SIZING AND OPTIMIZATION OF FIXED PITCH RPM-CONTROLLED ROTORS AT MULTIPLE DESIGN POINTS FOR PASSENGER-GRADE MULTIROTOR CONFIGURATIONS

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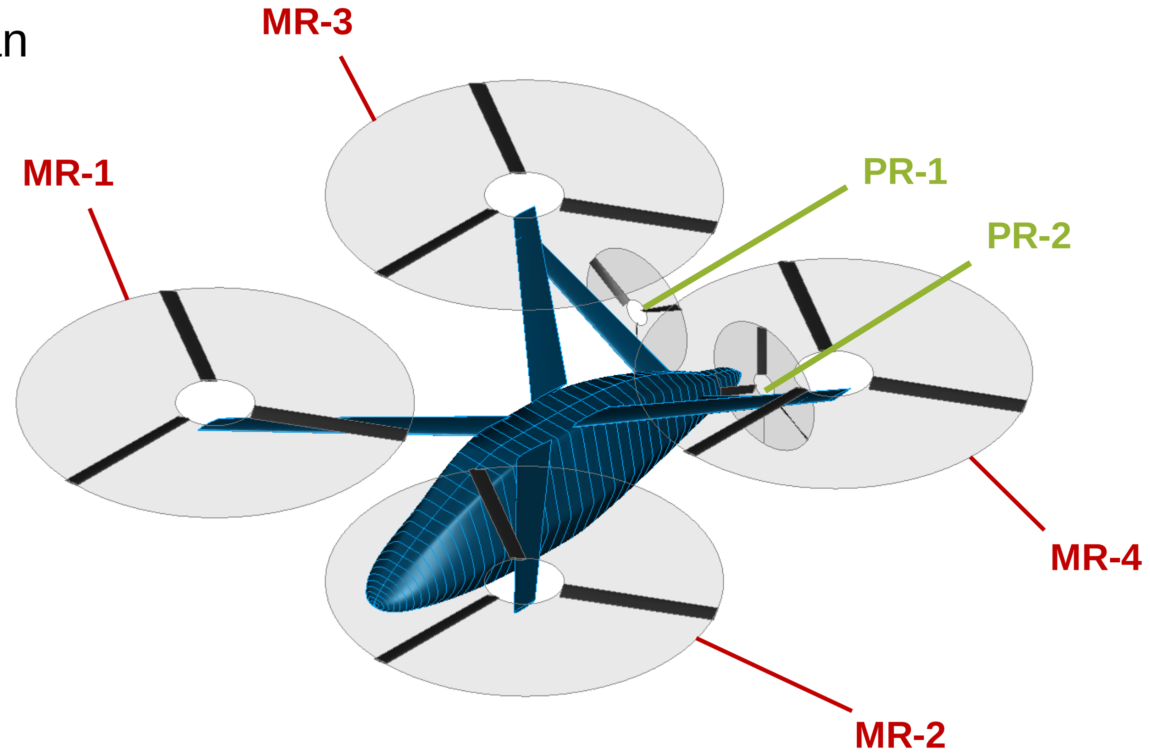
Introduction
The UAM Concept Vehicle

DLR Guiding Concept 4 (LK4S2a): The Medical Personnel Deployment Vehicle

- **Objective:** Rapid transport of the Emergency Physician during a first line emergency service
- Multirotor / Lift + Cruise configuration
  - 4 main rotors – **MR**, 2 pusher rotors – **PR**
  - Electrically driven rpm control (fixed pitch)
  - Initial design mass: $1000\ \mathrm{kg}$
- Control modes
  - **VFM:** Vertical Flight Mode
    - Vehicle control only by **MR**
    - **PR** inactive
  - **HFM:** Horizontal Flight Mode
    - **PR** for forward thrust and yaw compensation
    - **MR** for vertical thrust, roll and pitch control



Introduction

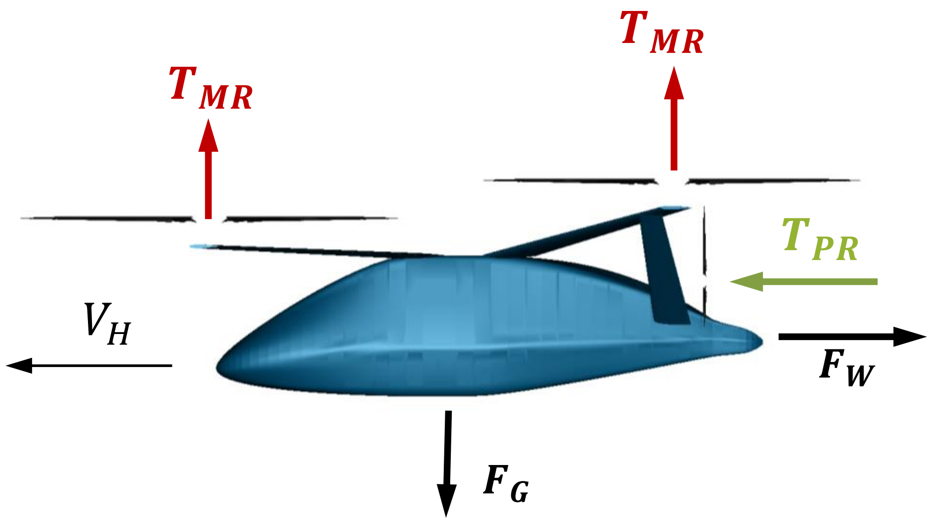
Requirements and Design Goals

- Performance requirements
  - Straight forward flight in **HFM**
  - Weight ($\boldsymbol{F_G}$) compensation merely by distributed $\boldsymbol{T_{MR}}$ at all times → $\boldsymbol{T_{MR}} = 250\ \mathrm{kg} \cdot 9.806\ \mathrm{m/s^2} = 2450\ \mathrm{N}$
- Flow conditions of **MR**
  - **VFM:** Axial stream (V_i)
  - **HFM:** High tangential freestream (V_∞)
- Design goals of **MR**

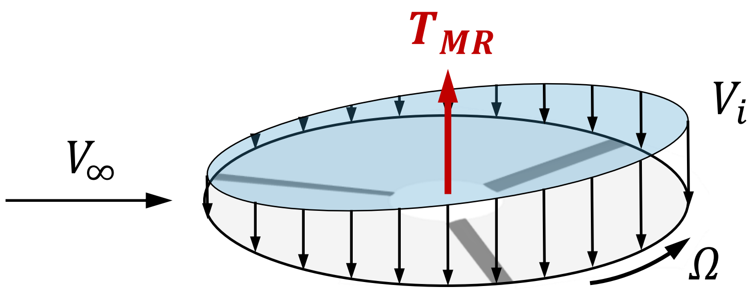
  Design Goal 1 – Min. required power in forward flight (P^*)

  Design Goal 2 – Satisfying the predefined design parameters in hover
- Blade element theory needed.
- Blade local pitch angle distribution has to be optimized for minimum power!

