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The 3rd Evolutionary Computation Competition
December 14, 2019

Conceptual design optimization problem of wind turbine
風車の概念設計最適化問題

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Outline

- Growth of wind energy
- Components of wind turbine
- Basic principles of wind energy
- Design constraints
- Conceptual design optimization problem
  - Design variables
  - Objective functions
  - Constraints

Growth of wind energy

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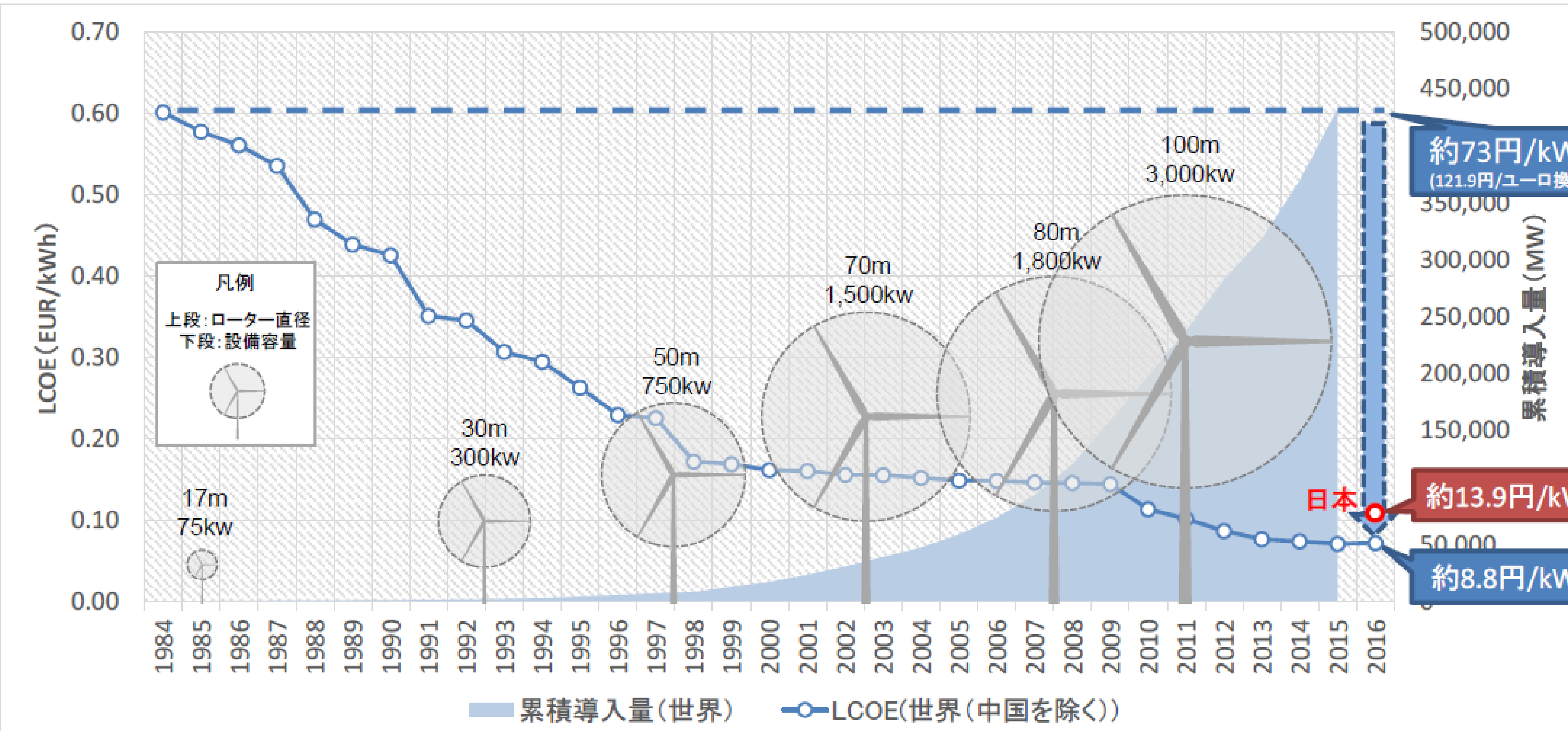
- Cost of wind energy has decreased to 8.8 Yen/kWh (≒ 0.08 USD/kWh) due to large-scale wind turbines
- Approximately 20% of electricity is supplied by wind energy in some European countries (e.g., Germany, Spain, UK)

