AERODYNAMICS IN F1 AND FORMULA STUDENT

JONAS PANGERL

AERODYNAMICIST

WILLIAMS RACING

CONTENTS

ABOUT ME

- University: UAS Esslingen
- Formula Student (Sub-team Aerodynamics and CFD) from 2017-2021
- Master Thesis at Williams Racing about high fidelity CFD simulations
- Engineering Design Judge at FS East 2022
- Aerodynamicist at Williams Racing

FUNDAMENTALS

AERODYNAMIC COEFFICIENTS

Why coefficients?

- Normalization of variables
- Compare different driving speeds
- Compare different dimensions of the car (WT and full size)

Lift: C_L

Drag: C_D

Static pressure: C_p

Total pressure (energy): total $C_p \rightarrow C_pT$

AERODYNAMIC TESTING RESTRICTIONS IN F1

- Defined in the FIA Formula 1 Sporting Regulations
- Goal: limit development time, balance performance between teams, limit costs
- CFD
  - RATG: restricted aerodynamic test geometry → limits number of different geometries to be simulated
  - MAUh: Mega Allocation Unit hours → limits solving effort over all RATGs

Requires high efficient simulations

- Wind tunnel
  - Runs → limits number of wind tunnel runs
  - Wind On Time → limits time where tunnel airspeed is above 5 m/s
  - Occupancy → limits working time in/around the tunnel
- Track
  - Testing to take place only in official Free Practice sessions

Championship Classification	P	1	2	3	4	5	6	7	8	9	10+ or New Team
Value of C	%	70	75	80	85	90	95	100	105	110	115

FIA 2022 Formula 1 Sporting Regulations

FORMULA 1 AERODYNAMIC DEVELOPMENT

DEVELOPMENT PATH

- Regulations
- Idea generation
- CFD development
- Wind tunnel testing
- Track testing

Aero testing restrictions (ATR)

IDEA GENERATION

- Flow field targets
- Onset CpT and wake management
- Yaw and ride height characteristics
- Cooling performance
- Load distribution

→ Geometry comes from aero perspective

CFD

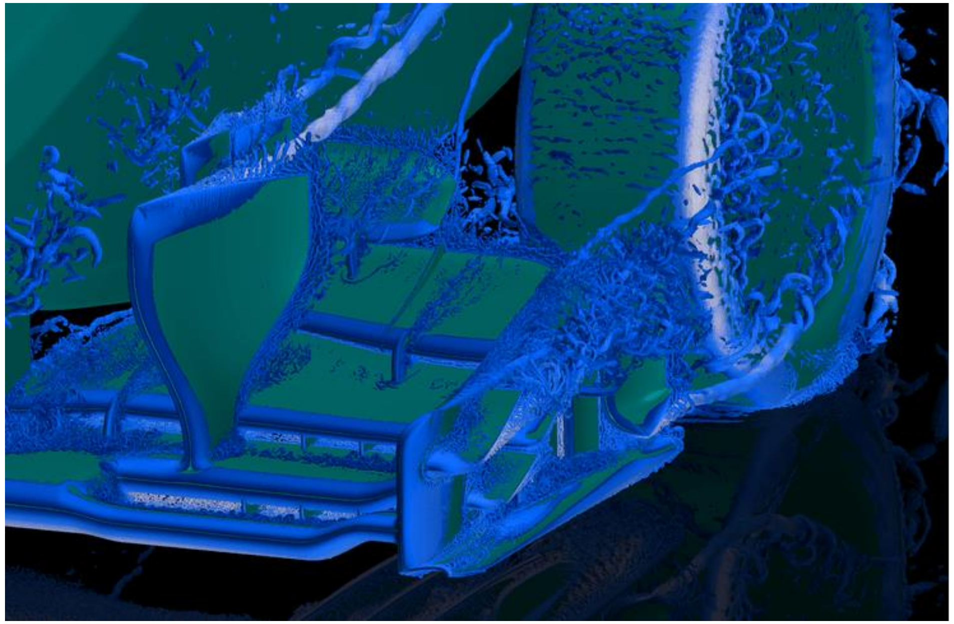
- CFD is first design tool
- Allows a deep insight in flow field
- Quick turnaround times
- Balancing between accuracy and efficiency (RANS, DES, …)
- Automated investigation available (Adjoint solver, …)
- Run limited number of conditions

→ Be aware of limitations!

TRANSIENT CFD

- Resolves transient effects
- More accurate but computationally expensive

→ Understand where it is needed and how you can use the data



Wall resolved Large-Eddy-Simulation

WIND TUNNEL TESTING

- Physical aerodynamics testing at scale
- External aerodynamics modelling
- Regulated by ATR
- Develop a stable and predictable car
- Fewer options for detailed analysis
- Compromised cornering simulation compared to CFD and track

WIND TUNNEL TESTING

Off-surface flow field data:

- Particle Image Velocitimetry (PIV)
- Rakes
- Kiel probes

WIND TUNNEL TESTING

Off-surface flow field data:

- Particle Image Velocitimetry (PIV)
- Rakes
- Kiel probes

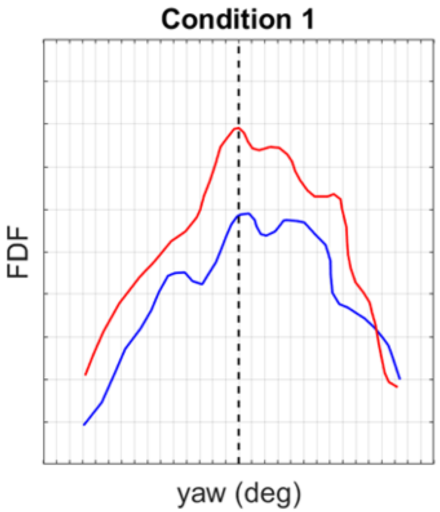
On-surface flow field data:

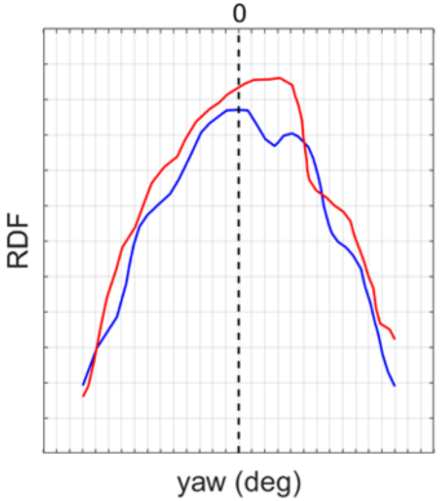
- Pressure tappings
- Flow Viz
- Wool Tufts

WIND TUNNEL TESTING

Develop a stable and predictable car:

- Smooth sweeps, remove peaks
- Performance where you want to set-up the car (high rake vs low rake)
- Understand where structures break down, flow separates, …





BASELINE
OPTION

WIND TUNNEL TESTING

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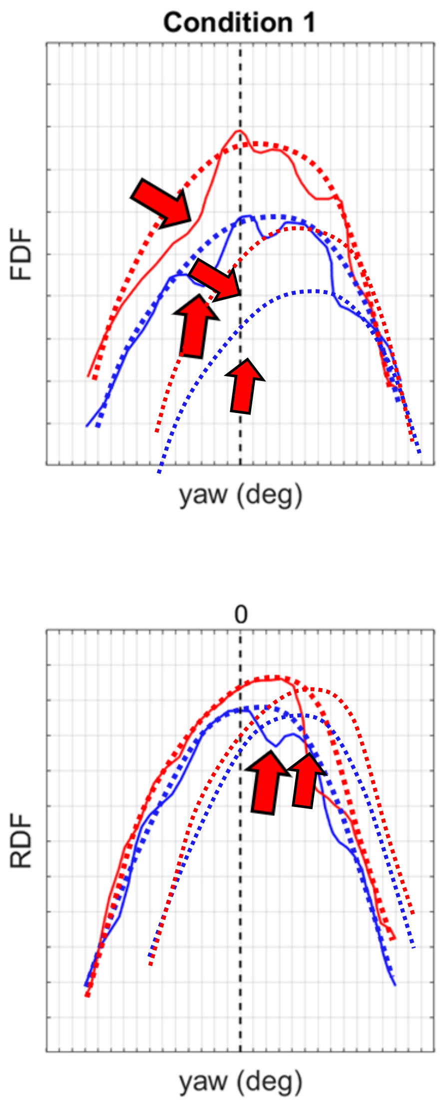


