CHALMERS
UNIVERSITY OF TECHNOLOGY

An Optimization Platform for High Speed Propellers

FT2016 – Paper 24545

A. Capitao Patrao*, G. Montero Villar*
J. Takachi Tomita**, C. Bringhenti**
R. Avellan***, A. Lundbladh***
T. Grönstedt*

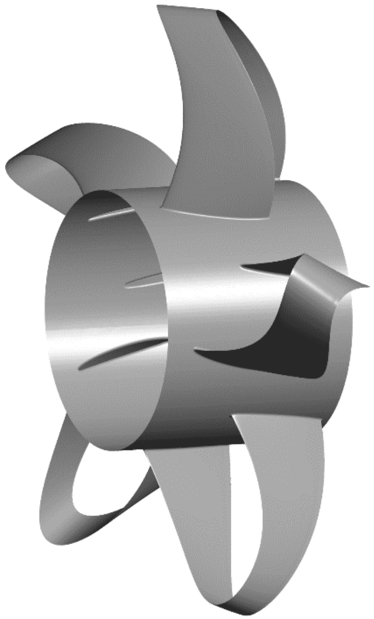
*Chalmers University of Technology
**Instituto Tecnológico de Aeronáutica
***GKN Aerospace

Purpose of the presentation

1. **Present an optimization platform developed for the design of high speed propellers.**

2. **Demonstrate the optimization platform on a unique, novel open rotor propeller: The Boxprop.**

3. **Provide insights from both the development and application of the optimization platform.**



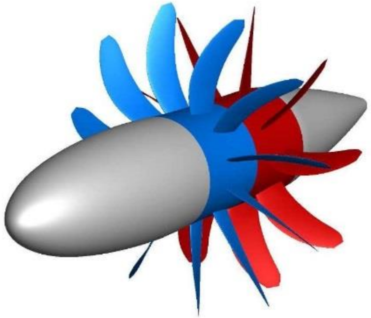
Example of a Boxprop designed for cruise.

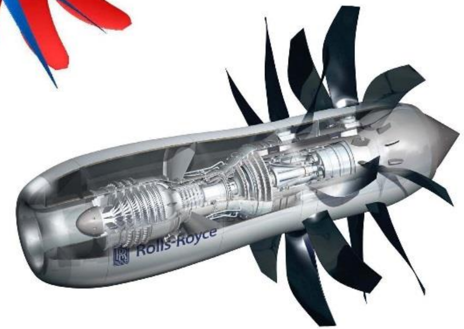
Background

- Open rotors offer potential fuel savings in the order of 20-35% and are currently being researched in the US and in Europe.

- The highly three-dimensional shape of modern propeller blades is challenging to model with classical propeller models (Blade Element Model, lifting-line).

- More sophisticated optimization methods coupled with CFD are desired.





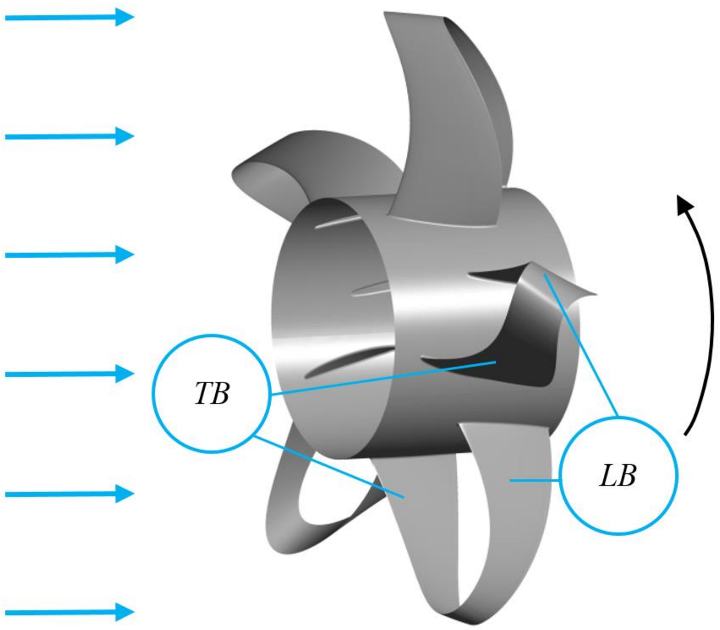
The Boxprop

- New, unique, and radically different propeller shape. The **Boxprop consists of** pair-wise tip joined blades.

- The main hypotheses are:
  - Surpressed tip vortex – lower interaction noise
  - **Higher structural integrity**
  - **Forward-swept blades**

- **Classical propeller designs are** not applicable.

More sophisticated design & optimization methods are required.



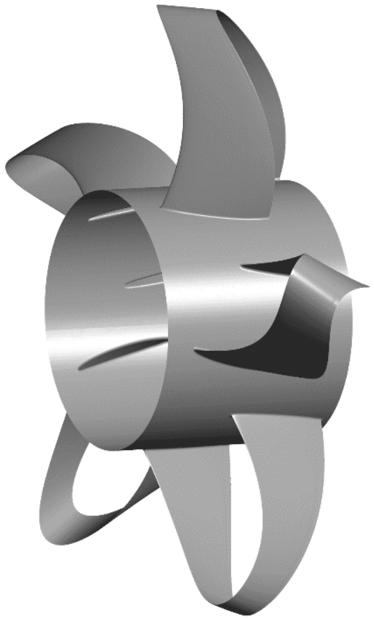
Leading Blade (LB)
Trailing Blade (TB)

Purpose of the presentation

1. **Present an optimization platform developed for the design of high speed propellers.**

