Evolution of load simulation methods in a systems engineering perspective

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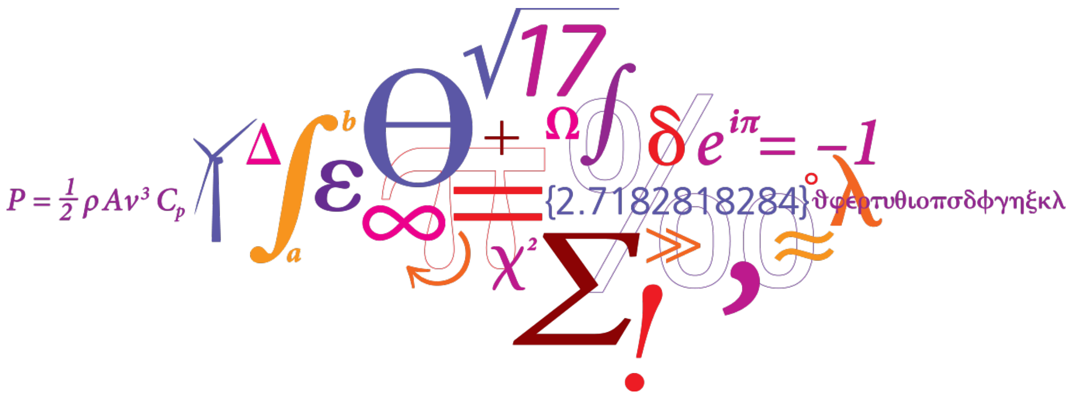
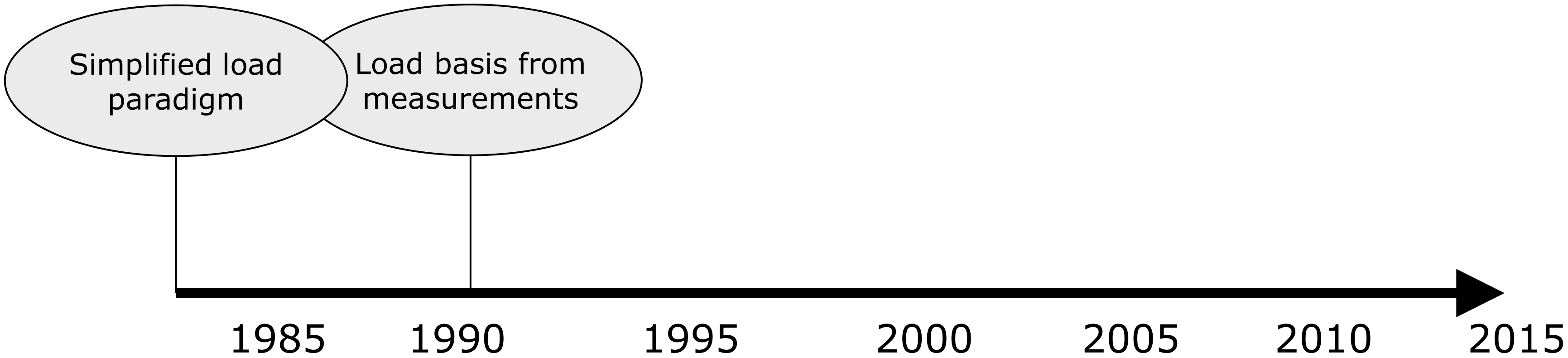


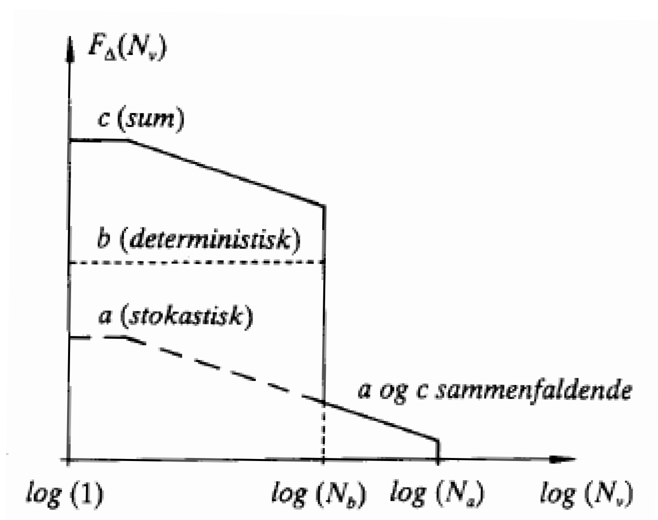
DTU Wind Energy
Department of Wind Energy

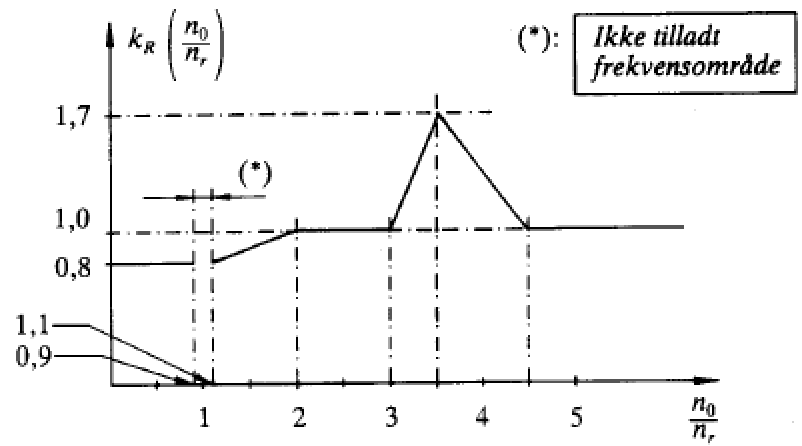
Selected highlight in the model development



