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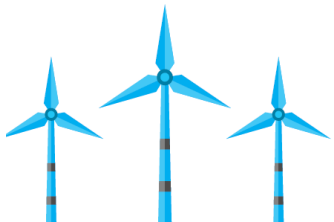
Towards closed-loop wind farm control under time-varying inflow conditions

A yaw-based wake steering solution leveraging FLORIS

Wind Energy Systems Engineering, Pamplona, Spain.
October 2, 2019

Bart Doekemeijer and Jan-Willem van Wingerden
Delft University of Technology



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Introduction

The issue of wake formation in wind farms

The Horns Rev offshore wind farm (Vattenfall) under foggy conditions. Photograph by C. Steiness, February 2008

[1] Barthelmie et al., 2010: Quantifying the Impact of Wind Turbine Wakes on Power Output at Offshore Wind Farms. *J. Atmos. Oceanic Technol.*, **27**, 1302–1317

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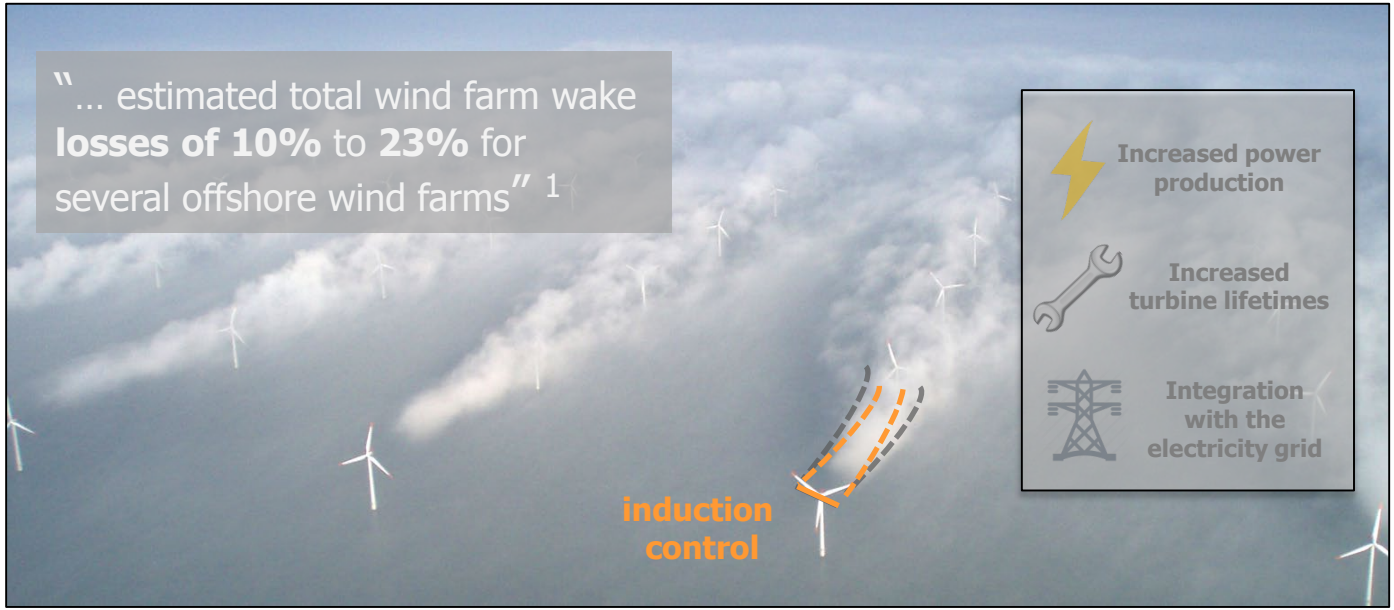

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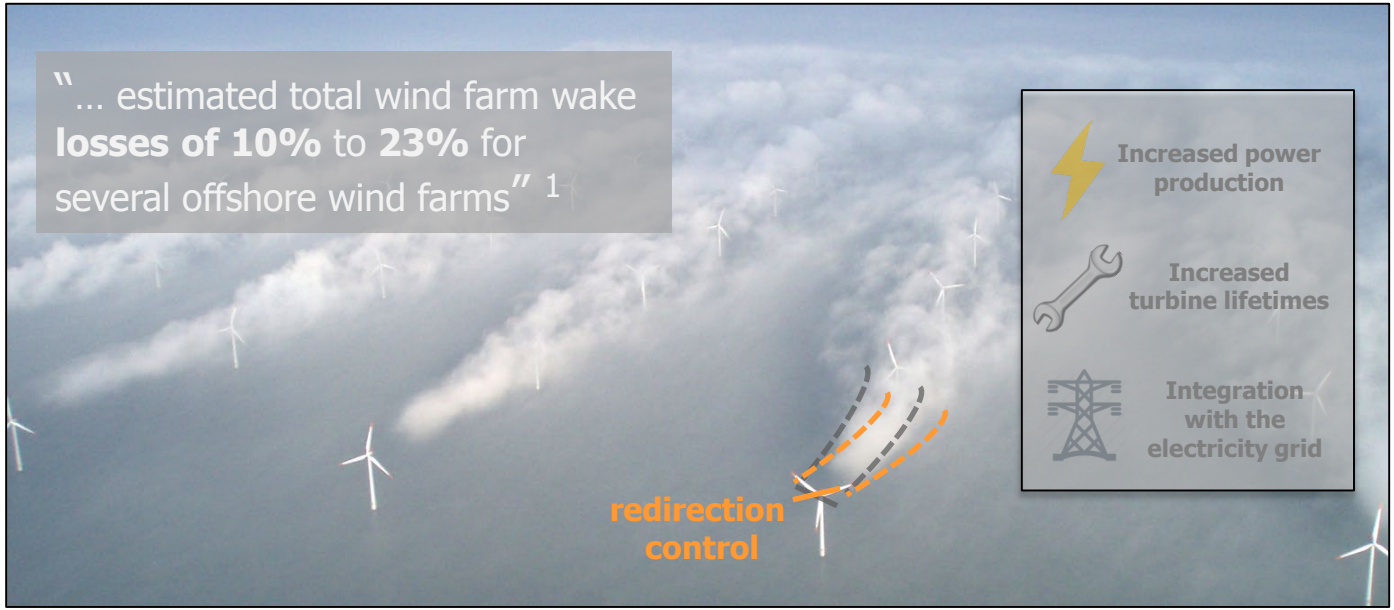