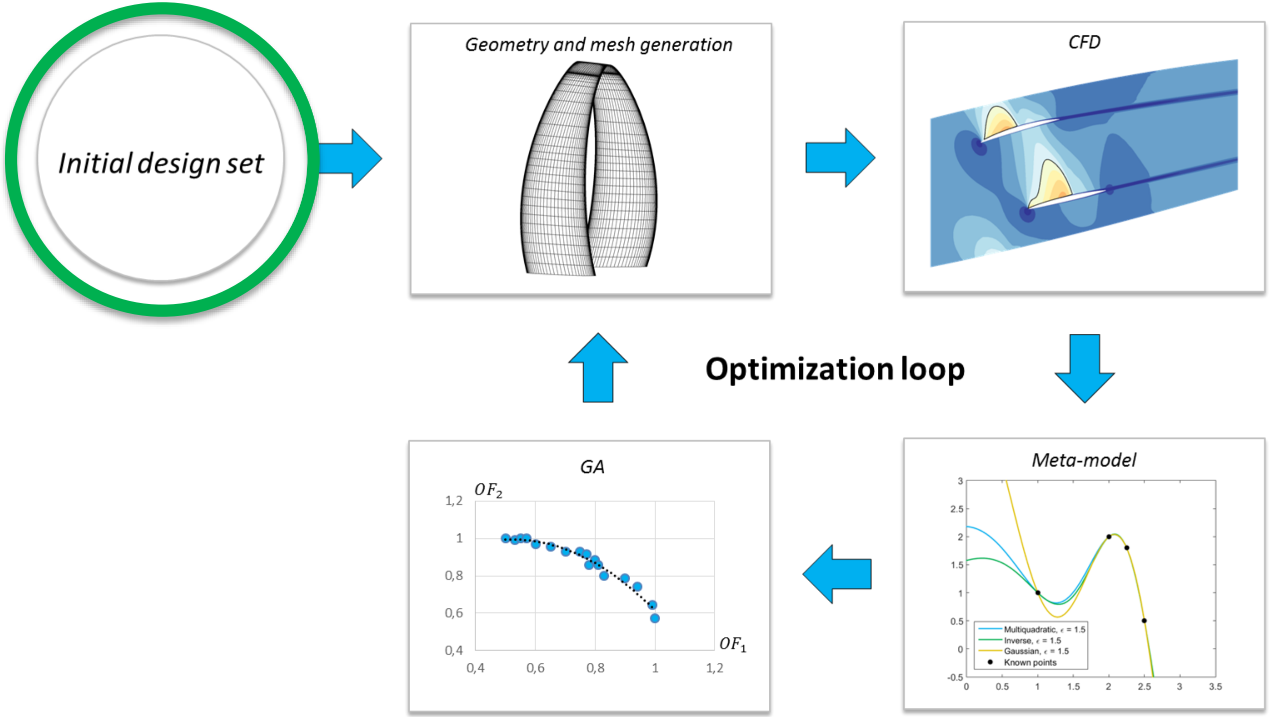
2. **Demonstrate the optimization platform on a unique, novel open rotor propeller:
The Boxprop.**

3. **Provide insights from both the development and application of the optimization platform.**

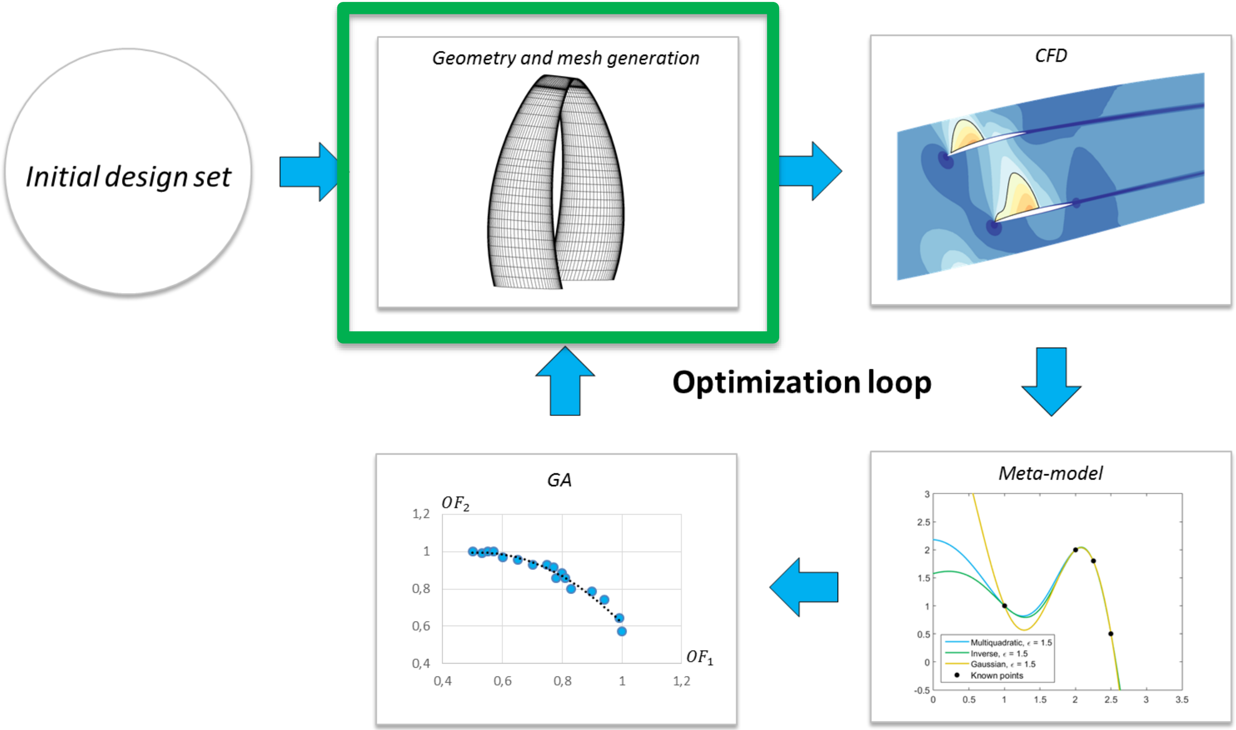


Example of a Boxprop designed for cruise.

Optimization platform



Optimization platform



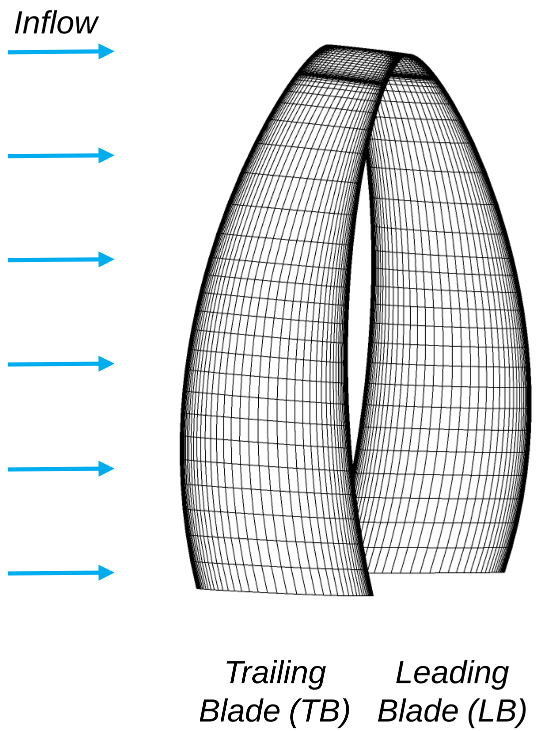
Geometry generation

Blade parametrization

The blade parametrization has two main objectives:

1. **Enable individual adjustment of sectional blade angles and profile camber.**