Simplified load basis

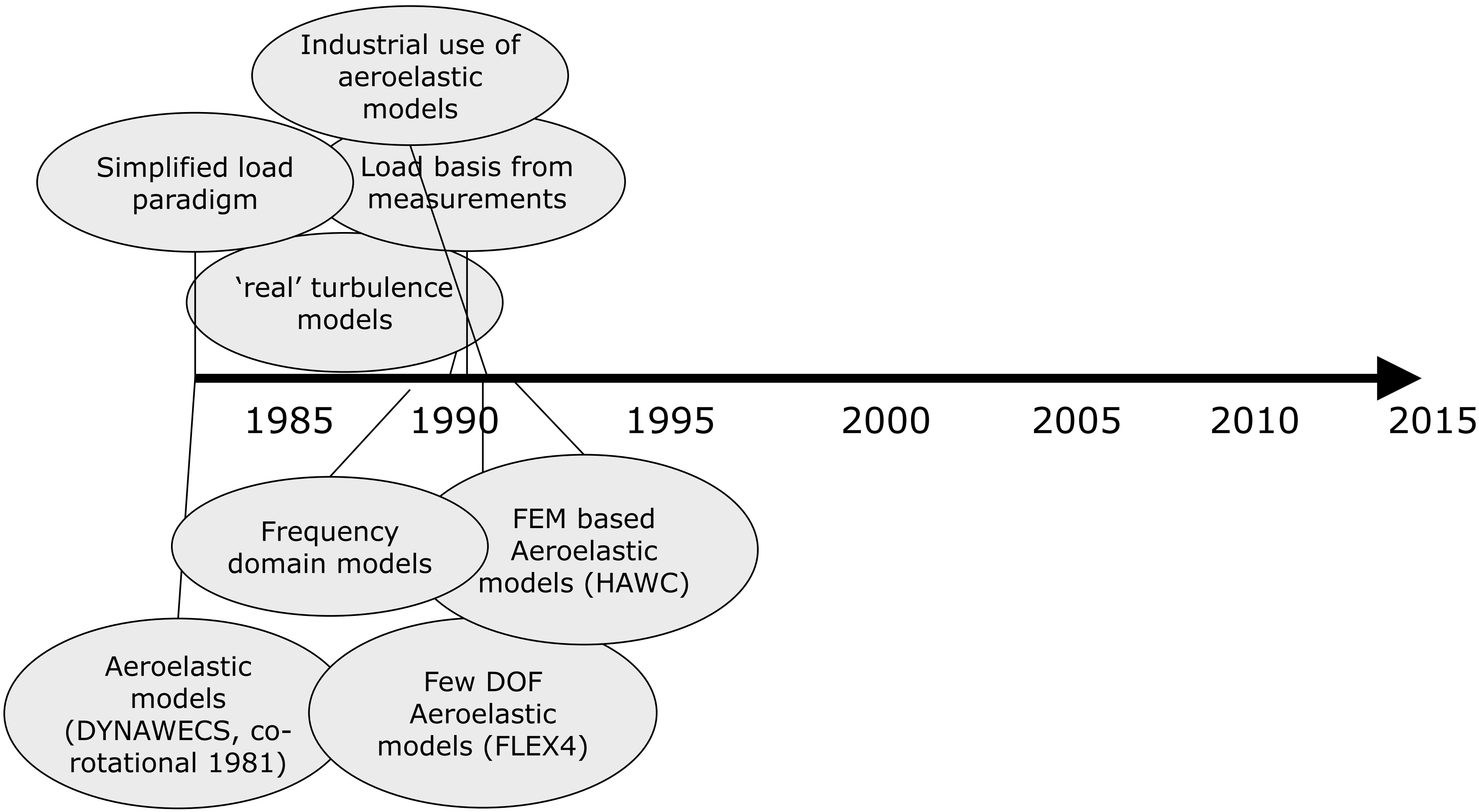
- From 300 N/m^2 to standardized load spectrum based on measurements





- Combination of stochastic and deterministic loads
- The importance of frequency coincidence

Selected highlight in the model development

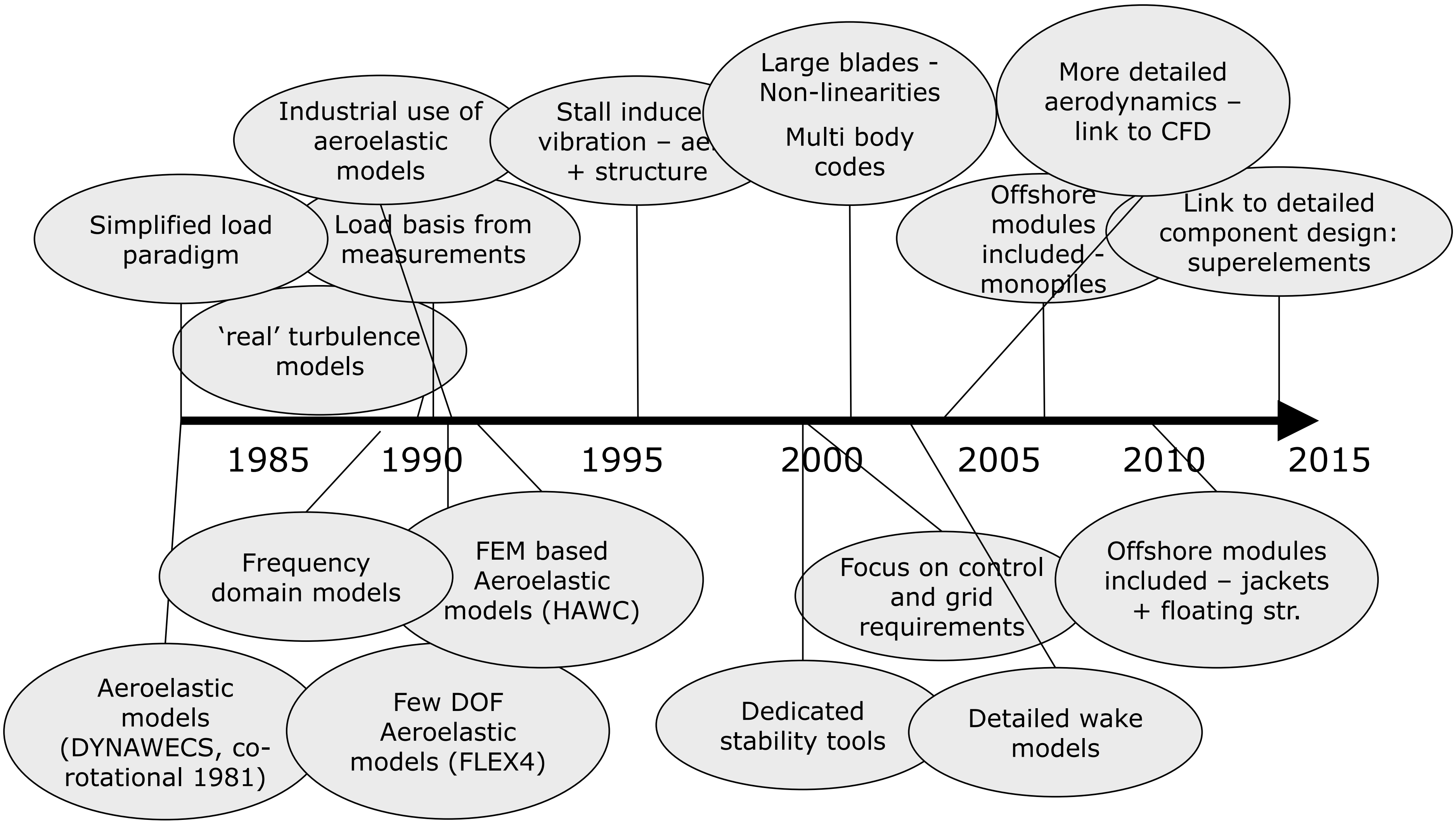


Industrial use of aeroelastic models

- The industry matured
- Turbines grew – cost and safety became issues
- Models developed from separate aerodynamics and load tools to combined aeroelastic tools
- The need for standardization was recognized