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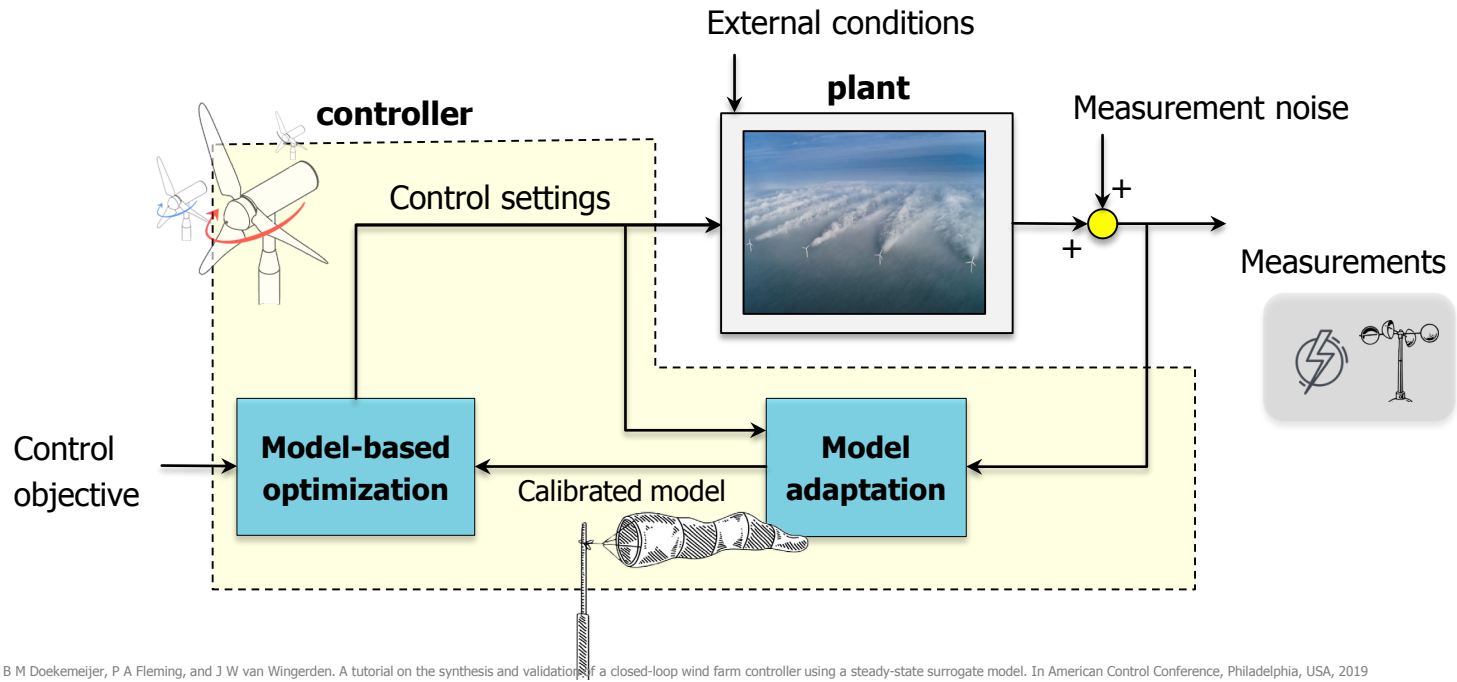
The model-based closed-loop wind farm control framework



B M Doekemeijer, P A Fleming, and J W van Wingerden. A tutorial on the synthesis and validation of a closed-loop wind farm controller using a steady-state surrogate model. In American Control Conference, Philadelphia, USA, 2019