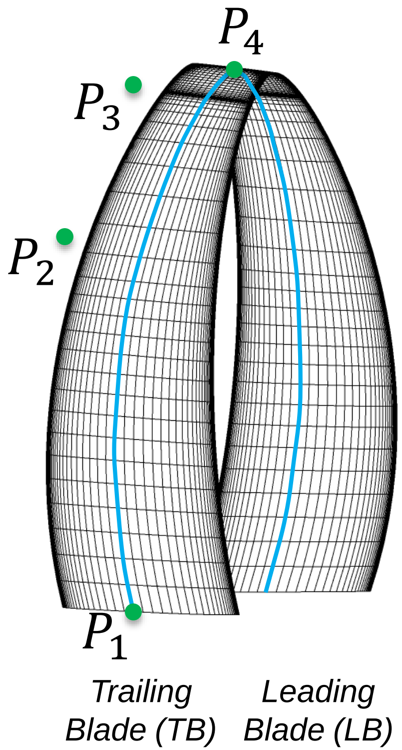
2. **Enable different spacings between the blade halves. Previous work has discovered that a low pressure area (blade interference) forms in the region between the LB and TB. The blade interference heavily influences the ability to load the blade closer to the tip.**



Geometry generation

Blade parametrization

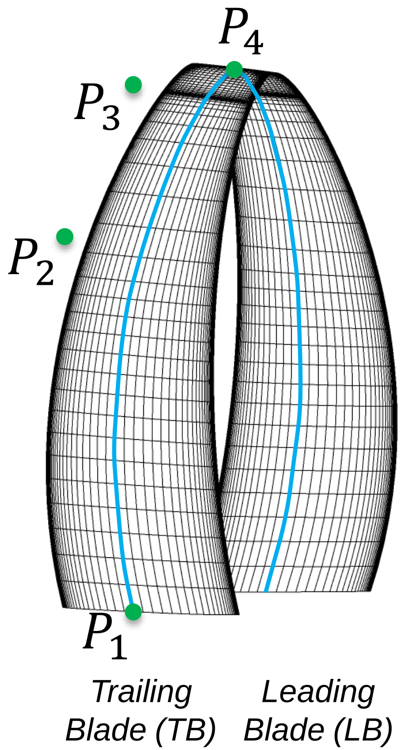
- The blade is constructed by stacking NACA 16 profiles along a stacking line (–).
- The stacking line is defined with two cubic Beziér curves, one for the LB and one for the TB.
  - The Beziér curve is defined using control points $P_1, \dots, P_4$ (●).
- Chord and thickness are quadratic functions with respect to radius.
- Camber and angle-of-attack are defined with quartic Beziér curves as functions of radius.



Geometry generation

Blade parametrization

- The complete parametrization encompasses 33 design variables.
  - The demonstration of the optimization platform will use a reduced set of 17 variabes.
- Chord and camber are kept fixed during the optimization.
- 7 variables control the stacking line shape.
- 10 variables control the angle-of-attack distribution.

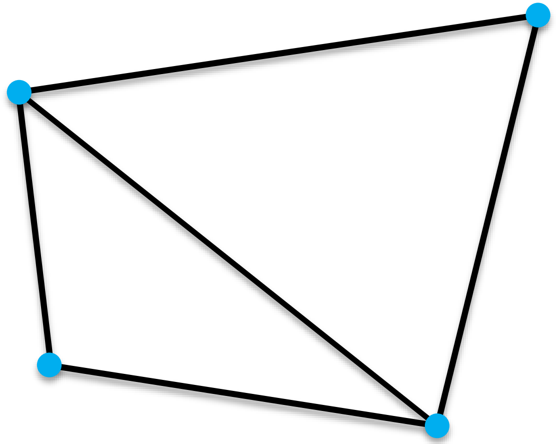


Geometry generation

Geometric representation

- All geometry is created using in-house developed scripts using the Python programming language.

- The geometry output is set as STL files, a common CAD file format for rapid prototyping.
  - Triangular patches are used to describe the surface.
  - Pro's & con's:
    + STL files can be created with open source Python modules.
    + Fast
    + Robust
    - Discontinuous slope and
    - Non-existing curvature.



STL triangular patch representation of a quadrilateral.

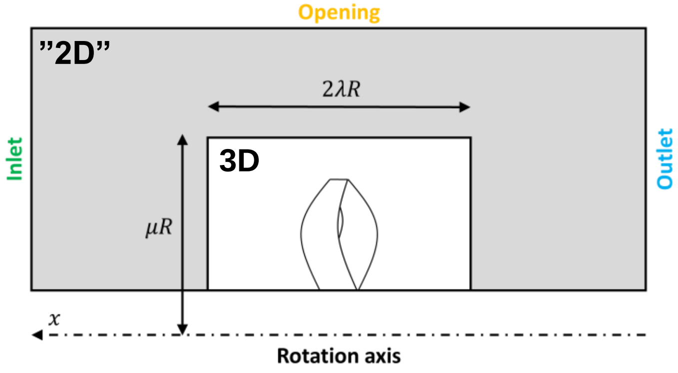
Geometry generation

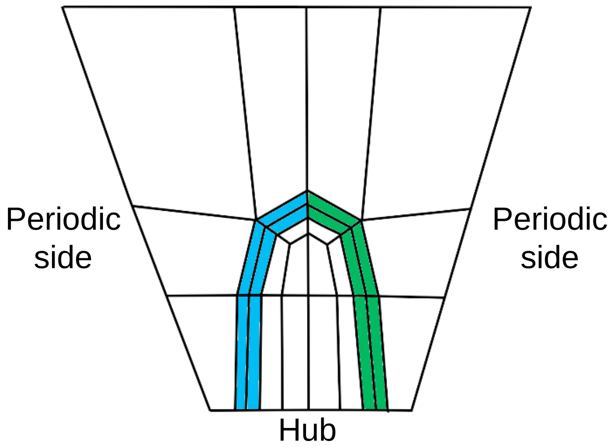
Computational domain and mesh

- **Computational domain consists of:**
  - **An inner 3D domain containing one Boxprop blade.**
  - **An outer quasi-2D domain which extends far away from the blade.**