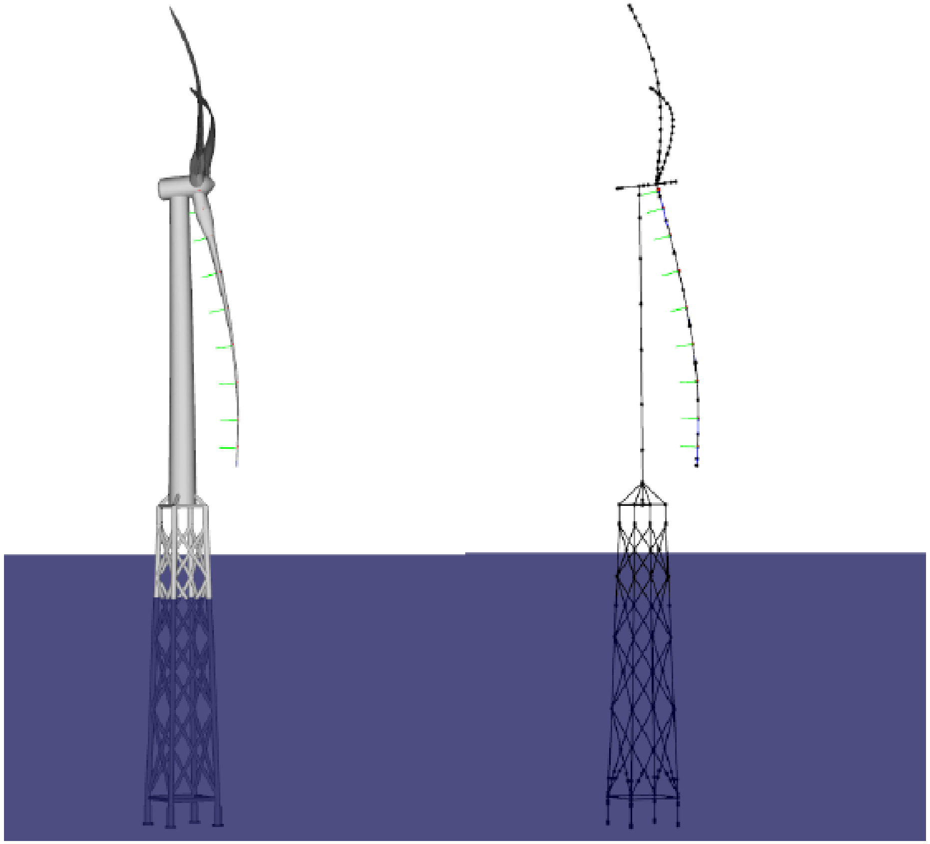
- The triggering points in the model development became partly the development of the turbine technology, partly issues experienced in the field
- Depending on the task at hand, the fidelity level needed varies

Selected highlight in the model development



State of the art aeroelastic modelling

- Handling of non-linear large deflections
- Various aerodynamics models fully coupled to the structural model (from BEM to CFD)
- Fully integrated turbine controller
- Integrated support structure modelling
- Offshore modelling capabilities
- Option for separate frequency domain analysis of modal characteristics



HAWC2 model developed as part of the OC4 project DTU-I-0240(EN)

Typical full-IEC load setup for design

All possible situations are simulated

Various combinations of mean wind and turbulence

...and fault conditions

Name	Description	WSP	Wdir				Gust	Fault
DLCxxx		Wind speed [m/s]	Wind direction [deg]				None, EDC, NTM	
DLC12	Normal produc							None
DLC13	Normal produ							None
DLC14	Normal produ							None
DLC15	Normal produ							None
DLC21	Grid loss							Grid loss at 10s
DLC22y	Extreme yaw e							Abnormal yaw error
DLC22b	One blade stu							1 blade at fine pitch
DLC23	Grid loss							Grid loss at three diff. times
DLC24	Production in							Large yaw error
DLC31	Start-up							None
DLC32	Start-up at fou							None
DLC33	Start-up in ED							None
DLC41	Shut-down							None
DLC42	Shut-down at six							None
DLC51	Emergency shut-down	Vr+2/Vr-2/Vout	0	NTM	12	0.2	None	None
DLC61	Parked in extreme wind	V50	-8/8	0.11	6	0.11	None	None
DLC62	Parked grid loss	V50	0:15:345	0.11	1	0.11		
DLC63	Parked with large yaw error	V1	-20/20	0.11	6	0.11		
DLC64	Parked	4:2:0.7*Vref	-8/8	NTM	7	0.2		
DLC81	Maintenance	Vmaint	-8/8	NTM	6	0.2		

Will we continue to see development towards more complex models and more requirements ?

Yes, but for Systems Engineering the answer could be different

In total 1-2000 simulations onshore

How simple can a load model be ?

