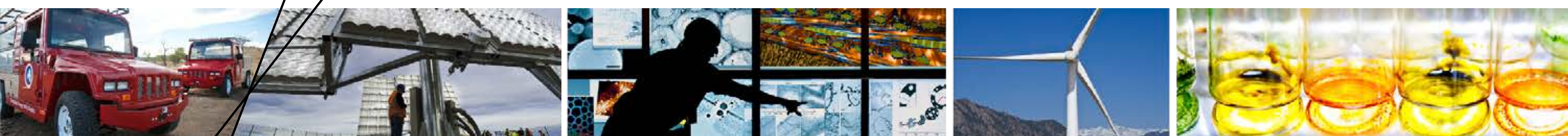
Innovation in Wind Energy: A Systems Engineering Perspective



Paul Veers

Chief Engineer: NREL's National Wind Technology Center

Systems Engineering Workshop

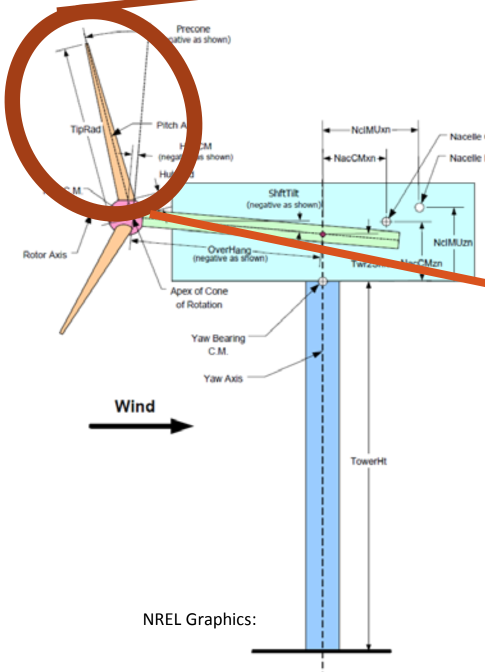
29 January 2013

Analysis

- **Analysis: "the separating of any material or abstract entity into its constituent elements"**
  - Sandia Labs application – physical modeling
  - NREL/EERE application – economic modeling

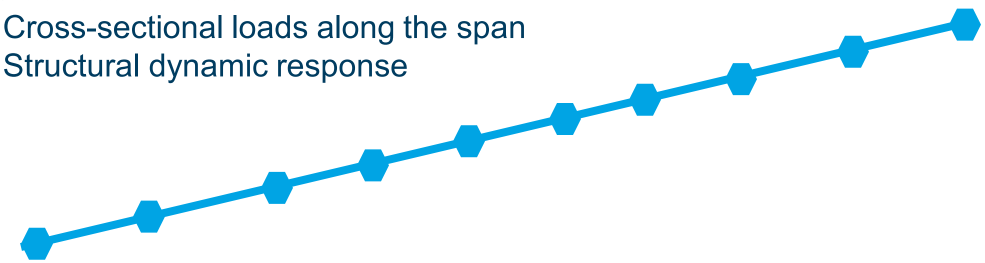
An Analysis Approach to Modeling

3 dof modal representation - Dynamics

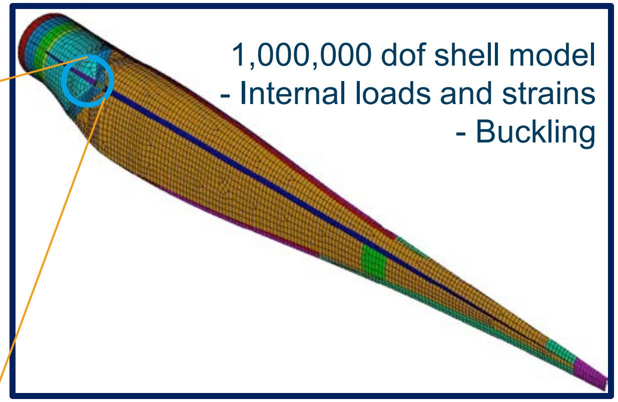


NREL Graphics:

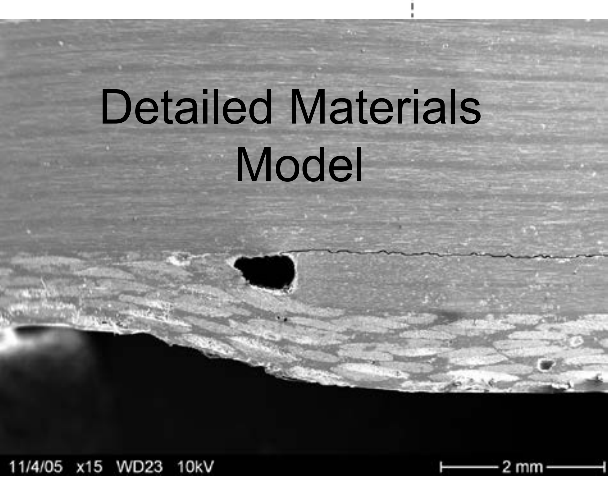
60 dof beam model
– Cross-sectional loads along the span
– Structural dynamic response