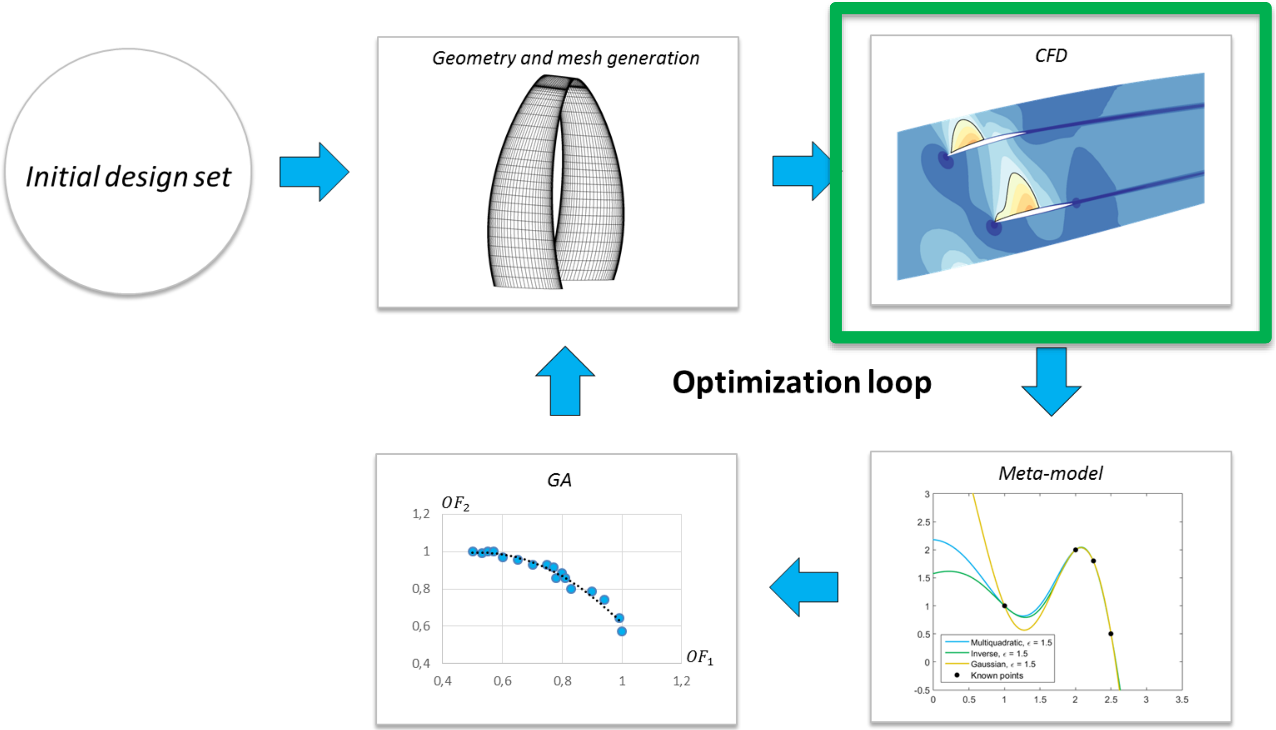
- **Hexahedral mesh**
  - **Complex blocking structure.**
  - **Requires a large amount of support geometry in order to obtain good mesh quality.**
  - **Meshed using ICEM CFD. Meshings scripts generated by in-house Python script.**
  - **Average first node height adheres to $y^+_{ave} = 1$.**

- **Domain and mesh study lead to a mesh size of 1.15 million cells, a compromise between computational cost and fidelity.**





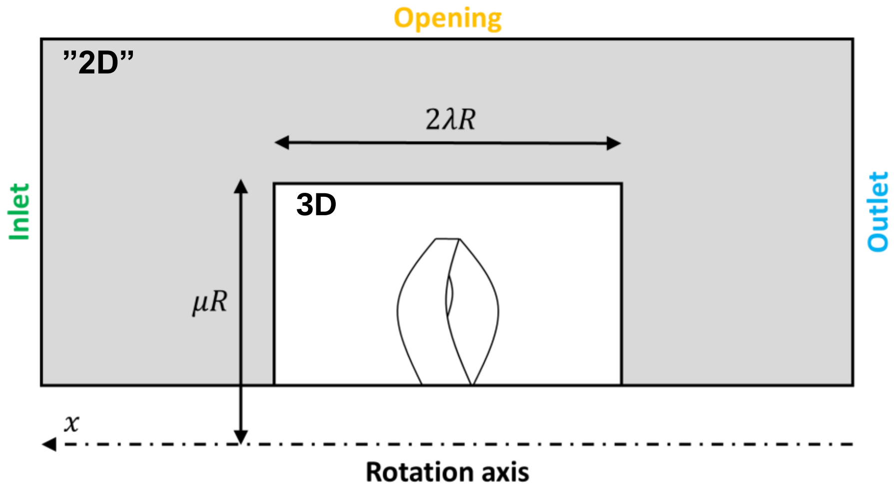
Optimization platform



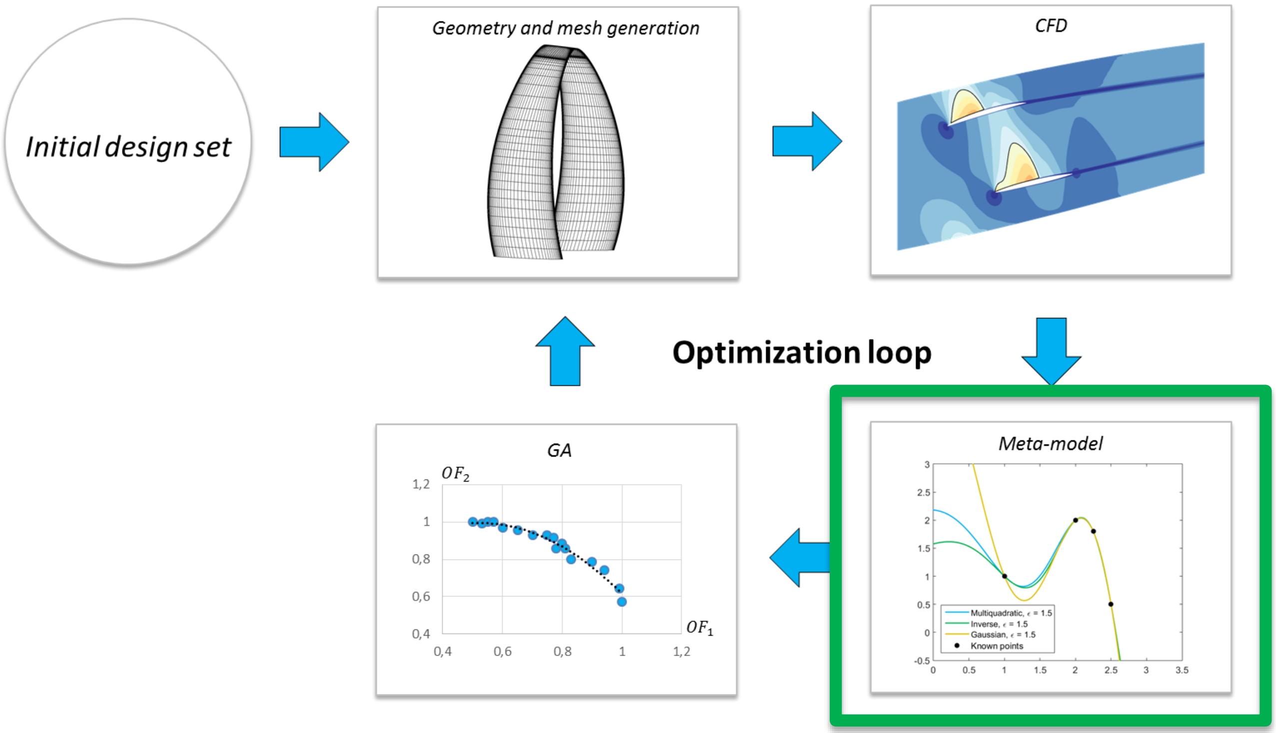
CFD

Computational setup

- ANSYS CFX
- Favre-averaged N.S. equations
- $k - \omega$ SST turbulence model
  - Low-Re near wall formulation.
- Inner rotating domain (3D) and outer stationary domain (”2D”).
- Inner and outer domains connected through Frozen Rotor interfaces.