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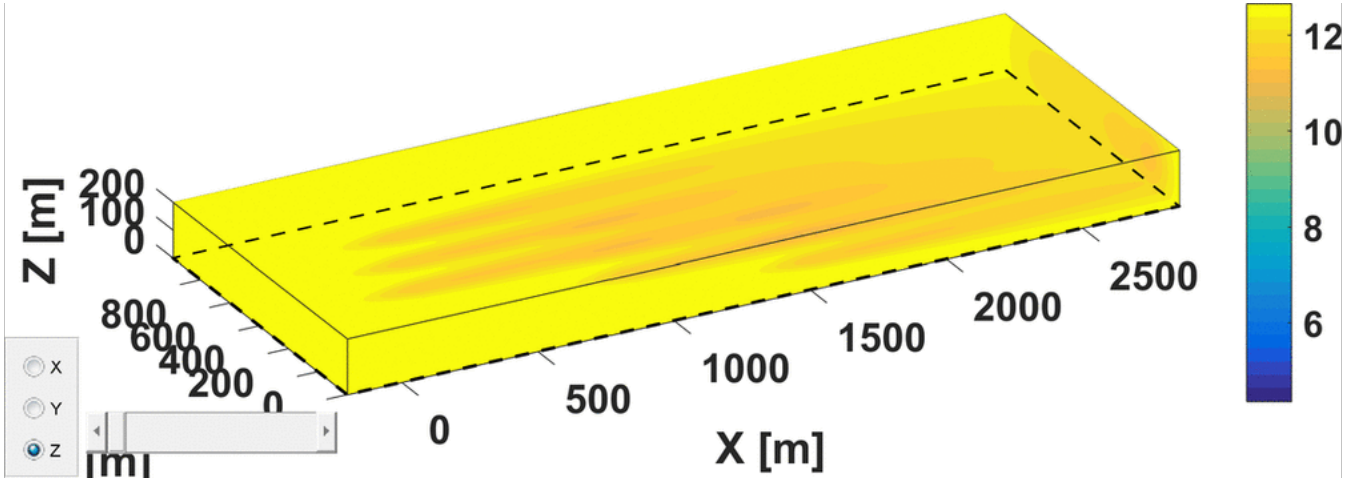
CONTROLLER SYNTHESIS USING FLORIS

Controller synthesis

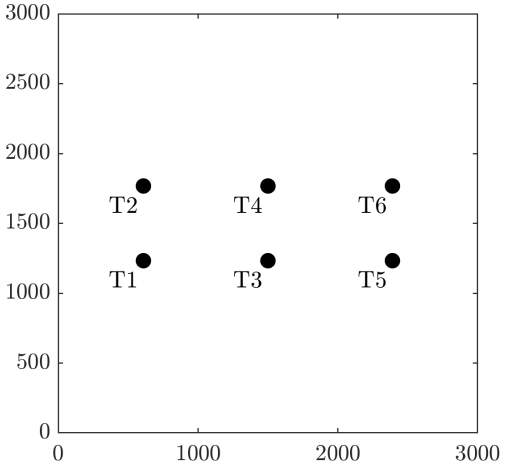
Surrogate model selection: FLORIS

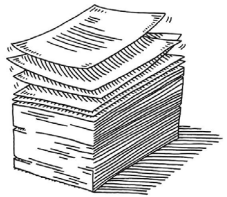


https://github.com/TUDelft-DataDrivenControl/FLORISSE_M

Controller synthesis

Model adaptation – prior information





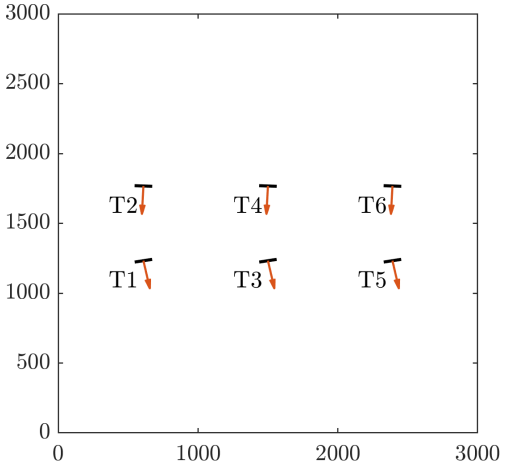
Prior information

To be estimated variables

Wind direction ☐ Wind speed ☐ Wake recovery factor ☐

Controller synthesis

Model adaptation – wind direction



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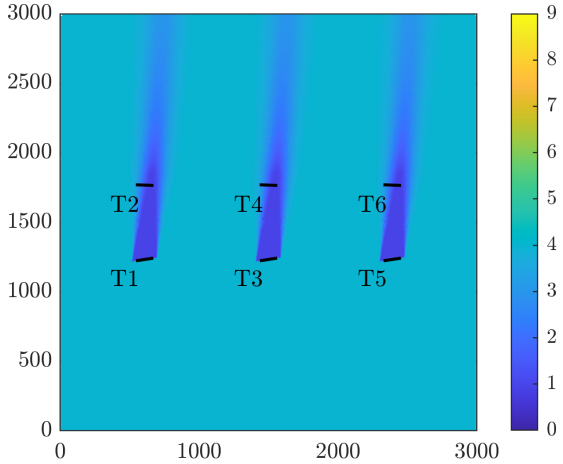
Real-time wind vane measurements