BASELINE
OPTION

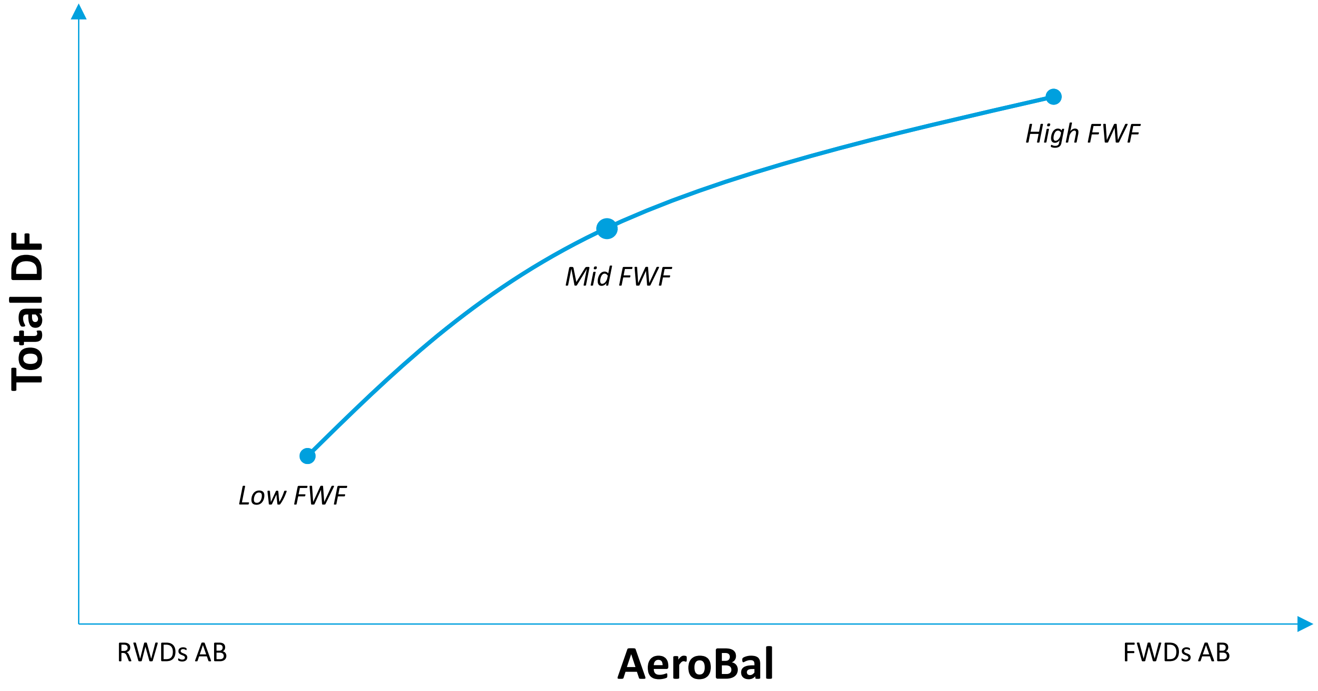
TRACK TESTING

- Real world testing
- Driver feedback
- Unstable and noisy conditions
- Less data
- Limited time

UNDERSTANDING DEVELOPMENT METRICS

FRONT WING POLAR

- Front Wing Flap (FWF) to adjust aerodynamic balance between front and rear axle

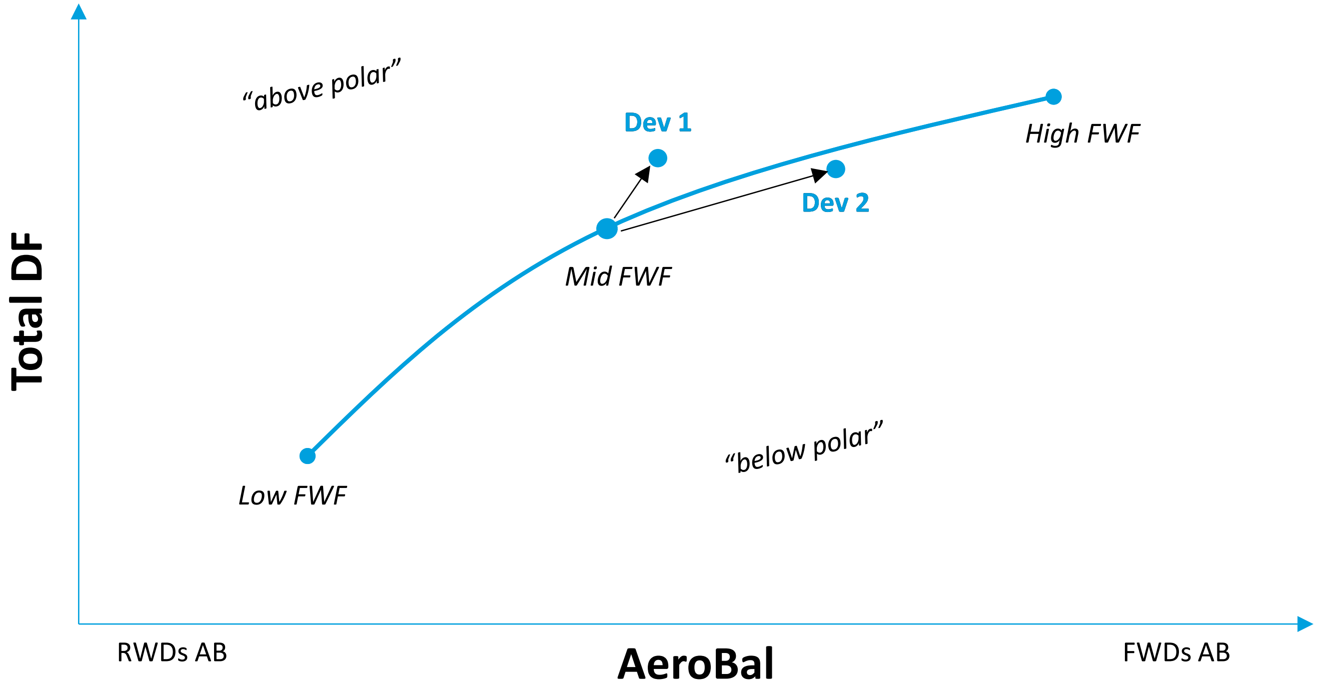


FRONT WING POLAR

- Front Wing Flap (FWF) to adjust aerodynamic balance between front and rear axle
- Development options need to be „*above*“ polar to improve overall performance

→ Otherwise we could just crank up the FWF to get the same aero balance and also more downforce

→ Consider new behaviour over FWF angles



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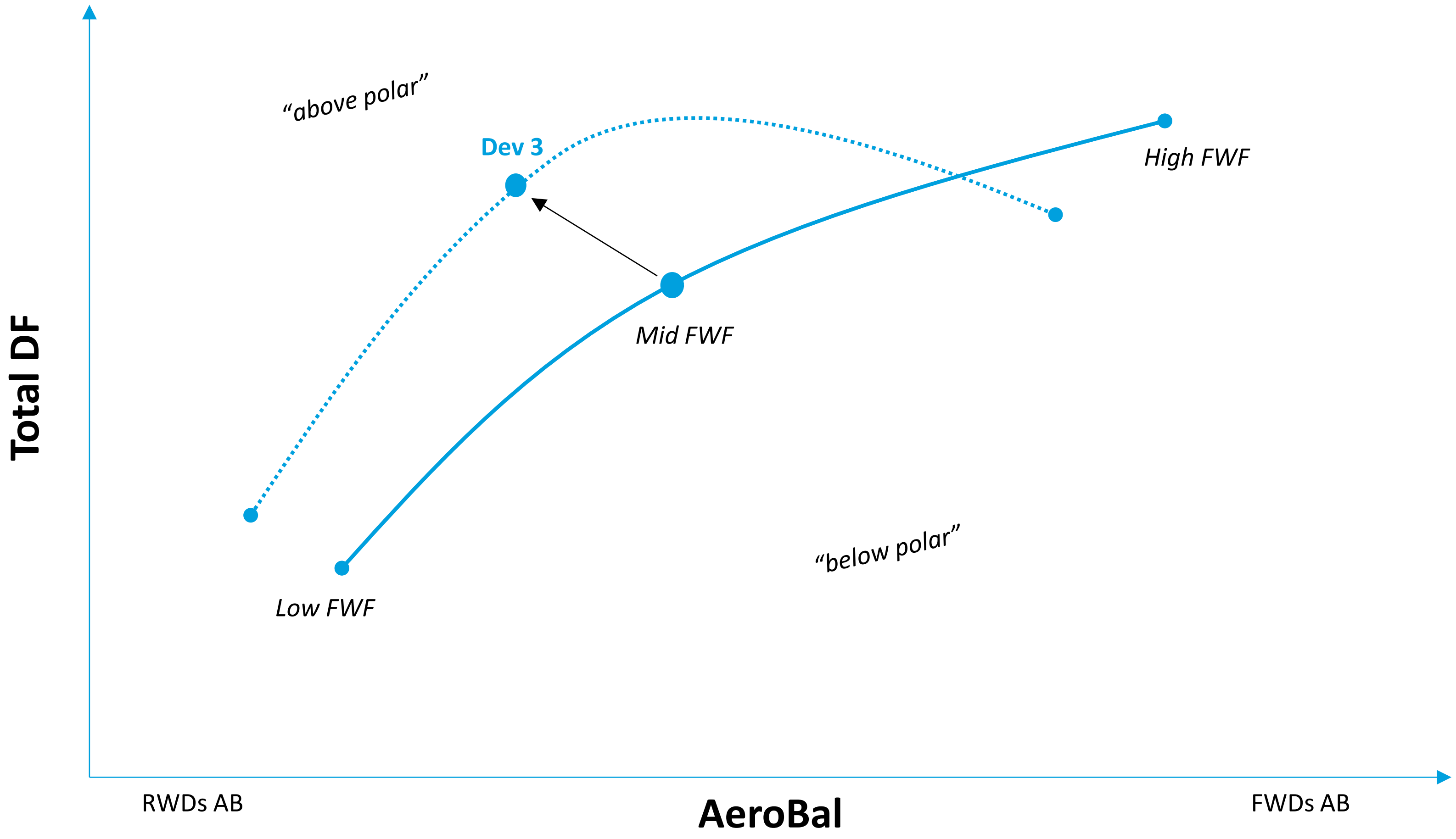
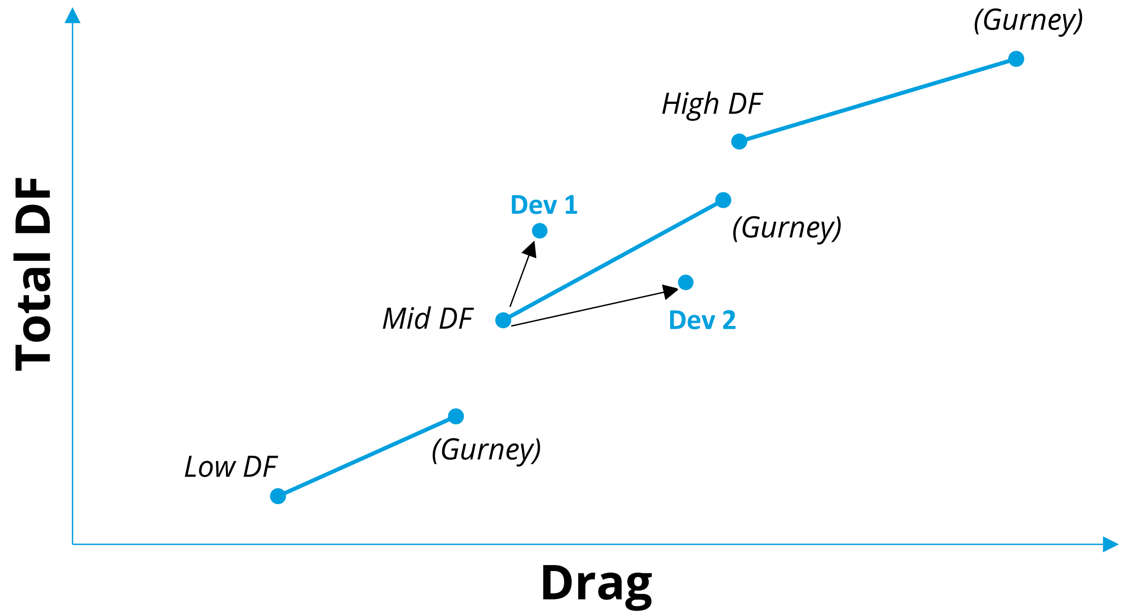