Optimization platform



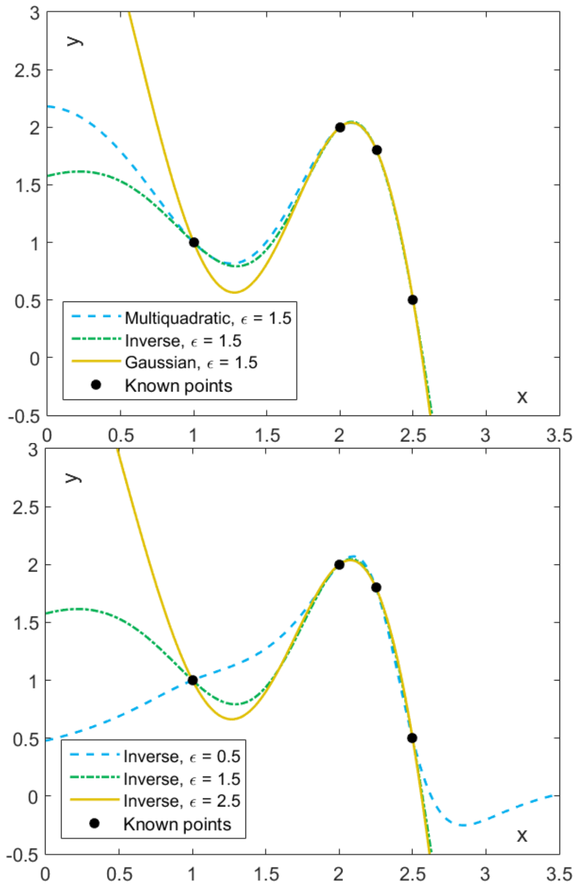
Meta-model

Radial Basis Functions (RBF)

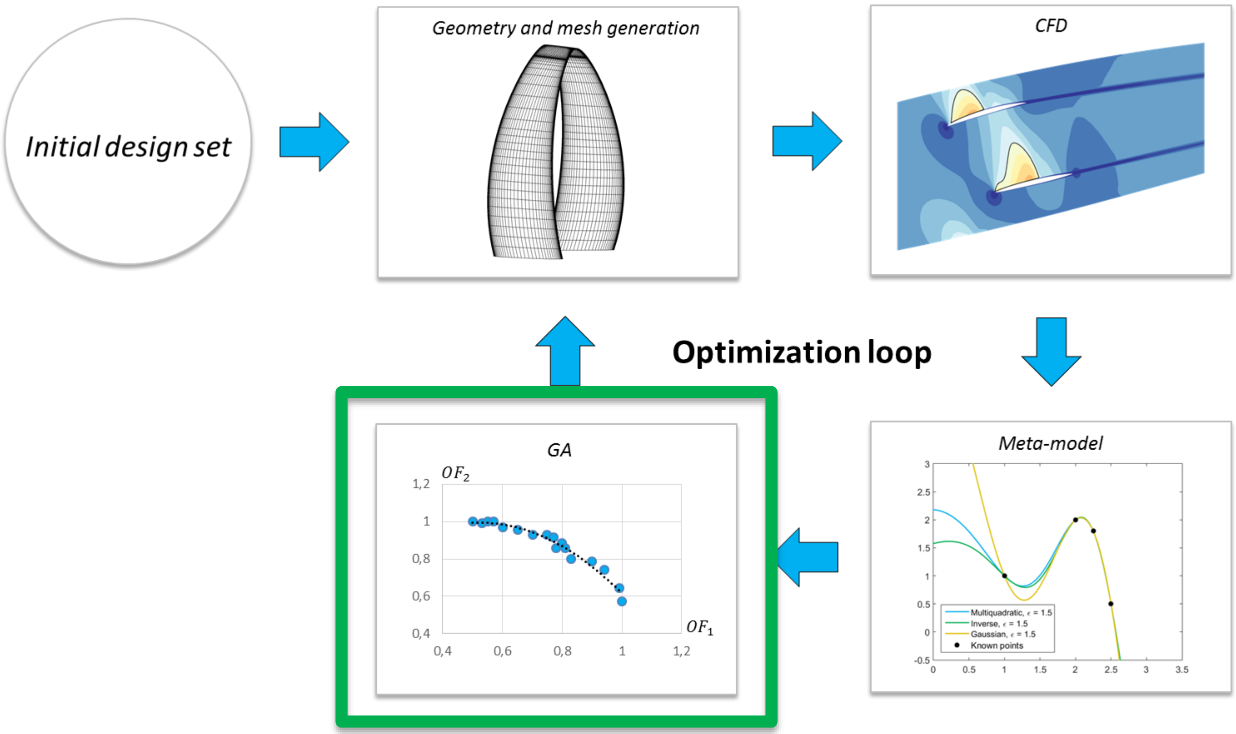
- Radial Basis Functions (RBF) are used for the interpolation of objective function values.

- RBF’s always intersect known data points, but its behaviour outside of the data points can vary considerably depending on:
  - Choice of basis
  - Value of tuning parameter (ϵ).

- The best combination of basis and tuning parameter has to be chosen.