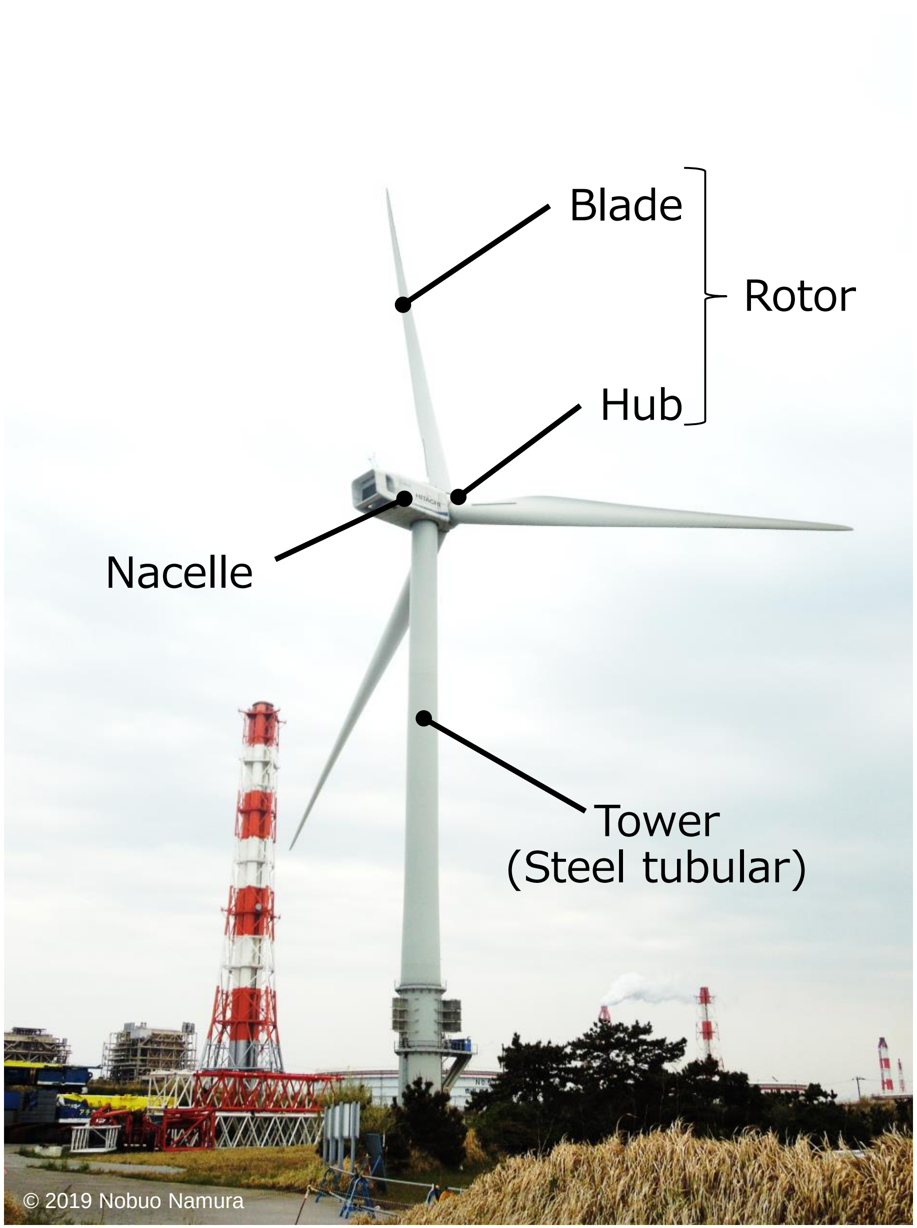
REN21: Renewables 2019 Global Status Report,
https://www.ren21.net /wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf

LCoE: Levelized cost of energy

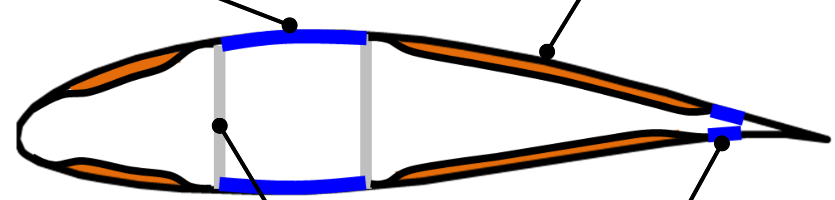


Ministry of Economy, Trade and Industry (経済産業省　風力発電競争力強化研究会報告書)
https://www.meti.go.jp/committee/kenkyukai/energy_environment/furyoku/pdf/report_01_01.pdf

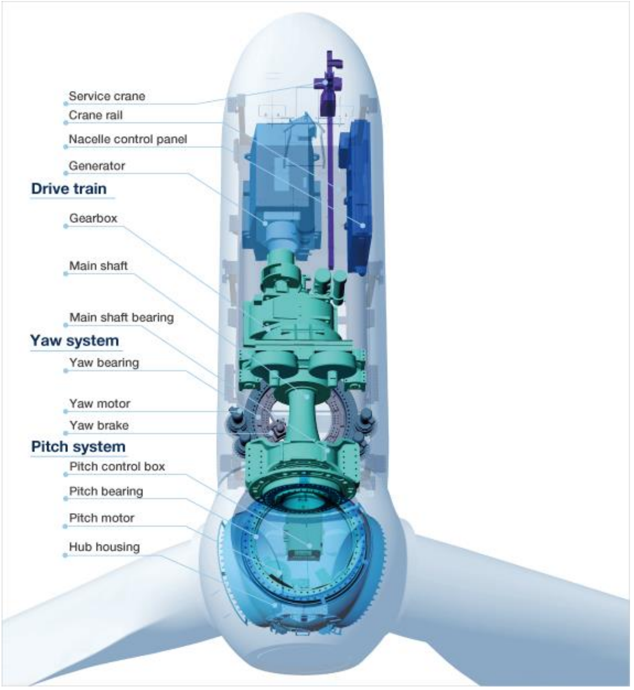
Components of wind turbine



Cross-section of blade



Inside of Nacelle



Hitachi, Ltd.
http://www.hitachi.com/products/energy/wind/products/htw2000_80/nacelle/index.html

Basic principles of wind energy

Calculation of energy production

Inflow volume per unit time

Increase rotor plane!