Boundary Conditions:
Interface Loads

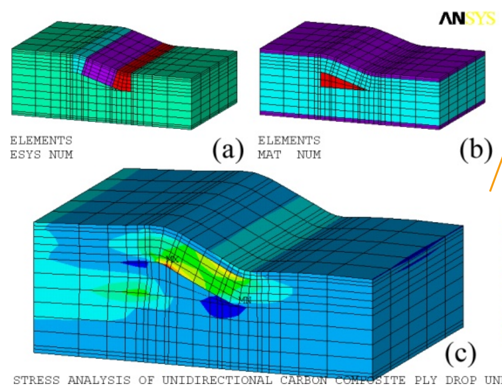


1,000,000 dof shell model
- Internal loads and strains
- Buckling



Detailed Materials Model

Manufacturing Details



SMN =-.274E+09
SMX =.125E+10

Graphics: Courtesy Sandia Labs

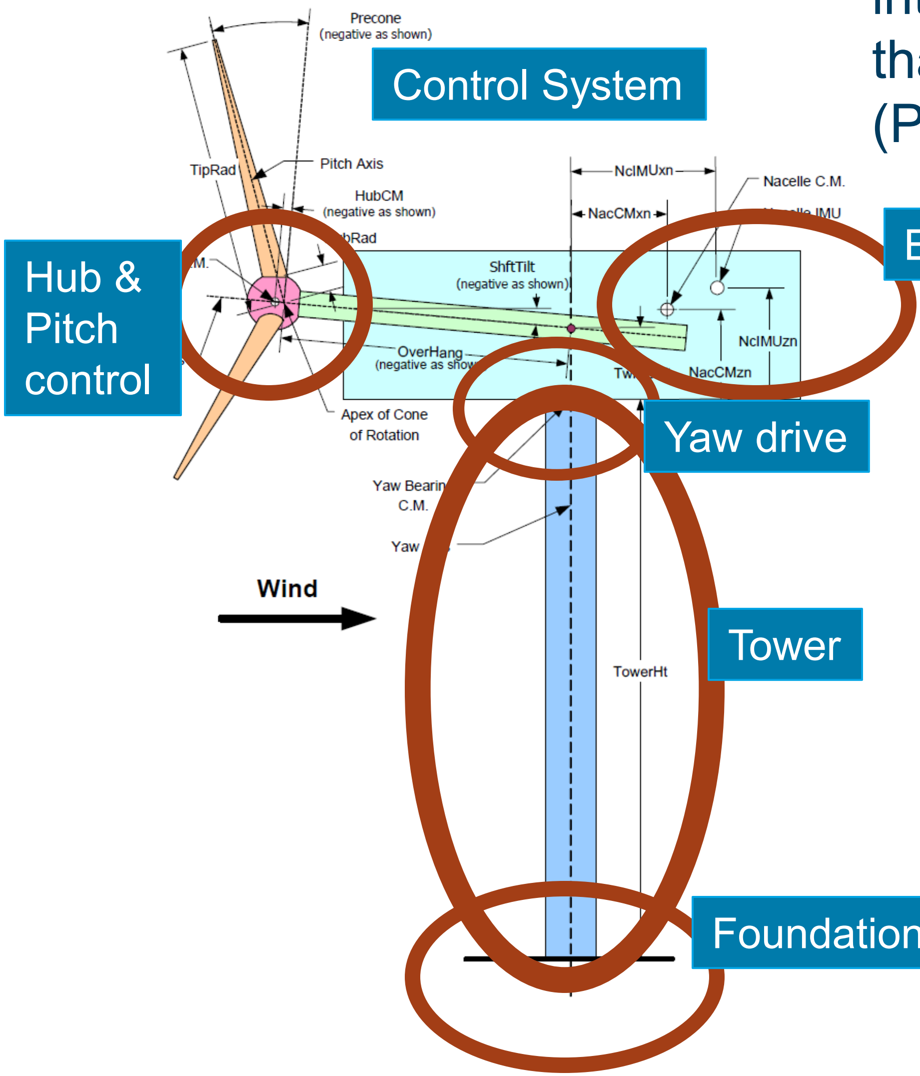
- **Scales represent different criteria in the design space of wind turbine blades**

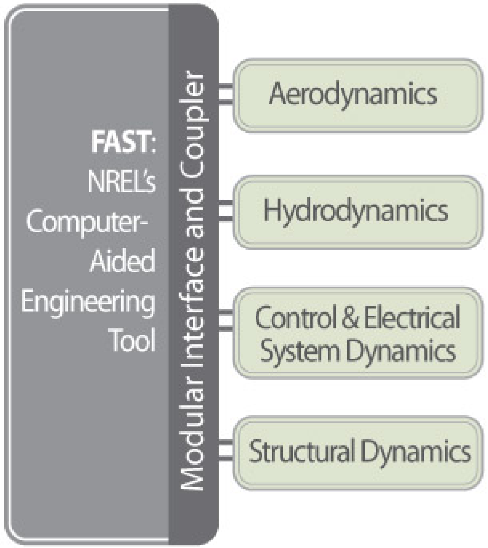
Synthesis:

- **Synthesis: "the combining of the constituent elements of separate material or abstract entities into a single or unified entity"**
  - Innovation
  - Systems Engineering

Modeling Depends on Interfaces

Each subsystem needs to be integrated into an operational whole that satisfies the system demands (Performance and Durability)





Wind Plants puts turbines in the wake of other turbines

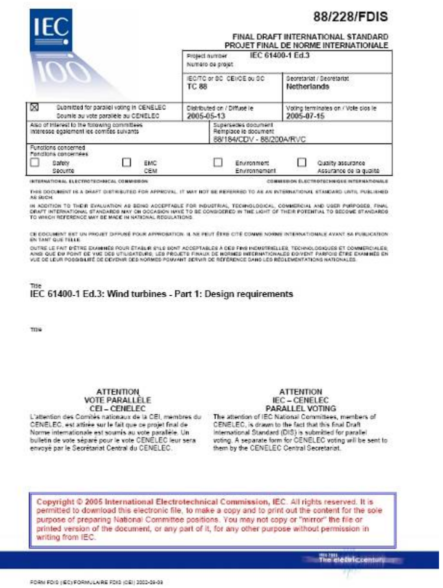
- **The wind plant is more than the machine alone:**

- **Turbine**
- **Foundations**
- **Electrical collection**
- **Power conditioning**
- **Substation**
- **SCADA**
- **Roads (or ships)**
- **Maintenance facilities**
- **…**

System Perspective (Dykes)

The desired end state if a system engineering capability that accurately captures all the **interrelationships** between the various subsystems (including turbine interactions, O&M, transportation, environmental constraints, etc.) while meeting the **design requirements** for each subsystem.

Turbine *Specifications* – Design Standards



88/228/FDIS

FINAL DRAFT INTERNATIONAL STANDARD
PROJET FINAL DE NORME INTERNATIONALE

Project number / Numéro de projet: IEC 61400-1 Ed.3	
IEC/TC or SC / CEI/CE ou SC: TC 88	Secretariat / Secrétariat: Netherlands
☒ Submitted for parallel voting in CENELEC / Soumis au vote parallèle au CENELEC	Distributed on / Diffusé le: 2005-05-13 — Voting terminates on / Vote clos le: 2005-07-15
Also of interest to the following committees / Intéresse également les comités suivants	Supersedes document / Remplace le document: 88/184/CDV - 88/200A/RVC
Functions concerned / Fonctions concernées: ☐ Safety / Sécurité ☐ EMC / CEM ☐ Environment / Environnement ☐ Quality assurance / Assurance de la qualité	

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Title
IEC 61400-1 Ed.3: Wind turbines - Part 1: Design requirements

Titre

ATTENTION
VOTE PARALLÈLE
CEI – CENELEC
L'attention des Comités nationaux de la CEI, membres du CENELEC, est attirée sur le fait que ce projet final de Norme internationale est soumis au vote parallèle. Un bulletin de vote séparé pour le vote CENELEC leur sera envoyé par le Secrétariat Central du CENELEC.