Vehicle Overall Force Equilibrium

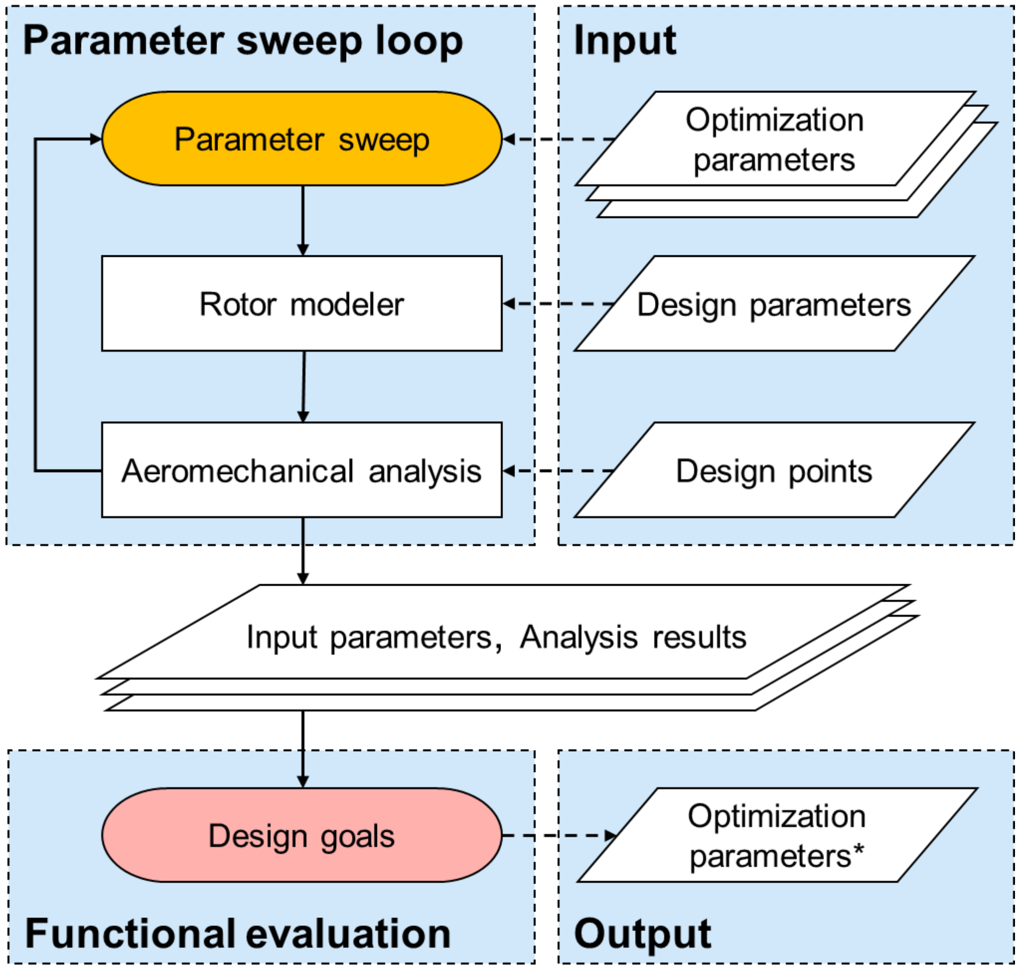


Flow Conditions



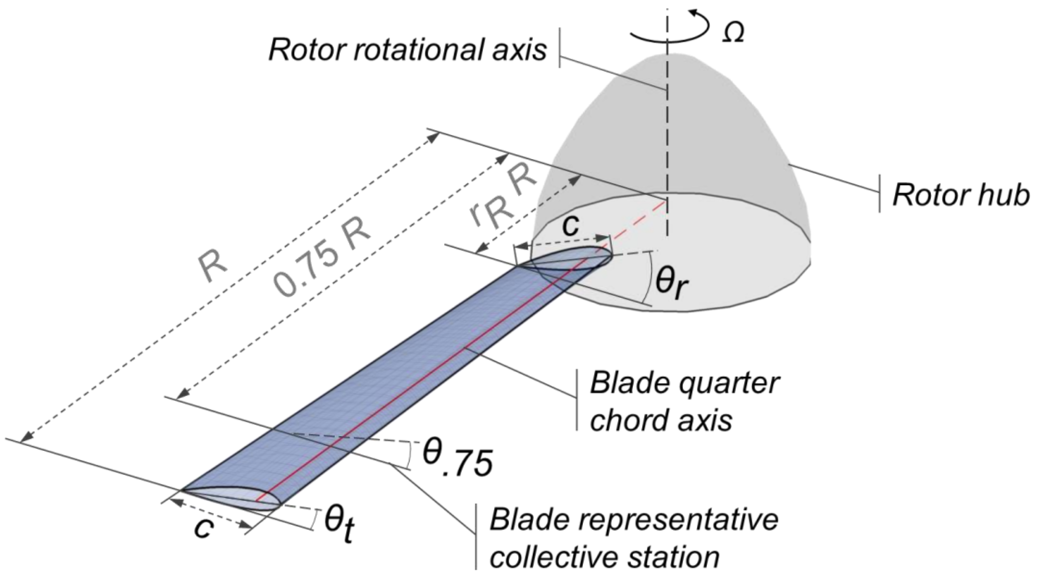
Rotor Sizing and Optimization Framework
Process Overview

- **Objective:** Finding the optimum blade pitch distribution that fulfills the design goals
- **Input**
  - Rotor Design parameters
    - Fixed design parameters
    - Variable design (sizing) parameters
  - Optimization parameters (*blade twist and collective*)
  - Design (trim) points
- **Parameter sweep loop:** Stacking of datasets containing the input parameters and the output data from aeromechanical analysis
- **Functional evaluation**: Predefined design goals of **MR**
- **Output**: Optimization parameters of which the blade geometry is fulfilling the functional evaluation



Rotor Sizing and Optimization Framework

Rotor Geometry Parameterization



1) Fixed Design Parameters

Parameter	Symbol	Unit	Value
Design thrust	T	N	2450
Blade number	N_b	–	3
Hover tip speed	$v_{tip} = \Omega R$	m/s	150
Root cutout	r_R	–	0.2
Blade airfoil	NACA 23012		

2) Variable Design (Sizing) Parameters

Parameter	Symbol	Unit	Value
Disc loading	DL	$\mathrm{N/m^2}$	200
└> Radius	$R \sim 1/\sqrt{DL}$	m	1.97
Blade loading	$BL = C_T/\sigma$	–	0.08
└> Chord	$c \sim 1/((\Omega R)^2 BL)$	m	0.187

3) Optimization Parameters

Parameter	Symbol	Unit	Range
Root section pitch	θ_r	°	$[5, 45]$
Tip section pitch	θ_t	°	$[5, 25]$
└> Linear blade twist	θ_{tw}	°/R	
└> Collective at $0.75R$	$\theta_{.75}$	°	

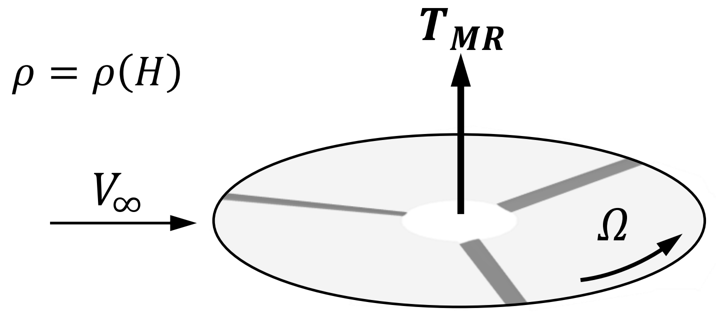
Rotor Sizing and Optimization Framework
Aeromechanical Analysis

- Isolated rotor trim in wind tunnel setting

Trim Points	Description	V_∞ in $\mathrm{km/h}$	H in m
DP1	Hover @ VFM	0	0
DP2	Cruise @ HFM	150	500

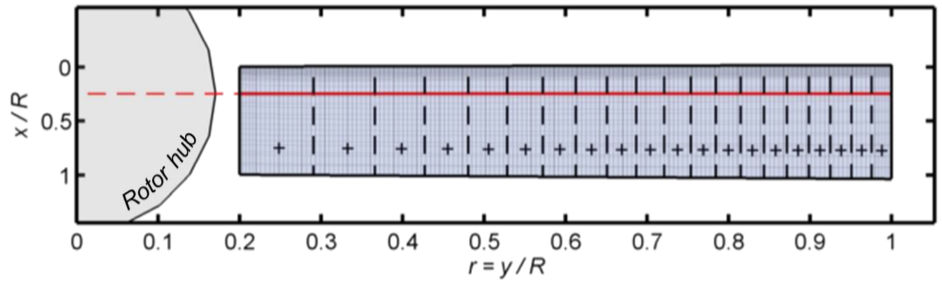
- Output parameters
  - Rotor power components - P_i, P_0
  - Blade loading - C_T/σ
  - Blade tip speed - ΩR
- Computations using HOST (*Airbus Helicopters*)
  - Numerical discretization with 20 blade elements
  - Pitt & Peters inflow model
  - No rotor interactions
  - Newton–Raphson method

