also be designed to operate over a long time period, and consideration of this entire life is important for system design with respect to key performance and cost metrics. Thus, wind energy is well suited for a systems engineering approach to research, design, and development.

In order to address how a systems engineering approach might be used to design a wind turbine and/or plant, a survey was compiled of methods within systems engineering that may be applicable or which have already been tested for use in wind turbine and plant design. In general, these can be partitioned into design tools related to physical system design, methods related to supply chain and logistics, and other methods such as reliability and cost engineering. Within the first set, there are several methods related to physical system design as it relates to individual turbine or plant design. Of these, MDO is featured because it has been used extensively in aerospace applications—where optimization across several disciplines and system attributes is important. MDO allows the integration of different disciplinary design objectives into an overall system design optimization. As a first phase of development for a WESE tool, NREL tools that allow for the multidisciplinary design of wind turbines via aeroelastic design codes might be integrated formally into an MDO tool along with NREL's cost model tools in order to allow for analysis of design variable changes on overall system performance and cost, as well as to perform system-wide optimization across a number of design variables (similar to Crawford and Haines 2004 and Vlahopoulos et al. 2011). Similar approaches could be used for integrating not just turbine and cost models but also full-scale plant models that incorporate siting and turbine interaction effects on energy production and O&M, as well as siting, turbine, and layout design considerations on BOS.

However, the discussion of MDO was followed by consideration of MOO, which looks at evaluating different design objectives on equal footing. Such methods are particularly appropriate when there are multiple stakeholders who have conflicting interests for system design. As another stage of development for a WESE design tool, incorporation of models that represent these various stakeholder interests would allow for wind energy system design for non-traditional performance criteria such as grid interaction, community, and environmental impacts. MOO may also be relevant when there is uncertainty in aggregating design outcomes together and one wants to evaluate a set of designs along various dimensions, such as wind energy system production, weights, and reliability. A unique aspect of MOO techniques is that they may result in a trade space of designs that can be compared using visual and statistical techniques. These evaluation tools and trade space visualization may also be of interest for evaluating trade-offs between very different wind energy system designs or architectures rather than focusing on sensitivity to design parameters for a single, detailed design.

Supply chain considerations are important to wind energy system design both in terms of initial plant design—including transportation, installation, and assembly logistics—as well as to long-term O&M. Long-term development of a WESE tool may incorporate more and more advanced models for BOS and O&M of wind plants that integrate supply chain model techniques such as network analysis. In addition, reliability engineering and cost engineering are also closely related to BOS and O&M aspects of wind energy system design. Each of these development steps will be done separately—with layers of complexity added to a tool at each step—in order to ensure that a tool is able to support short-term research objectives as it continues to evolve.

While today there are many applications of systems engineering implicit in the design of wind energy systems, there is a lot of potential for explicit development of a systems engineering approach to research, design and development of wind energy systems. Such methods allow for entire analysis of the complex system and account for the broad range of stakeholders that may impact or be affected by the system design. The long-term development of a WESE tool incorporates layer after layer of evolving complexity in each aspect of system design, which includes the components, turbines, and plants, as well as larger system impacts. Software architecture of a tool will be developed for attributes that will allow a tool to evolve and continually aid in research, design, and development. These attributes include flexibility and extensibility, component compatibility, composability, open platform, security of intellectual property, portability, maintainability, performance and scaling, and usability. A tool will cater to users from a wide variety of backgrounds, including the DOE and government; NREL and other design labs; industry companies such as component suppliers, manufacturers, and developers; as well as academia. Significant work will focus on upfront design of the system architecture to allow for these long-term design goals and software design attributes to ensure the practical value of a WESE tool during all phases of development.

In summary, wind energy systems engineering represents a bold effort to address a variety of issues that impact the current and future development of the wind energy sector. Because wind is a large-scale, complex technical system with various social impacts, a systems perspective and approach must be taken to the research, design, and development of these systems in order to meet the myriad of goals for future development of the technology. The inherent complexity of the physical stream leads directly to a multidisciplinary approach to the design of the turbine itself, but also to the plant level and beyond, taking into consideration the impacts that the plant will have on local utilities, communities, and environments. Systems engineering, which has a long history of development and application to a variety of industries such as aerospace and automotive, and thus shows significant potential for addressing these systems design challenges in the wind industry and will be a useful framework and tool for guiding and coordinating wind energy research and design activities.