To be estimated variables

Wind direction ☑ Wind speed ☐ Wake recovery factor ☐

Controller synthesis

Model adaptation – wind speed

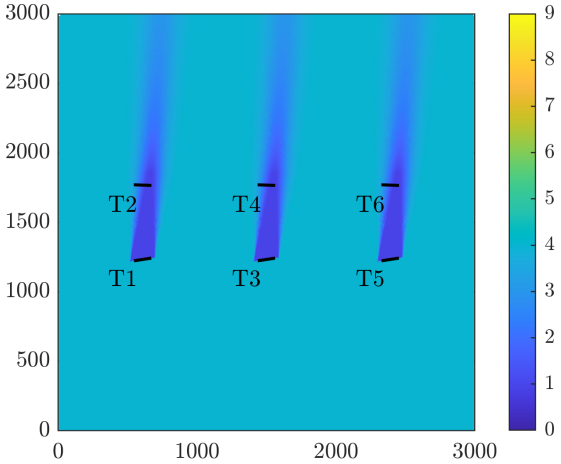


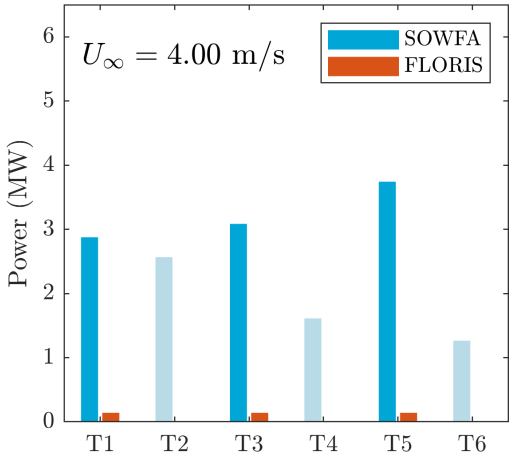
To be estimated variables

Wind direction ☑ Wind speed ☐ Wake recovery factor ☐

Controller synthesis

Model adaptation – wind speed





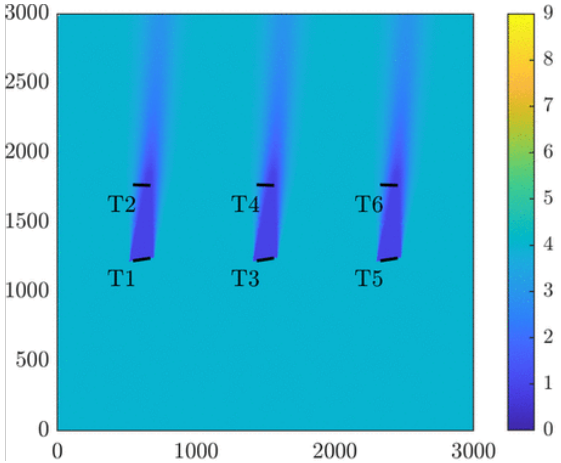
Real-time turbine power measurements (upstream)

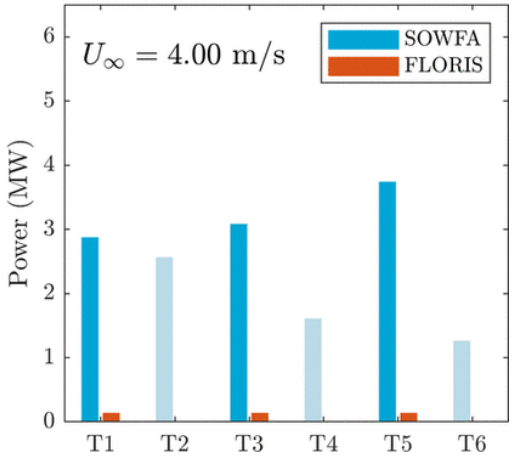
To be estimated variables

Wind direction ☑ Wind speed ☐ Wake recovery factor ☐

Controller synthesis

Model adaptation – wind speed





Real-time turbine power measurements (upstream)

To be estimated variables

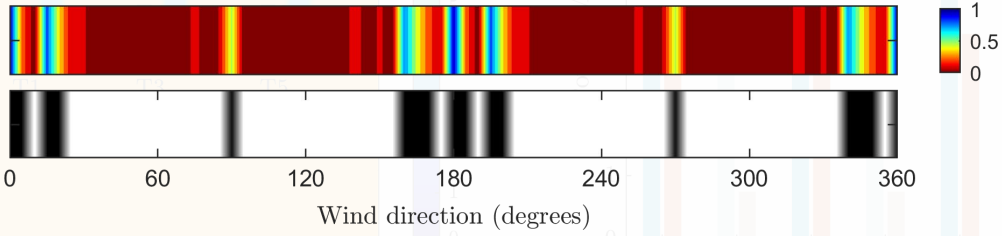
Wind direction ☑ Wind speed ☑ Wake recovery factor ☐

Controller synthesis

Model adaptation – wake recovery factor

"When can we estimate the wake recovery?"

