Wind Engineering Departement

Performance Team

11/06/2025

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Power Curve risk analysis: Cp Ct

Wind Engineering Department :
The mission of performance engineer in EDF renouvelables

- **Reduce the project risk associated with emerging technologies**
- **Measure the benefits for potential opportunities**

Performance Verification Strategy

Wind Assets Operational Assessment

Reforecast Study & Methods Update

PC Risk evaluation

Commercial Power Curve

Document review

- Version Control
- Site representativity
- Past PCVT review

A PC risk from document review
(e.g. PCVT results)

Cp analysis

Is Cp max in a reasonable range?

A PC risk from unrealistic Cp calculated from adjusted Cpmax

Ct analysis

- Is Cp Ct trend in the empirical range?
- Is Ct consistent in different version?

A PC risk from unrealistic/inconsistent Ct calculated from adjusted Ct

Sommaire

1. Theories
2. Cp Ct verification
3. Risk quantification

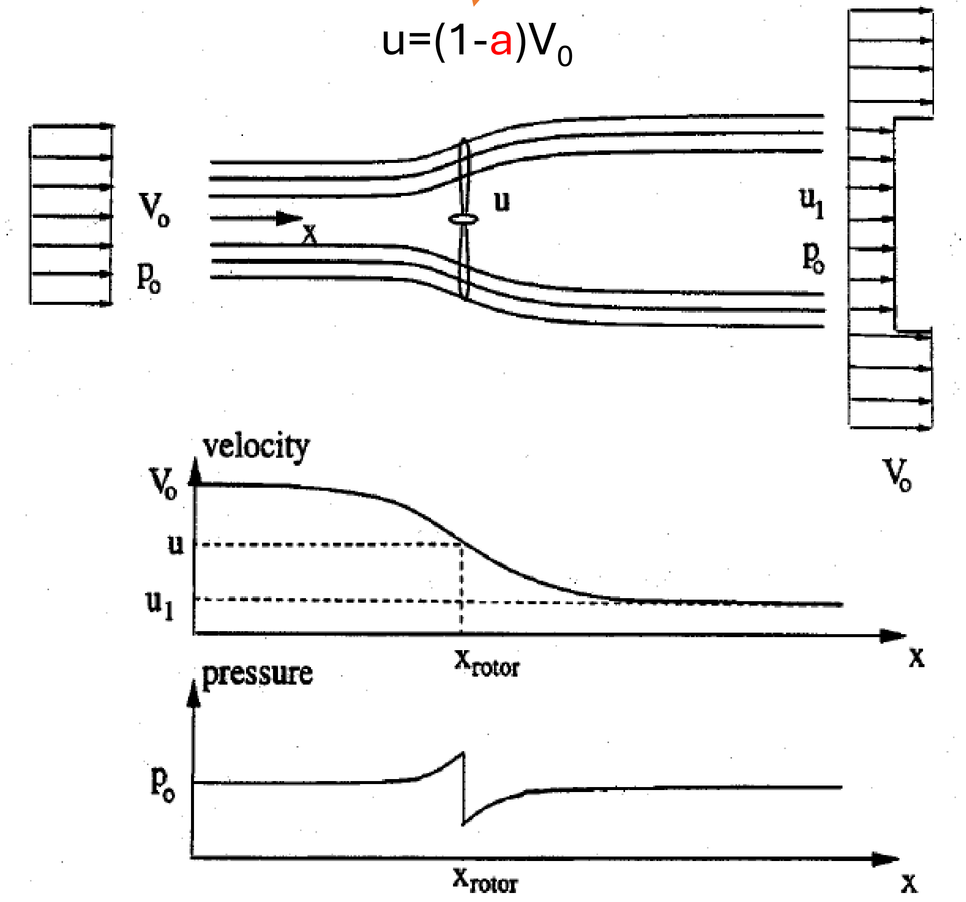
•1 Theories

Introduction: Disc Theory (Momentum Theory)
Relationship between Cp, Ct and a

axial induction a

$u_1=(1-2a)V_0$

$u=(1-a)V_0$



For a <0.5

$Cp=4a(1-a)^2$

$Ct=4a(1-a)$

Cp max at a=1/3

For a >0.5,

theory needs to be corrected

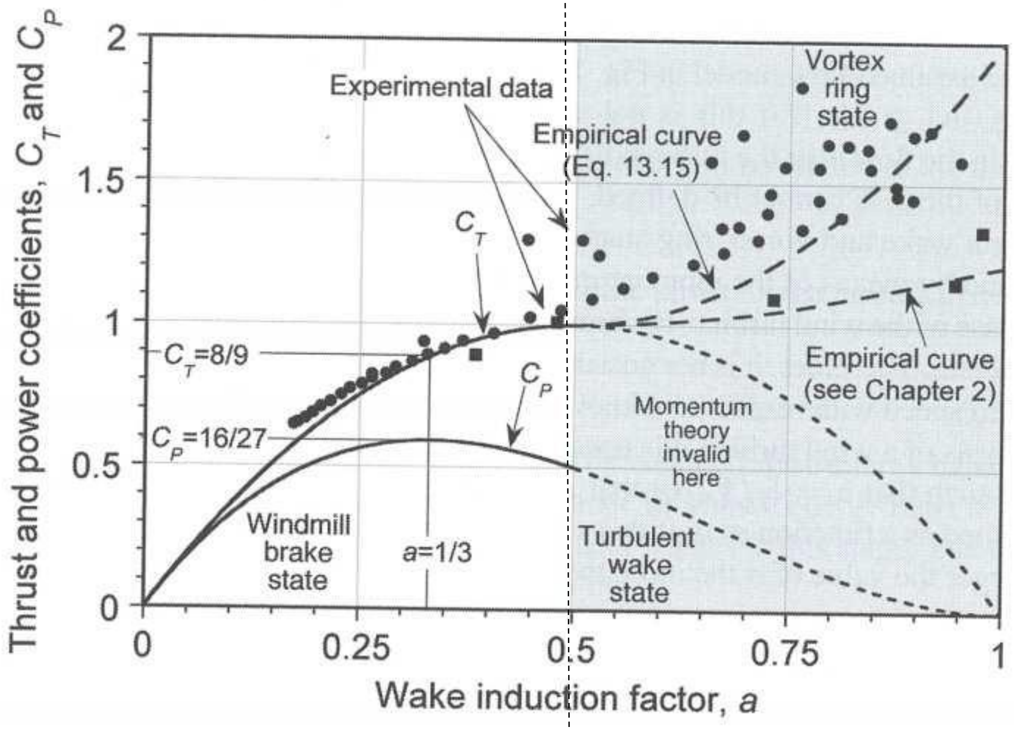
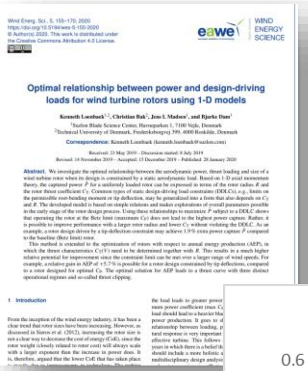
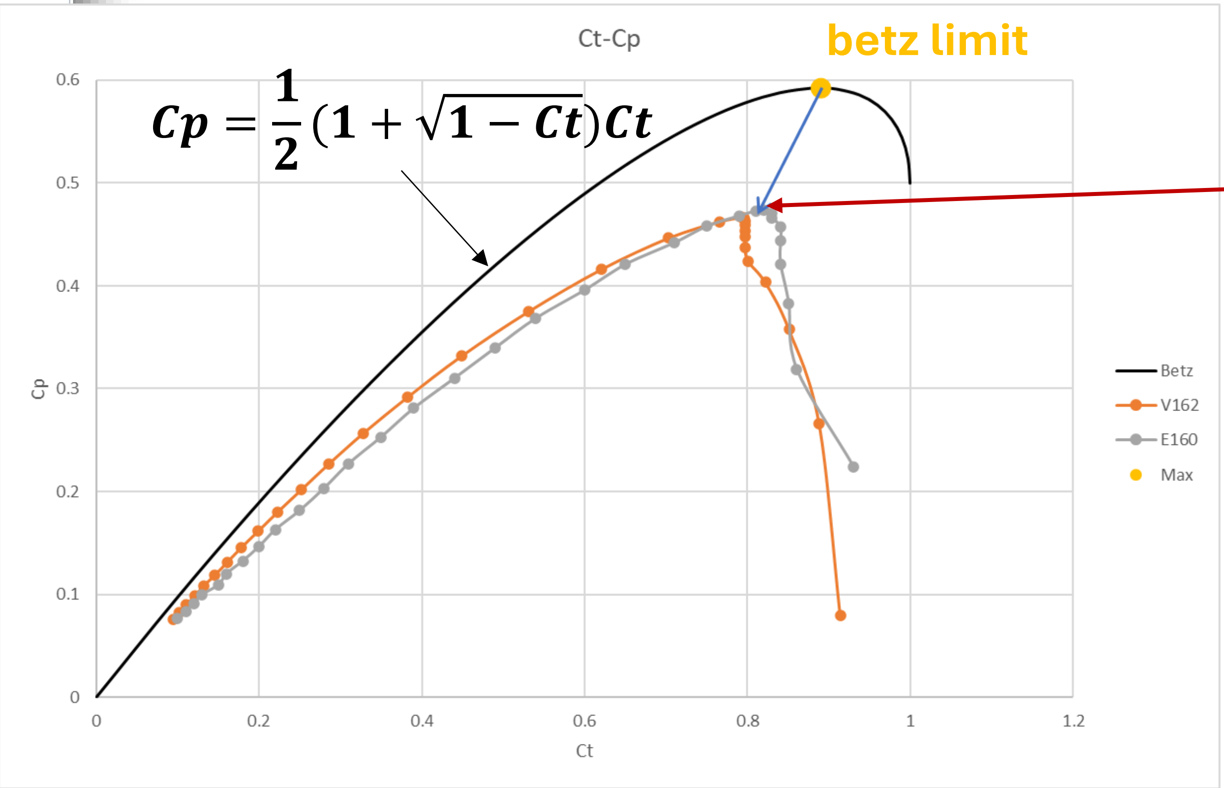