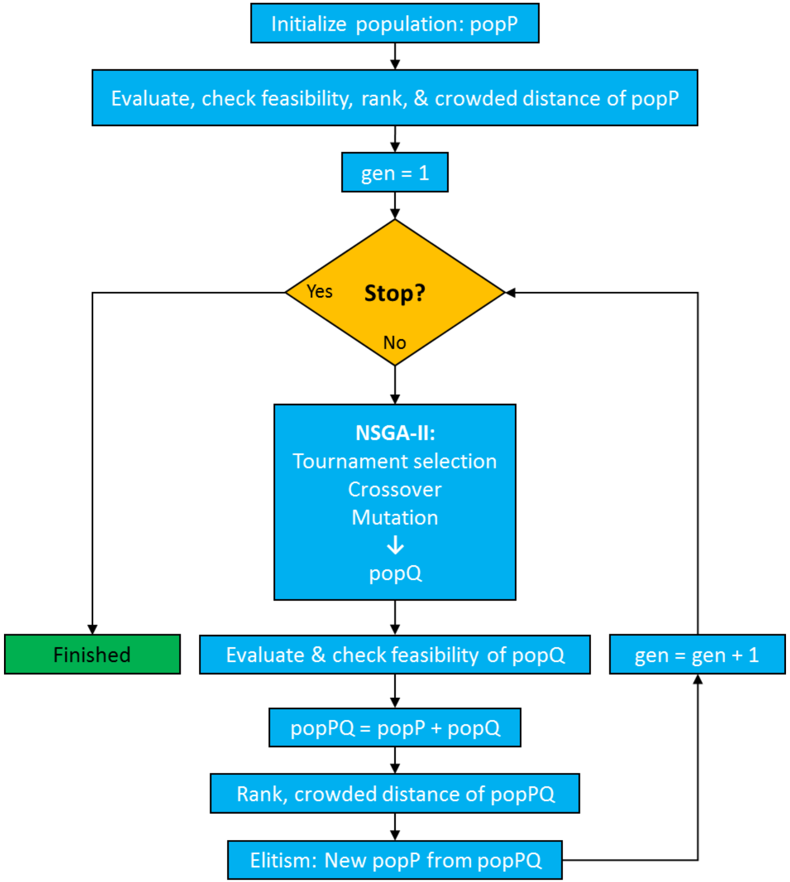


Optimization platform



Genetic Algorithm

- Based on the NSGA-II genetic algorithm.
- Widely used
- Multi-objective
- Features:
  - Ranking
  - Tournament selection
  - Crossover
  - Mutation
  - Elitism

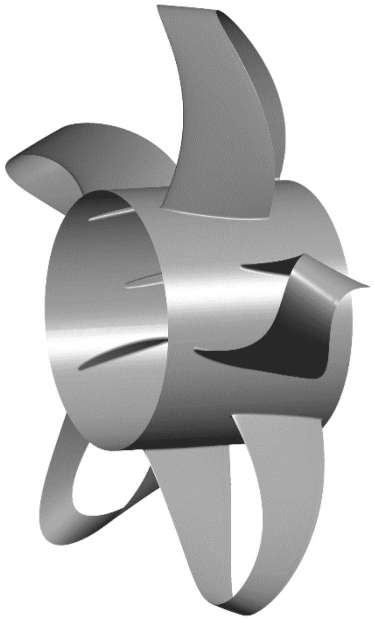


Purpose of the presentation

1. Present an optimization platform developed for the design of high speed propellers.

2. Demonstrate the optimization platform on a unique, novel open rotor propeller:
The Boxprop.

3. Provide insights from both the development and application of the optimization platform.



Example of a Boxprop designed for cruise.

Demonstration of the optimization platform

Optimization of the Boxprop

- The optimization platform was unleashed on the Boxprop with the following objectives:
  - Maximize thrust.
  - Maximize efficiency.

- Operating point was chosen as cruise at Mach 0.75 and 35 000 ft in altitude.

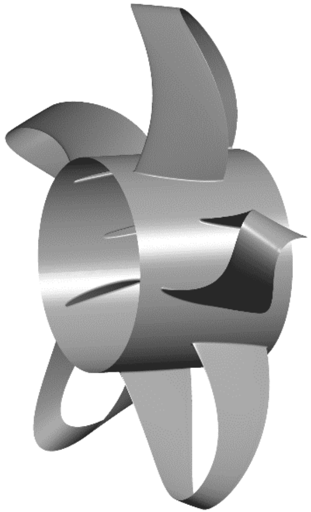
- A previously published Boxprop (GPX701) shares the same properties except for the diameter and rotational velocity.

$D\ [m]$	4.267
HTR	0.4
J	3.56
$n\ [1/s]$	14.64
M_∞	0.75
$H\ [m]$	10 668

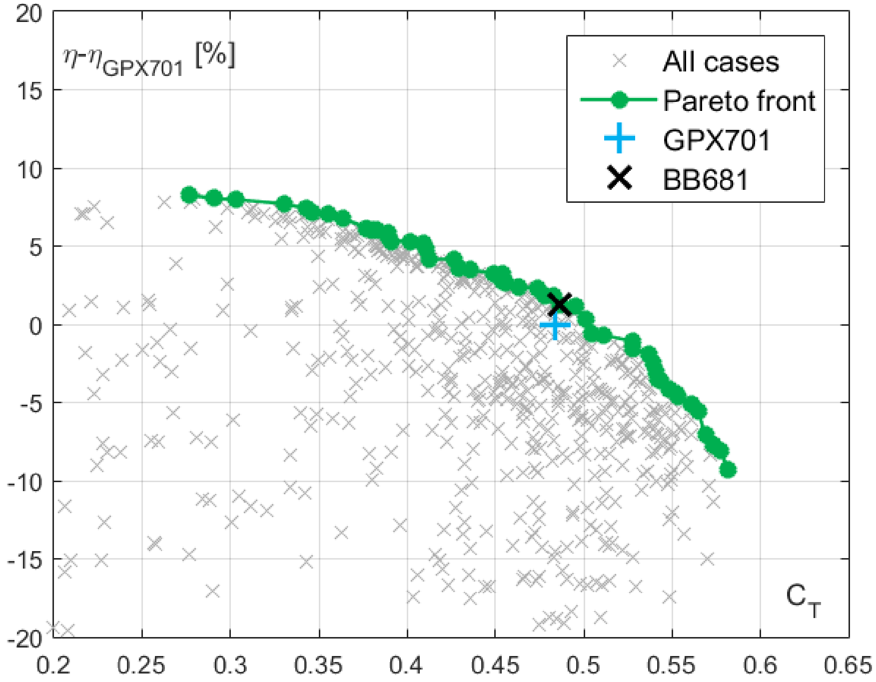
Demonstration of the optimization platform