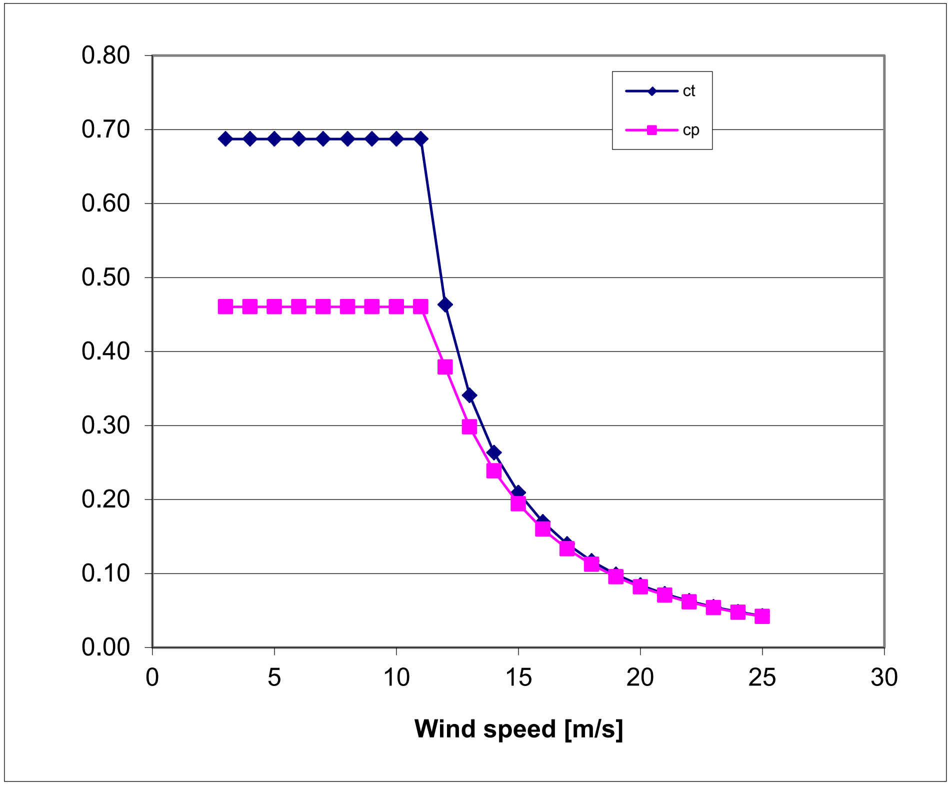
- Sometimes we need a fast estimate on main load signals – typical for product scoping, conceptual evaluation or for systems engineering/ optimization

- How low can we go ?

- **Rated power** and **diameter** combined with some engineering experience ?