Figure 13.4 Momentum theory solution for a wind turbine in axial flow in terms of the induction ratio. Measurements from several sources including Lock (1925).

Power curve Analysis:
a) Power curve acceptability


Optimal relationship between power and design-driving loads for wind turbine rotors using 1-D models

Ct: represents the ratio between the force exerted by the wind turbine on the flow (and vice versa) and the dynamic pressure force in the incoming flow. ***It influences the wake downstream.***



KPI: Relationship between Cp and Ct
Source: *wes-5-155-2020.pdf* (page 157)

Ct and Cp basically depend on a,

When a =1/3, reaching Betz limit

- Cp =16/27 (0.593)
- Ct = 8/9 (0.89)

The actual Cp-Ct curve is relative to Betz's, with max at 0.8Cp, 0.9Ct:

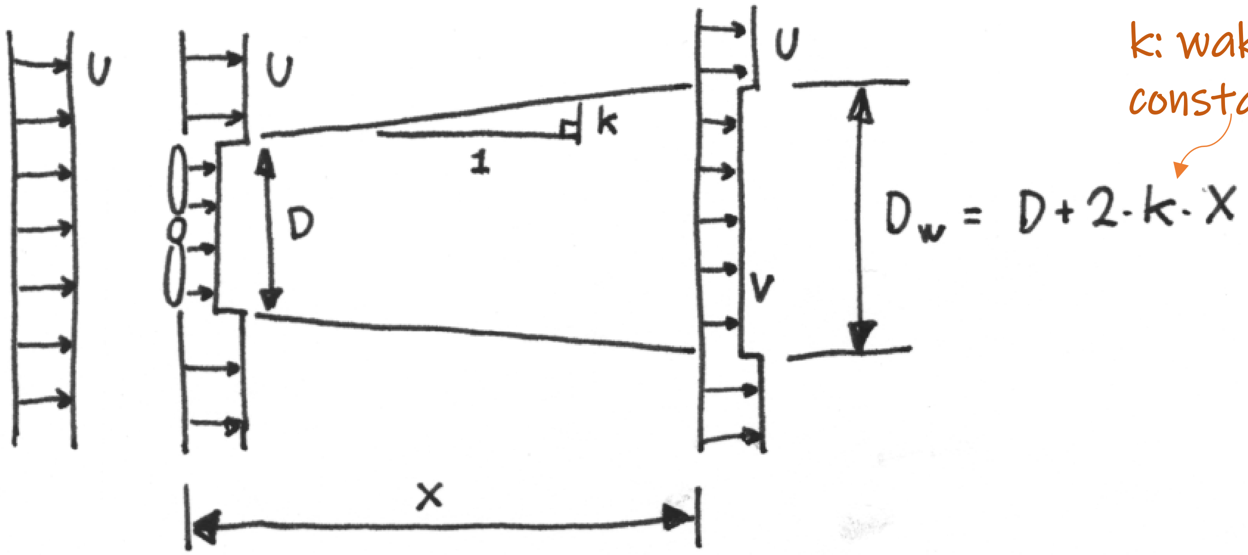
Considering tip loss, Cp and Ct will both decrease by ~10%;

Considering wake rotation loss and electrical mechanical loss, Cp will further decrease by ~10%.