(Doekemeijer et al., 2019, Wind Energy, in review)



To be estimated variables

Wind direction ☑ Wind speed ☑ Wake recovery factor ☐

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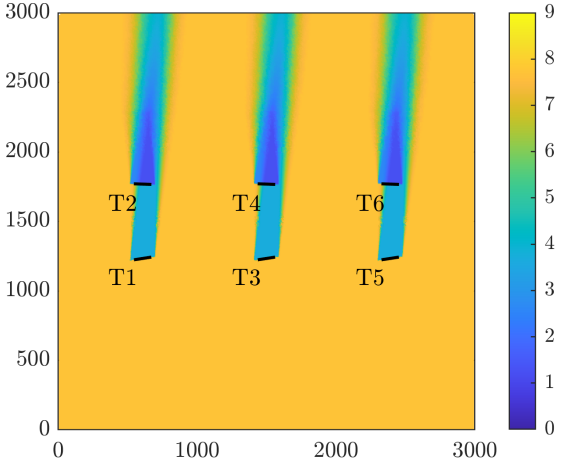
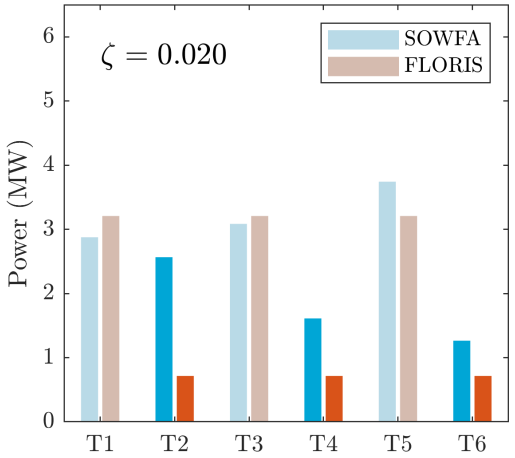
Controller synthesis

Model adaptation – wake recovery factor





Real-time turbine power measurements (downstream)

To be estimated variables

Wind direction ☑ Wind speed ☑ Wake recovery factor ☐

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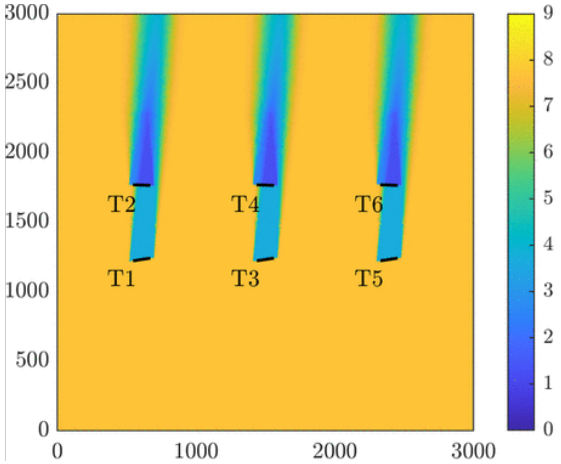
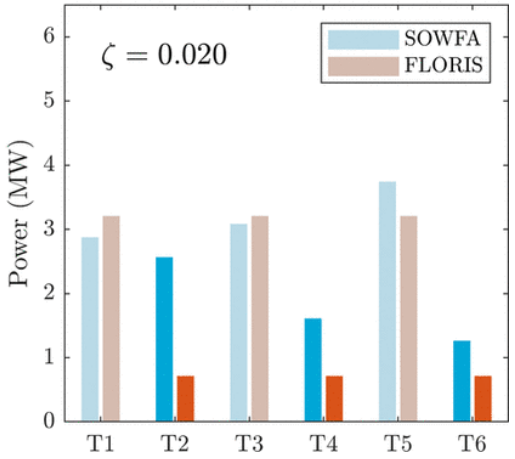
Controller synthesis

Model adaptation – wake recovery factor





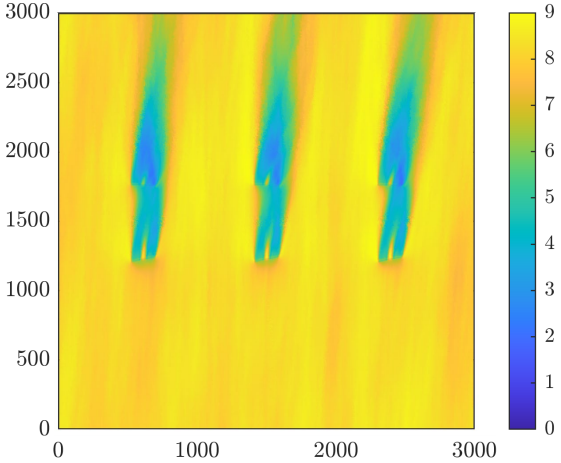
Real-time turbine power measurements (downstream)