Isolated Rotor in Wind Tunnel Setting



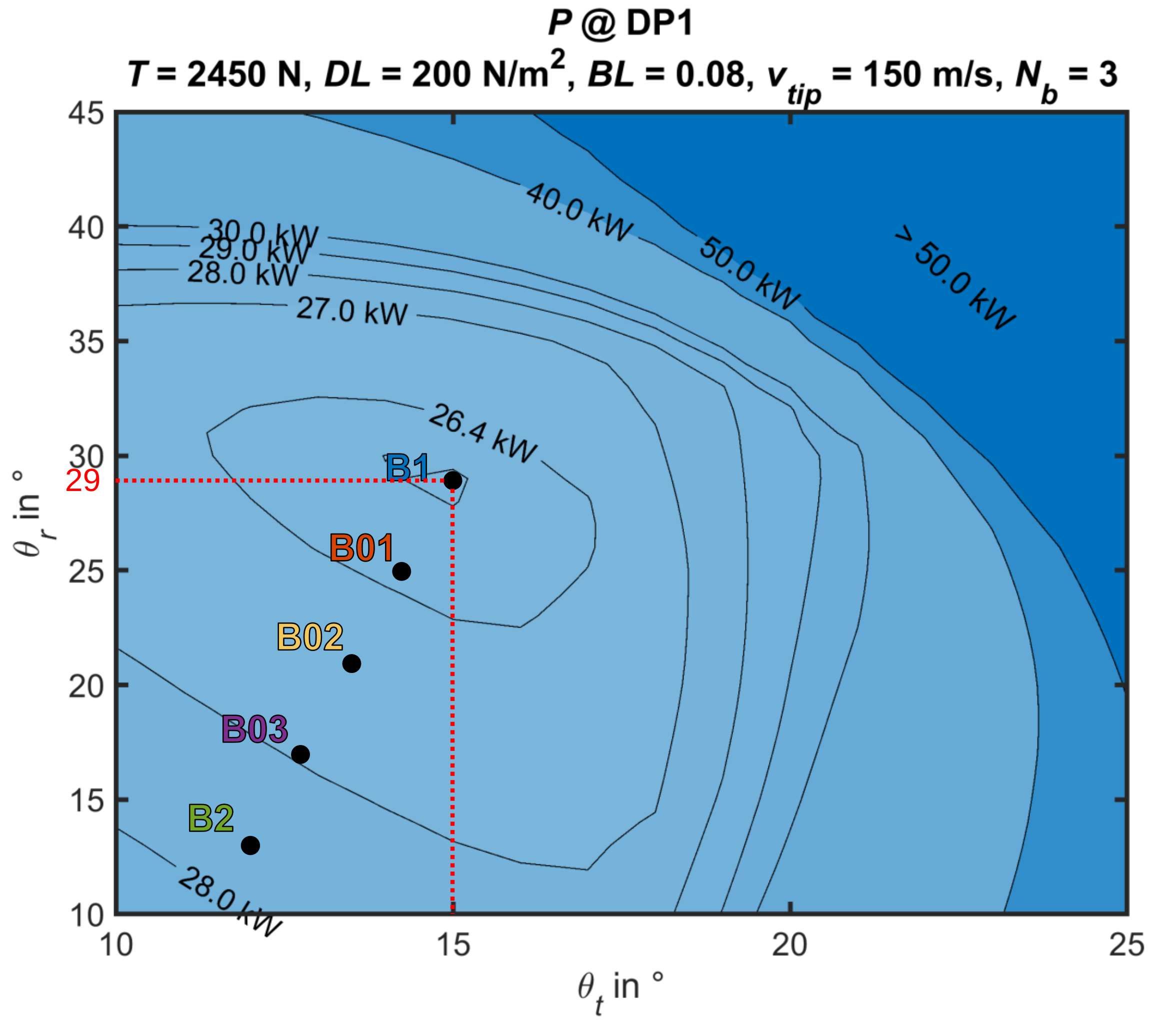
- **Fixed DoF**: $T_{MR} = 2450\ \mathrm{N}$
- **Free DoF**: Ω
- Iteration of Ω until $T_{MR} = 2450\ \mathrm{N}$

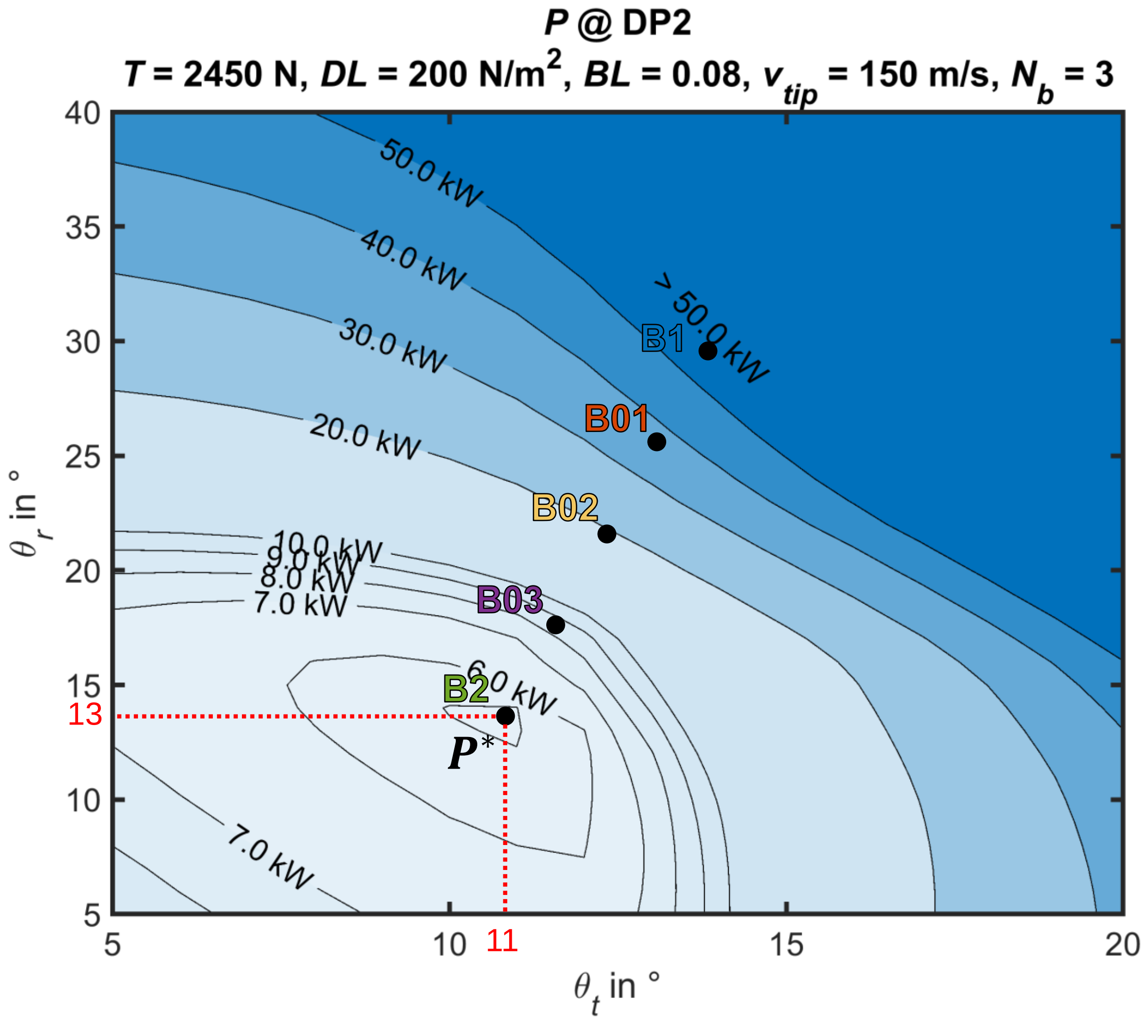
Blade Element Discretization



Design Point Optimization

B1	DP1 Optimum
B2	DP2 Optimum
B01, B02, B03	Intermediate Blades





Design Point Optimization

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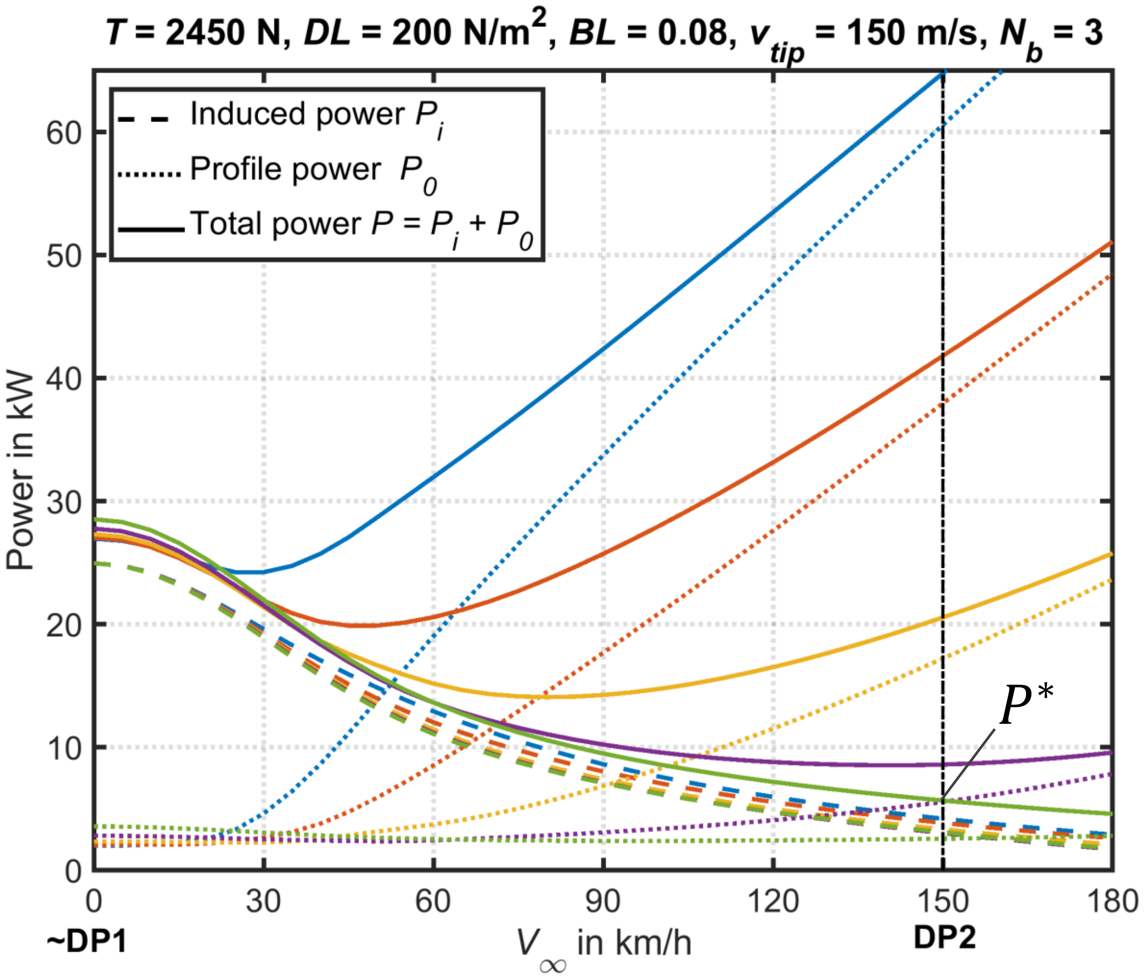
- **Design Goal 1:** $P^* = \min[P(\textbf{DP2})]$
  - In hover, all blades require almost identical power
  - Profile power is the main cause for the power surge
  - **B2** requires the lowest power in **DP2** with a slightly higher power requirement in ~**DP1**