For the actual wind turbine design, to reduce load, the optimal Cp will choose a <1/3, especially for the tip part.

Impact of Ct on wake loss: example of single wake calculation

The N.O. Jensen wake model :



k: wake decay constant

$$1 - V/U = \left(1 - \sqrt{1 - C_T}\right) / \left(1 + 2kX/D\right)^2$$

The wind speed directly after the turbine ($x = 0$): $V_0/U = \sqrt{1 - C_T}$

The Higher Ct is, the lower V_0 is!

=> Higher wake losses!

From concepts to reality

Power curve:

Risk covered through the contract with IEC testing and WL

Cp

Obtained from the power curve

No warranty but information available

Ct

Impact on wake losses!

Mitigating the risk of bias is not possible!

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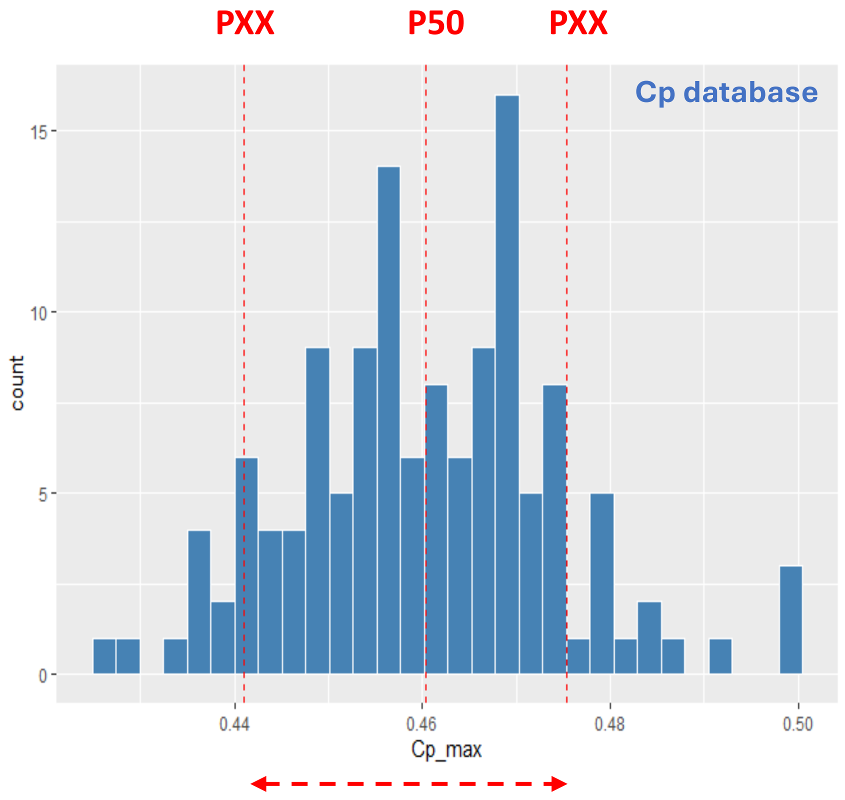
Cp Ct verification