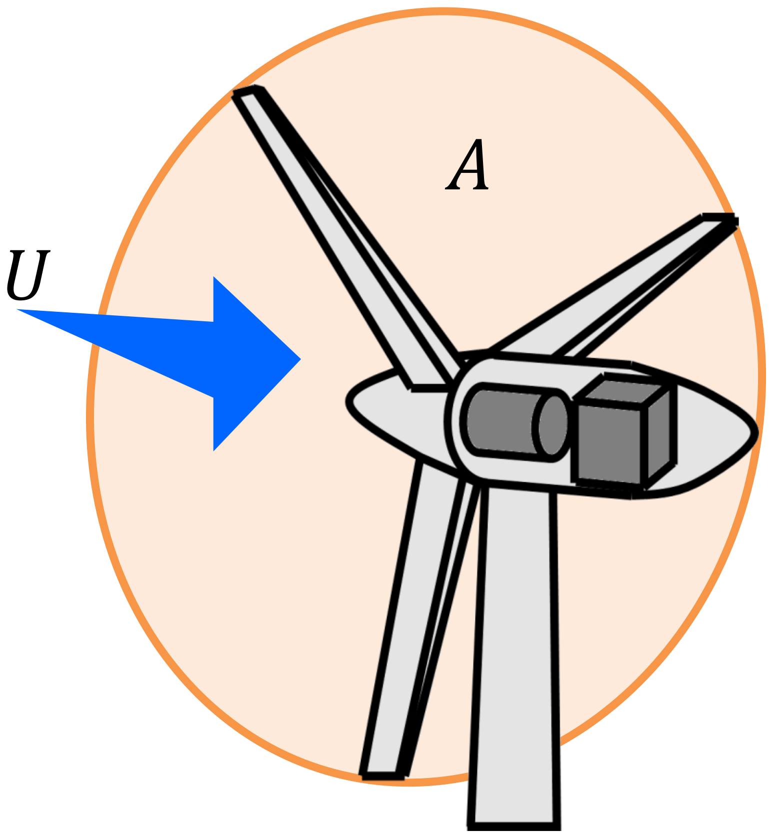
$$P = \frac{1}{2}\rho U^2 \times UA \times C_P = \frac{1}{2}\rho U^3 A C_P$$

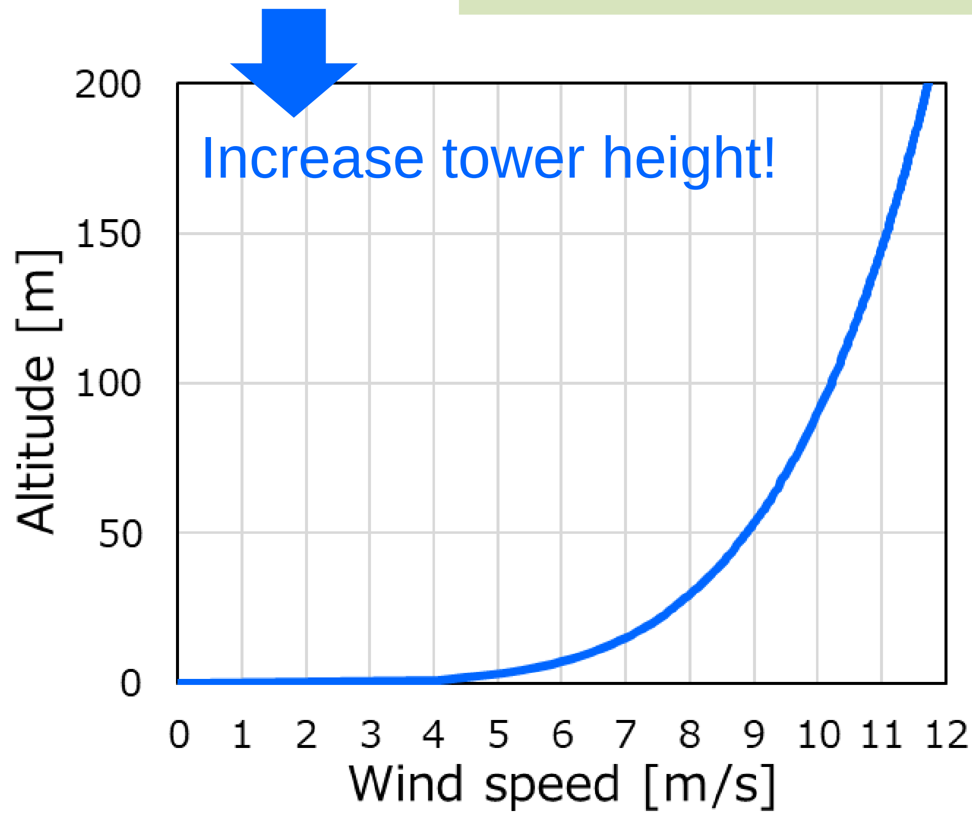
Kinetic energy

Efficiency

Increase wind speed!