~DP1 = DP1 @ 500 m

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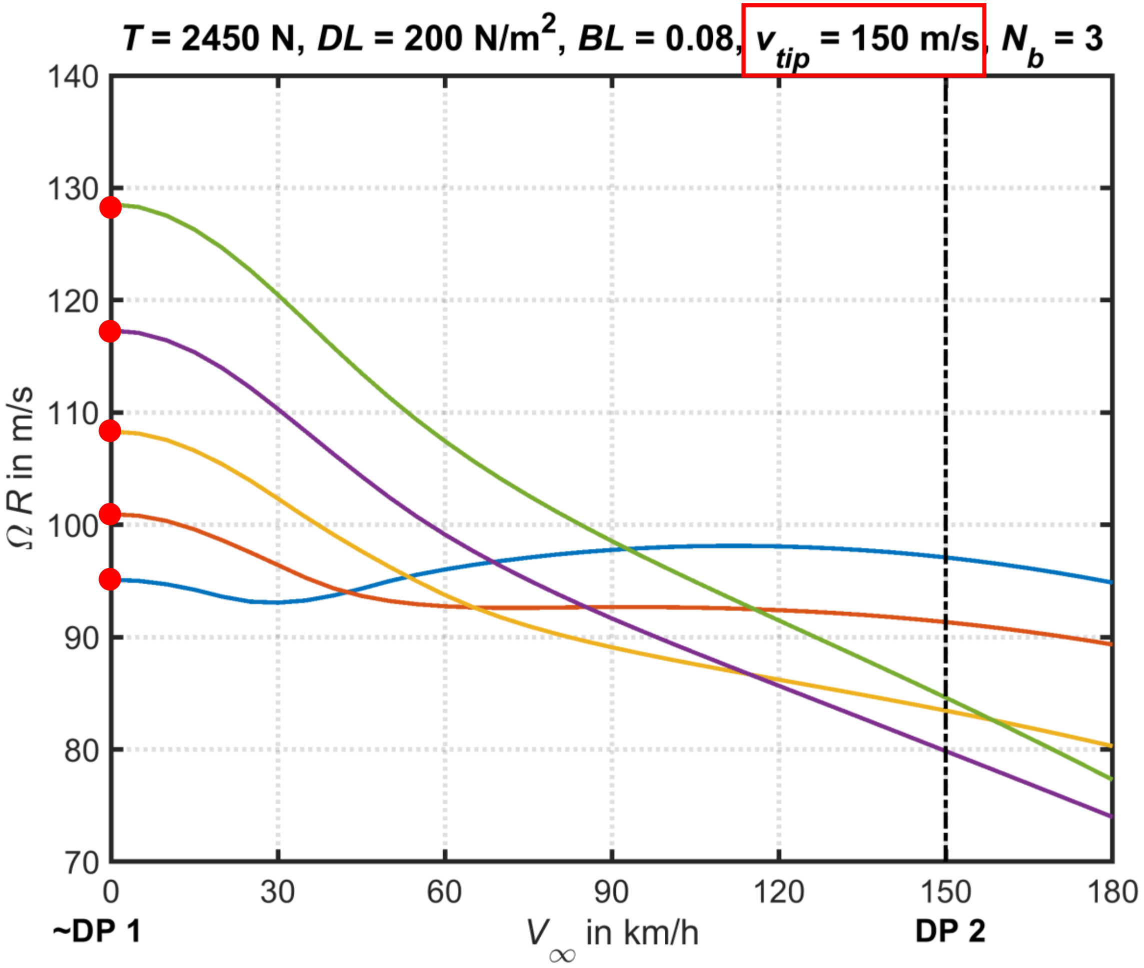
  - B2 has the highest tip speed at ~**DP1,** gradually decreasing towards **DP2**
  - Still lower than $v_{tip} = 150\ \mathrm{m/s}$



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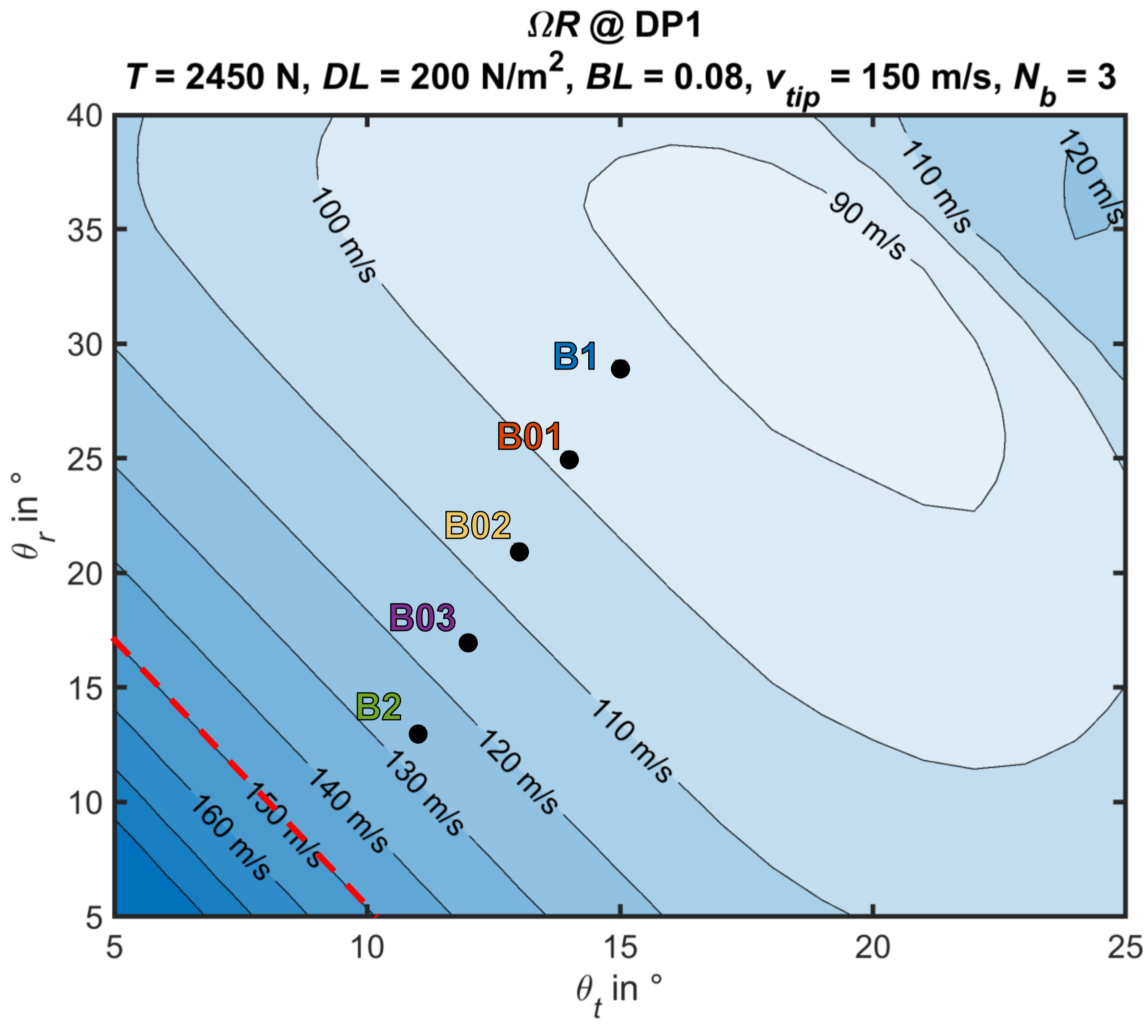
  - Blade optimization alters C_T and therefore Ω