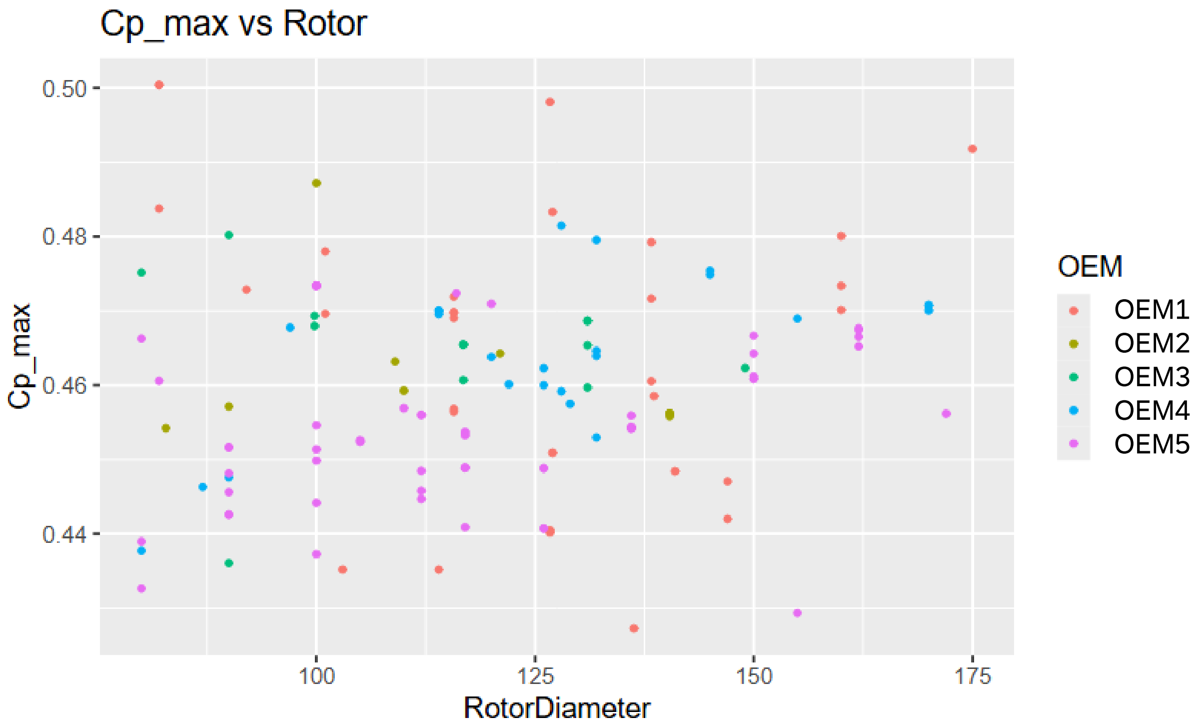
Let’s start with Cp

Cp max is one of the KPI checked to insure acceptability of the Power Curve

The coefficient of performance (Cp) is typically supplied by the turbine manufacturer, accompanied by relevant power curve data. A comprehensive database can be developed utilizing the existing documentation.



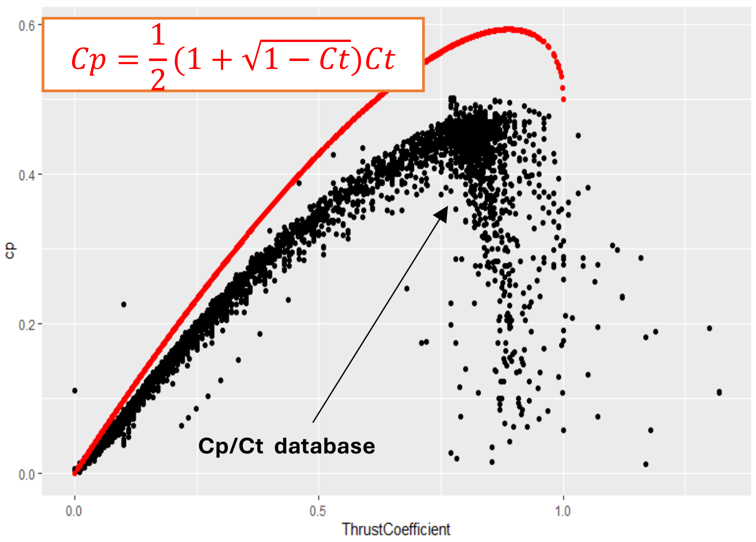
Probability acceptance to be defined based on WTG technology, size, ect