REAR WING POLAR

- Different rear wings to select the right drag level for the given circuit
- Development options (not only rear wings) need to beat polar to provide an overall benefit

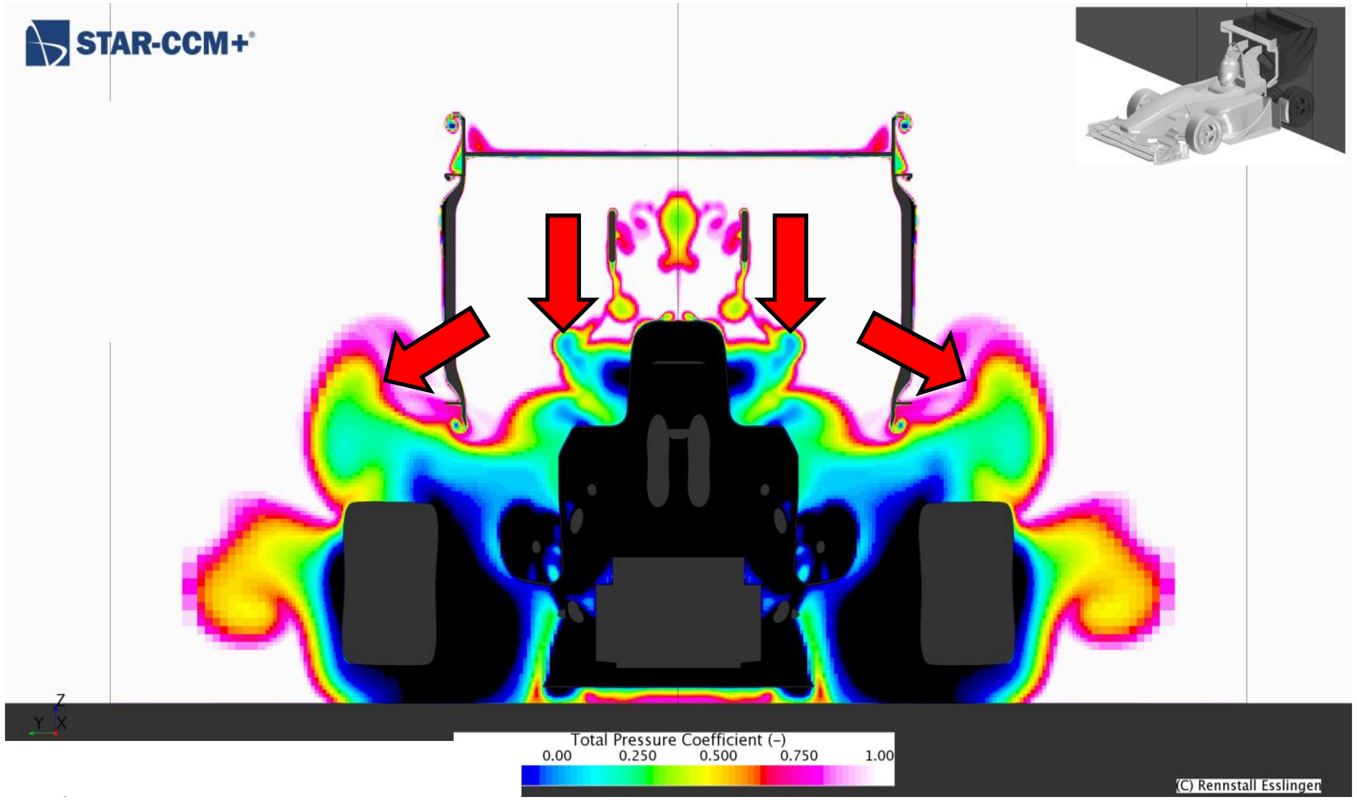


HOW TO IMPROVE YOUR DEVELOPMENT PROCESS

IDEA & CONCEPT GENERATION

Statement: ***"Most Formula Student cars lack a comprehensive flow field concept."***

1. Analyse your current concept:
   - Where could I improve onset CpT



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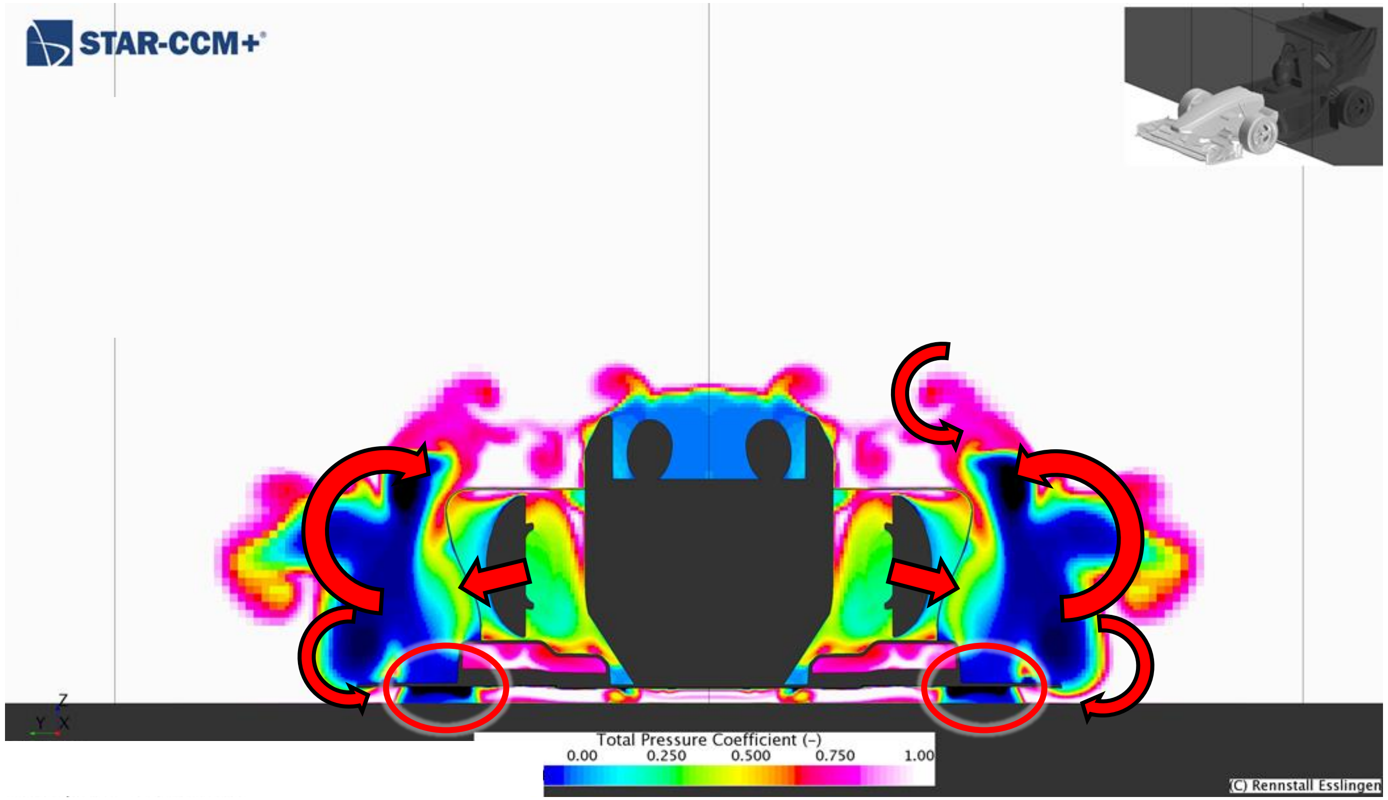
1. Analyse your current concept:
   - Where could I improve onset CpT
   - How is the wheel wake management