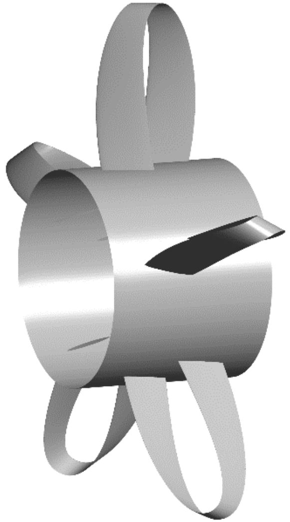
Results: Pareto-front

1.3% improvement in efficiency



GPX701



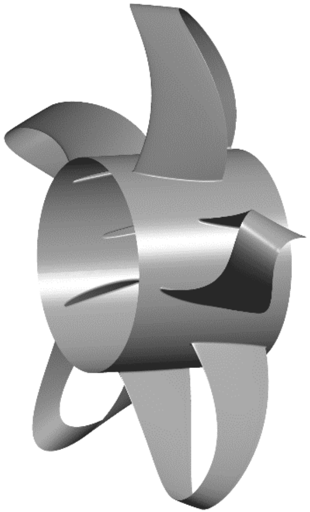


BB681

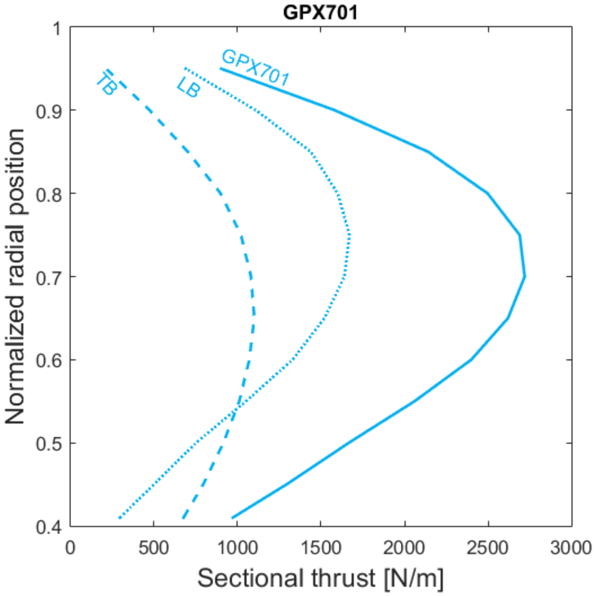
Demonstration of the optimization platform