Increased by optimizing blade shape
Commercial : 0.4～0.5
Theoretical : ～0.593





Design constraints

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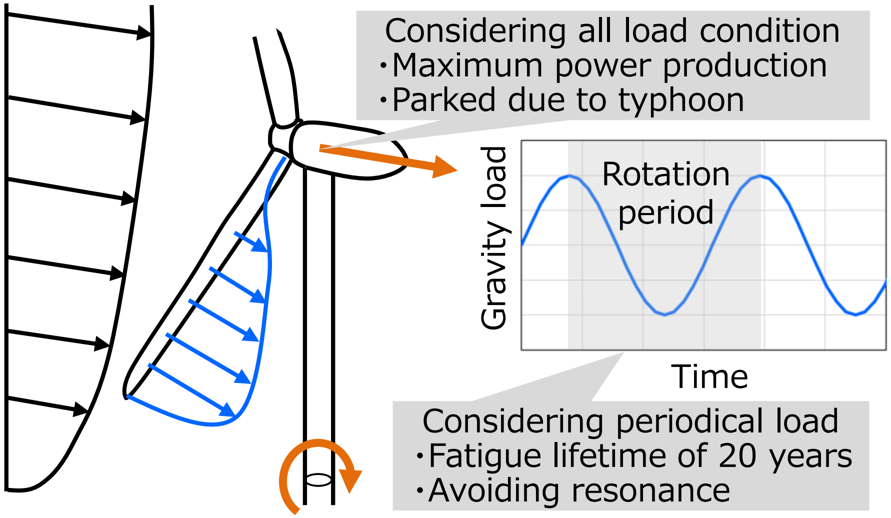
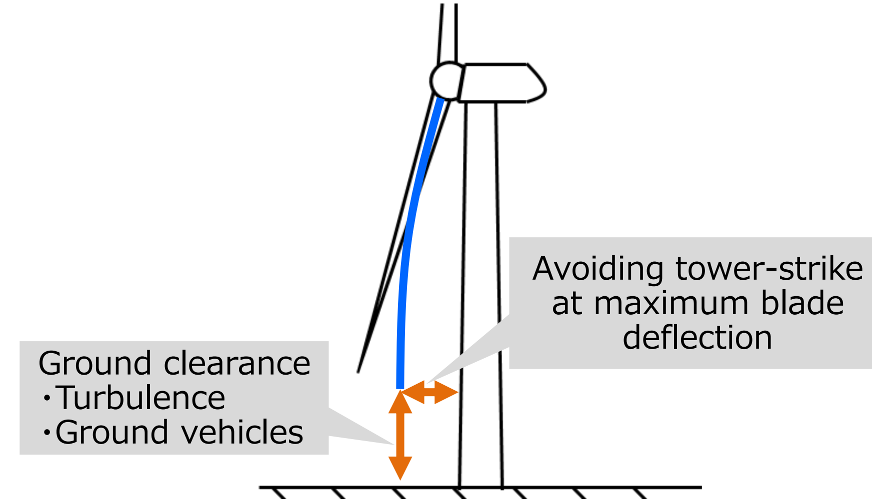
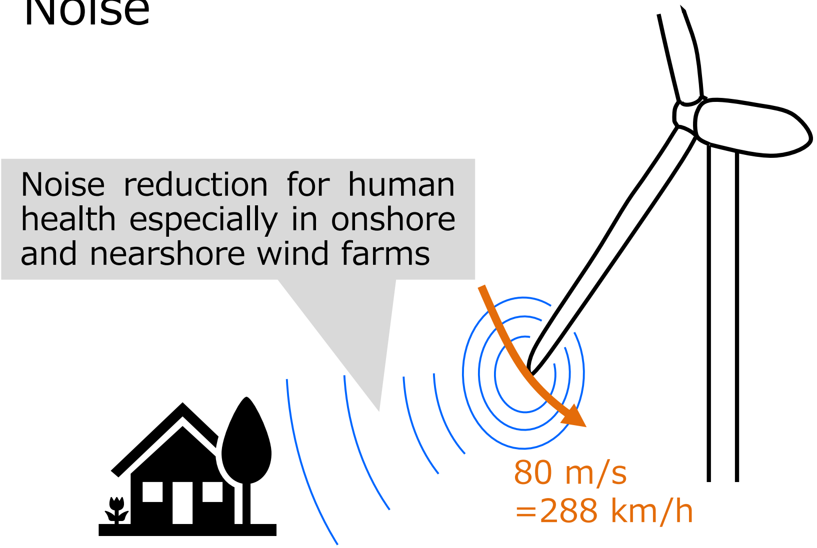
Strength and natural frequency



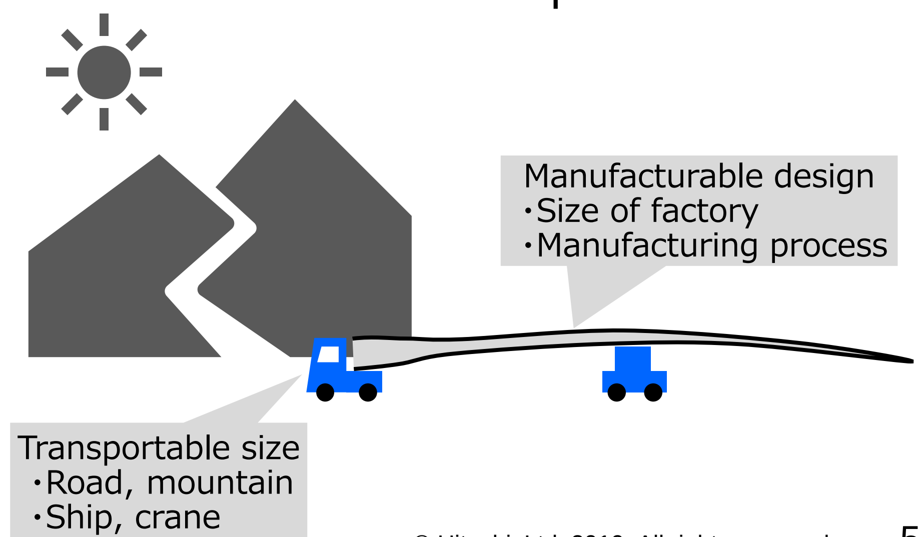
Clearance (deflection, ground)