Appendix A: Detailed Overview on State-of-the-Art in MDO Methods and Associated Optimization Algorithms and Post-Processing Techniques

MDO Overview and Methods

A high-level overview of the history of MDO established a few key aspects of MDO design. MDO can be segregated into either single-level or multi-level optimization. For both types of optimization, there may be analysis performed at the system level or solely at the discipline level. That is to say, that models that run and determine the values of system parameters may be wholly contained in the disciplinary analysis or there may be some analysis completed at the system level (Depince et al. 2007, Allison et al. 2005, and Yi et al. 2007). An example of this from the wind turbine perspective may be a cost analysis that runs at the system level (Vlahopoulos et al. 2011) versus an optimization process that contains optimization of cost-surrogates at the disciplinary level (Crawford and Haines 2004).

Approaches to multidisciplinary design optimization can be segregated into several types. First, there is the question of whether a multidisciplinary analysis is important at all. If not, then traditional optimization techniques similar to those of Schmit (1971) are more appropriate. The next question has to do with stakeholder interests (or customers or decision makers) and whether there are multiple system-level objectives of interest or a single dominant interest. In the former case, one moves to include multiple objectives via an MOO process. In either case, the approach can then be further broken down by considering whether or not optimization is needed at the disciplinary level or if it can be contained within the system level (i.e., moving toward either single-level or multi-level MDO). Finally, there is the consideration of whether there is any system-level analysis of interest or not, which should be addressed in the optimization process.

As mentioned before, analysis in which optimization occurs only at the system level is referred to within MDO as *single-level MDO* (Cramer et al. 1994, Depince et al. 2007). Beyond Multidisciplinary Feasibility, there are a few other main types of single-level MDO, including All-At-Once (AAO) and Individual Discipline Feasible (IDF) (Depince et al. 2007). In AAO, all variables (design, coupling, and state) are treated as design variables and the iterative analysis at the discipline levels is skipped (i.e., the analysis is performed all at once). For IDF, auxiliary variables of coupling variables are created so that disciplines are decoupled and the entire system will only be feasible at the end of the optimization. IDF is seen as a compromise between strict Multidisciplinary Feasibility, which obtains a feasible solution at each iteration but requires many costly subsystem analyses, and AAO, which has massive numbers of design variables and constraints and may not guarantee feasibility (Depince et al. 2007).

Beyond the choice of method, which is derived mainly from the type of system and the problem of interest, there are a number of methodological decisions in particular within the multi-level MDO space regarding how to handle the discipline versus system-level optimizations and analyses. At a high-level, some important classifications in terms of the design of a particular MDO method include the choices between: nested or alternating formulations, open or closed design constraints, and open or closed consistency constraints (Tosserams et al. 2008). A nested formulation of a multi-level MDO problem is one in which all the disciplinary optimization problems are solved, and then subsequently the system level optimization problem is solved. In an alternating formulation, an alternating sequence of optimizations between discipline and system levels is performed. The open or closed nature of design constraints has to do with whether or not a disciplinary optimization (at a given optimization step) is allowed to violate a design constraint through the use of penalty functions. If it is open, then violations are allowed and if not, the design constraint must be upheld during every single sub-optimization step.

Similarly, for open consistency constraints, copies of the interlinked/coupled global variables are used in the disciplinary optimization and matched to their global counterparts through a penalty function—in a closed system, no copies are made and global variables must be consistent across all disciplines and the system level. Various multi-level MDO methods that have been popular in the literature were classified according to these criteria and are shown in Table 5.