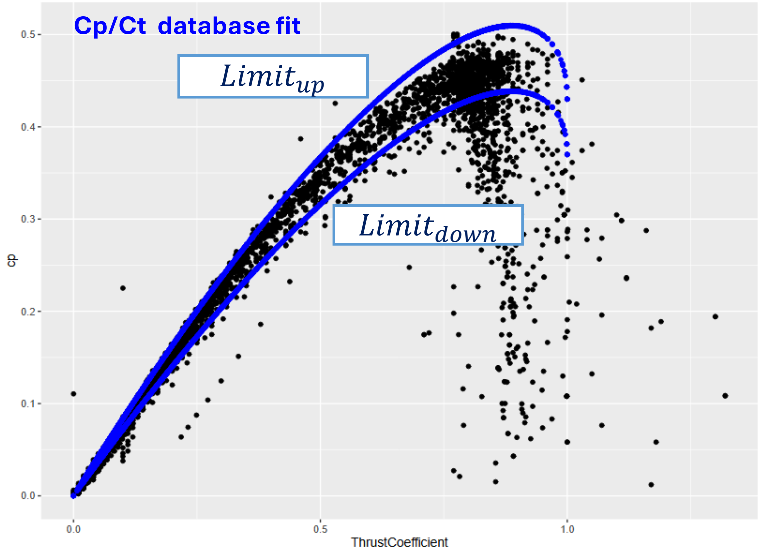


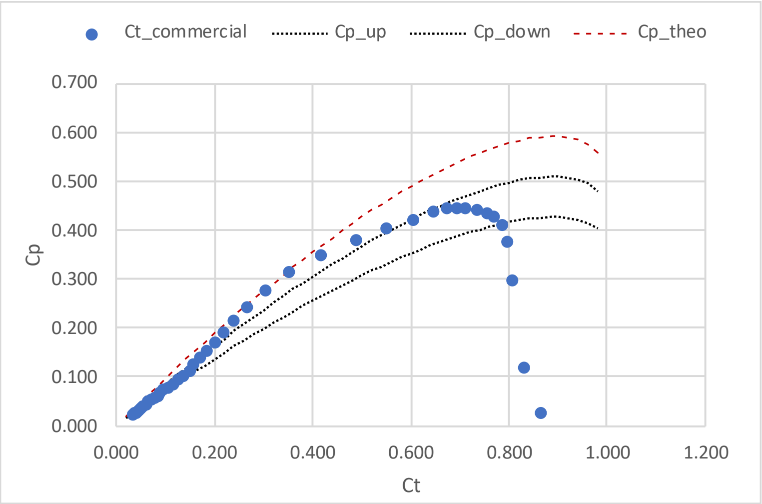
No obvious trend is identified between Cpmax and Rotor size.

edf renouvelables

Empirical relationship between Cp Ct







Cp max cannot reach Bezt limit:

Scaled at Cp_max/Bezt limit.

The empirical range is used to

represent the trend.

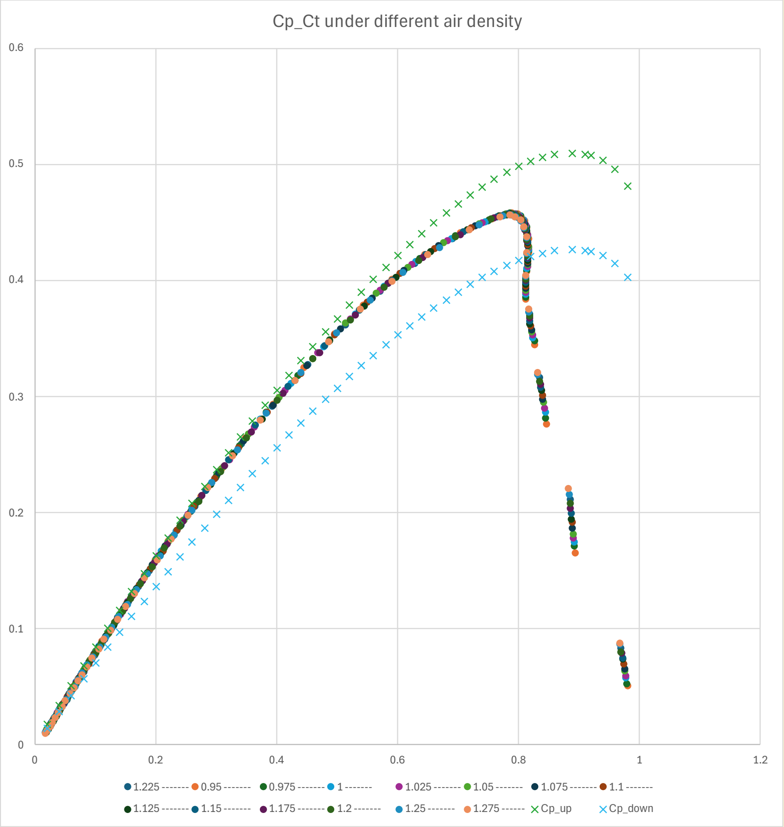
Exemple of the trend of Ct Cp OEM

is out of the limit.