Noise



Production and transportation



Conceptual design optimization problem

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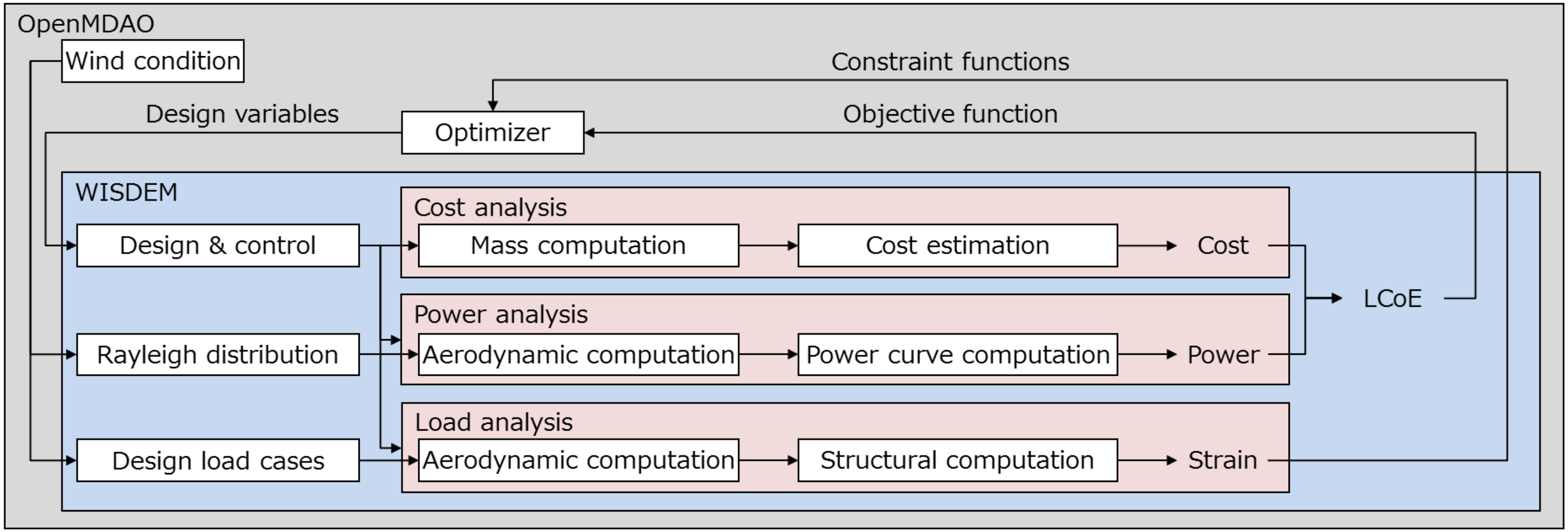
Design target and condition

- Blade and tower of 5MW onshore wind turbine
- IEC Class IA: Annual average wind speed of 10m/s, maximum wind speed of 70m/s (3 [s] average), strong turbulence
- Conceptual design: low-fidelity analysis for rough estimation

Evaluation

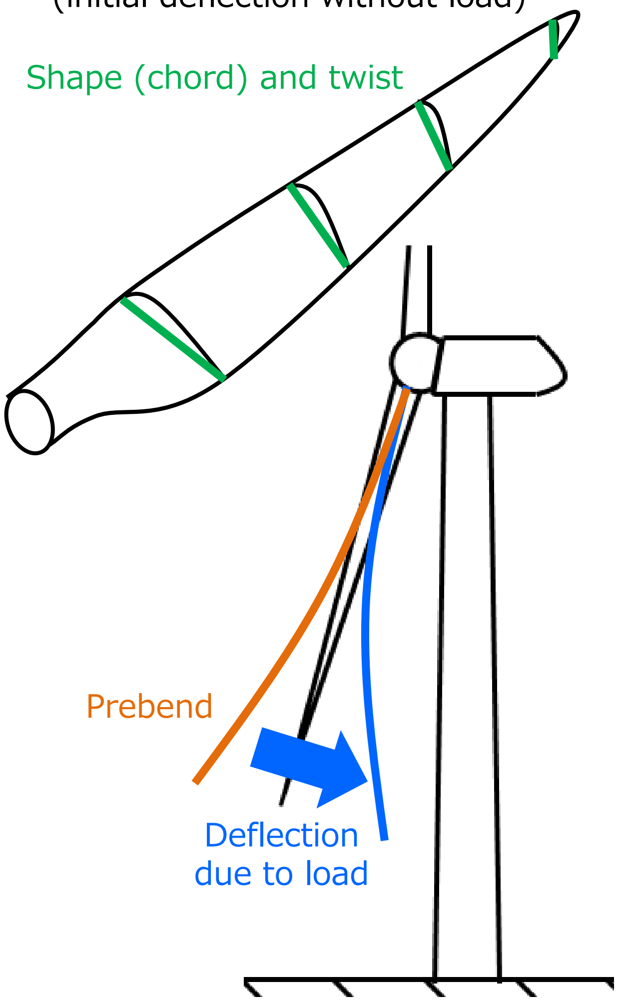
- OpenMDAO : optimization flamework developed by NASA (https://openmdao.org/)
- WISDEM : wind plant model developed by NREL (https://nwtc.nrel.gov/WISDEM)