Table 5. Classification of key multi-level MDO methods (after Tosserams et al. 2008)

Constraint Relaxation		Formulation	
Design	**Consistency**	**Nested**	**Alternating**
Closed	Closed	Bender's Decomposition	
Closed	Open	Collaborative Optimization (CO)	Analytical Target Cascading (ATC), Enhanced Collaborative Optimization (ECO)
Open	Closed		Concurrent Subspace Optimization (CSSO), Bi-level Integrated System Synthesis (BLISS), MDO Based on Integrated Subspaces (MDOIS)
Open	Open		

There can be various differences in approaches within MDO based on the level of model fidelity used in the analysis as well as information transfer methods. Model fidelity can range from a parametric model to a low-fidelity physics-based model to a high-fidelity and computationally complex model of each of the different disciplines in the system (Agate et al. 2010). Information transfer has to do with what information gets transferred from sub-problem to the higher-level problem (i.e., transfer of a single-point design or some range including sensitivity analysis and the use of a response surface or other metamodel) (Tosserams et al. 2008).

Optimization Techniques for MDO

A taxonomy of optimization may subdivide the field on a number of axes: types of search variable, nature of constraints, existence of gradients, local versus global methods, size of problem, complexity of solver, fidelity of solver, stochastic versus deterministic, heuristic, and others. Many excellent "optimization decision trees" may be found on the Web that guide a user to a particular optimization method based on the characteristics of the problem with respect to these axes, such as the "Decision Tree for Optimization Software" (Mittelmann 2010) from Arizona State University. This section describes some of the single-level methods that will form the ingredients of a multi-level MDO tool relevant to systems engineering for wind energy.

For search spaces of real variables involving differentiable functions, gradient-based methods are the norm (Nodecal 1999). Such spaces are at the heart of traditional engineering design and have a history going back to the invention of calculus. A variety of methods exist depending on knowledge of the characteristics of the objective function (e.g., specialized methods for quadratic functions). A typical example would be the conjugate gradient method for unconstrained convex minimization. For constrained nonlinear problems (the most general situation for the case of continuous search spaces), the common algorithm is sequential quadratic programming, in which a series of quadratic sub-problems is solved on the way to the solution of the general problem. Recently, so-called interior point methods have become competitive with sequential quadratic programming. Early structural optimization problems could be addressed by gradient-based techniques while most of today's MDO applications tend to use simulation-based methods as discussed below.

Many specialized methods exist for linear problems. The most well known are the simplex and dual simplex methods, but the interior point or barrier method is also often used. By exploiting the linear structure of the objective and constraints, problems with more than a million variables and constraints are routinely solved. Of special interest in the MDO context is a method known as the Bender's decomposition (Benders 1962), which could be thought of as a multi-level MDO method for linear problems. In Bender's decomposition, the overall optimum is achieved by iteratively solving a single master problem and a series of coupled sub-problems very much like the general MDO methods discussed above. Use of primal-dual relationships specific to the linear case makes this an extremely powerful method.

Recently so-called derivative-free methods have been developed (Conn et al. 2008). These methods come in a variety of flavors, but they can all be interpreted as working by sampling the objective function and building an analytical model of some kind, which is then used to decide where to sample next. The model—sometimes called a metamodel or a surrogate model—is then adjusted based on new information, and the process is repeated until convergence of some kind is reached. One of the important issues is the nature of the model. A strictly local model (e.g., in the extreme, a linear model built from finite difference gradients) is useful for taking a small step from the current search point. A global model (e.g., a Kriging model built from a space filling design) has the potential to quickly reveal vastly improved points in the search space, but such models obviously involve a trade-off between the computational resources devoted to building the model and the resources devoted to actual search (in the extreme, construction of an accurate model requires a direct enumeration of all the points of the search space up to some level of discretization, which is generally infeasible and always undesirable). Derivative-free methods are especially important in the increasingly simulation-based optimization discussed in this paper, where subsystem analysis codes rarely return derivatives with respect to input parameters (this is related to sensitivity analysis, discussed below). Such methods have been used in MDO for both wind (Vlahopoulos et al. 2011) and non-wind design applications (Hart 2010).