$$\frac{C_T}{\sigma} = \frac{T}{\rho\,(\Omega\,R)\,N_b\,c\,R}$$



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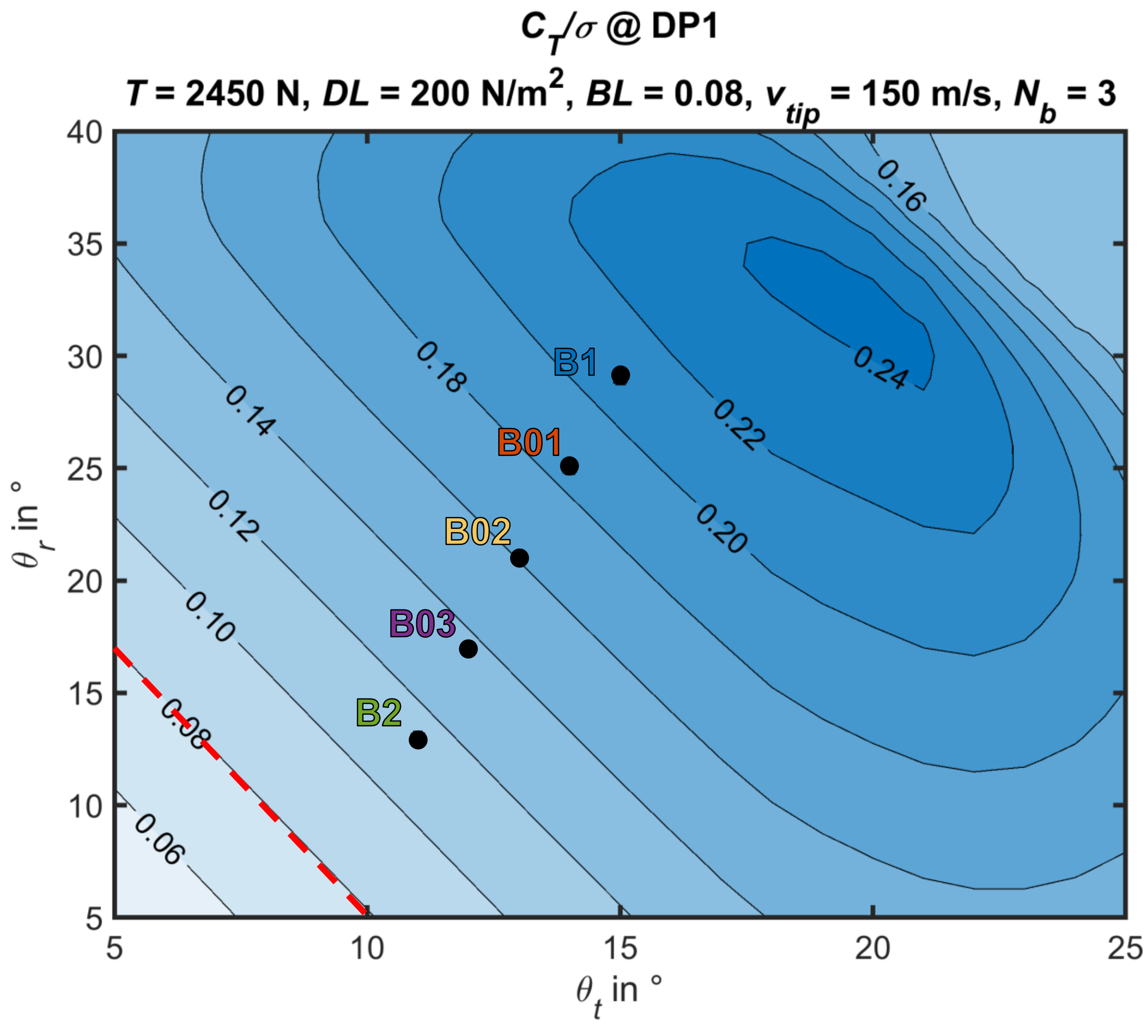
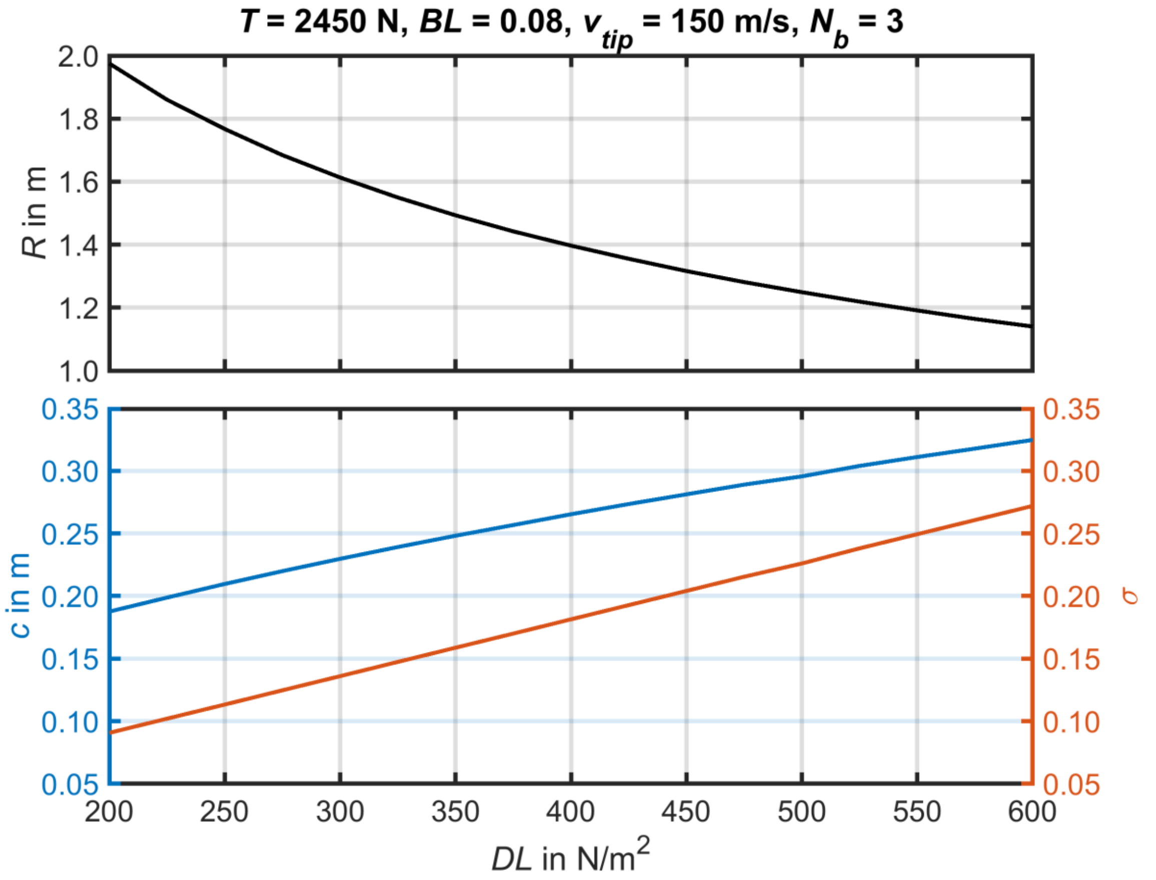
- B2 has to be resized and reoptimized!