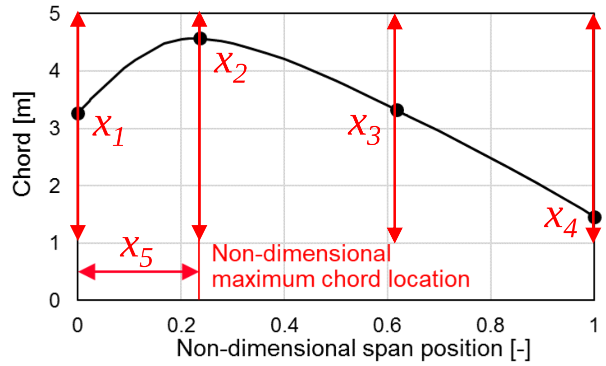


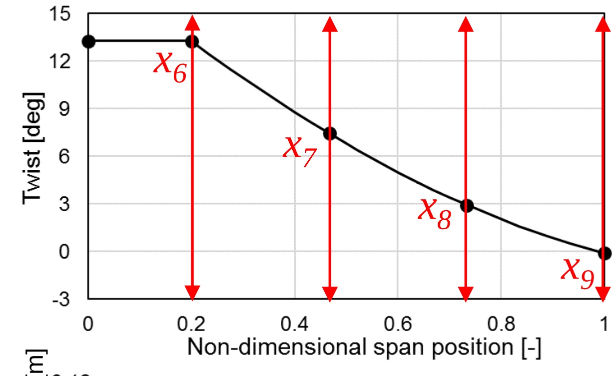
NASA: National Aeronautics and Space Administration,
NREL: National Renewable Energy Laboratory, WISDEM: The Wind-Plant Integrated System Design and Engineering Model

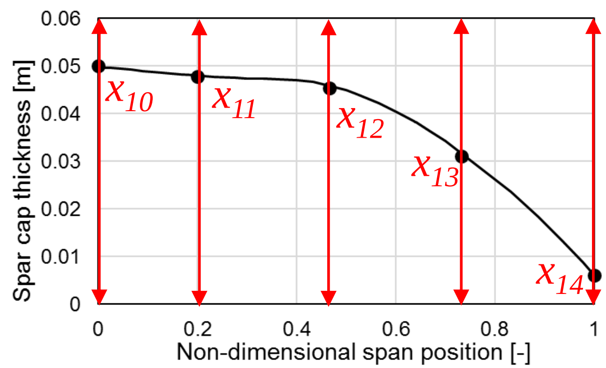
Design variables: 32 (1/2)

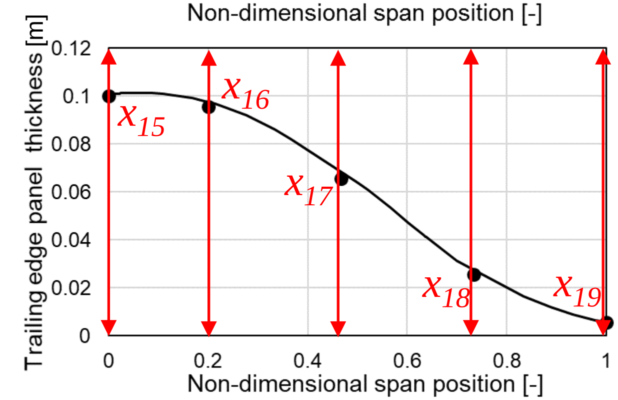
- Blade shape and twist
- Thickness of structure
  (spar cap and trailing edge panel)
- Prebend
  (initial deflection without load)