Optimization over spaces of discrete variables, a field known as combinatorial optimization or integer programming, is especially difficult (Jünger et al. 2010). In general, these problems involve the search for a global optimum because the lack of a continuous search variable makes the notion of a local solution somewhat ill defined. The classic deterministic global method for integer programming is branch-and-bound, in which a tree (the "branch" part) that would represent an enumeration of the entire search space is gradually pruned (the "bound" part) so that the global optimum is guaranteed to be found, hopefully with some degree of efficiency. However, the branch-and-bound method has two problems, though, that make it difficult to apply to simulation-based problems. First, it requires a so-called relaxation, in which the objective function is evaluated at non-integer design points. Most simulations do not come equipped with relaxations. Second, it generally requires a large number of objective function evaluations, so it is impractical for optimizations based on expensive simulations. However, it can fit in the MDO context for wind energy as the means to globally optimize integer-based analytic surrogate models. Fortunately, there are few discrete variables in the design of a complex physical system such as a wind turbine. However, when evaluating system architectures for wind energy, a number of discrete choices may be present relating to different system configurations. Therefore, the appropriate optimization for a design problem may vary depending on the particular question being asked or the stage in the design problem.

Practical optimization over discrete search spaces generally involves so-called meta-heuristics (Nikolaev 2010). Meta-heuristics (or just heuristics) are rules of thumb, methods based on practice, often based on analogy with natural processes and usually involving some degree of non-determinacy. They have been found immensely useful in optimization (especially global optimization). The most famous such algorithm is undoubtedly the genetic algorithm, pioneered by John Holland in the 1970s (Holland 1975), and built on an analogy to the process of natural selection in evolution. Today many such algorithms exist, such as the following:

- Simulated annealing, based on the natural tendency of a material system to minimize its energy in the presence of controlled reduction from an elevated temperature
- Scatter search, incorporating geometric notions of interpolation and extrapolation
- Tabu search, derived from the insight that humans solve search problems by subtle use of memory (we do not return immediately for further search in places we have just searched, but eventually, if all else fails, we do)
- Swarm intelligence optimization (ant colony optimization, particle swarm optimization), based on modern theories of collective intelligence, in which large numbers of autonomous agents follow simple rules that lead to intelligent behavior (in this case, finding a numerical optimum) of the whole

In general, heuristics are advantageous when a "good enough" rather than a true global optimum solution is desired. Often local search methods (either derivative-free or gradient-based) are combined with heuristic methods; these are often called hybrid methods, and can be extremely powerful. An area of especially active research today is problems involving mixtures of real and discrete variables. These mixed integer nonlinear programming (MINLP) problems are some of the most difficult, but also some of the most important, because modeling of real-world, complex systems almost always leads to such formulations. The case of wind energy is clearly one in which even discipline-specific, single-level problems of an MDO will most likely require solution of MINLPs. The methods for MINLP are generally hybrids of those for continuous and discrete problems, including the mixing of heuristics with branch-and-bound, the use of surrogate models for both real and discrete spaces, and a growing number of tricks supporting solution of such problems "by any means necessary."

MDO Support Tools and Post-Processing

There are a variety of tools that have been developed and exploited for the support of MDO. Tools that support the decomposition process and ultimately the structuring of the MDO model, such as DSM, have become important as the trend toward multi-level MDO has progressed (Agate et al. 2010). DSM tools can be used to express either physical relationships in the design of a technical system (object-based DSM) or used to express the process relationships in the management of the design of a technical system (task-based DSM). The discussion of the latter is important in the systems engineering sub-field of concurrent engineering and design, which will be discussed in a following section. Object-based DSM, also called a design dependence matrix or an N-squared diagram, involves a square matrix where each system element (design variables) is listed both along columns and rows, and off-diagonal cell are used to represent the relationships between the different elements (Smith and Eppinger 1997). For instance, if an element in row I affects an element in column J, then there is a mark in that off-diagonal cell to reflect that relationship.

This information can be used to analyze the feedback relationships within a system and ultimately is a tool for structural analysis of the system, which can lead to improved system structural design (Van Eikemma Holmes 2008). Various network relationships can be analyzed with respect to the system modularity and dominance to identify potential weaknesses and bottlenecks in the system architecture. With respect to MDO, DSM is a tool that aids in the decomposition process that is reflected in the structural design of multi-level MDO models and has been used to support various well-known multi-level MDO models such as Collaborative Optimization (CO), Concurrent Subspace Optimization, (CSSO) and Bi-level Integrated System Synthesis (BLISS) (Agate et al. 2010).