ATTENTION
IEC – CENELEC
PARALLEL VOTING
The attention of IEC National Committees, members of CENELEC, is drawn to the fact that this final Draft International Standard (DIS) is submitted for parallel voting. A separate form for CENELEC voting will be sent to them by the CENELEC Central Secretariat.

The electric century

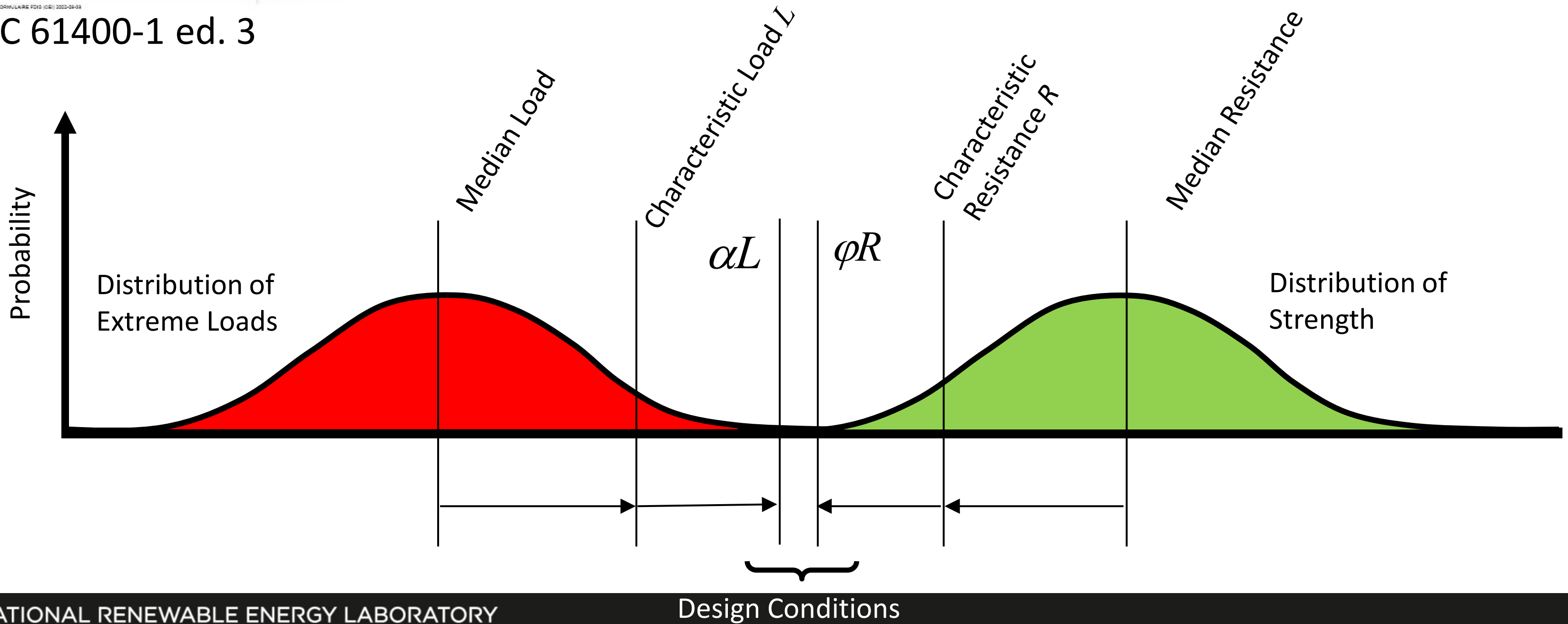
FORM FDIS (IEC)/FORMULAIRE FDIS (CEI) 2002-08-08

IEC 61400-1 ed. 3

- Characteristic Loads
  - Suite of "Design Load Cases" (DLCs)
  - Uses aeroelastic model to apply atmospheric conditions to the dynamic structure
- Characteristic Strength
  - Material properties
  - Damage rules
  - Statistical variation

Design Criteria

$$\alpha L < \varphi R$$



IEC Standards have a suite of Design Load Cases (DLCs)

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r$±2 m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, V_r± 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, V_r± 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r$±2 m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r$±2 m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0,7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

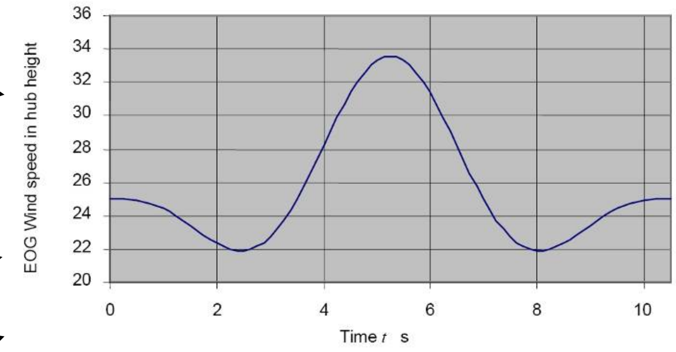


Figure 2 – Example of extreme operating gust

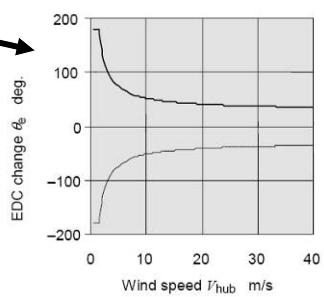


Figure 3 – Example of extreme direction change magnitude

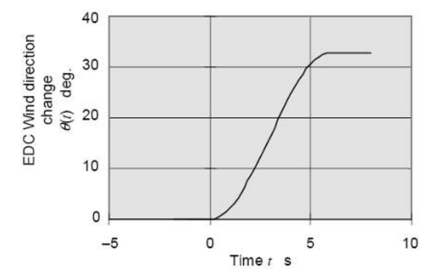


Figure 4 – Example of extreme direction change

The Standard requires load extrapolation for extreme loads and load spectra for fatigue