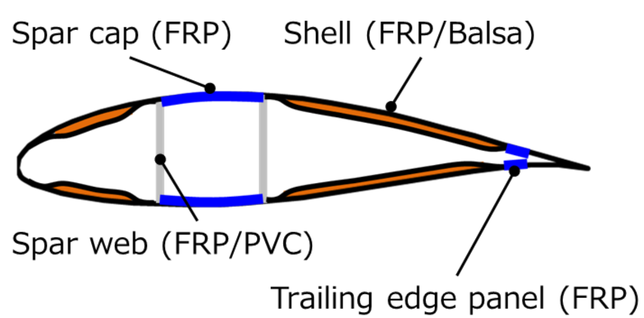


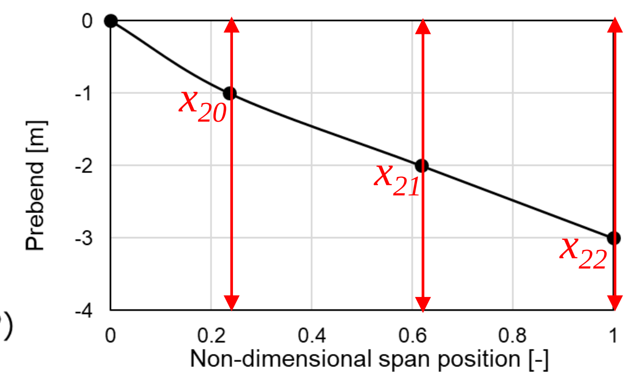






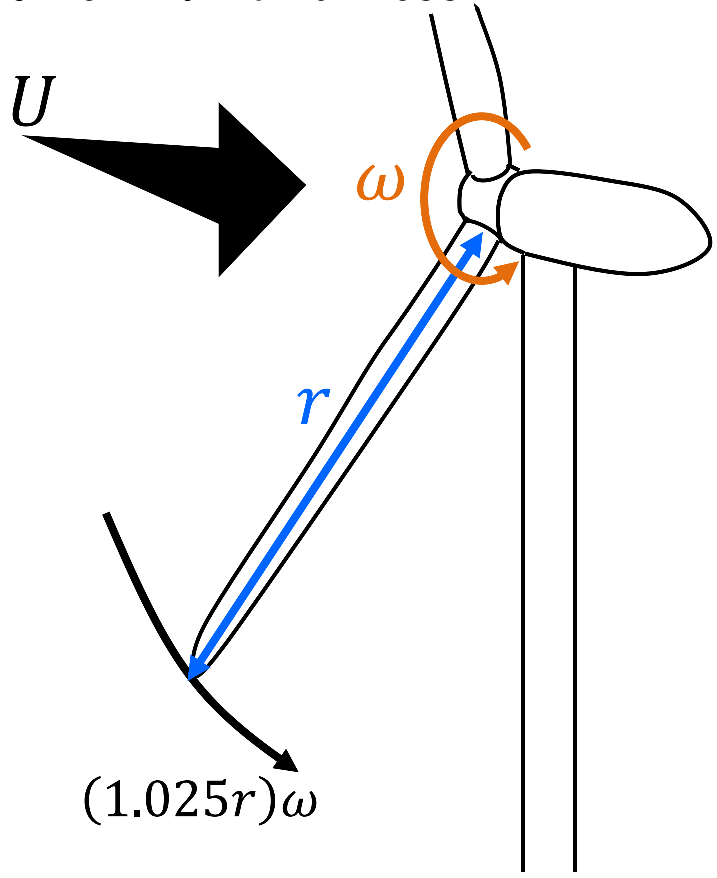


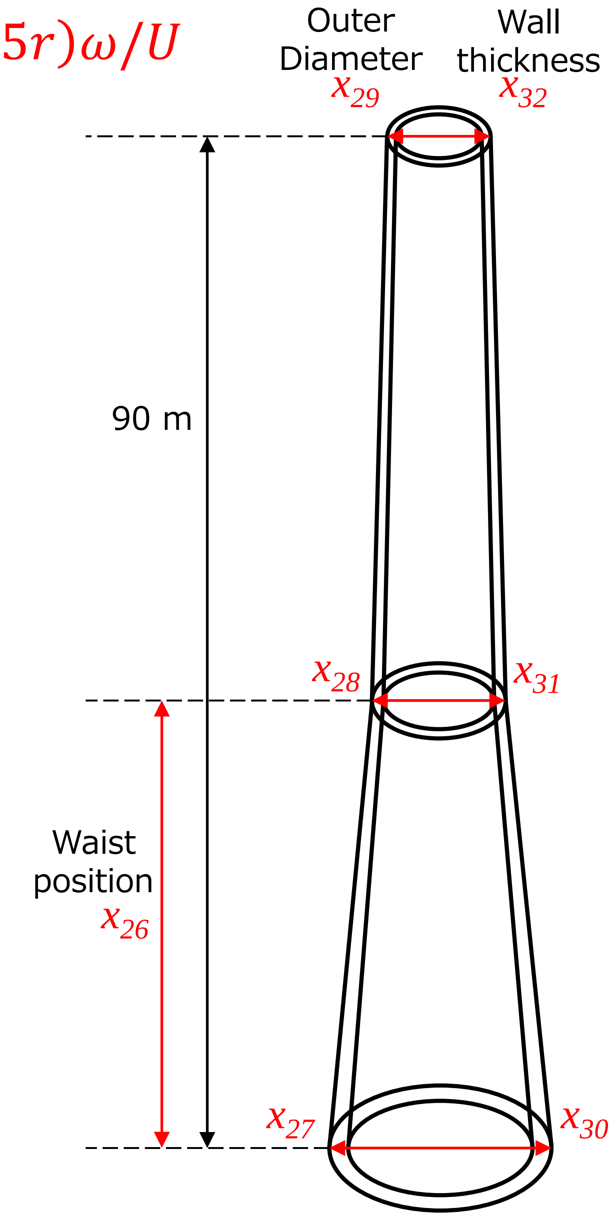




Design variables: 32 (2/2)

- Design tip speed ratio $x_{23} = (1.025r)\omega/U$
- Max. rotational speed $x_{24} = \omega_{max}$
- Blade length $x_{25} = r$
- Tower waist position
- Tower outer diameter
- Tower wall thickness





Objective functions

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Single-objective problem

$$\min \quad Levelized\ Cost\ of\ Energy\ [USD/kWh] = \frac{Levelized\ Annual\ Cost}{Annual\ Energy\ Production}$$

Multi-objective problem (5 objectives)

① $$\max \quad Annual\ Energy\ Production\ [kWh] = \int Power(U) \times Frequency(U) dU$$

② $$\min \quad Levelized\ Annual\ Cost\ [USD] = \frac{Total\ Cost}{Lifetime\ of\ Wind\ Turbine}$$

Assumption: 20 years

③ $$\min \quad Tower\ Base\ Moment\ [Nm] = Maximum\ Thrust\ Force\ at\ Hub \times Hub\ Height$$

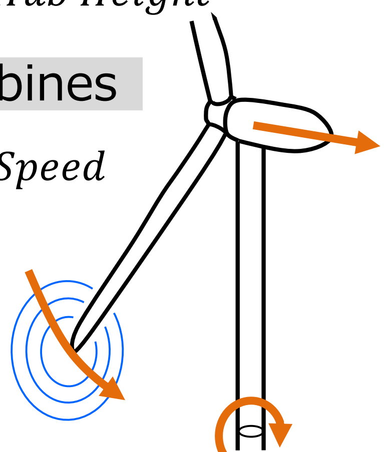
Cost reduction of foundation for offshore wind turbines

④ $$\min \quad Blade\ Tip\ Speed\ [m/s] = Rotor\ Radius \times Maximum\ Rotational\ Speed$$

Noise reduction

⑤ $$\min \quad Fatigue\ Damage = \frac{Number\ of\ Cycle\ during\ Lifetime}{Number\ of\ Cycle\ to\ Failure}$$