In addition to model structure, the transfer of data between sub-models in MDO is critical to the validity of results of any holistic and multidisciplinary analysis. As discussed above, the use of metamodels, or surrogate models, has been of particular importance in aiding the MDO optimization process (Tosserams et al. 2008, Simpson et al. 1998, Simpson et al. 2008). Metamodels, coined by Kleijnen in 1987, are essentially models of models that try to capture as much of the fidelity of a higher-order model as possible while allowing for the quick computation and exchange of information of a lower-order model (Simpson et al. 1998). They can be produced prior to and used by an MDO analysis or they can be an output of such an analysis for post-processing applications. The development of metamodels is an important part of the overall process of design and analysis of both physical experiments as well as for computer experiments (DACE) (Simpson et al. 1998). The general process in developing a metamodel has been described thoroughly in Simpson et al. 1998 and is shown in Figure 28.

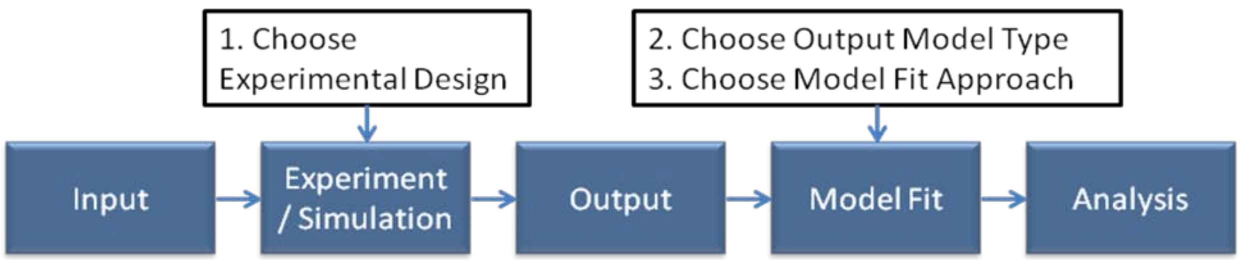

Figure 28. Metamodel development process (as described in Simpson et al. 1998)

In general, the use of approximations in simulation characterization and optimization can be broken down into three categories: (1) low-fidelity simulations, (2) statistical models, and (3) physics-based surrogates. The first simply use an existing simulation with a smaller basis set or rougher mesh, etc. The second are the metamodels discussed here. The third involve domain-specific approximate models of the actual physics of a subsystem. The metamodeling techniques can be categorized in several ways. Of these, we note the distinction between local methods (e.g., classic response surface methods) and global or *space filling* methods (e.g., a Kriging model), and between methods involving analytic statistical models whose parameters we fit (e.g., a quadratic model) and methods involving "black box" input-output relationships derived by machine learning algorithms (e.g., neural networks). The latter provide greater flexibility over the form of model functions at the expense of the confidence and utility of explicit knowledge of the model function. Another option for constructing low-order models includes model reduction techniques which involve the projection of the governing equations from a higher fidelity model. Much more detail of such methods and their use in MDO analysis is possible and the reader is directed to the references for further discussion.

Scenario Analysis and System Architecture

The previous sections centered on a discussion MDO centered on optimization of a single objective at the highest level (for instance, wind energy LCOE). Post-analysis tools were briefly described in Section 2.1.1.1 and can be used to explore sensitivities of design outcomes to variation in input design parameters. Various metamodels and statistical techniques can be used to gain insight into system design. However, there are other types of analysis that assist in developing insight into the design process as well as evaluating and comparing designs at a higher level. Scenario analysis and system architecture analysis are two distinct but applicable tools in this category.