IDEA & CONCEPT GENERATION

Statement: ***"Most Formula Student cars lack a comprehensive flow field concept."***

1. Analyse your current concept:
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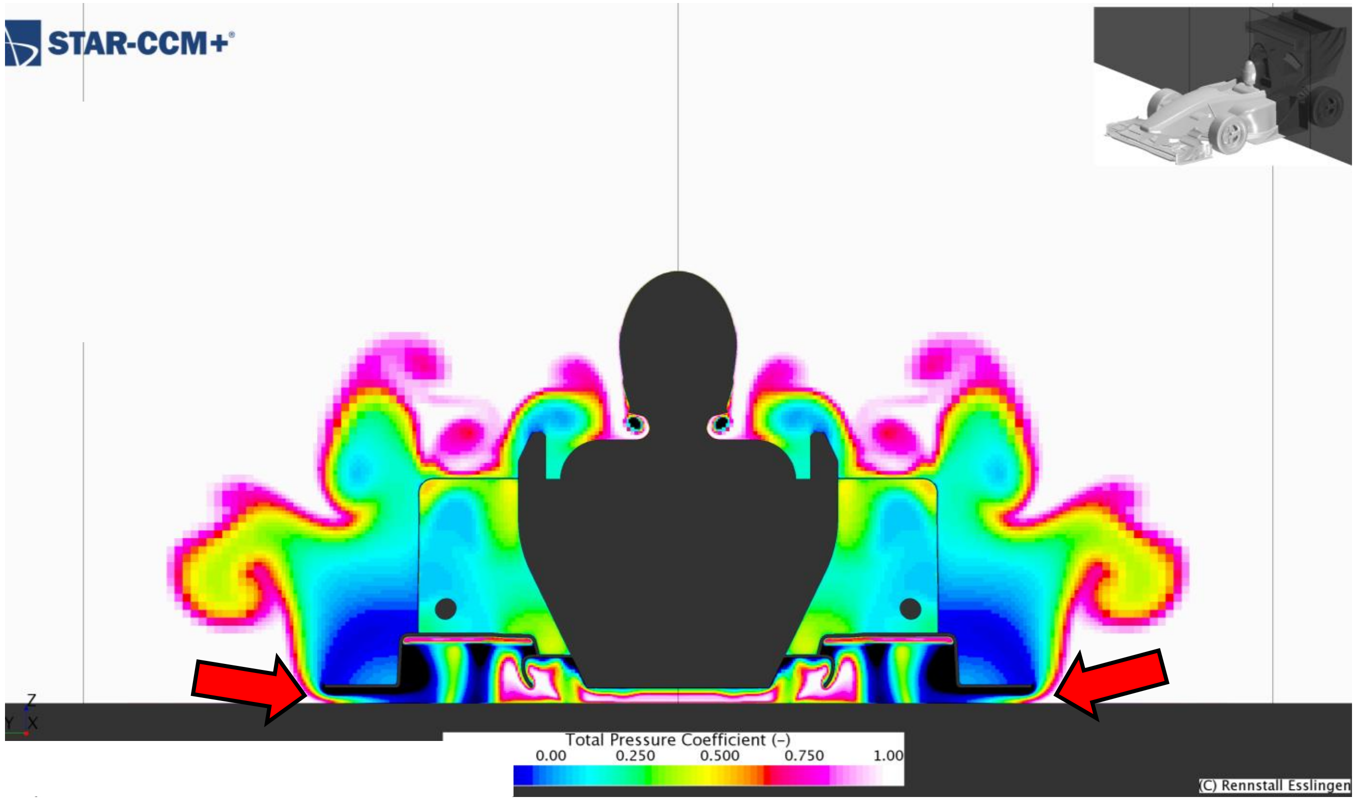
   - Where do I need more "fresh" air



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1. Analyse your current concept:
   - Where could I improve onset CpT
   - How is the wheel wake management
   - Where do I need more "fresh" air
   - What happens in cornering/under yaw or at extreme ride heights
   - How could I improve my radiator performance
   - Where do I want to put my wasted air
   - Where could I have instabilities (vortex brake down, separation, …)
   - How could I improve the interaction between different components

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   - How could I improve the interaction between different components
2. Decide on your **flow field** objectives

   → NOT: where could I put a wing to see what it does!

IDEA & CONCEPT GENERATION

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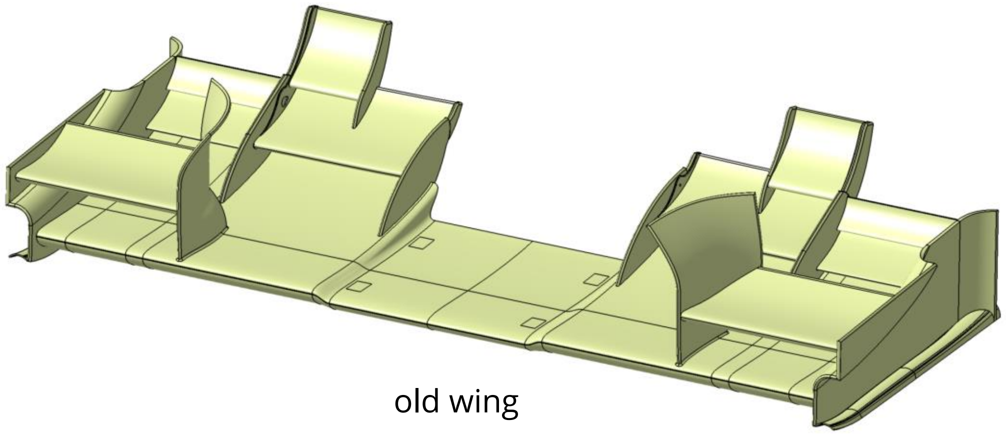
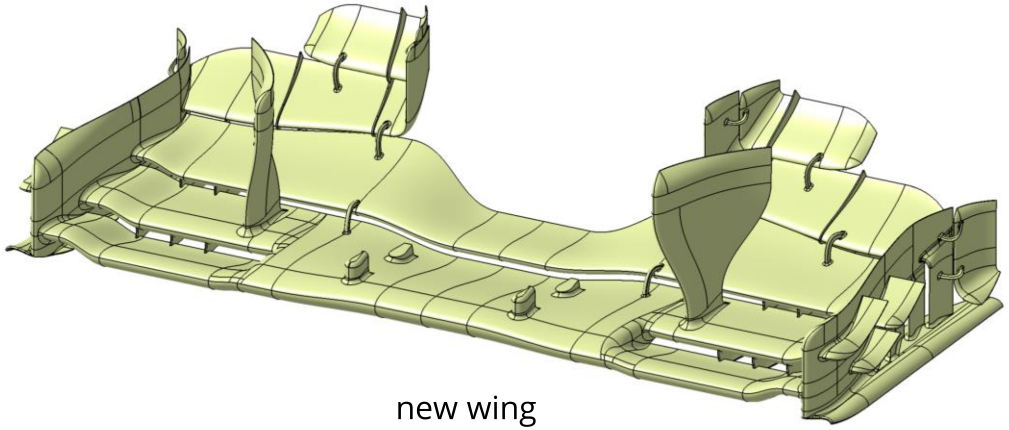
   - Where do I want to put my wasted air
   - Where could I have instabilities (vortex brake down, separation, …)
   - How could I improve the interaction between different components
2. Decide on your **flow field** objectives
3. Develop towards your target, **do not focus on numbers** at the beginning
4. Try **different concepts**, do not waste time with too much detailing
5. Decide for a concept and refine it

IDEA & CONCEPT GENERATION - EXAMPLE



old wing



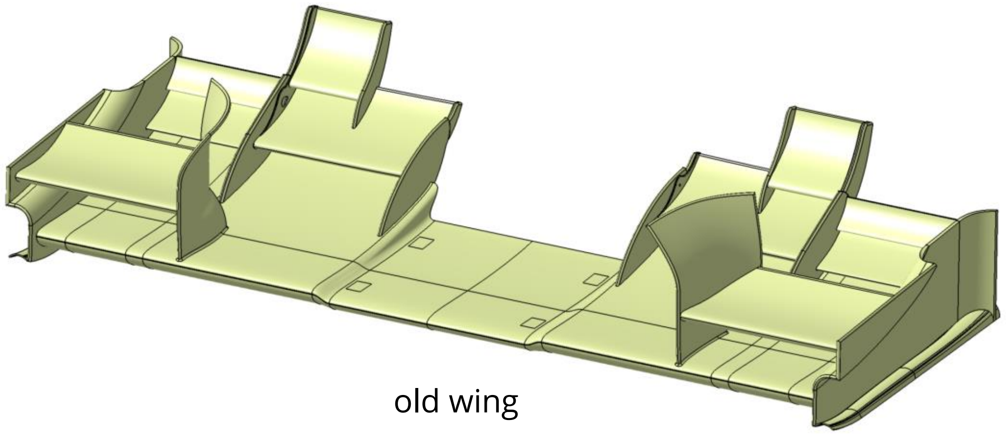
new wing

Example Rennstall Front Wing development

Flow field objectives:

- Improve onset CpT to rear
- More continuous behaviour through yaw and ride height
- More downforce
- Adjustable aero balance

IDEA & CONCEPT GENERATION - EXAMPLE



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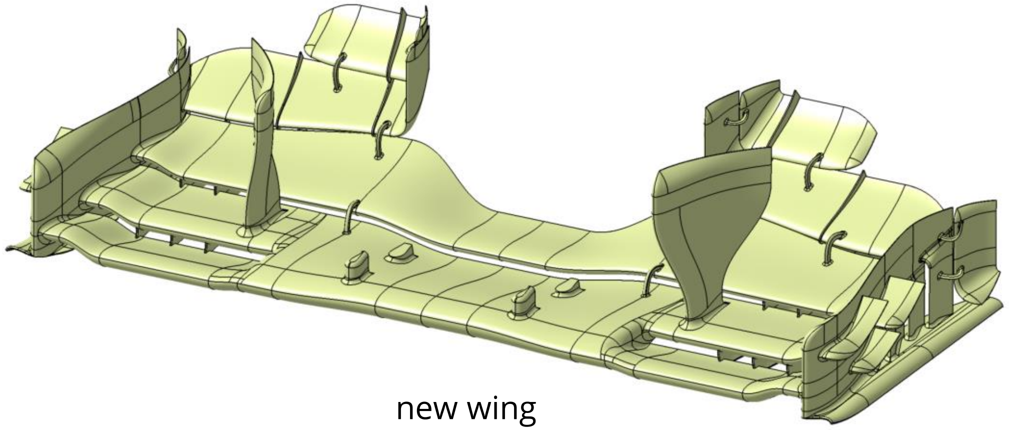

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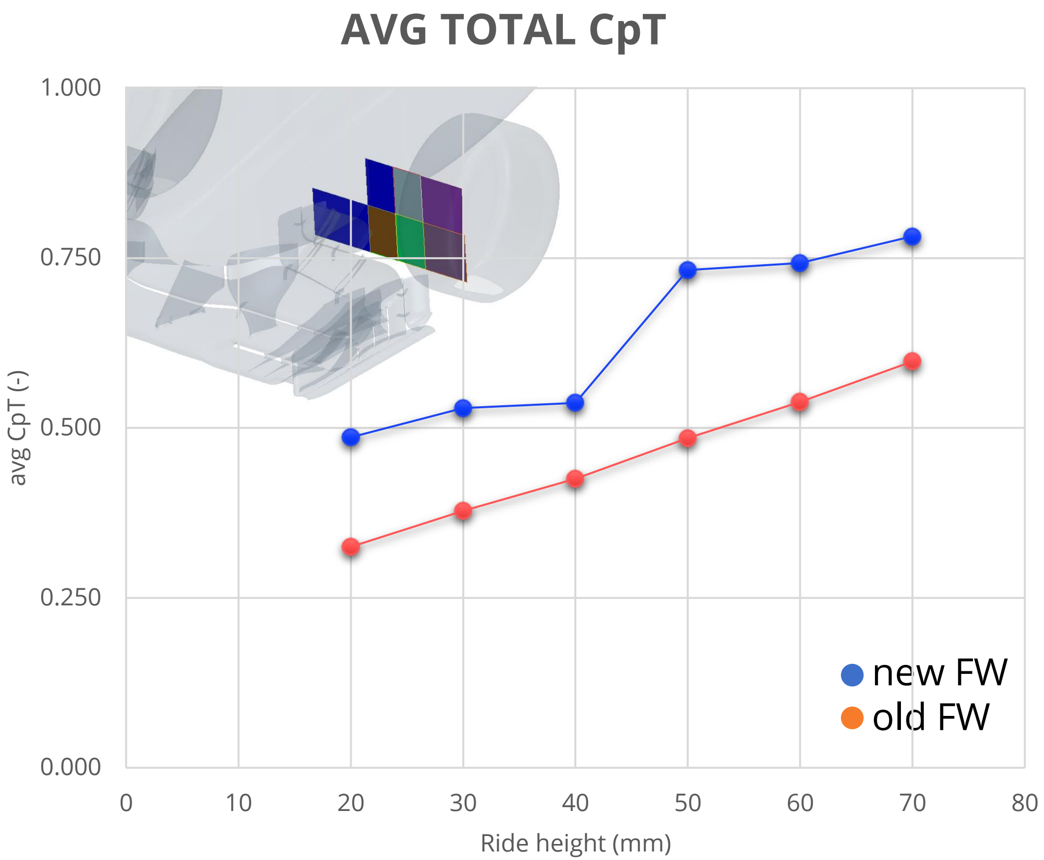

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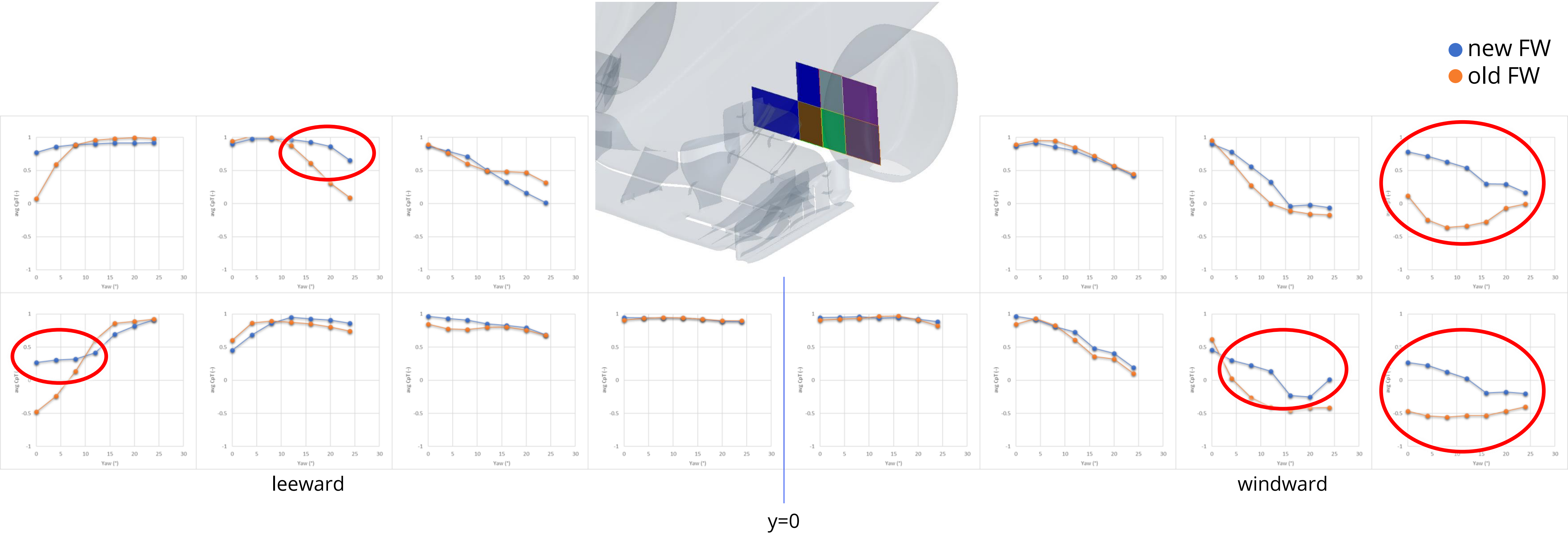
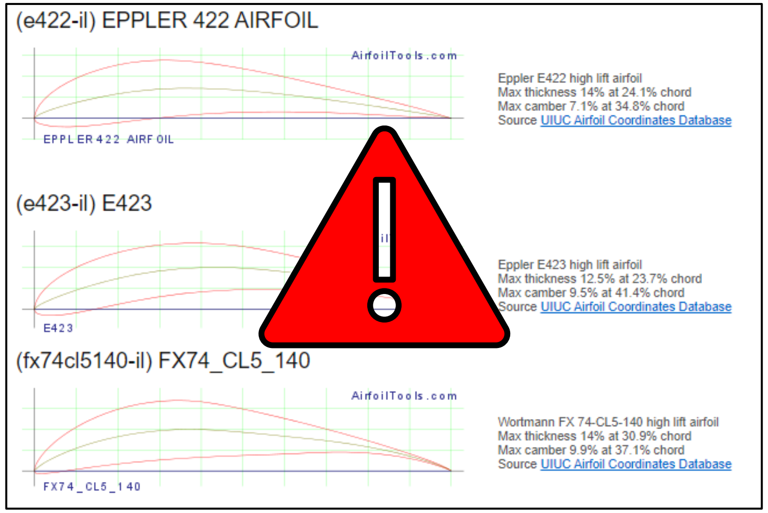
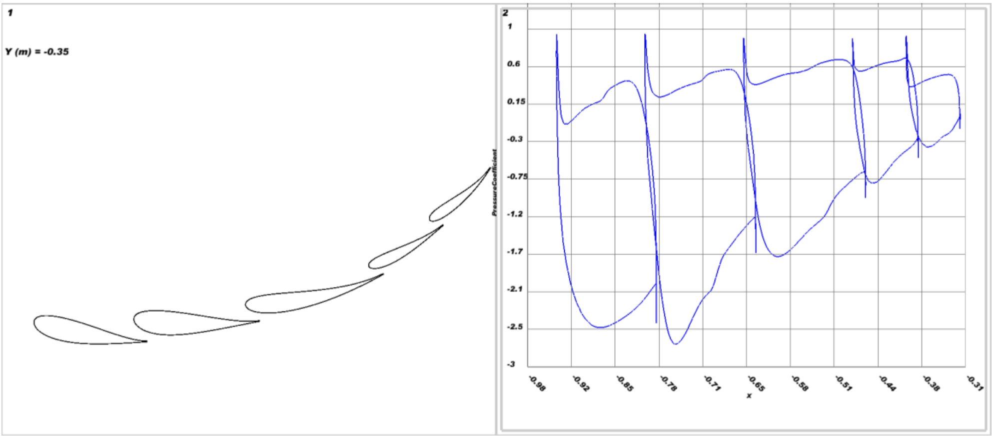