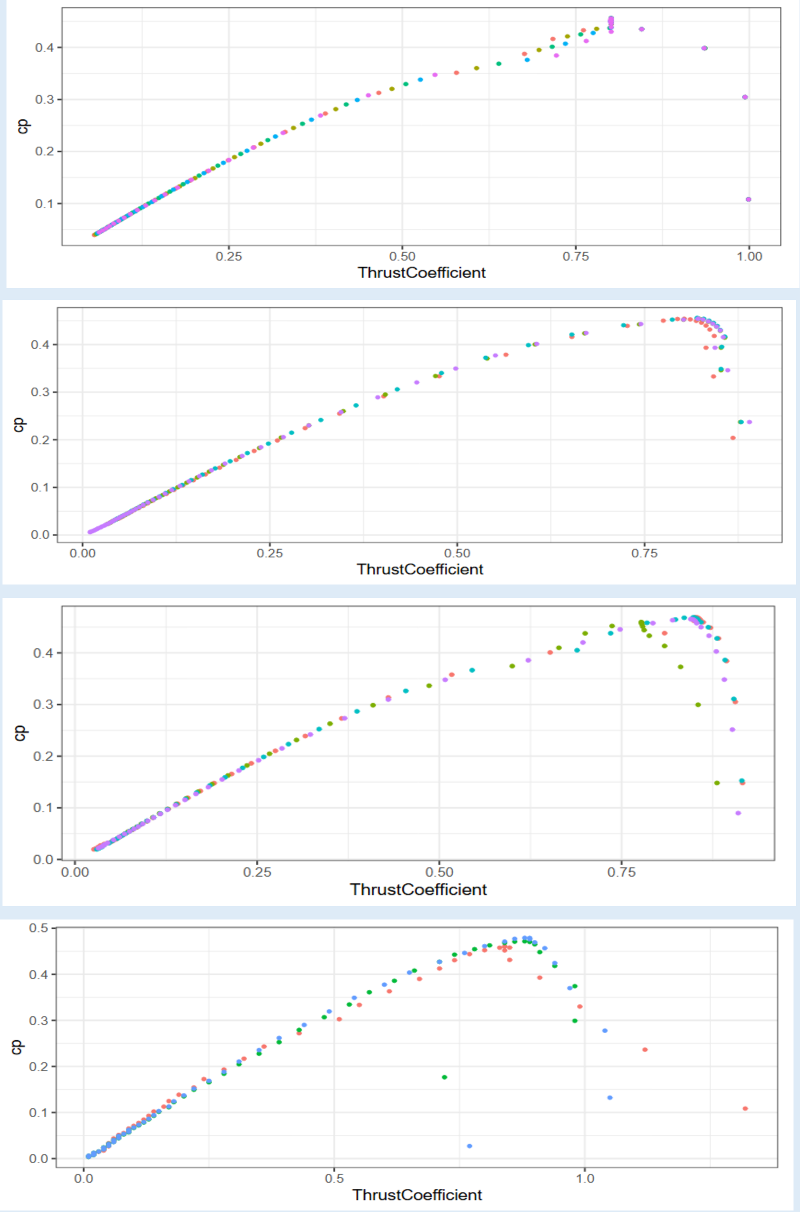
How Cp-Ct relationship varies?

For the same turbine type, Cp-Ct relationship stays similar when **air density** or **rated power** vary