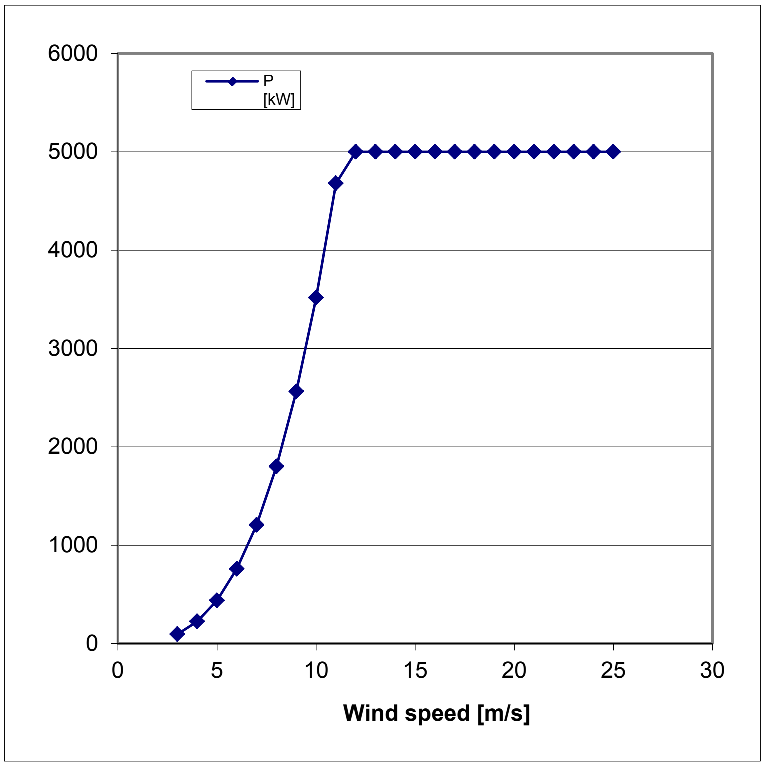
Thrust and power coefficients

$$C_t = 4a(1-a)F \qquad C_p = 4a(1-a)^2F$$

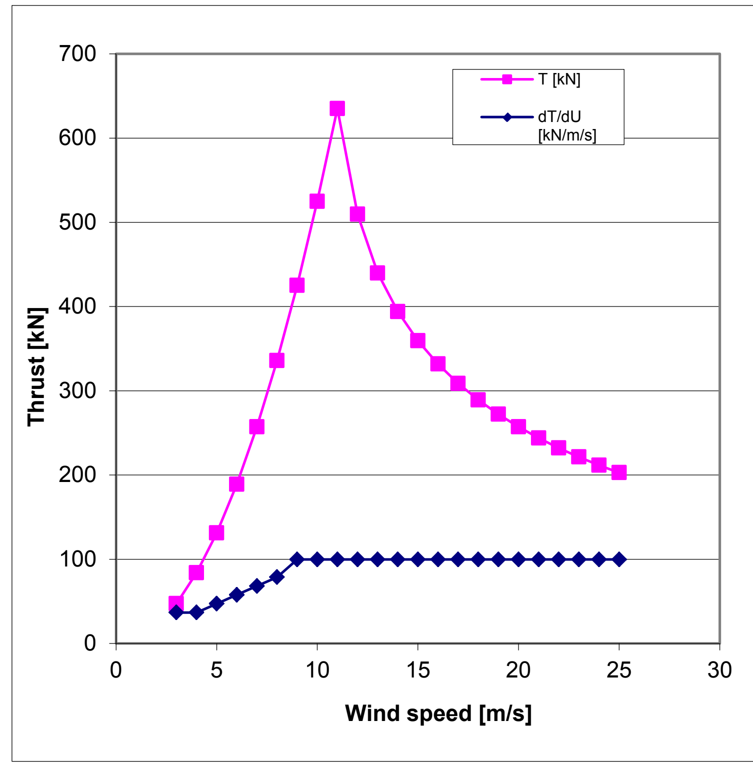


Power, thrust force and its gradient

$$P = \frac{1}{2} \rho A V^3 C_p$$



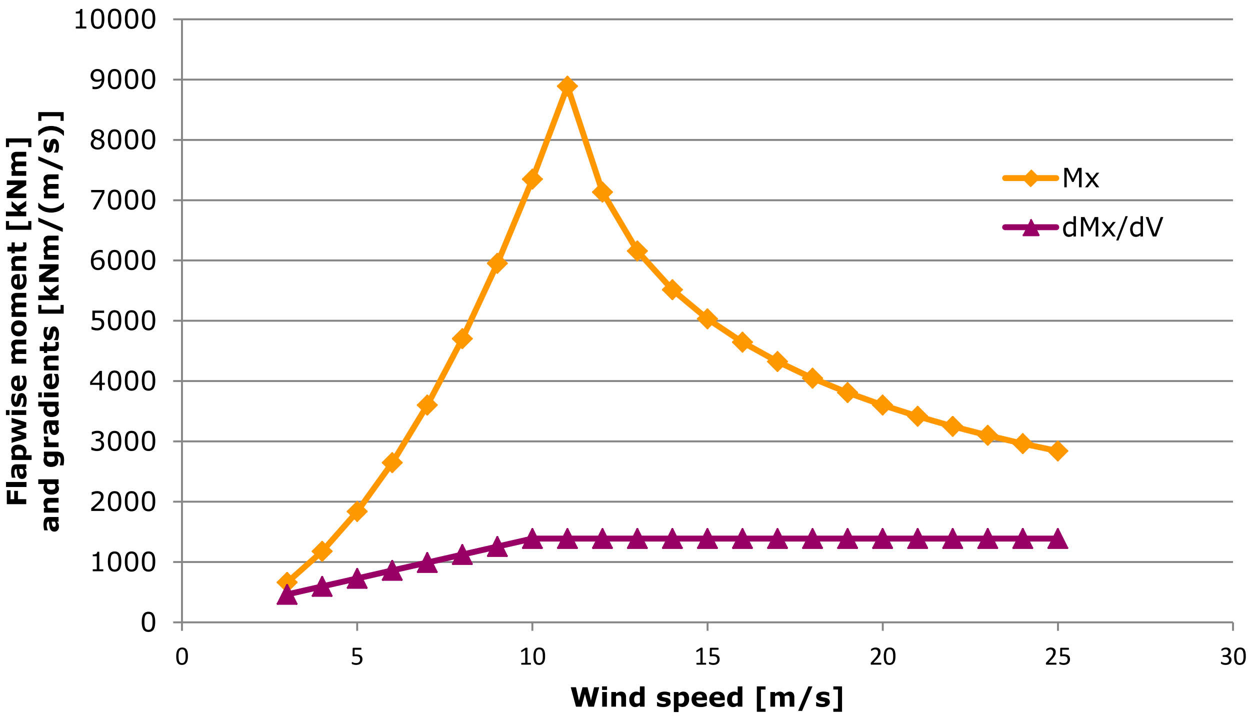
$$T = \frac{1}{2} \rho A V^2 C_t \qquad \frac{dT}{dV} \approx \frac{T_{i+1} - T_i}{V_{i+1} - V_i}$$



Flapwise moment and its gradient

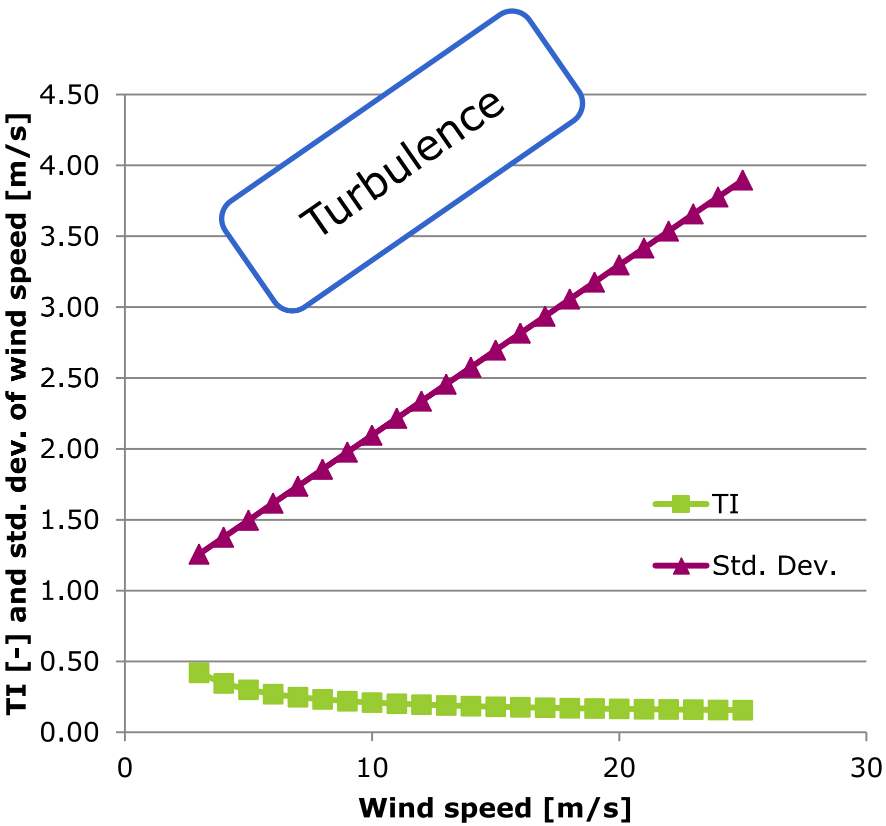
Assuming triangular blade load distribution: $M_x \approx \int_0^R \frac{2}{3}\frac{T}{R^2} r^2 dr \ = \frac{2}{9} TR$

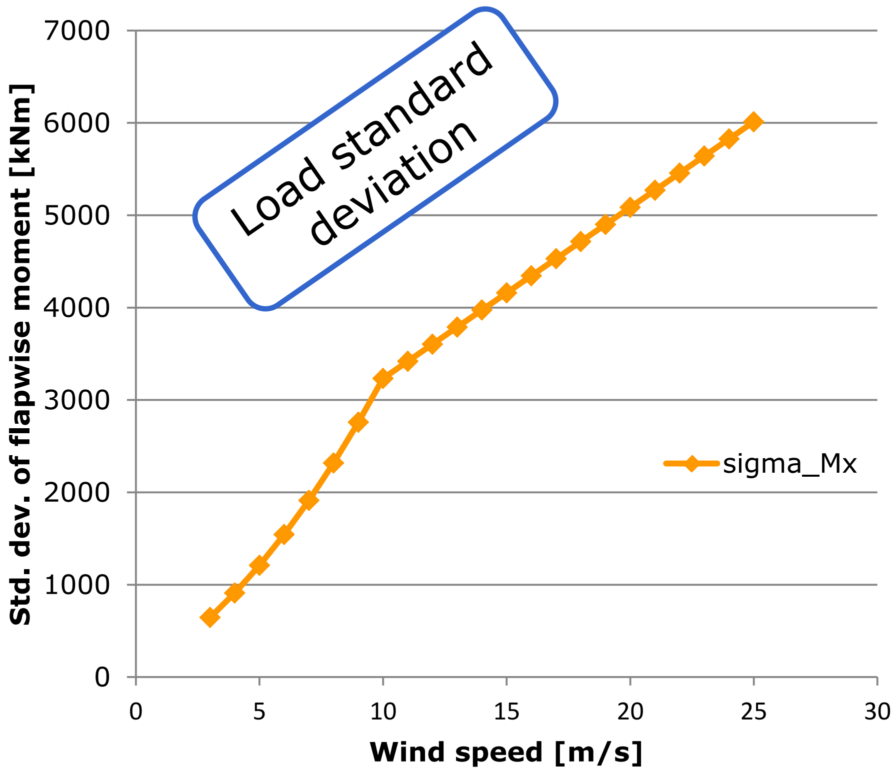
$$\frac{dM_x}{dV} \approx \frac{M_{x,i+1} - M_{x,i}}{V_{i+1} - V_i}$$