CAD AND AIRFOILS

CAD

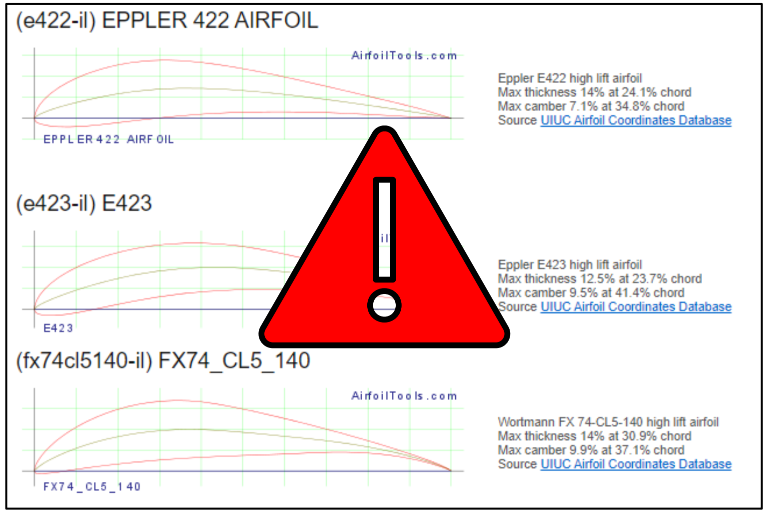
- Create your own airfoils, do not use predefined ones

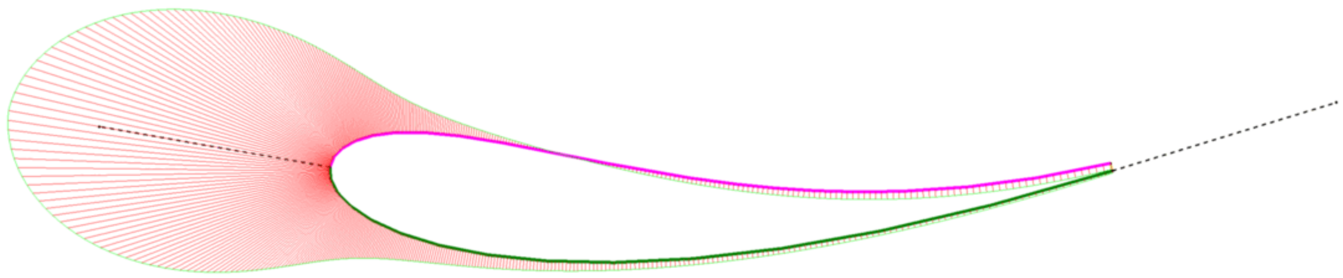




CAD

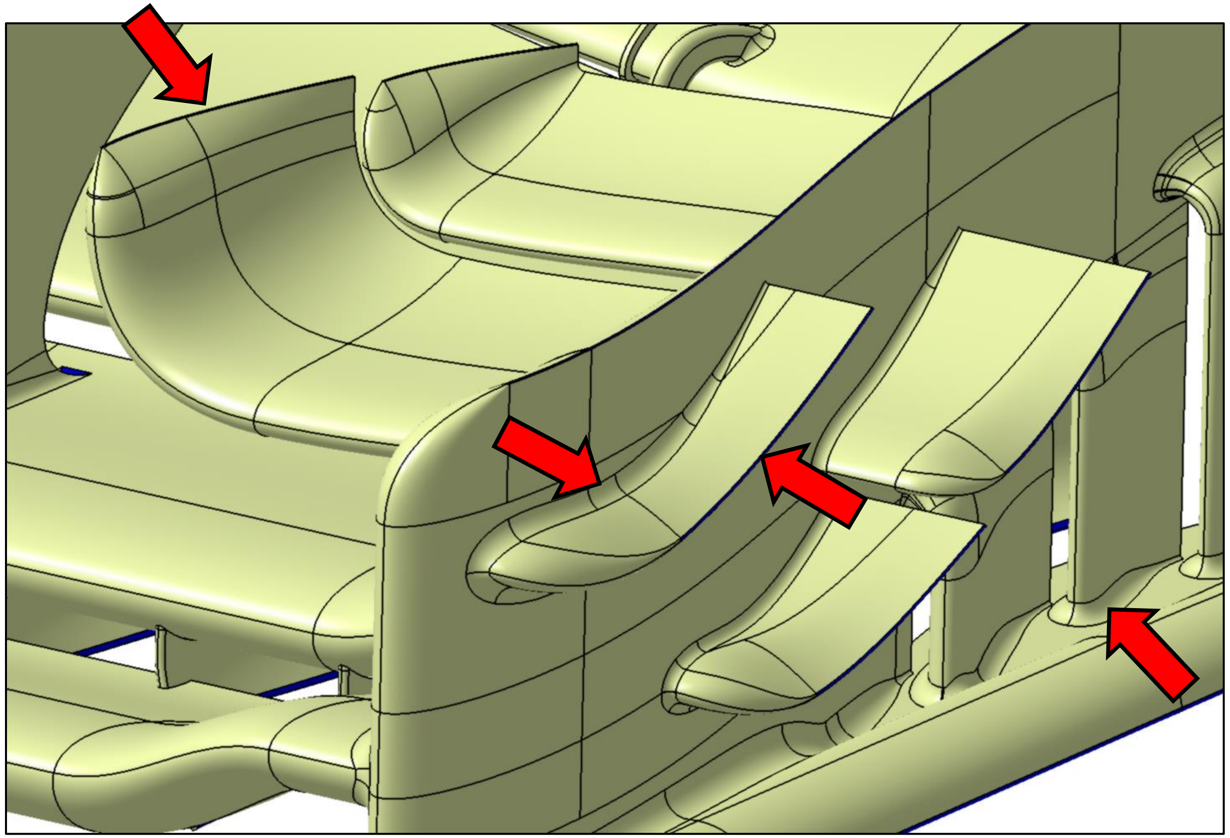
- Create your own airfoils, do not use predefined ones
- make the airfoils adjustable:
  - Onset angle
  - LE thickness
  - Curvature distribution
  - Departure angle
- Keep an eye on curvature





CAD

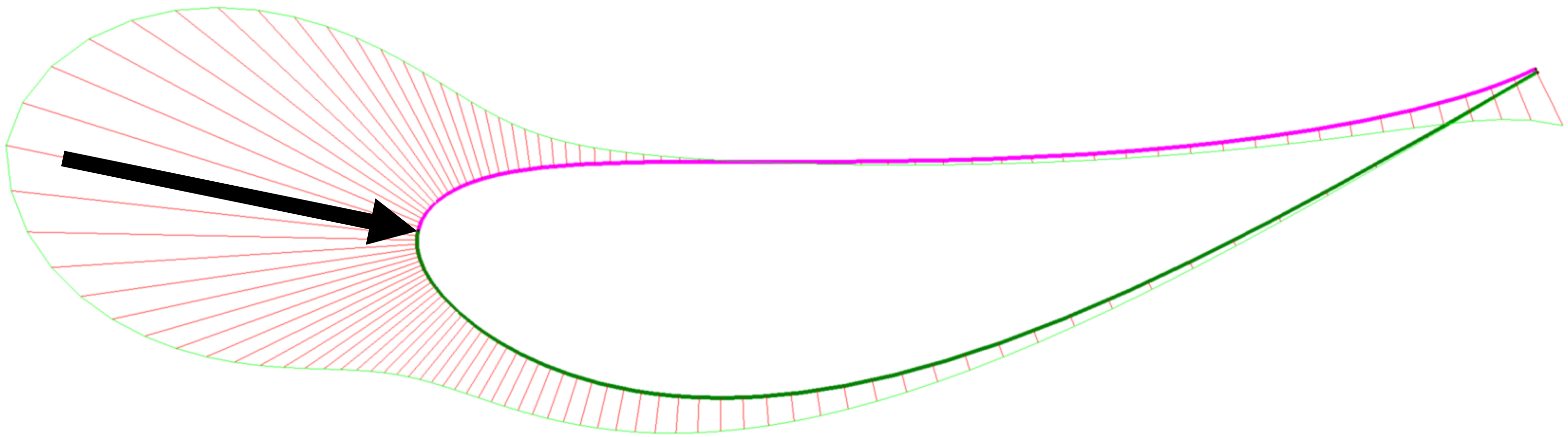
- Create your own airfoils, do not use predefined ones
- make the airfoils adjustable:
  - Onset angle
  - LE thickness
  - Curvature distribution
  - Departure angle
- Keep an eye on curvature
- Avoid sharp angles and transitions → use blends and fillets
- Keep shedding edges sharp



AIRFOILS

Onset Flow

- Stagnation point on leading edge
- Highest curvature on stagnation point
- Curvature continuity between pressure and suction side
- Increase leading edge radius (decrease curvature) in case of variable onset angles