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N

7.6.2 Ultimate strength analysis

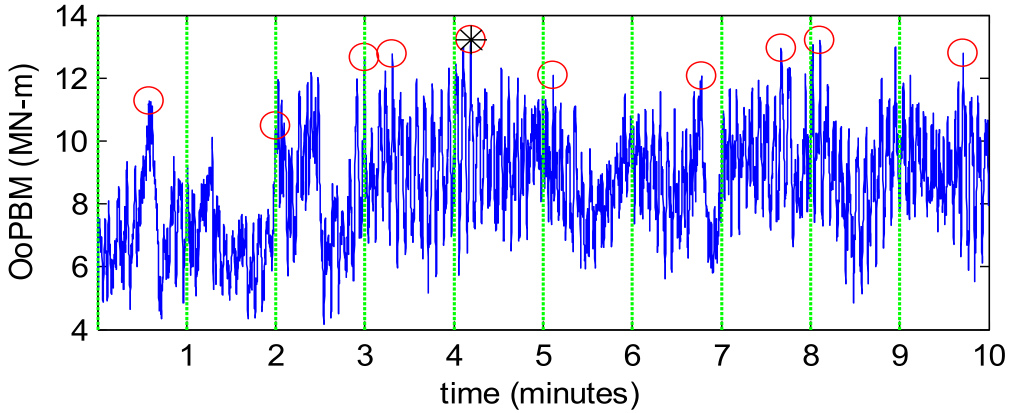
The limit state function can be separated into load and resistance functions S and R so that the condition becomes

$$\gamma_n \cdot S(F_d) \leq R(f_d) \quad (30)$$

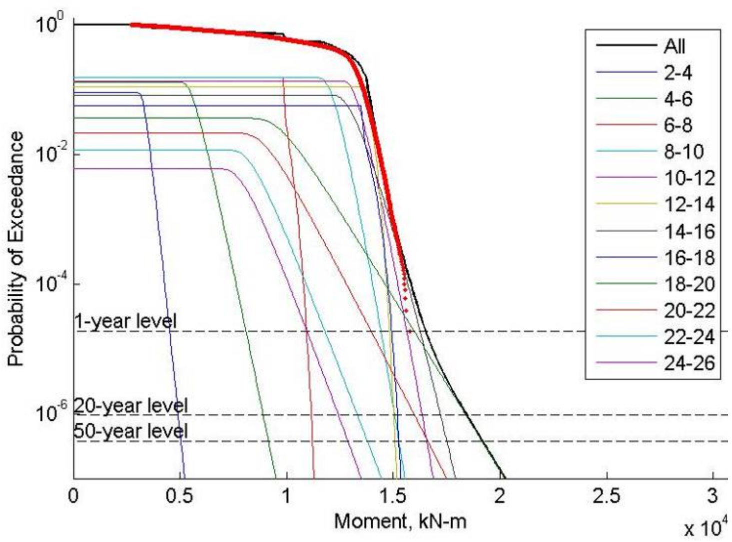
The resistance R generally corresponds with the maximum allowable design values of material resistance, hence $R(f_d) = f_d$, whilst the function S for ultimate strength analysis is usually defined as the highest value of the structural response, hence $S(F_d)=F_d$. The equation then becomes

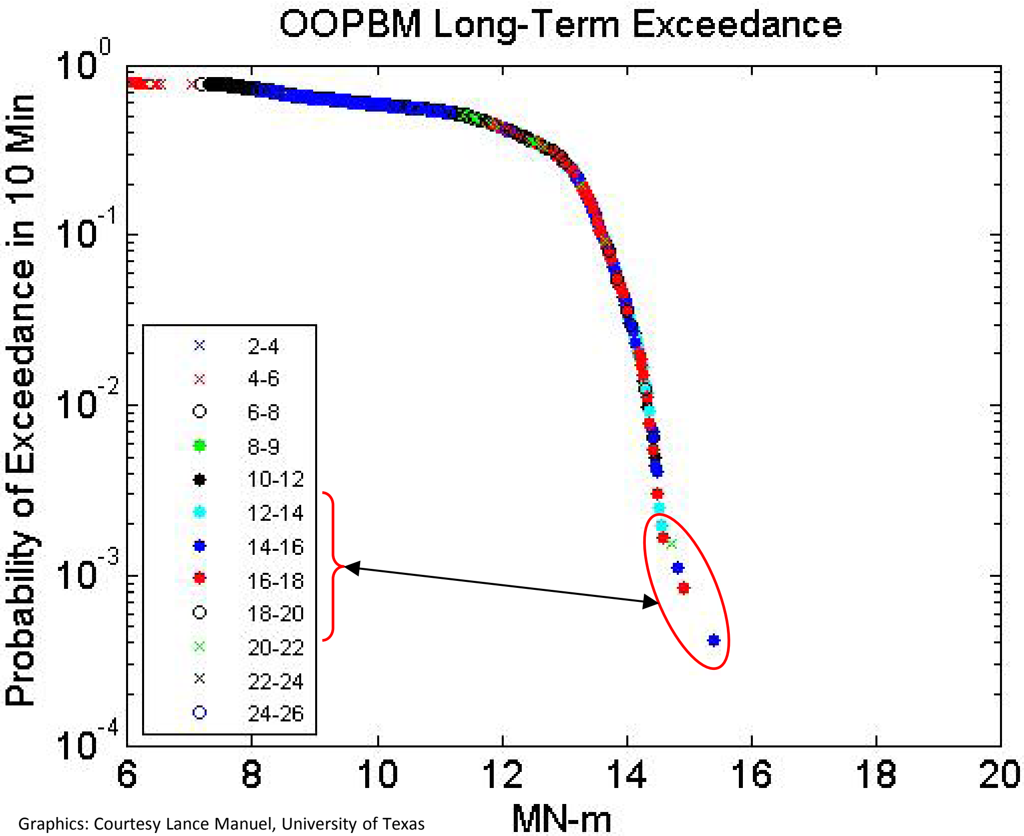
$$\gamma_f F_k \leq \frac{1}{\gamma_m \gamma_n} f_k \quad (31)$$

Load Extrapolation : Extreme Design Loads



- **Load extrapolation uses many short operational simulations to estimate a long term extreme**