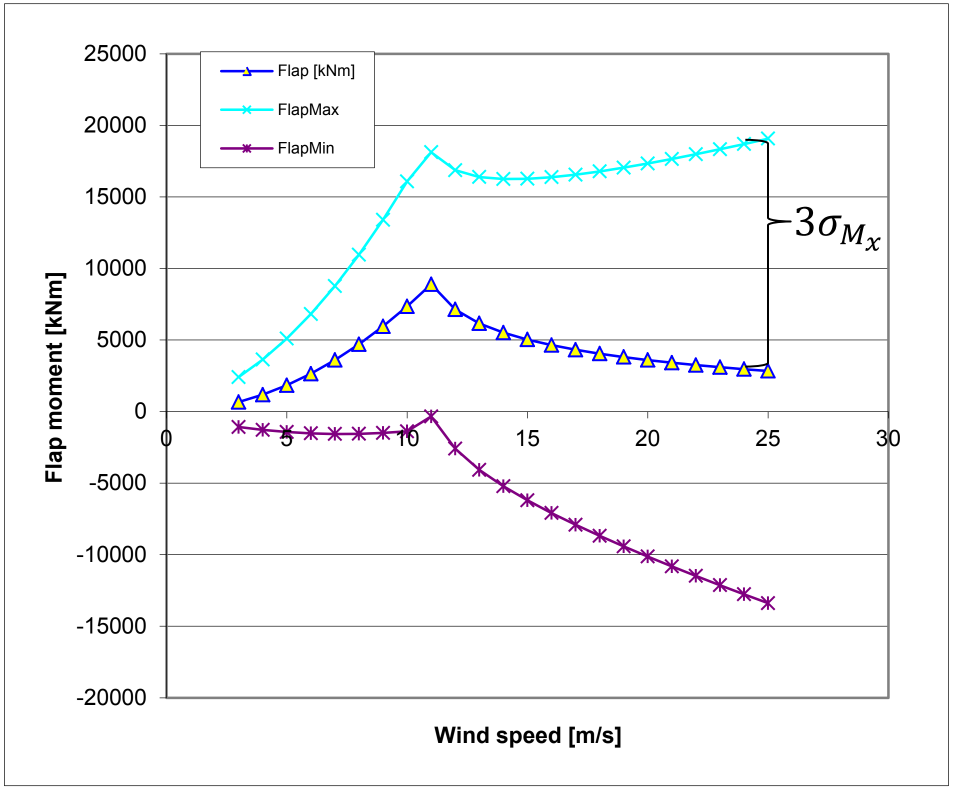
From turbulence to load variation

$$\sigma_{M_x} \approx \sigma_V \frac{dM_x}{dV}$$





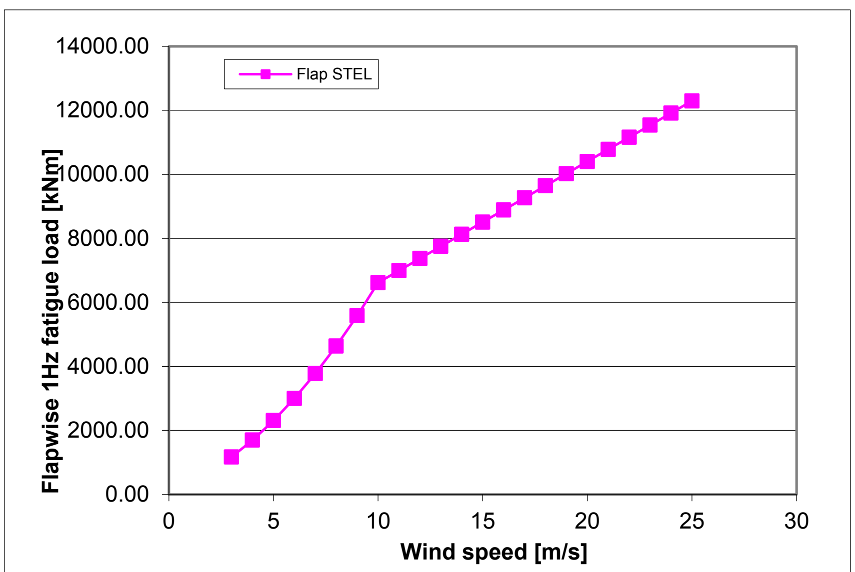
From std. dev. of loads to extreme loads



From std. dev. of loads to STEL

Assuming that flapwise moment has
a dominating 1P component with period T_{1P}
and adjusting its range with the factor a_σ:

STEL: $$R_{eq} = \left(\left(2 a_\sigma \sigma_{M_x}\right)^m \frac{600}{T_{1P}} \right)^{\frac{1}{m}}$$



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Site-Specific Design Optimization of 1.5–2.0 MW Wind Turbines

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A method is presented for site-specific design of wind turbines where cost of energy is minimized. A numerical optimization algorithm was used together with an aeroelastic load prediction code and a cost model. The wind climate was modeled in detail including simulated turbulence. Response time series were calculated for relevant load cases, and lifetime equivalent fatigue loads were derived. For the fatigue loads, an intelligent sensitivity analysis was used to reduce computational costs. Extreme loads were derived from statistical response calculations of the Davenport type. A comparison of a 1.5 MW stall regulated wind turbine in normal onshore flat terrain and in an offshore wind farm showed a potential increase in energy production of 28% for the offshore wind farm, but also significant increases in most fatigue loads and in cost of energy. Overall design variables were optimized for both sites. Compared to an onshore optimization, the offshore optimization increased swept area and rated power whereas hub height was reduced. Cost of energy from manufacture and installation for the offshore site was reduced by 10.6% to 4.6 ¢. This reduction makes offshore wind power competitive compared with today's onshore wind turbines. The presented study was made for one wind turbine concept only, and many of the involved sub models were based on simplified assumptions. Thus there is a need for further studies of these models. [DOI: 10.1115/1.1404433]