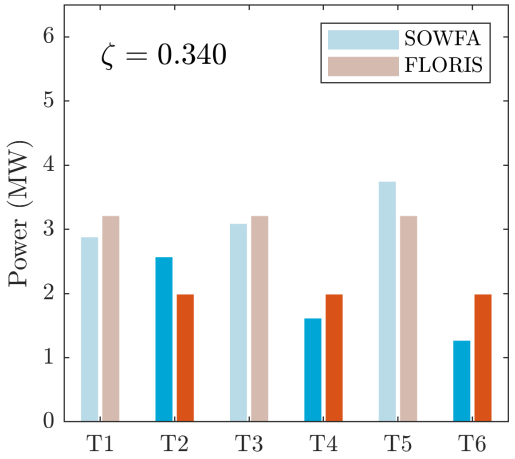
To be estimated variables

Wind direction ☑ Wind speed ☑ Wake recovery factor ☐

Controller synthesis

Model adaptation – wake recovery factor





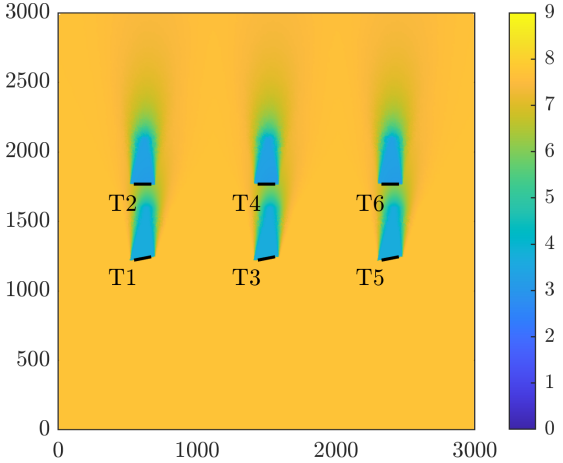
Real-time turbine power measurements (downstream)

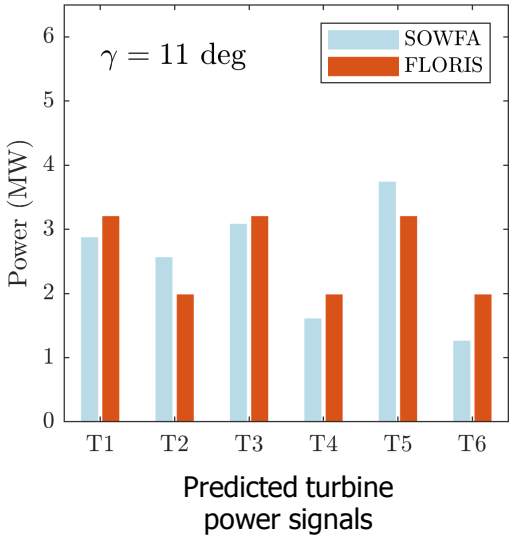
To be estimated variables

Wind direction ☑ Wind speed ☑ Wake recovery factor ☑

Controller synthesis

Model optimization – yaw-based wake steering





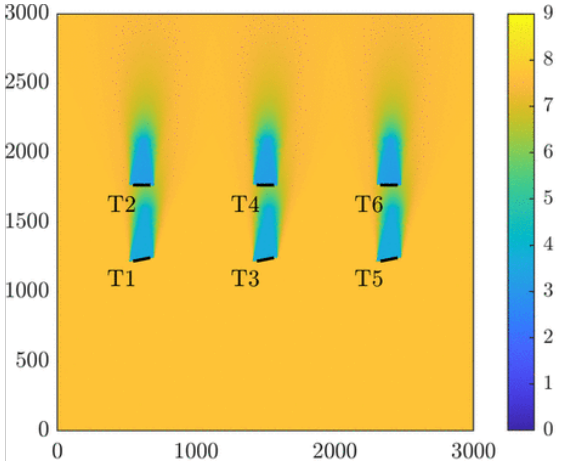
Predicted turbine power signals

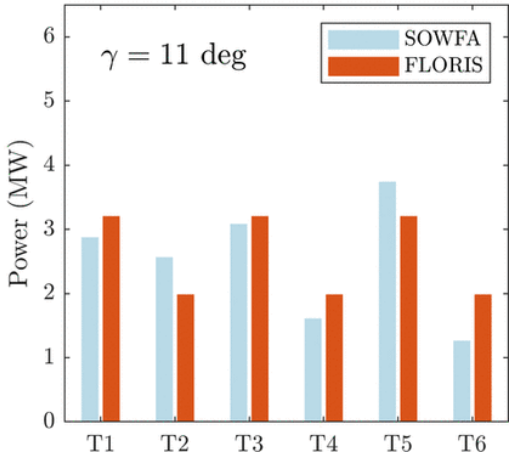
To be optimized variables

Yaw angles of upstream turbines ☐

Controller synthesis

Model optimization – yaw-based wake steering





Predicted turbine power signals

To be optimized variables

Yaw angles of upstream turbines ☑

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Controller synthesis

And a bunch of extra stuff…

- Wind direction **bias** and **drift detection** (turbine side)
- Appropriate **time averaging** for the yaw angles, power signals, and SCADA measurements
- A flag whether a **steady-state** situation has arrived
- A flag whether there is sufficient **observability** over the specified time window
- A **robust optimization** method accounting for wind direction variability
- **Smoothing** between optimal yaw angles to reduce sensitivity to the estimated wind direction, wind speed and turbulence intensity