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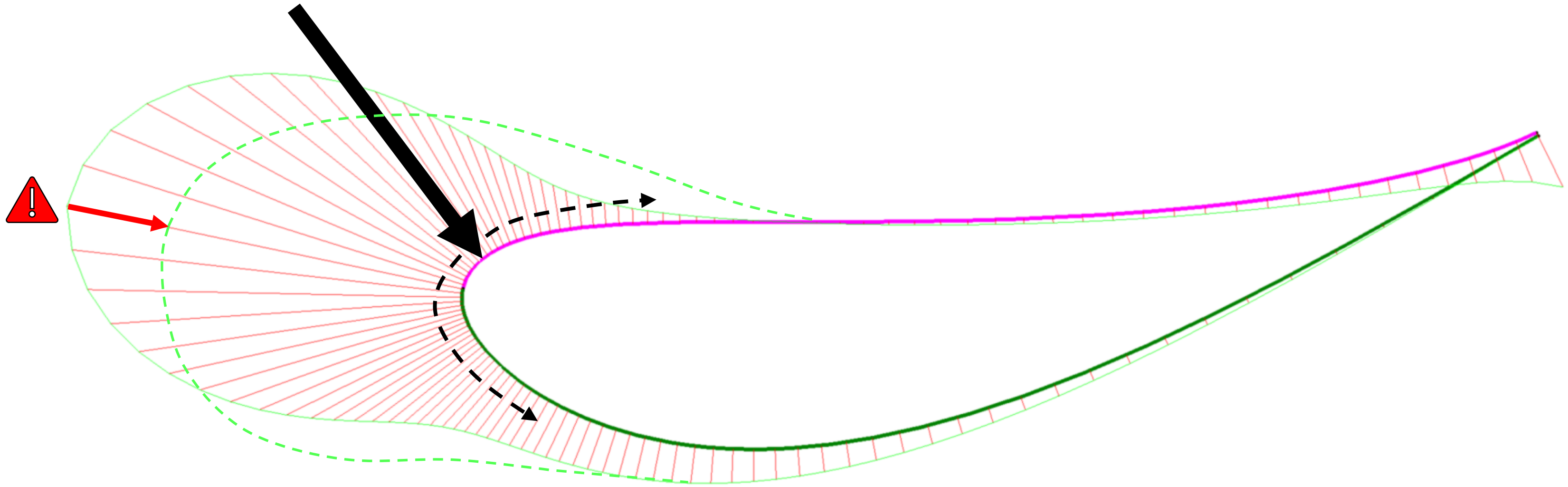
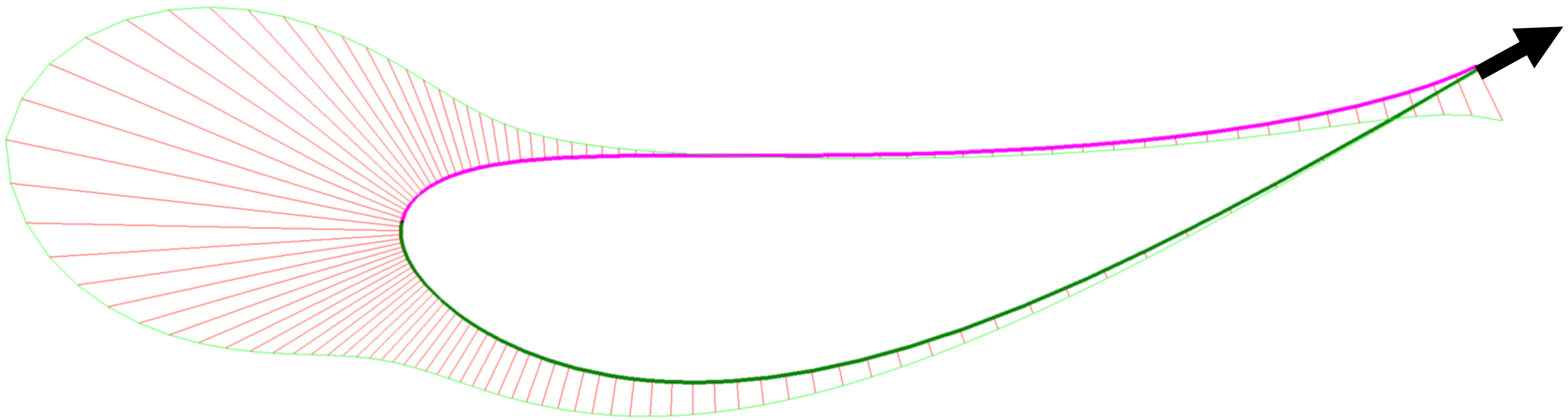


AIRFOILS

Departing Flow

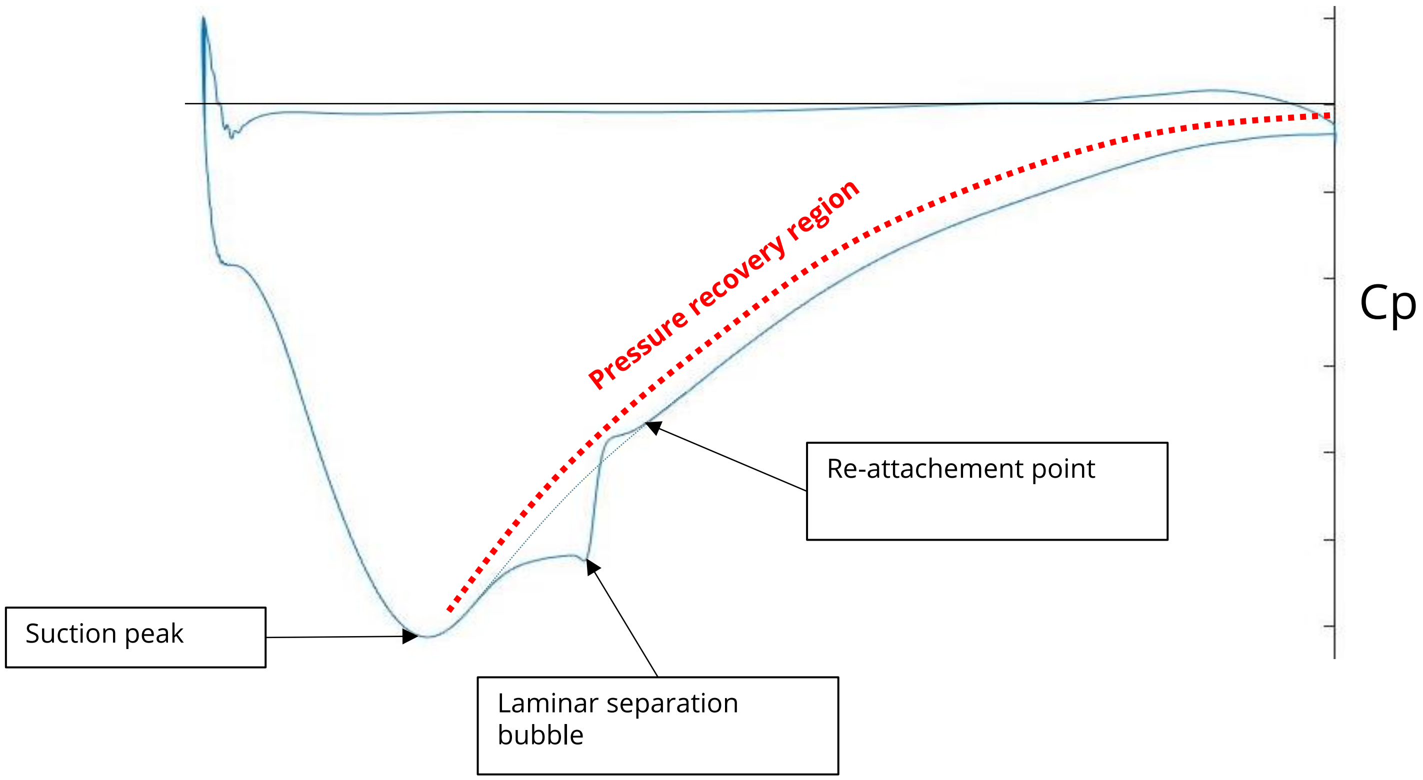
- Increase departure angle for higher load
- Decrease angle to keep flow attached