Optimized Rotor Sizing
Disc Loading Variation

- **Optimized rotor sizing**: variation of the sizing parameters (DL and BL) and optimizing with respect to **Design Goal 1**
- DL sweep between $200\ \mathrm{N/m^2}$ and $600\ \mathrm{N/m^2}$, $\Delta DL = 25\ \mathrm{N/m^2}$
- With $DL \uparrow$
  - Blade dimensions $R \downarrow, \sigma \uparrow, c \uparrow$



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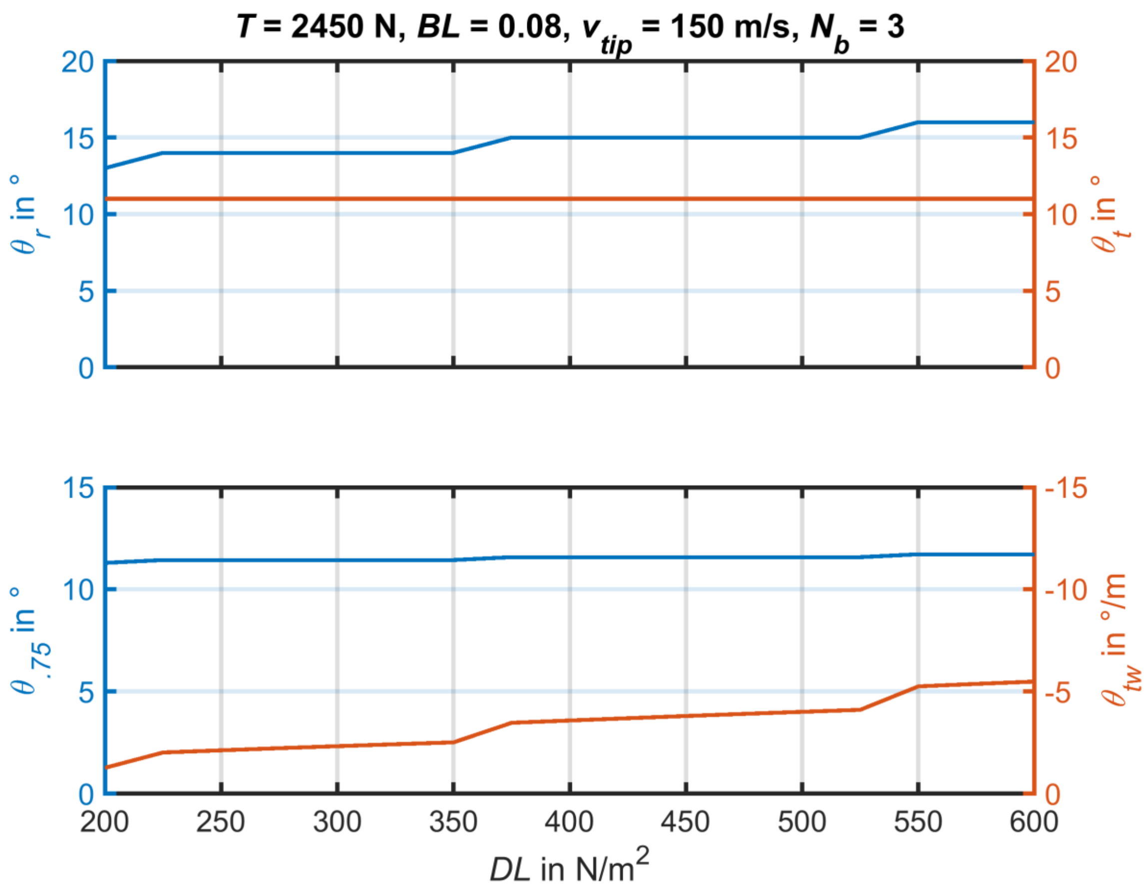
- With $DL \uparrow$
  - Blade dimensions $R \downarrow$, $\sigma \uparrow$, $c \uparrow$
  - Blade twist $\theta_{.75} -$, $\theta_{tw} \uparrow$



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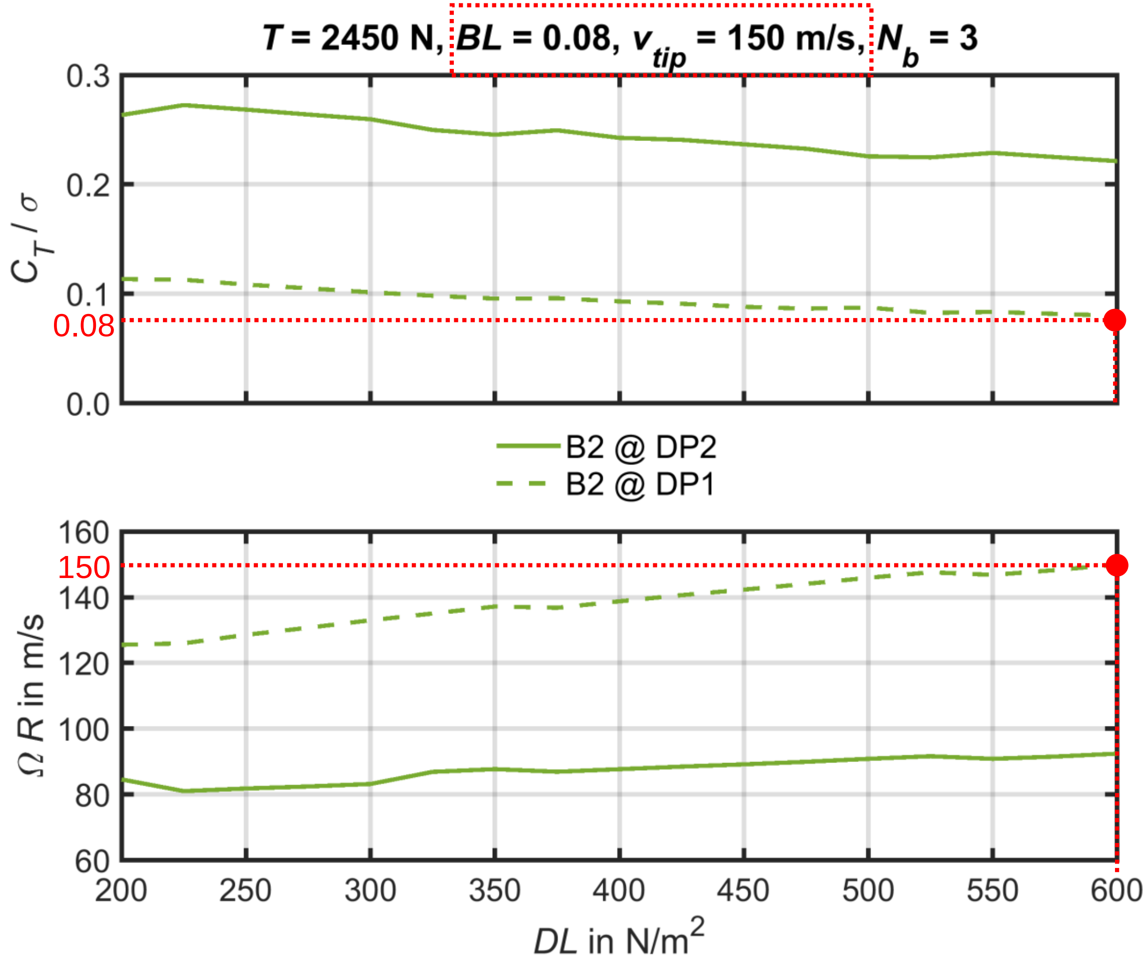
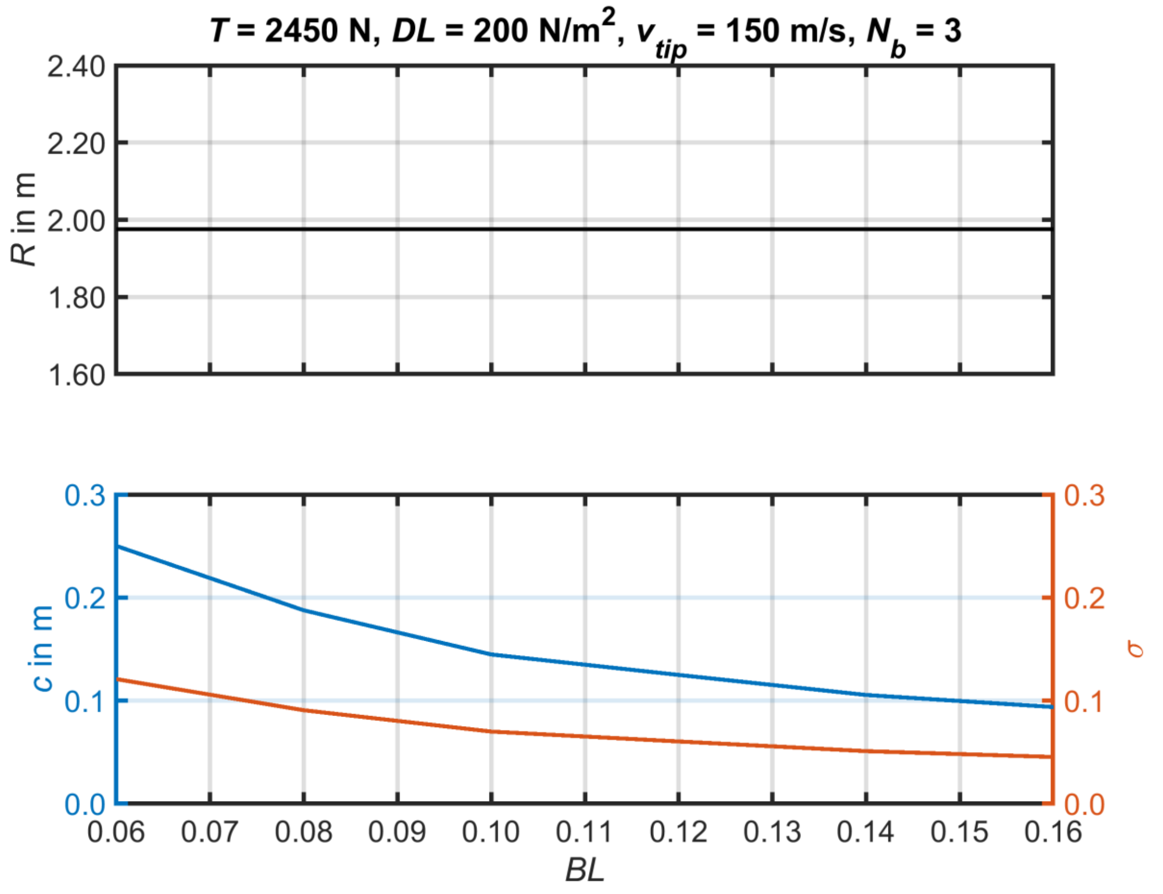
- With $DL \uparrow$
  - Blade dimensions $R \downarrow, \sigma \uparrow, c \uparrow$
  - Blade twist $\theta_{.75} -, \theta_{tw} \uparrow$
  - **DP1** $c_T/\sigma \downarrow, \Omega \uparrow$
  - **DP2** $c_T/\sigma \downarrow, \Omega \uparrow$
- **Design Goal 2:** $\Omega R = v_{Tip}$ and $C_T/\sigma = BL$ at **DP1**