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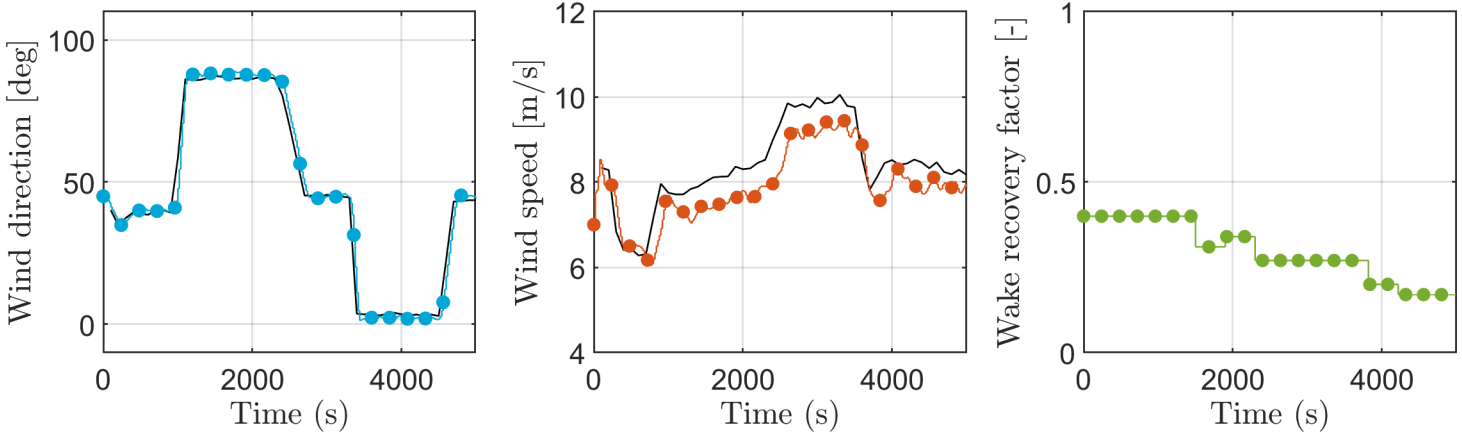
CONTROLLER VALIDATION IN SOWFA