- Different Air density



- Different Rated Power



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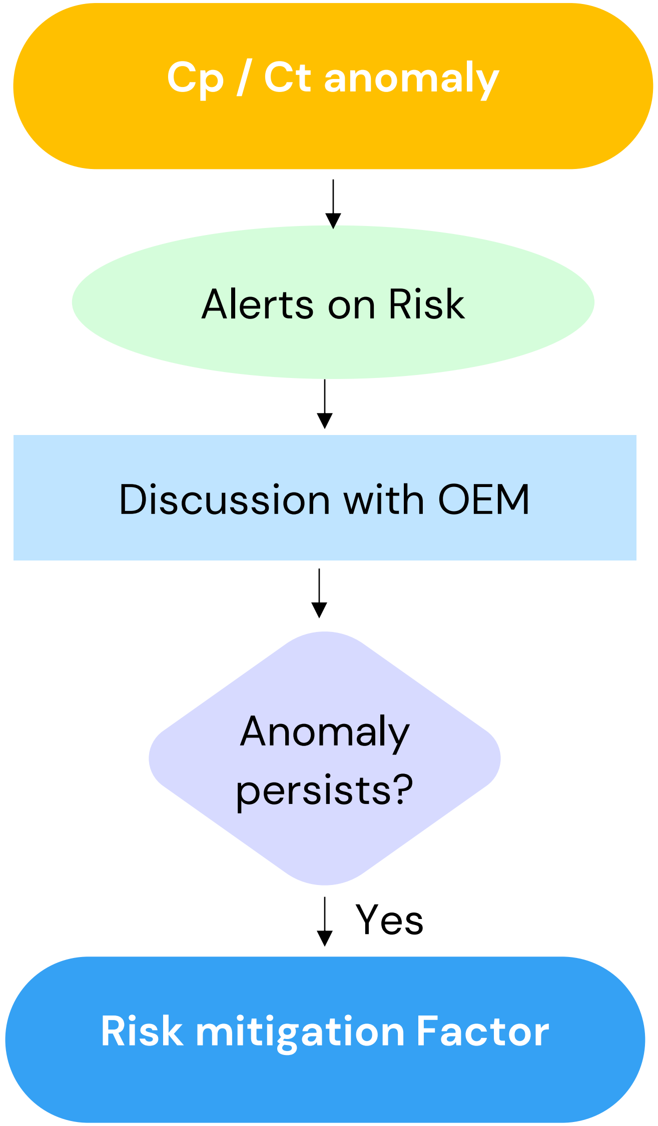
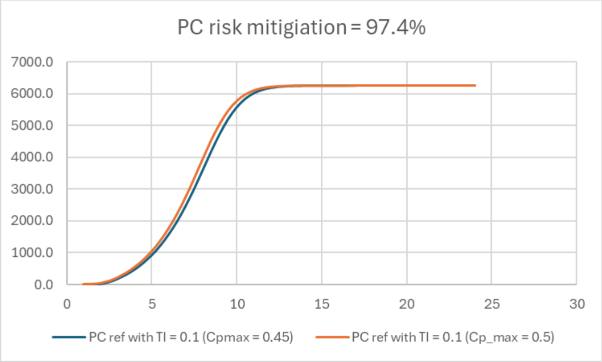
Quantify the PC risk

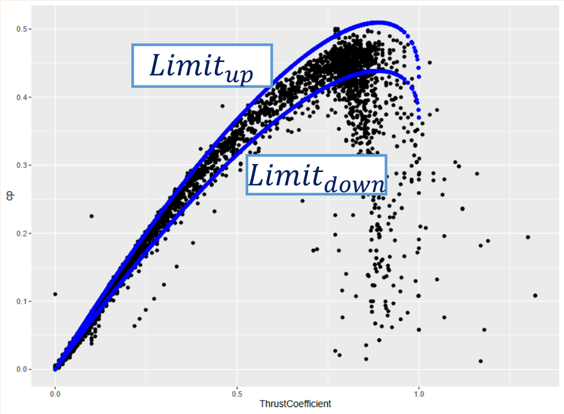


Cp max is too optimistic:

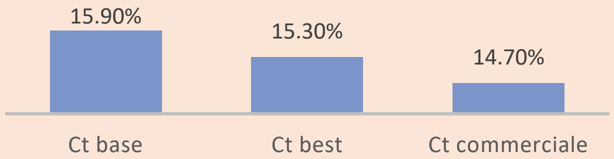


- Generate different PC with different Cpmax
- Compare AEP with site wind distribution

Ct is too optimistic:



- Generate different Ct curve different scenarios
- Compare the wake losses from generated curve and commercial curve.



Conclusion

- Verification of Cp and Ct anomalies helps to reveal potential risks in AEP estimation.
- Engaging in discussions with the OEM serves as the first remedy to lower this risk.
- When the clarification is insufficient, a risk mitigation factor can be calculated to quantify the risk.
- More sophisticated software tools (such as Bladed or Qblade) can facilitate further calculations; however, they may necessitate access to detailed data that turbine suppliers do not always provide.

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