Sometimes the largest loads come from moderate wind speeds

Graphics: Courtesy Lance Manuel, University of Texas

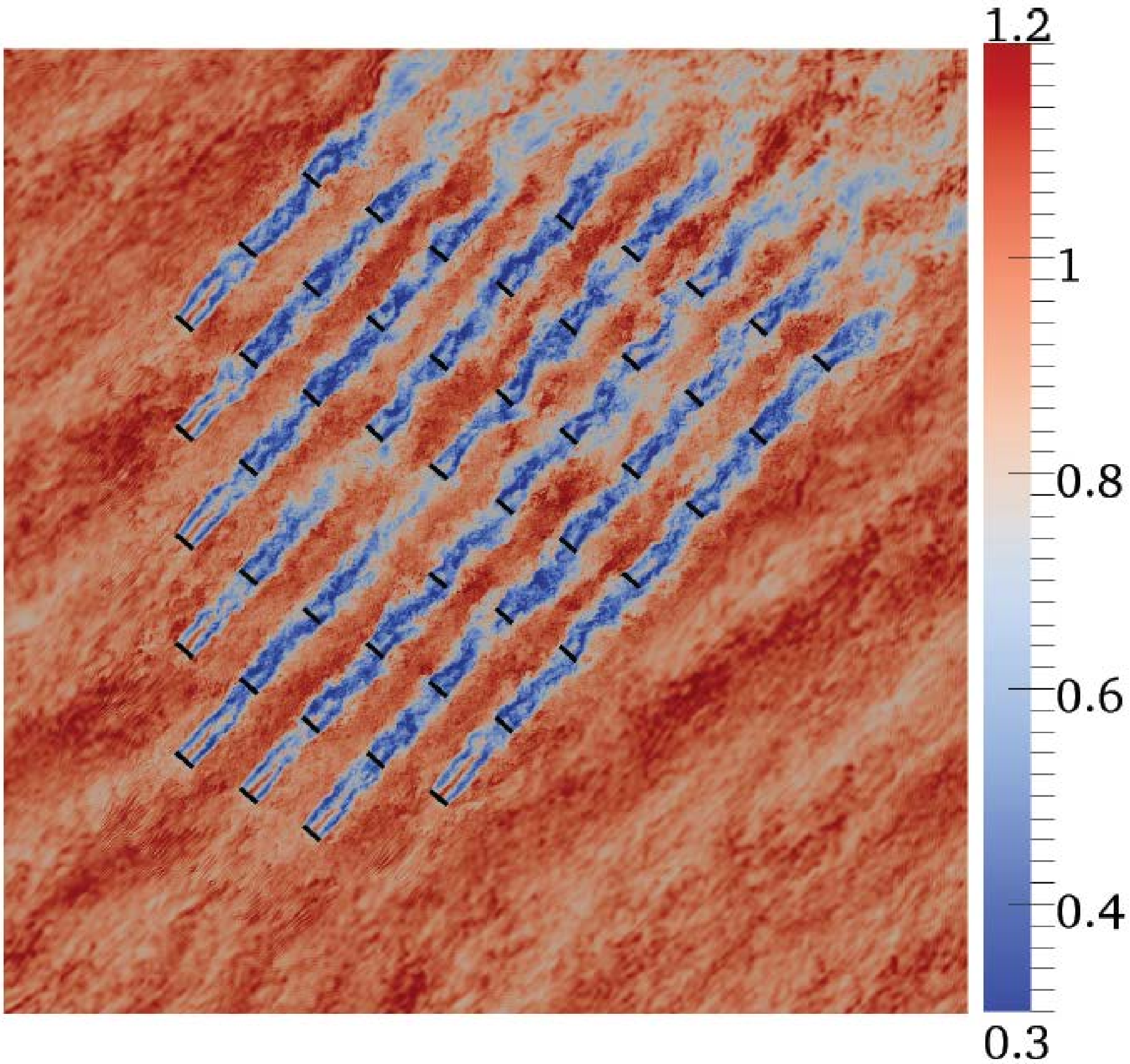
Wind Plant Effects Less Well Understood

The IEC standard requires assessment of wake effects

Current recommended approach is a simple inflation of turbulence levels (Frandsen model)

Potential improvement is to move to Dynamic Wake Meandering (DWM) model

Could turbines be designed differently for location within a plant?



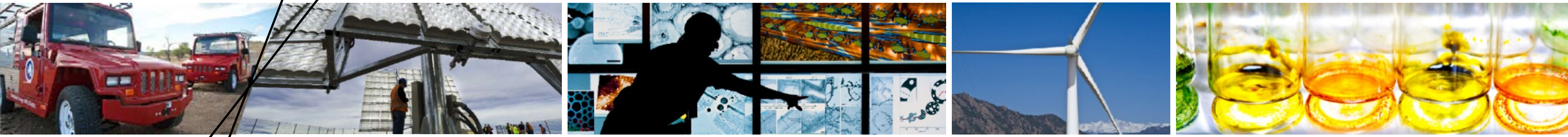
Summary of Design Requirement Issues

- The design standards used across the entire industry will drive both cost and reliability levels across all suppliers
- Any single innovation that does not promise improvement across all design load cases will not have value
- Modeling and simulation tools and System Engineering capabilities must be able to evaluate the ability to meet the requirements

NATIONAL RENEWABLE ENERGY LABORATORY

Case Study: Subsystem Design

Blade Study at Sandia Labs

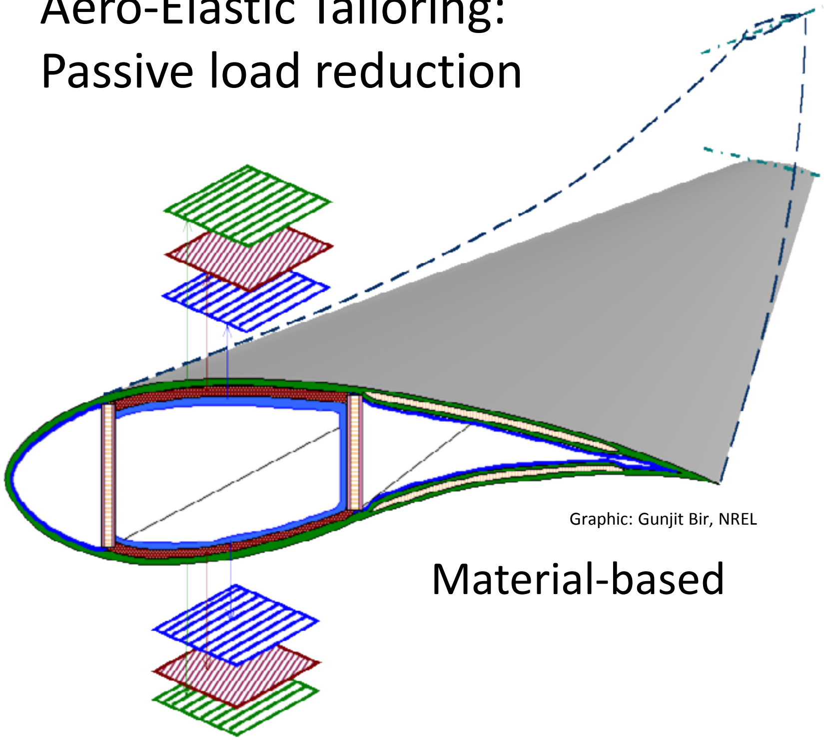


Historic approach to blade design

- **Define the aerodynamic envelop for maximum performance**
- **Design the internal structure for sufficient stiffness and durability**
- **Create a manufacturing process to produce the blade as designed**