Cost reduction by lifetime extension



Constraints: 22

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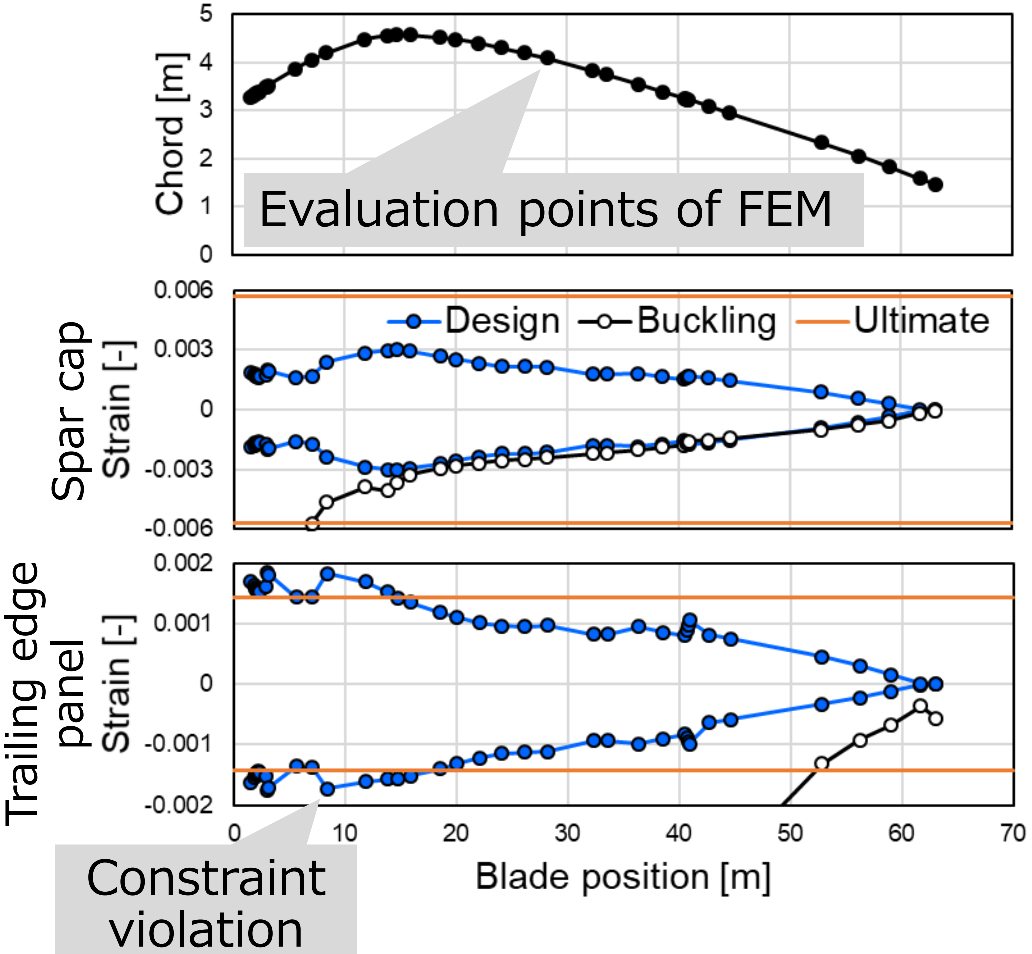
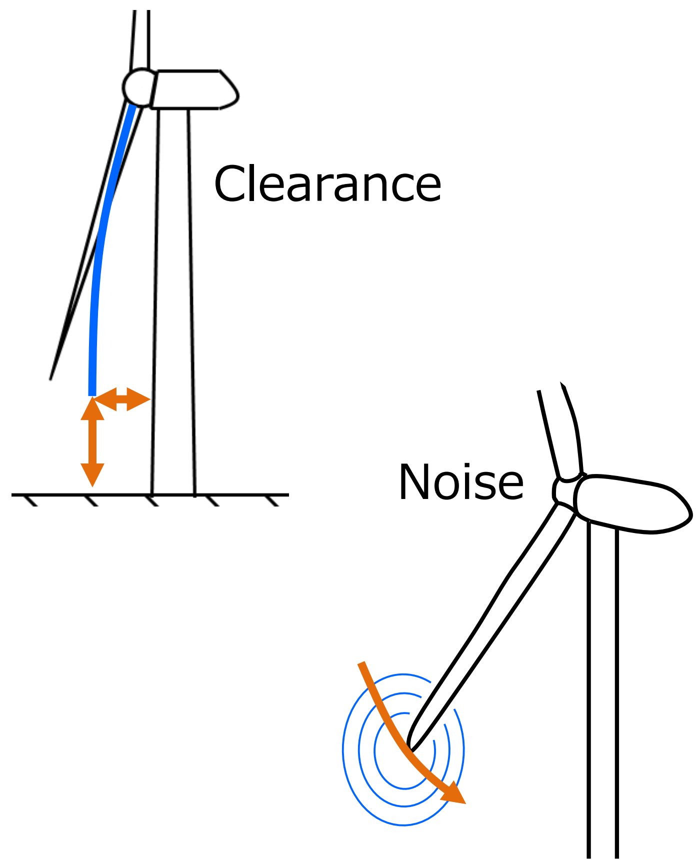
- 725 constraints are implicitly included due to FEM analysis for strength
- Resonance, clearance, noise, manufacturability
- Transportability implemented as domain of design variables (blade and tower size)





Thresholds (e.g. ultimate strength, safety factor) for constrains are from A. Ning and D. Petch, *Wind Energy*, 2016;19(12):2137-2152.

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