Introduction

In the development of new large megawatt size wind turbines, aerodynamic and structural optimizations have become subjects of considerable interest. Even marginal reductions in the kWh-price help to improve the competitiveness of wind power compared with other energy sources. This paper involves the combination of a numerical optimization algorithm with state-of-the-art aeroelastic calculations and cost modeling. This allows for advanced optimization of wind turbines that are specifically designed for operation at different sites and in different wind conditions.

Numerical optimization involves the determination of an optimum configuration that satisfies a certain objective subject to constraints. Compared with traditional engineering design and inverse design methods, numerical optimization algorithms provide large flexibility and allow a direct and automatic identification of the optimum design.

Based on numerical optimization, different design methods have been developed for determination of the optimum rotor shape [1,2]. Their objectives are maximum energy production with no or only few constraints on loads. However, optimum aerodynamics does not lead to minimum cost of energy since the loads very often become excessive. To include the importance of loads, the objective should be minimum cost of energy instead of annual energy production. Cost of energy is found from annual energy production and total manufacturing and installation costs. The manufacturing costs are determined partly from the loads on the entire structure.

Design tools based on this philosophy were recently developed and are now used to optimize turbines for onshore flat terrain conditions [3,4]. These tools can, however, also be well suited for application to other sites.

The wind climate in wind farms in mountainous, complex terrain or offshore conditions can be substantially different from that of a normal flat terrain [5,6]. This will affect the design assumptions and thus represent a potential for cost reduction by site-specific design. By installation of large wind farms, it is likely that the wind turbine overall dimensions can be designed for the specific site conditions.

The purpose of the present work was to identify the potentials in site-specific design for offshore wind farms by means of site-specific design optimization of a reference 1.5 MW stall regulated wind turbine. The optimization was carried out for two sites: 1) Offshore in a wind farm and 2) on-shore stand-alone. Design loads and the optimum configurations were compared to assess the influence on the optimum design from site specific wind farm and off-shore effects. The numerical design tool incorporated detailed wind climate information used in time domain aeroelastic calculations. A cost function was established for the main wind turbine components to evaluate cost of energy. To limit the computational costs, an intelligent gradient approach was used [3].

Method

The design tool was based on the combination of a numerical optimization algorithm with different calculation tools as sketched in Fig. 1.

Overall Design Method

The input for the design problem can be divided into information required for the numerical optimization algorithm and the operation conditions for the wind turbine:

The numerical optimization algorithm needs the objective function, which is cost of energy that is minimized by changing the design variables. The design variables can, in principle, be any shape and control parameter that influences cost of energy. This includes the rotor and tower shape, main dimensions, control and regulation parameters, and structural quantities. Points that form the basis for interpolated curves describe distributions. This ensures smooth shapes and few design variables so that calculation time is reduced and the effectiveness of the design space is increased. The constraints are upper or lower values for the design variables, but also limits on response values such as loads, stresses, strains, or rated power. Finally, we need an arbitrary initial guess on a design vector. The operation conditions for the wind turbine involves the wind climate, that includes the oncom-

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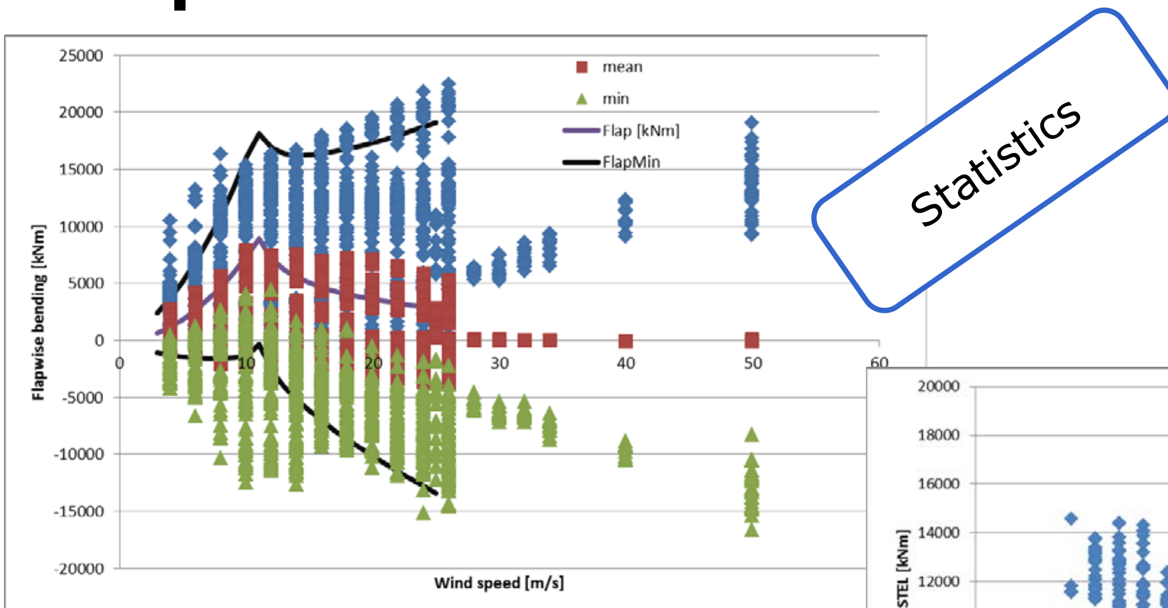
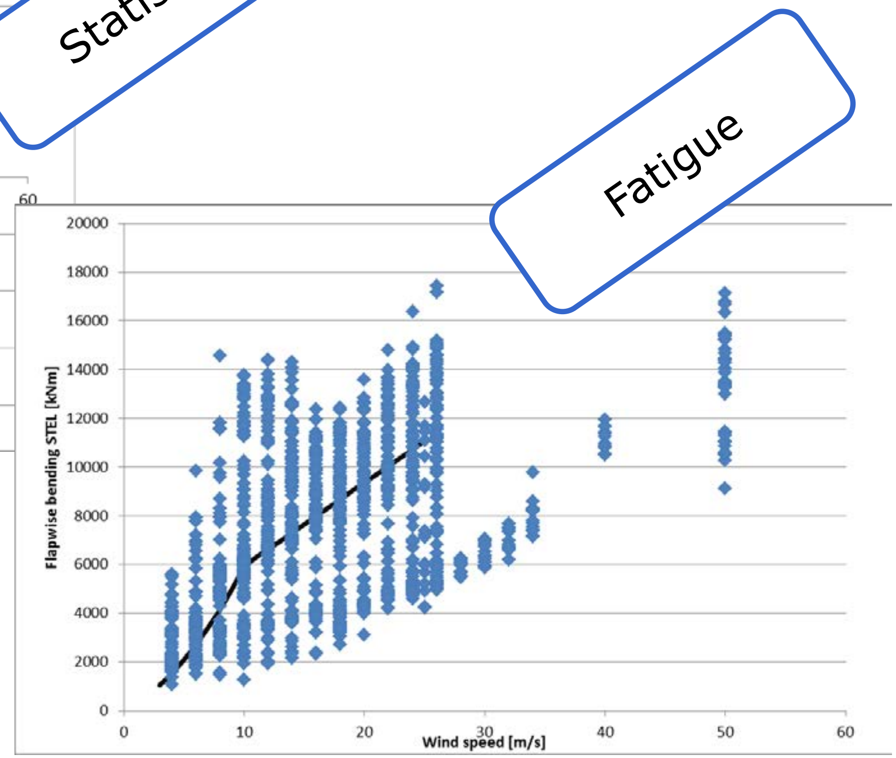
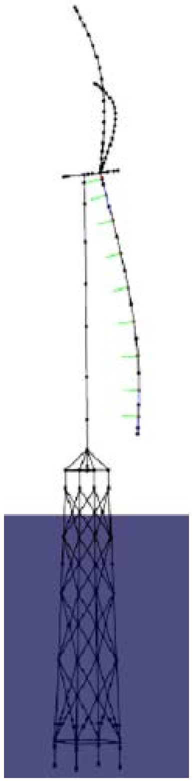
Simplified model and full model