Example of Fundamental Research findings

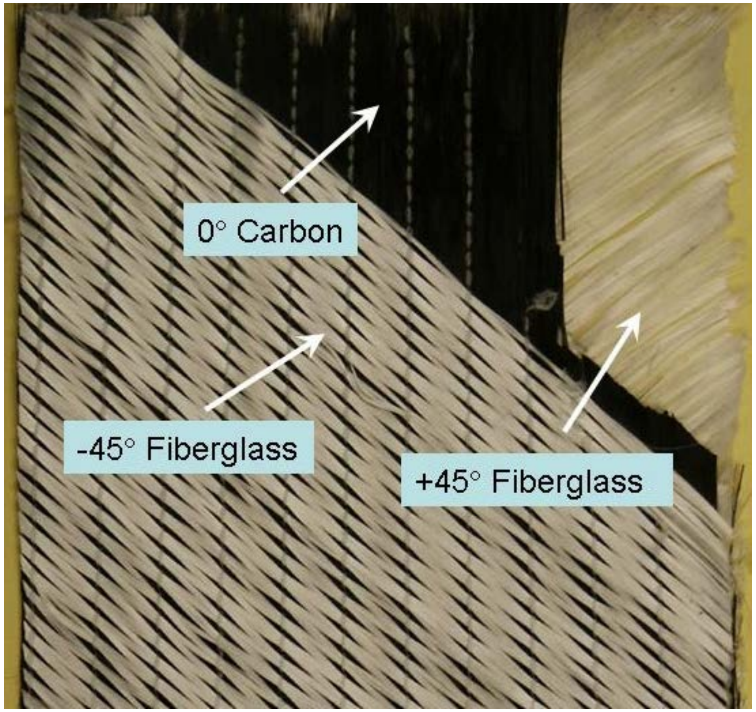
Aero-Elastic Tailoring:
Passive load reduction