In the first case, scenario analysis is typically used to evaluate several future scenarios that are typically very different from one another and for which there may not be a lot of information on the likelihood of realization of any given scenario. Therefore, scenario analysis does not take into account past developments and is not a forecast of future states but a way to bring to the forefront potential consequences of current decisions should certain events take place. For instance, the development of direct-drive technology in wind energy has received considerable attention in the last several years due to the historical problems associated with gearbox failures. Eliminating the gearbox through a direct-drive system is seen as a way to eliminate the largest source of reliability problems for turbines today. However, direct-drive technology often relies on generator types that are permanent magnet based and rely on rare-earth metals for their construction. One scenario analysis that might be considered through the integration of cost-modeling, design, and even supply chain analysis may be to look at how the shift to direct-drive designs may affect the cost of energy should a scenario of supply-side constraints on the cost of rare-earth metals become realized. The number of potential scenarios for analysis is infinite and builds directly upon the systems engineering development of tools such as MDO, MOO, and others.

The second topic of system architecture relates both to an area of theory and a methodological approach to system design and evaluation. System architecture is similar to scenario analysis in that specific and very different points in a large design space are compared. The definition of *system architecture* is the selection of the types of system elements, their characteristics, and their arrangement (Haskins et al. 2010). In other words, it is the high-level description of system design that, for wind energy, may include the configuration of each major subsystem.

Architecture methods might be used to explore unconventional designs such as vertical axis wind turbines or two-bladed horizontal axis wind turbines for offshore wind energy applications such as was done in the Opti-OWECS project (Kühn et al. 1997a, Kühn et al. 1997b). The scope could also be extended to consider integrated turbine-plant design architectures that account for wake interaction, wind plant layout, and impacts. Architecture analysis is also useful when there are a large number of design objectives in an MOO process, including time-dependent criteria such as system reliability (McManus et al. 2007, Ross 2006). The different methods of MDO and MOO using lower-fidelity metamodels may be used to compare different overall system architectures before, during, or in addition to detailed design studies of a specific design.

Visualization Techniques

Whether employing optimization techniques, design space exploration or system architecture analysis, the role of visualization and data processing techniques is very important. Statistical techniques and uncertainty quantification are used in tandem with visual analysis to provide critical information in a well-organized manner to aid the design process. Developing a design trade space may result in thousands of potential designs (Ross 2006) with just as many potential ways of slicing and filtering the data. Trade studies are a way of selecting designs from a very large set of designs within multiple architectures where requirements can be traded against constraints (Haskins et al. 2010). In general, visualization of information has received a lot of attention in recent years, partially inspired by revolutions in computing and computer graphics. The visual display of quantitative information is important as the complexity of a system increases. In particular, with multi-dimensional systems both in terms of input and output variables, methods and software tools have been developed to help reduce the complexity of the design consideration space when one wants to explicitly understand the trade-offs between large numbers of designs (Stump et al. 2004). In terms of exploring these designs from different angles, the area of visualization known as coordinated and multiple views has received research attention addressing data processing and preparation, view generation, exploration techniques, coordination, tools, human interface, and perception (Roberts 2007). Multiple views refers to any instance where data is represented in multiple forms (“windows”) at once while coordinated refers to linking across the views in terms of actions taken to create, modify, or inspect them (Roberts 2007). In order to bring increased tractability to design of large-scale complex systems, visualization techniques complement traditional design evaluation using statistical methods.

Summary on MDO and Associated Analysis Tools

This appendix has highlighted in more detail the state-of-the-art in MDO methods and associated optimization algorithms and post-processing techniques. The application of MDO methods to complex technical systems for aerospace and other applications has been highlighted. Wind energy system research, design, and development may similarly benefit from the application of MDO and related techniques, and several initiatives are under development, as discussed in Section 2. This appendix highlights some of the complexity and nuances related to implementation of MDO. A particular type of MDO must be selected depending on the application of interest and may involve either single- or multi-level methods. If multi-level, there are a variety of structures that can be used to pass information between the system and disciplinary levels and different ways to control the optimizations at the respective levels. In addition, the algorithm for optimization can as well as how models are represented at each level of analysis (i.e., they may incorporate detailed physical models or metamodels that are derived prior to analysis). Results of MDO analysis may be used for a variety of applications including development of metamodels, statistical processing, and even visualization. Careful consideration of all of these aspects is important in considering the application of MDO to the research and design of complex technical systems such as wind energy systems.

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