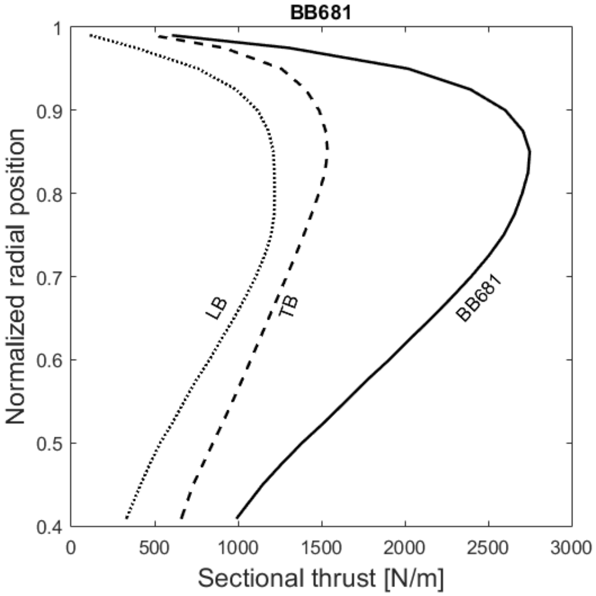
Results: Sectional thrust distributions

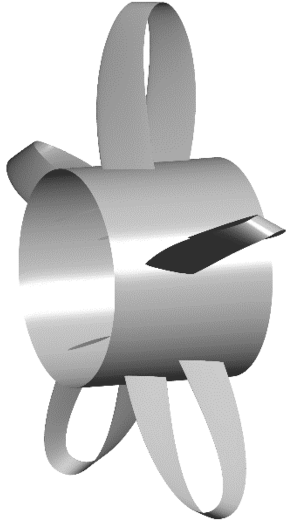
1.3% improvement in efficiency



GPX701

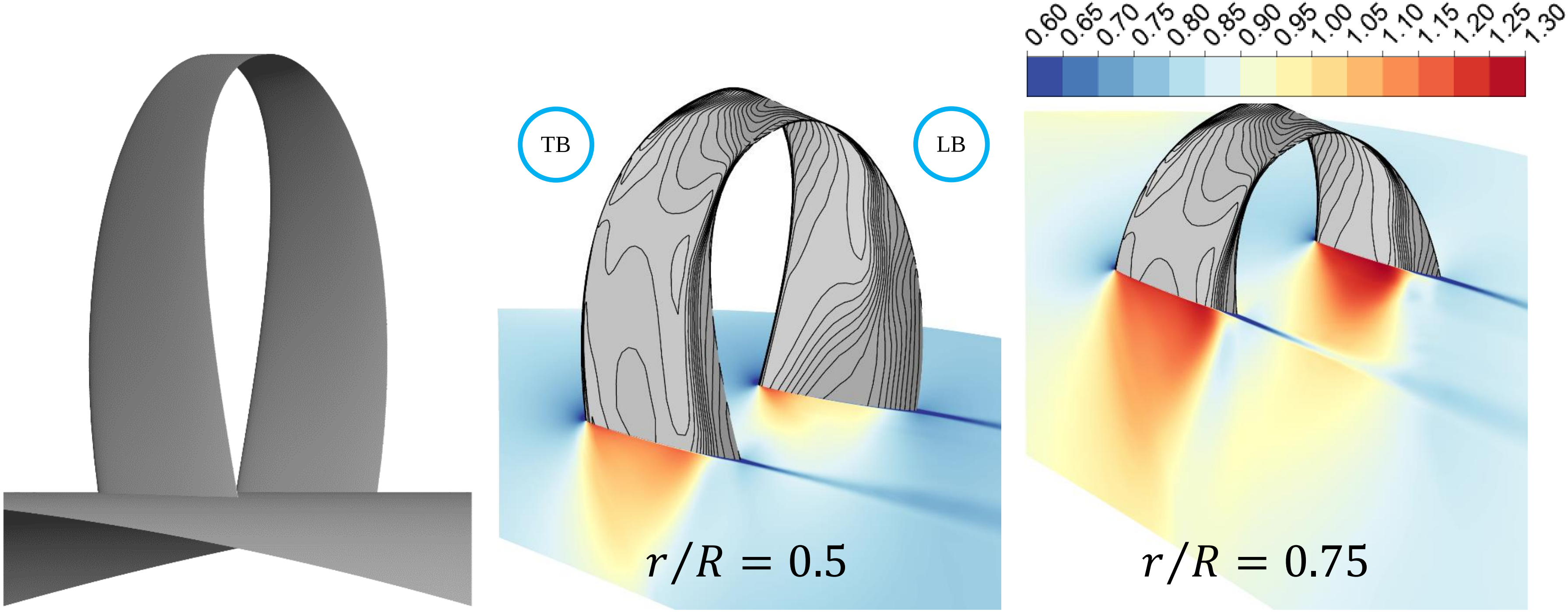




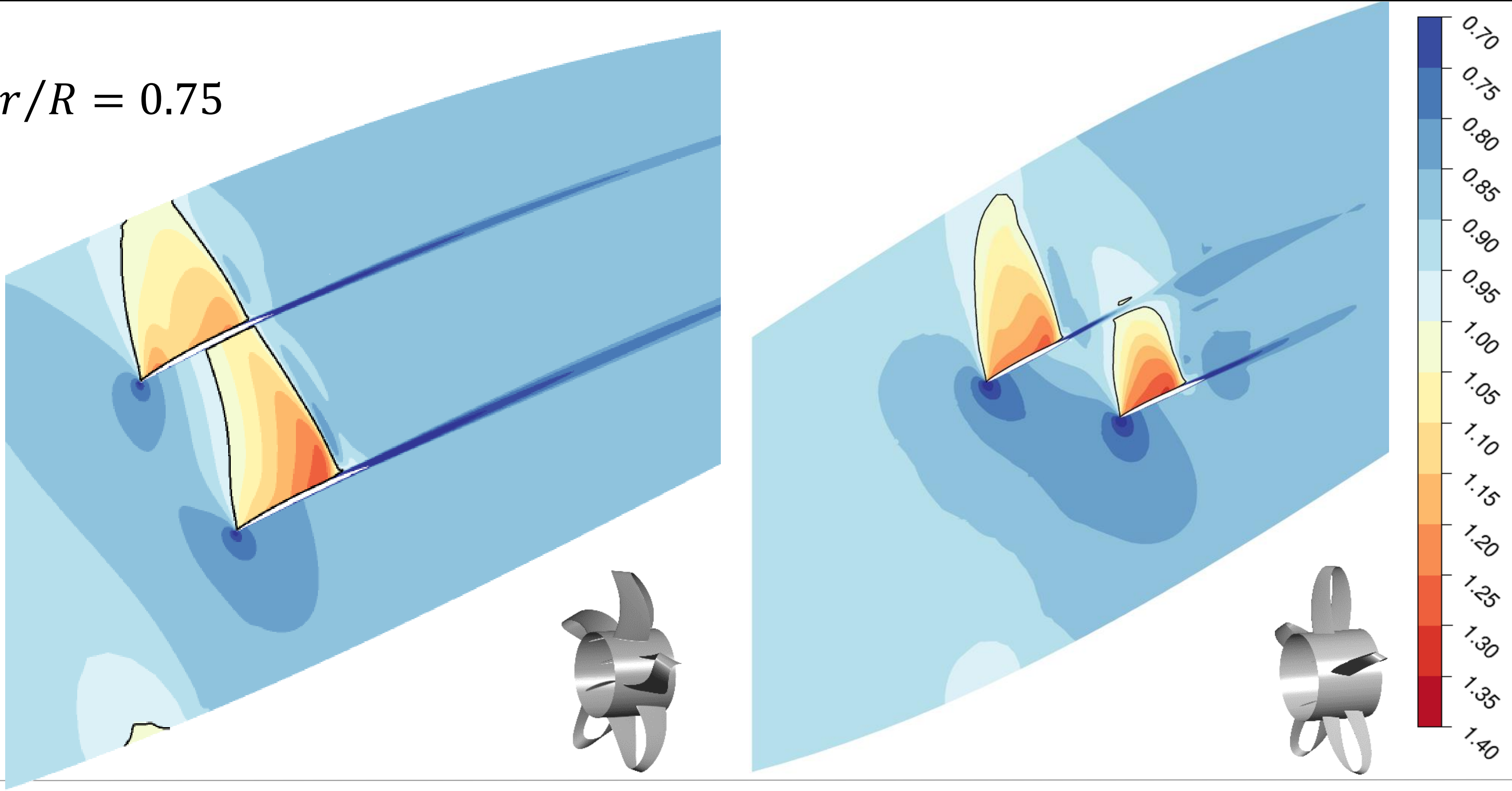


BB681

Demonstration of the optimization platform



$r/R = 0.75$

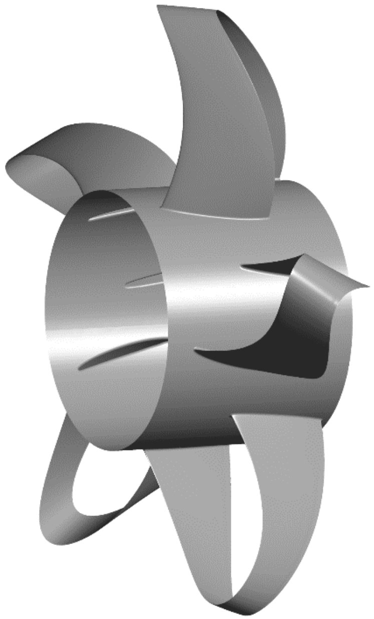


Purpose of the presentation

1. Present an optimization platform developed for the design of high speed propellers.

2. Demonstrate the optimization platform on a unique, novel open rotor propeller:
   The Boxprop.

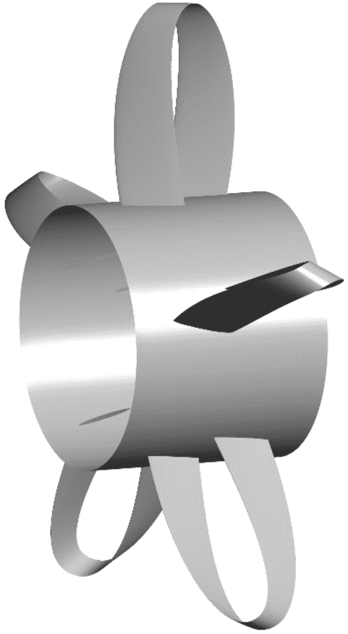
3. **Provide insights from both the development and application of the optimization platform.**



Example of a Boxprop designed for cruise.

Insights and lessons learned

- The GA has been shown to be effective in finding optimal Boxprop designs.
  - The GA has also been tested on compressors and wind tunnel components.
- Blade parametrization sucessful.
  - Allowed thrust to be produced closer to the tip.
  - Blade interference has been decreased.
- The reduced optimization of the Boxprop has yielded a modest efficiency improvement of 1.3% over previous Boxprop designs.
- The optimization framework is readily extendable to other optimization problems in the area of turbomachinery.



Future Swedish-Brazilian collaborative use

- In turbomachinery design small changes in geometry can radically influence flow behaviour.
  - This sensitivity requires considerable time and attention from the designer.
  - Optimization techniques are an essential tool for the refinement of turbomachinery design, reducing total design time and cost.
- The flexibility of the platform easily lends itself to a number of applications in the area of turbomachinery.
- Areas of collaboration that have a good foundation at both Chalmers University of Technology and ITA are fans, compressors, axial & radial turbines, pumps, hydraulic turbines, etc.

CHALMERS UNIVERSITY OF TECHNOLOGY

GKN AEROSPACE

VINNOVA

FÖRSVARSMAKTEN

FMV

C3SE Chalmers Centre for Computational Science and Engineering

Chalmers University of Technology — Göteborg University

AVANCEZ
1829
CHALMERS
UNIVERSITY OF TECHNOLOGY