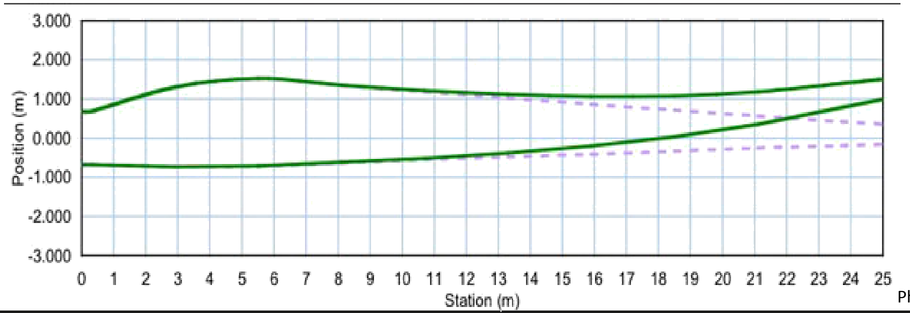
Graphic: Gunjit Bir, NREL

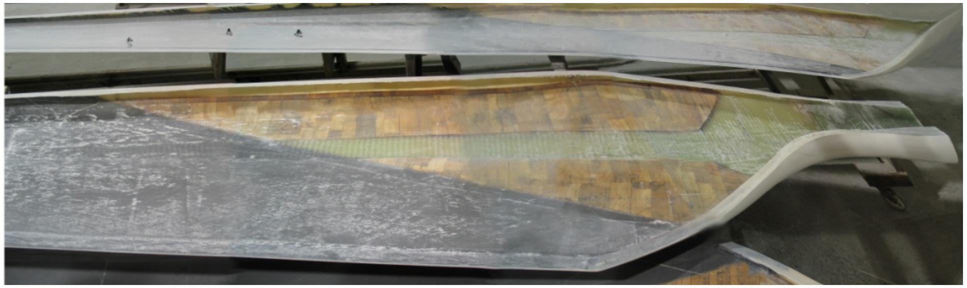
Material-based

New Materials – Carbon Fiber



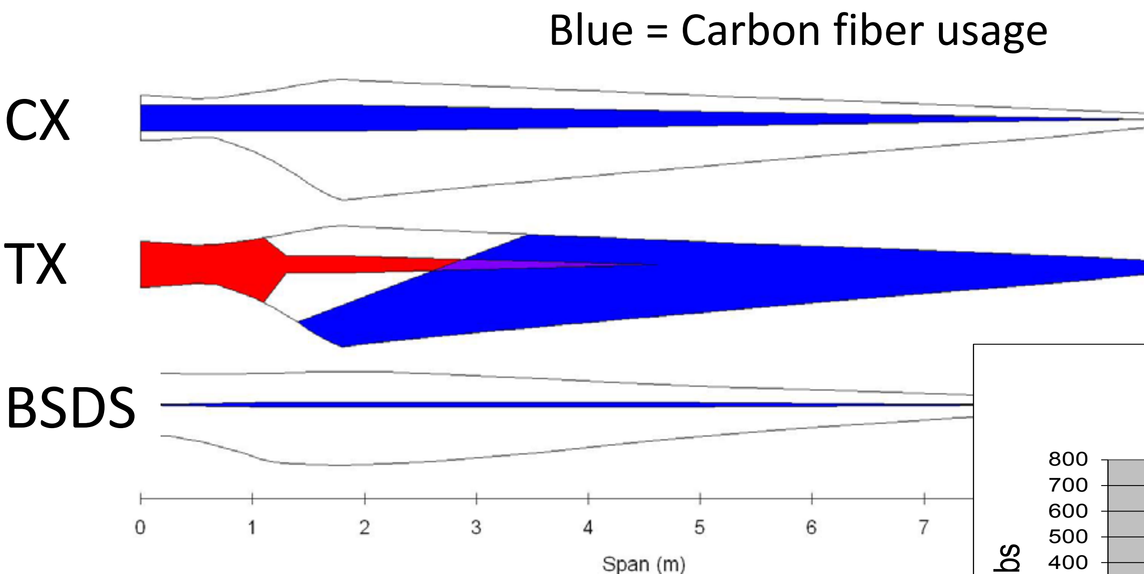
Geometry-based

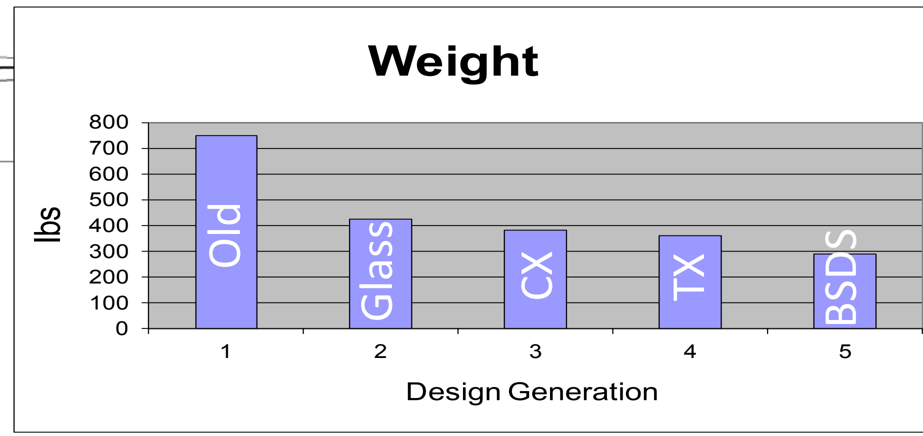


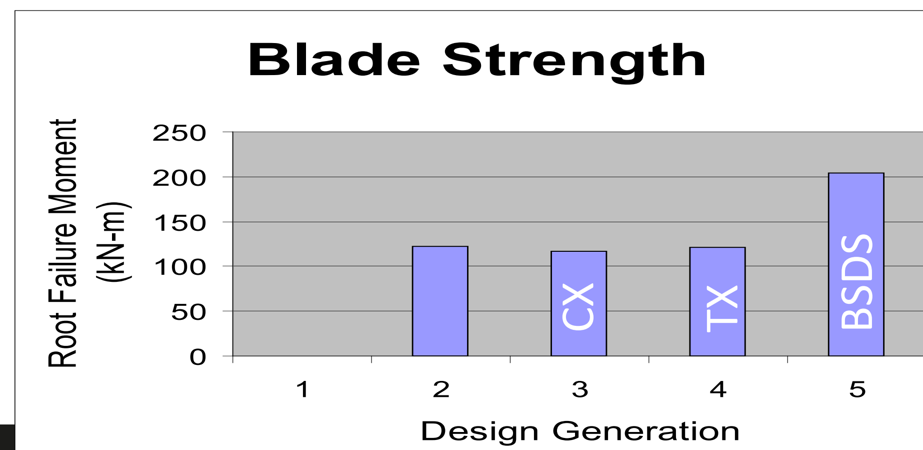


Photos and graphic: Courtesy Sandia Labs

Blade System Design Study (BSDS) at Sandia







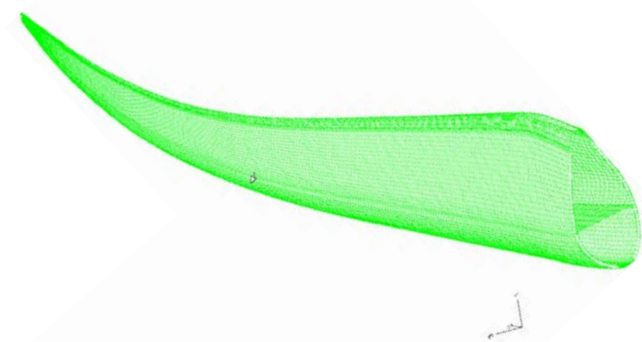
The BSDS blade incorporated a very small carbon spar cap, flat-back airfoils, and a novel root stud system.

Photo and Graphics: Courtesy Sandia Labs

Example of full-scale commercialization project

- Knight & Carver Demonstration
  - 27.1m swept blade
  - Replacement blades – Zond 750
  - 5-10% increased energy capture with longer blades
  - Maintained dynamic load envelop