Reached at $DL = 600\ \mathrm{N/m^2}$



Optimized Rotor Sizing
Blade Loading Variation

- **Optimized rotor sizing**: variation of the sizing parameters (DL and BL) and optimizing with respect to **Design Goal 1**
- BL sweep between 0.06 and 0.16, $\Delta BL = 0.01$
- With $BL \uparrow$
  - Blade dimensions $R -$, $\sigma \downarrow$, $c \downarrow$



Optimized Rotor Sizing
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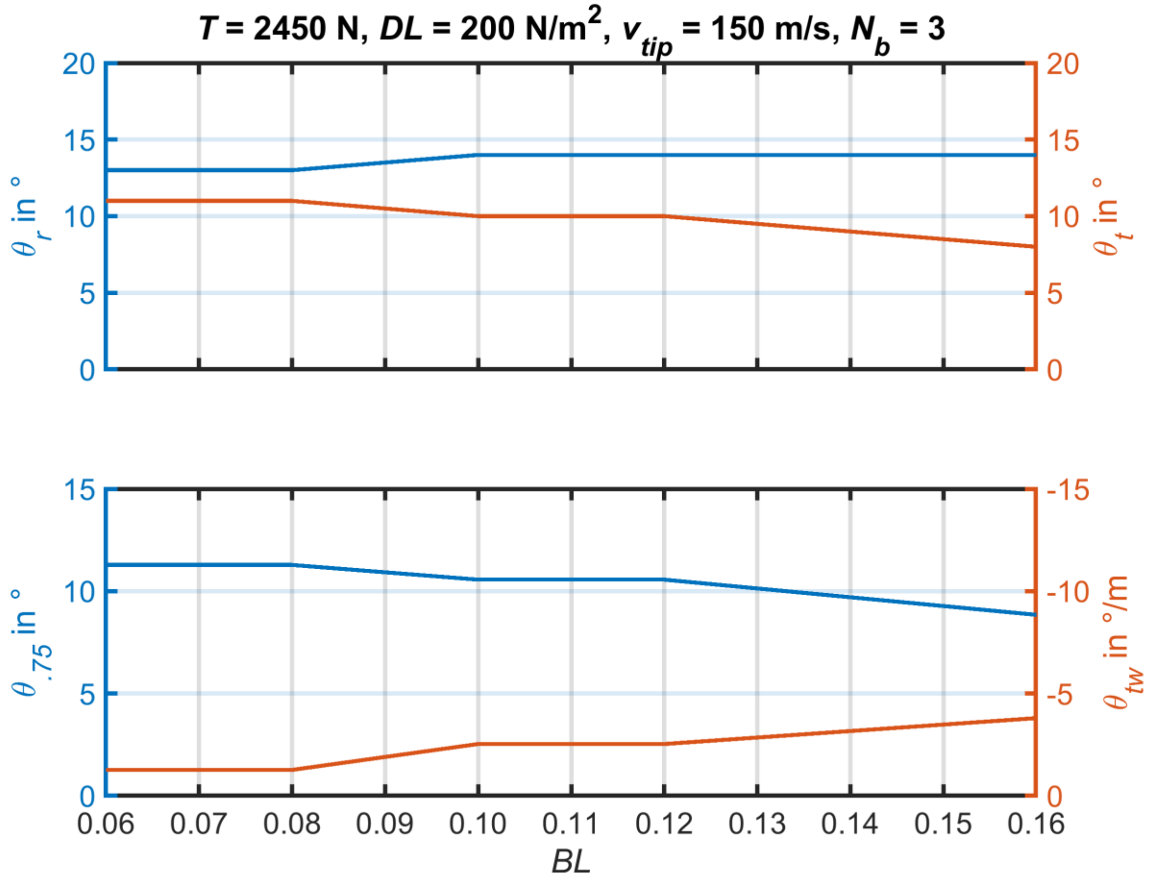


Optimized Rotor Sizing
Blade Loading Variation

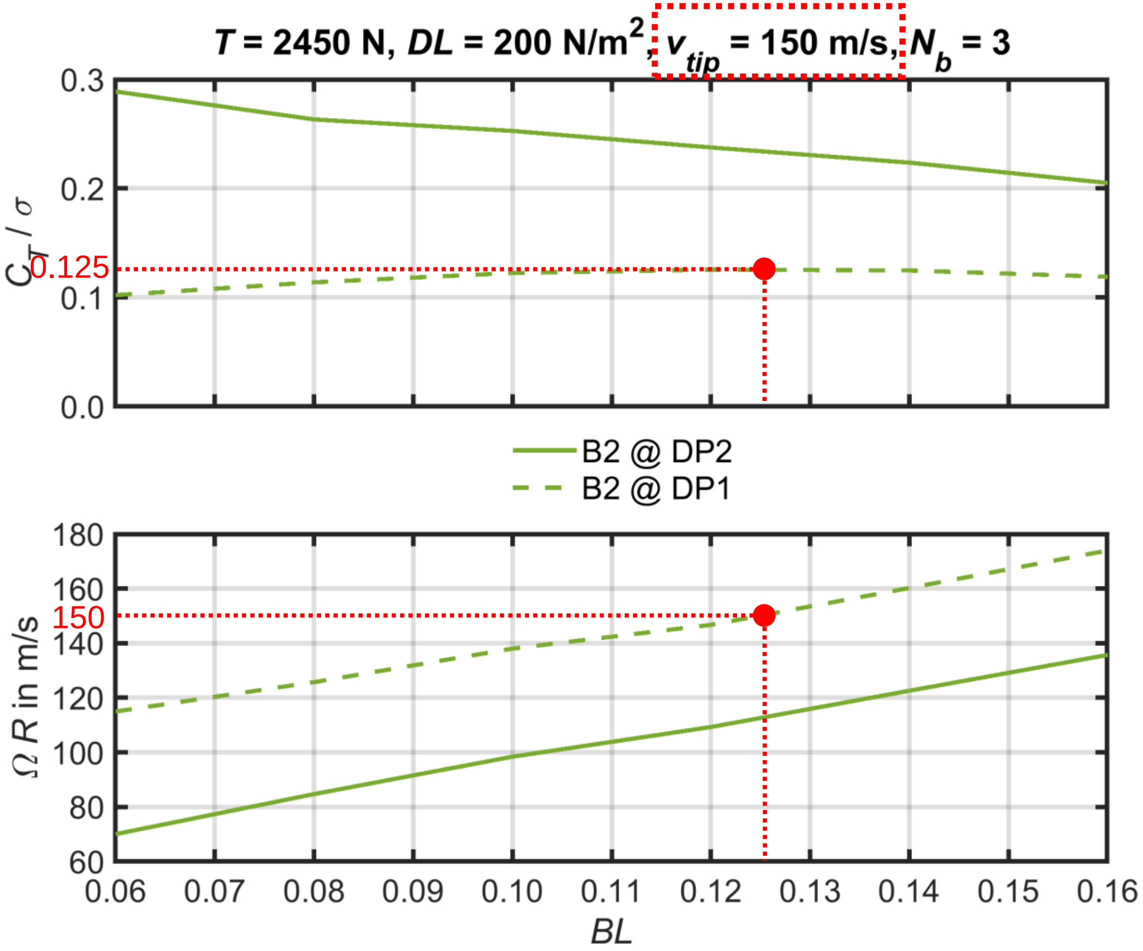
- **Optimized rotor sizing**: variation of the sizing parameters (DL and BL) and optimizing with respect to **Design Goal 1**