	Full	Simple
Maximum flap	22435	19070
Life time fat. flap	12380	11755
Maximum tower	168500	123300
Life time fat. tower	61280	61088

Needed modelling level depends on the task



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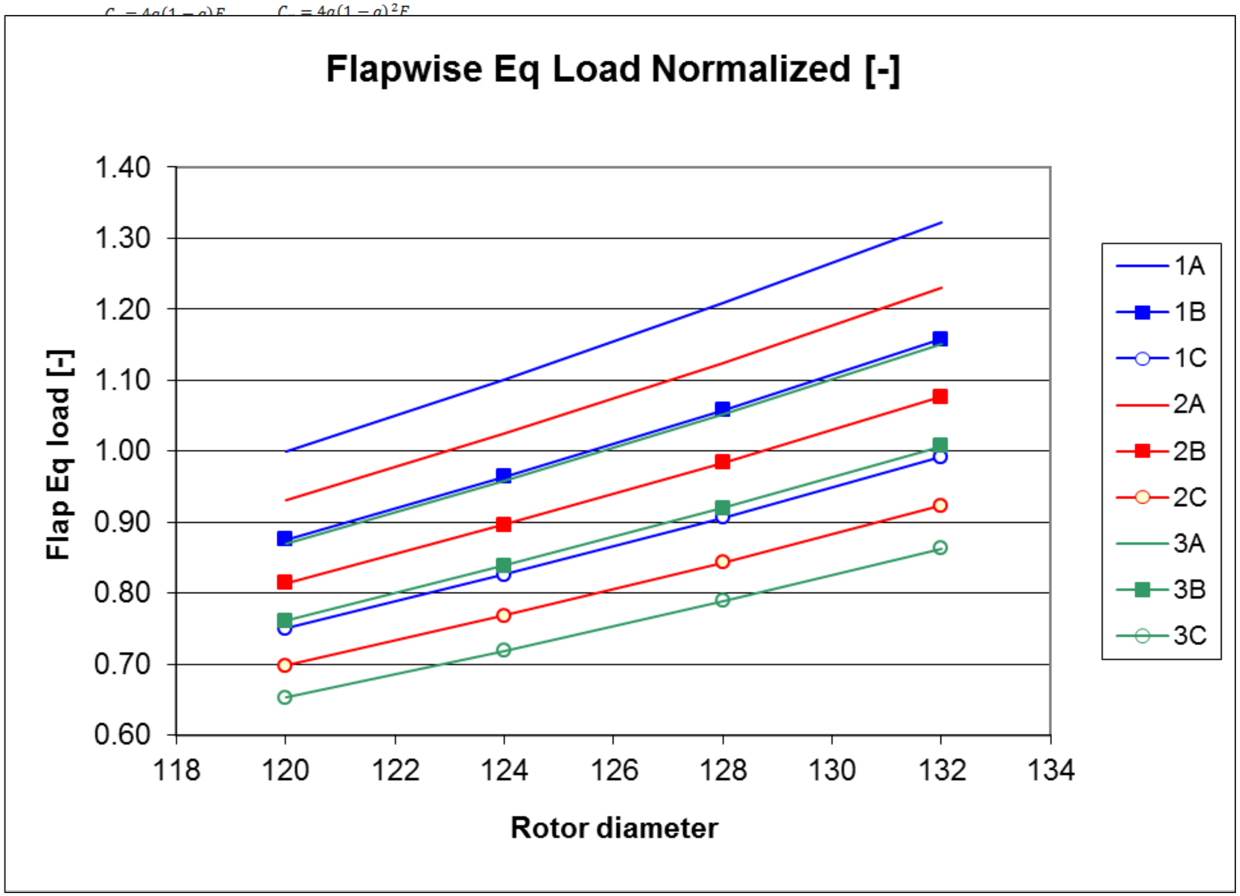

Development drivers and future perspective

Development drivers

- Turbine technology
- System requirements – e.g. grid requirements, flexibility, etc.
- Design optimization/design to limit – experience from field

Future perspectives

- One-system-design-process: integration of component and ‘system’ design
- Further coupling between aero-elastic and electrical modelling
- Inflow modelling – further development of turbulence models (and other external conditions)
- Validation methods, formal quantification of success criteria
- For different tasks we need different fidelity levels – both simple fast robust models but also high fidelity models with all details