Next Generation of Siemens Blades



Knight and Carver Blade
2006

Flat-back airfoil

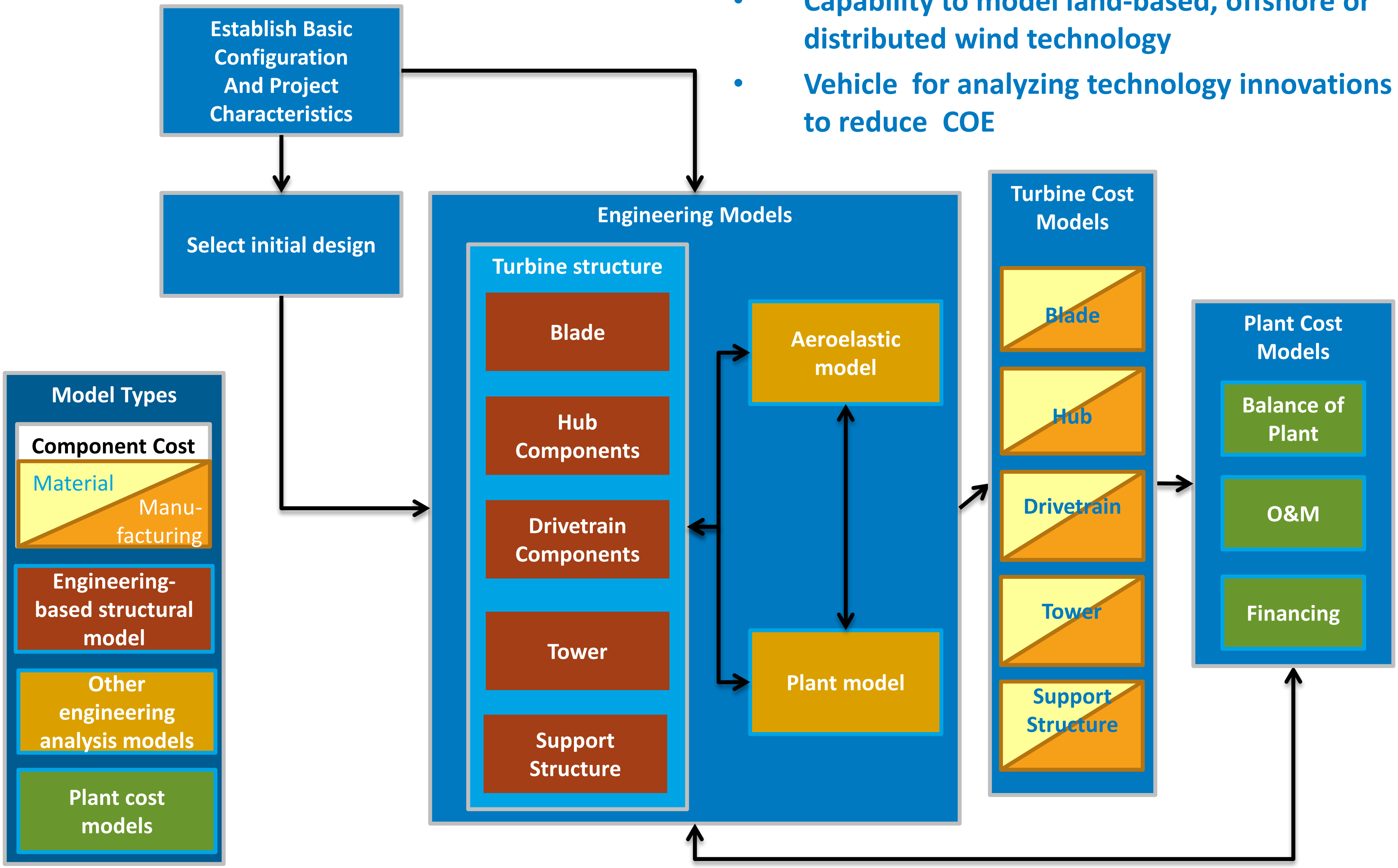
Siemens Blade
2012

These Siemens blades have flat-back airfoils and sweep for aeroelastic tailoring.

Graphics: Courtesy Siemens

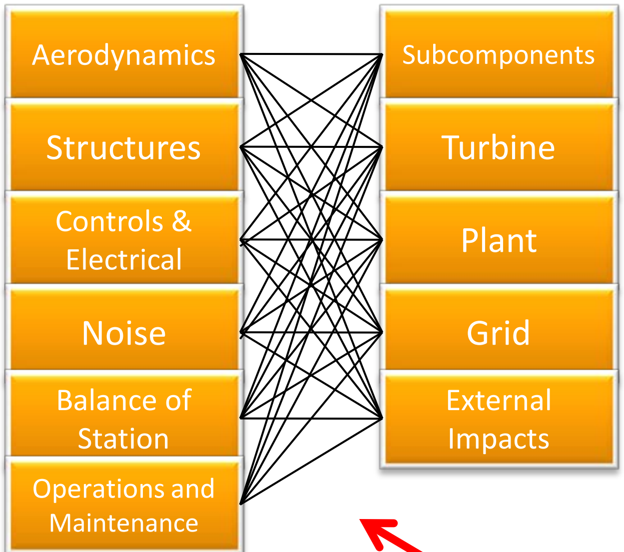
The System Engineering Framework Models All Critical Subsystems

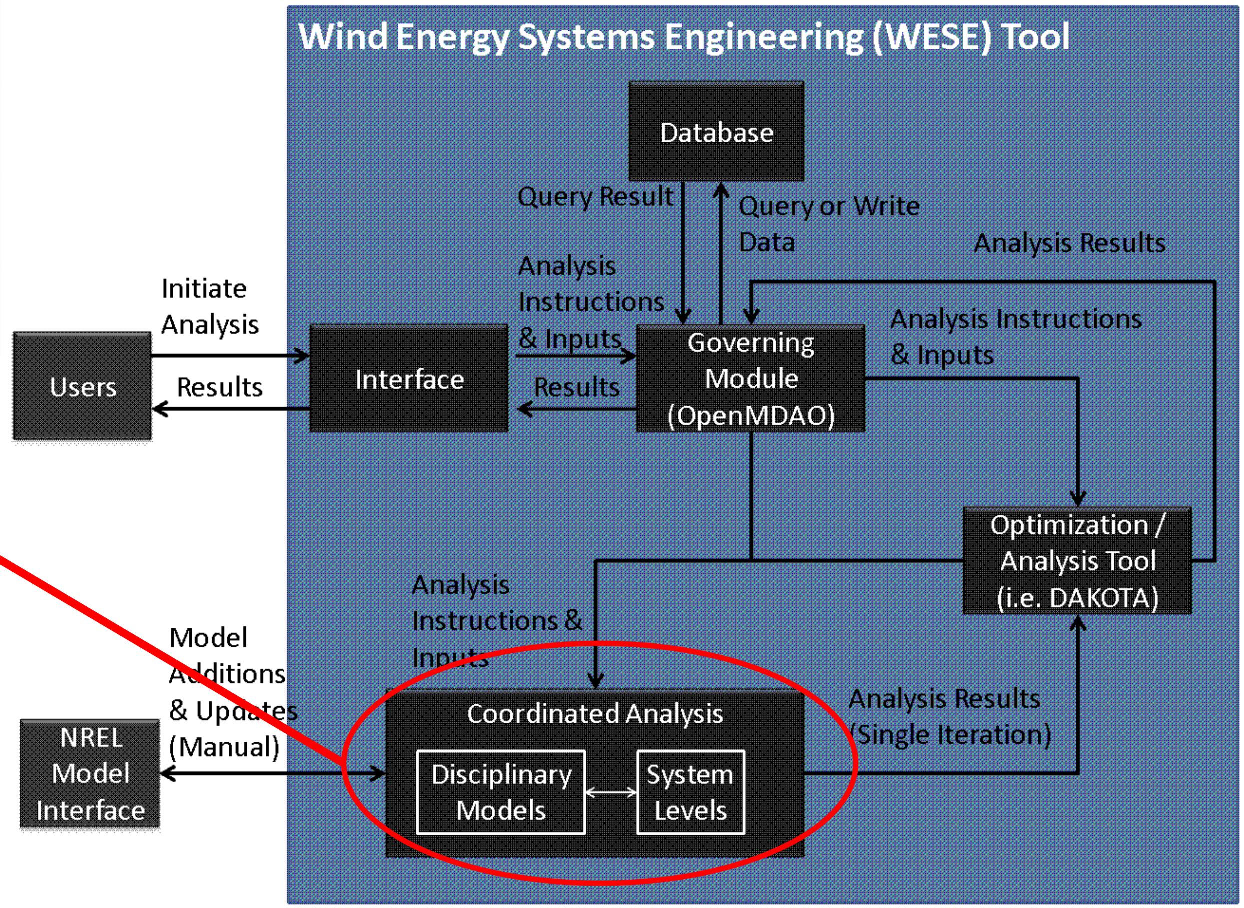
- Capability to model land-based, offshore or distributed wind technology
- Vehicle for analyzing technology innovations to reduce COE



Systems Engineering Framework Development

- **Tool development involves integration of wind system modeling, analysis / workflow management, and analysis driver software**





Coordinated Analysis:

- **integration of various models**
- **definition of subsystem interfaces**
- **full system representation**
- **different levels of fidelity representing different sub-systems**

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future