- BL sweep between 0.06 and 0.16, $\Delta BL = 0.01$

- With $BL \uparrow$
  - Blade dimensions $R -, \sigma \downarrow, c \downarrow$
  - Blade twist $\theta_{.75} \downarrow, \theta_{tw} \uparrow$
  - **DP1** $c_T/\sigma \uparrow - \downarrow, \Omega \uparrow$
  - **DP2** $c_T/\sigma \downarrow, \Omega \uparrow$

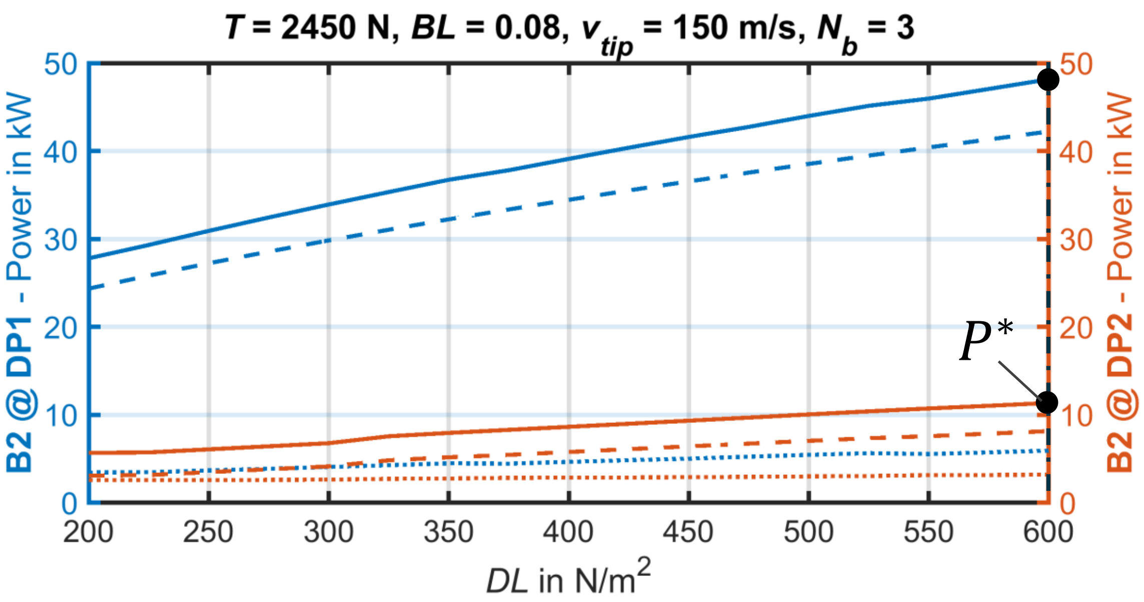
- **Design Goal 2:** $\Omega R = v_{Tip}$ and $C_T/\sigma = BL$ at **DP1**

Reached at $BL = 0.125$

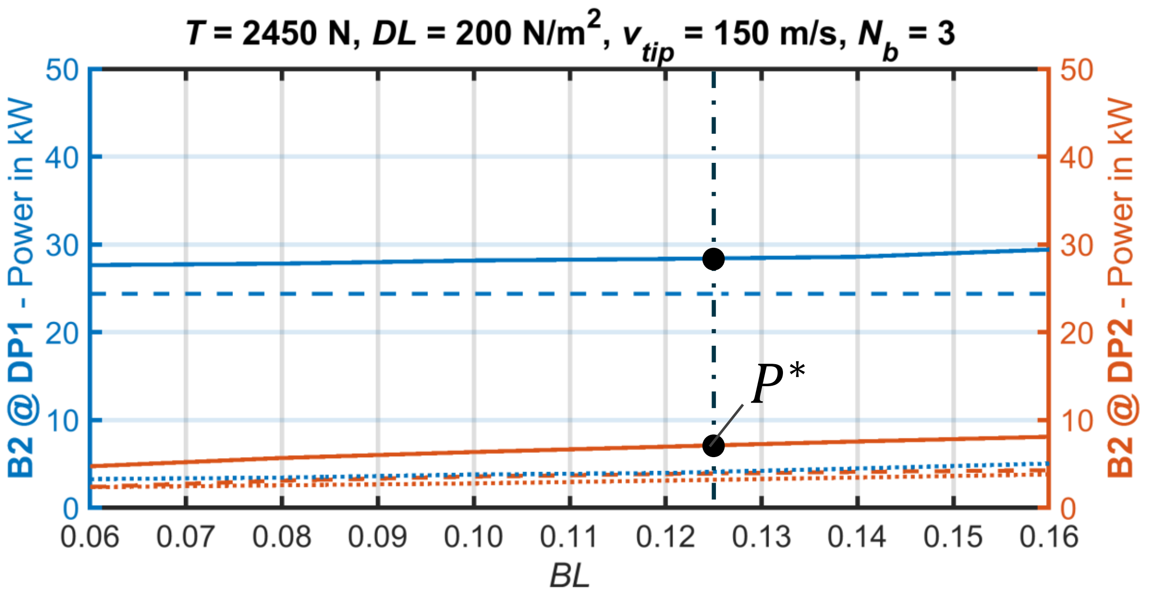


Optimized Rotor Sizing
Discussion

Sizing Result 1 ($DL = 600\ \mathrm{N/m^2}$)



Sizing Result 2 ($BL = 0.125$)



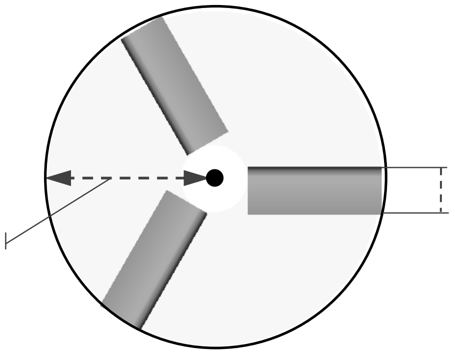
Induced power P_i · Profile power P_0 · Total power $P = P_i + P_0$

- Disc loading variation is less sensitive to Design Goal 2 (Start: $200\ \mathrm{N/m^2}$, End: $600\ \mathrm{N/m^2}$ - 16 steps).
- Increasing disc loading results in higher power (radius is changed).
- It is preferable to size the rotor through blade loading.

Optimized Rotor Sizing
Discussion

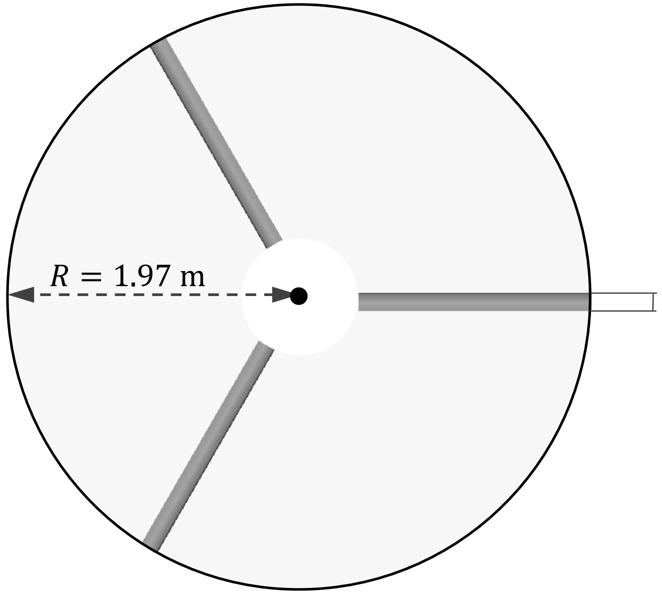
Sizing Result 1 ($DL = 600\ \mathrm{N/m^2}$)

T = 2450 N, BL = 0.08, v_{tip} = 150 m/s, N_b = 3



Sizing Result 2 ($BL = 0.125$)

T = 2450 N, DL = 200 N/m^2, v_{tip} = 150 m/s, N_b = 3



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- Increasing disc loading results in higher power (radius is changed).
- It is preferable to size the rotor through blade loading.

Conclusions

Summary

- There exists a combination of linear twist and blade collective, where the global minimum power is found
- Optimizing blade twist with respect to forward flight causes the rotor to deviate from hover design tip speed
- The rotor has to be iteratively resized and optimized until both design goals are satisfied
- Sizing through blade loading provides quicker solutions with negligible changes in the rotor power

Outlook

- Implementation of an optimization module, which automatically finds a rotor geometry satisfying the two introduced design goals
- Integration of the fixed pitch rotor modeling framework to design process of the Medical Personnel Deployment Vehicle
- Study of the constrained design optimization for fixed pitch rotors
- Analysis of dynamic loads acting on the rotor hub

THANK YOU
FOR YOUR ATTENTION!

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Appendix
Blade Angle of Attack Distribution