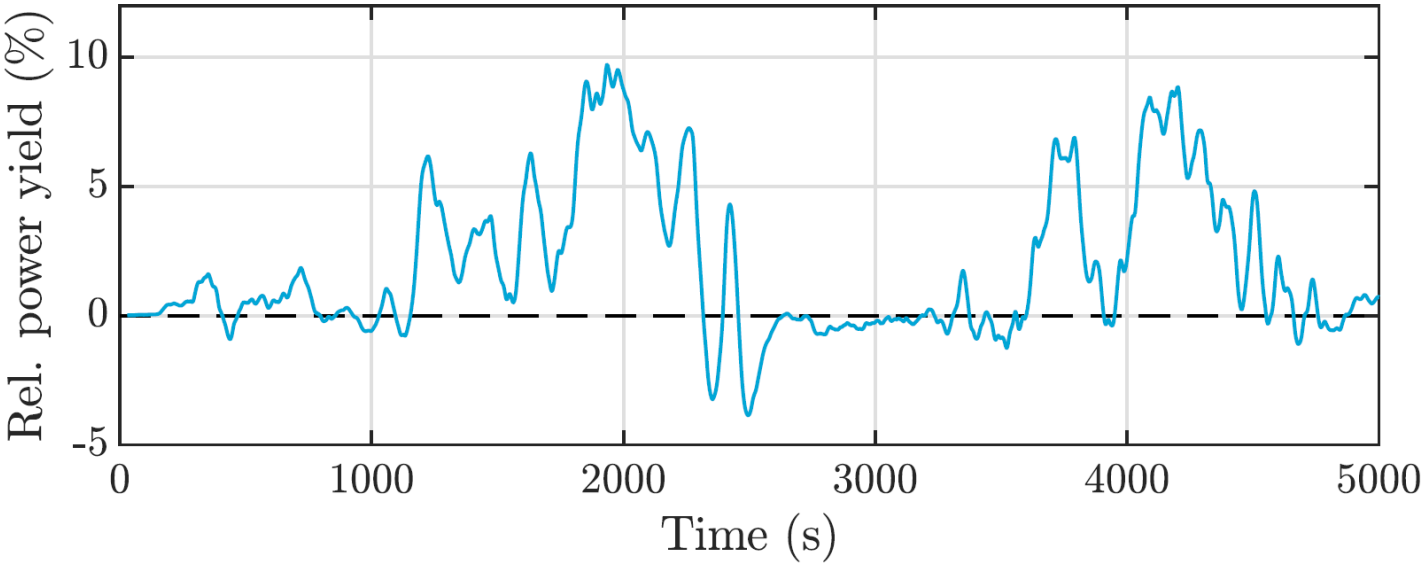
Controller validation

SOWFA – Estimation performance of the controller



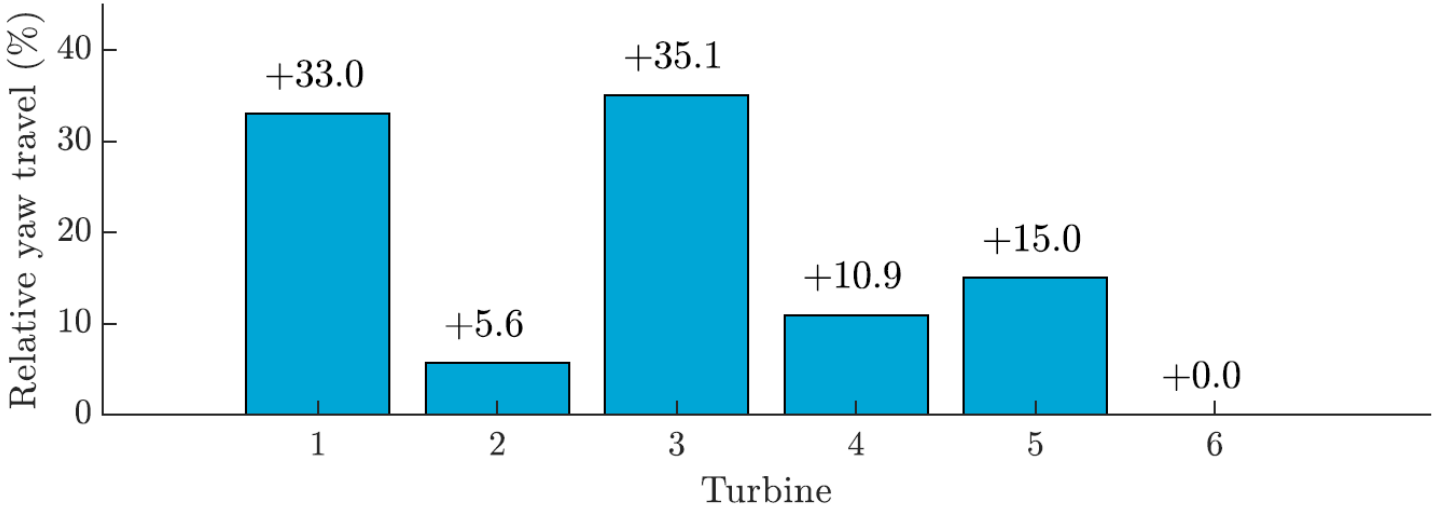
Controller validation

SOWFA – Power extraction compared to baseline operation



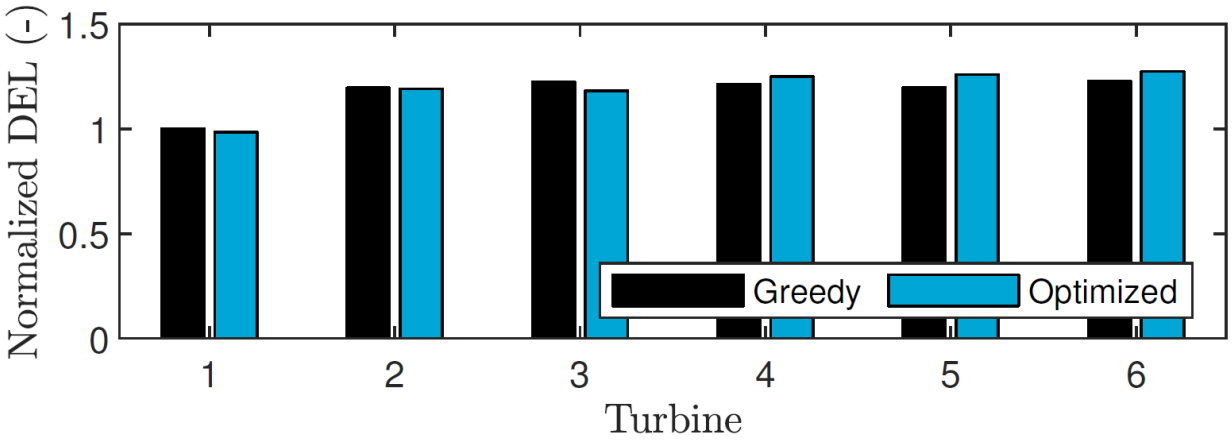
Controller validation

SOWFA – What happens with the yaw actuator duty cycle?



Controller validation

SOWFA – What happens with the blade OOP fatigue loads?



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Conclusion and outlook

What did we do and what's next?

- FLORIS-based wind farm controller **survived stress-test**
- An increase of up to **+10%** in instantaneous **energy yield**
- An increase in **yaw actuator duty cycle** of up to **+35%**

- Reducing the **conservatism** in the control solution
- Experimental **validation**
- (Re)exploring a **dynamic FLORIS**

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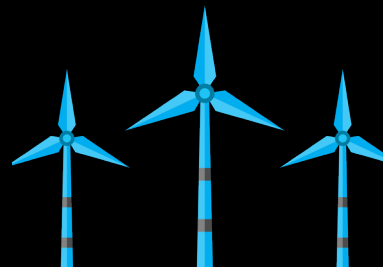
Thank you!

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