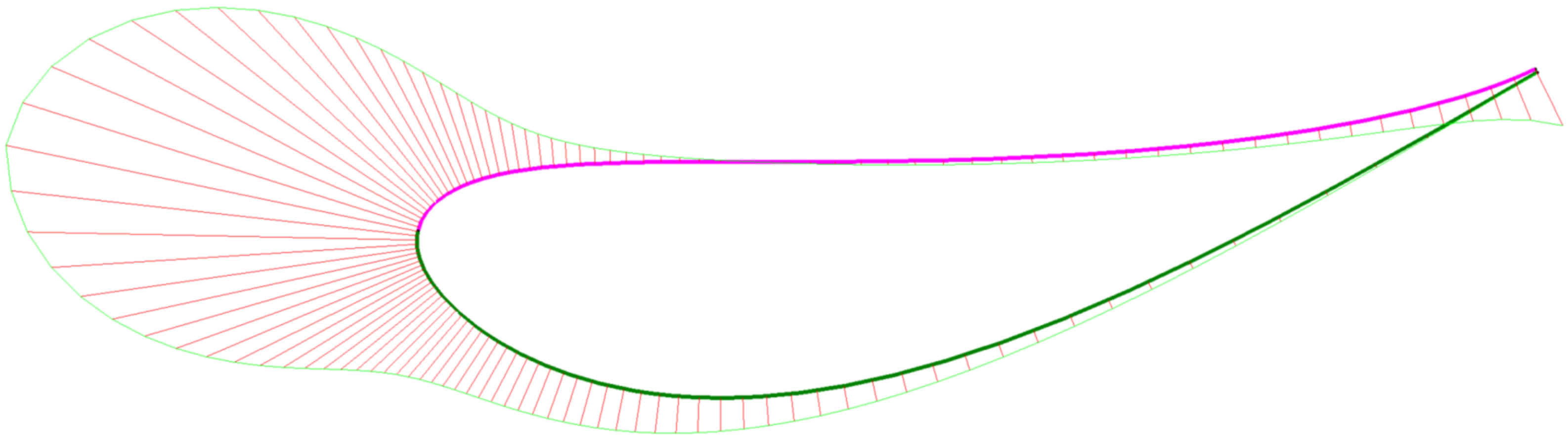


AIRFOILS

Curvature distribution

- Defines pressure distribution
  - Cp peak
  - Adverse pressure gradient (length & gradient of Cp recovery)
  - Drag and thrust components
- Move curvature forwards to
  - Support upstream profiles
  - Reduce drag
  - Increase recovery length and gradient
  - Force transition





AIRFOILS

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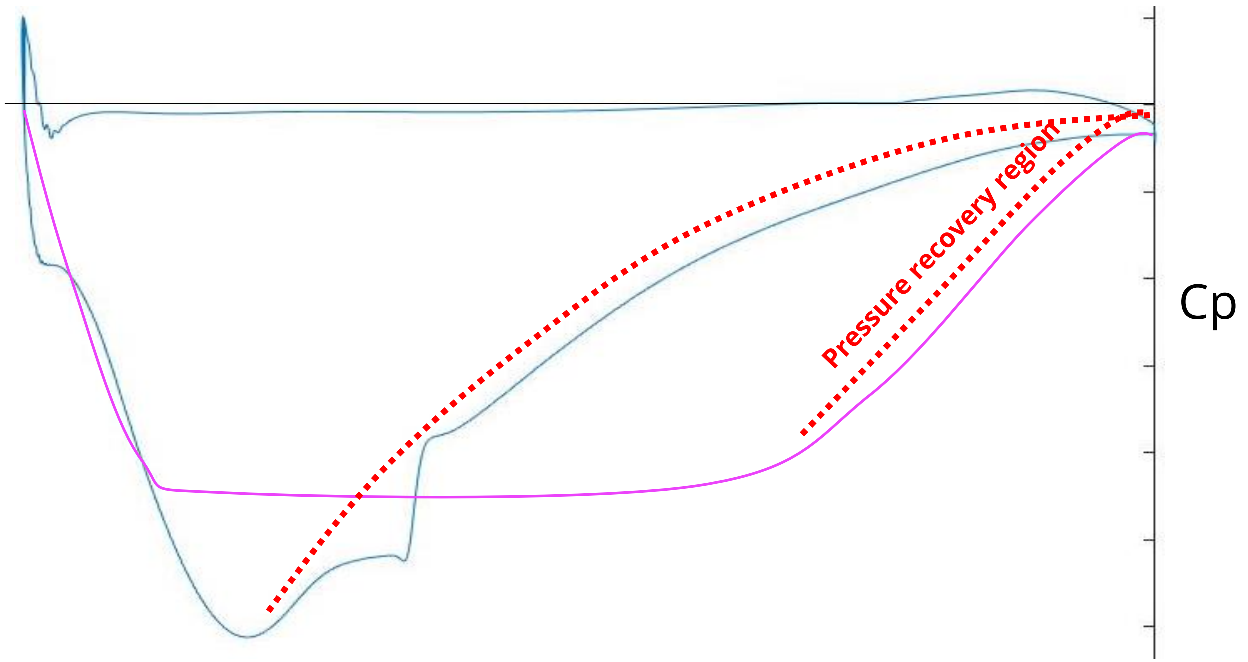
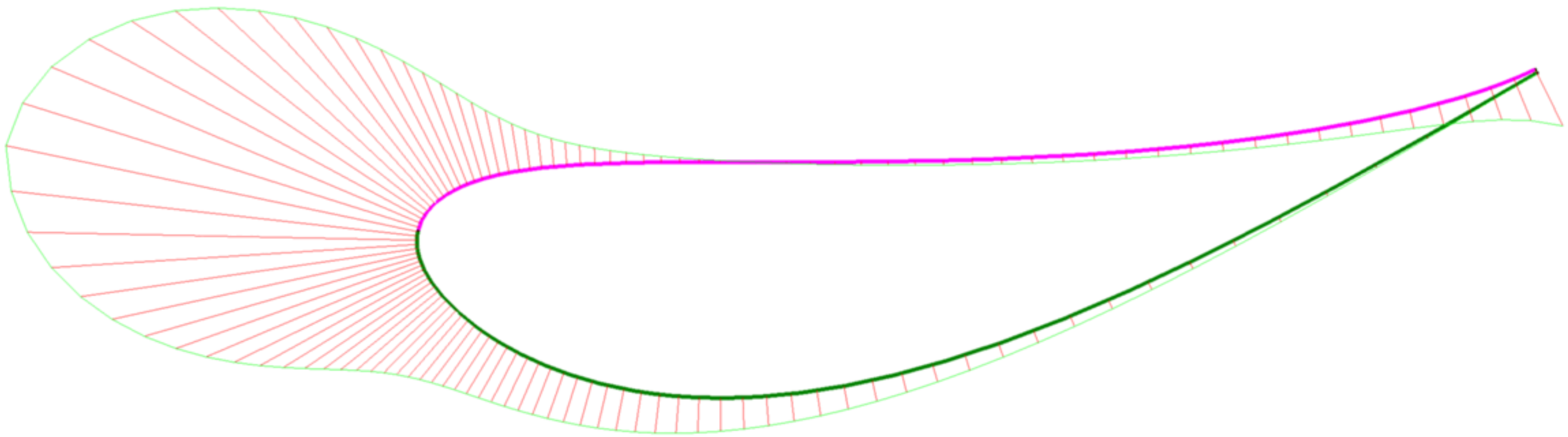
- Defines pressure distribution
  - Cp peak
  - Adverse pressure gradient (length & gradient of Cp recovery)
  - Drag and thrust components
- Move curvature forwards to
  - Support upstream profiles
  - Reduce drag
  - Increase recovery length and gradient
  - Force transition
- Equally distribute curvature to
  - Reduce boundary layer growth
  - Create maximum load
  - ⚠ needs support from downstream geometry





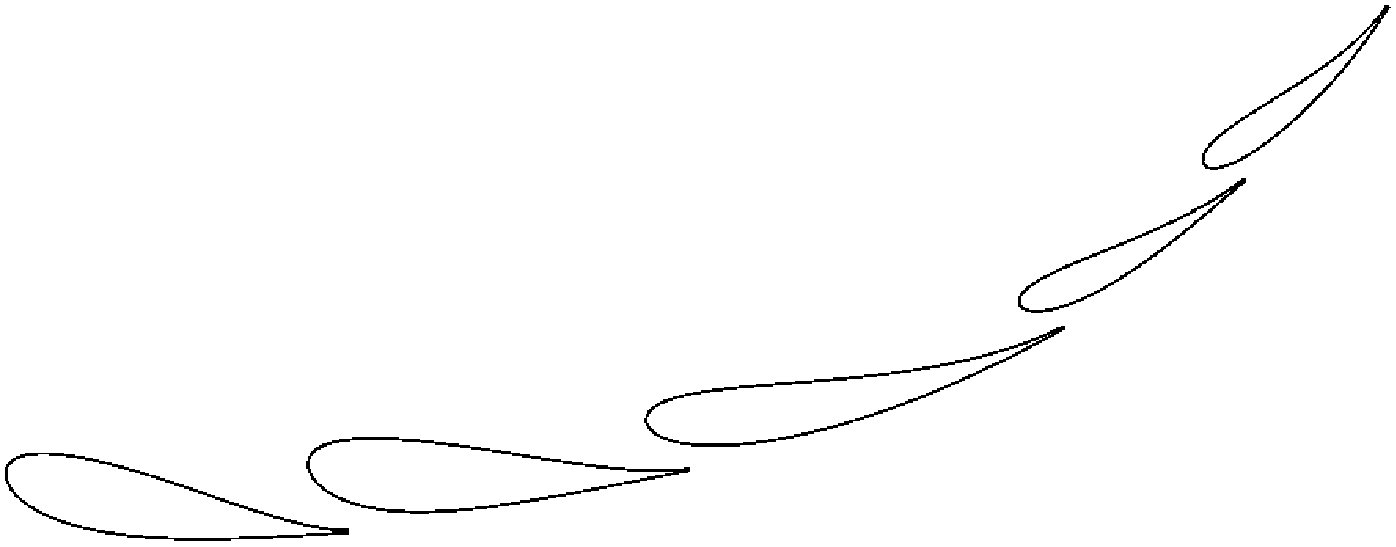
MULTI ELEMENT WING CASCADES

Why more elements?

- Re-energize boundary layer on suction surface
- Increase capability of flow turning
- DRS implementation (rear wing)
- Delay/avoid stall at low ride heights (front wing)

Why less elements?

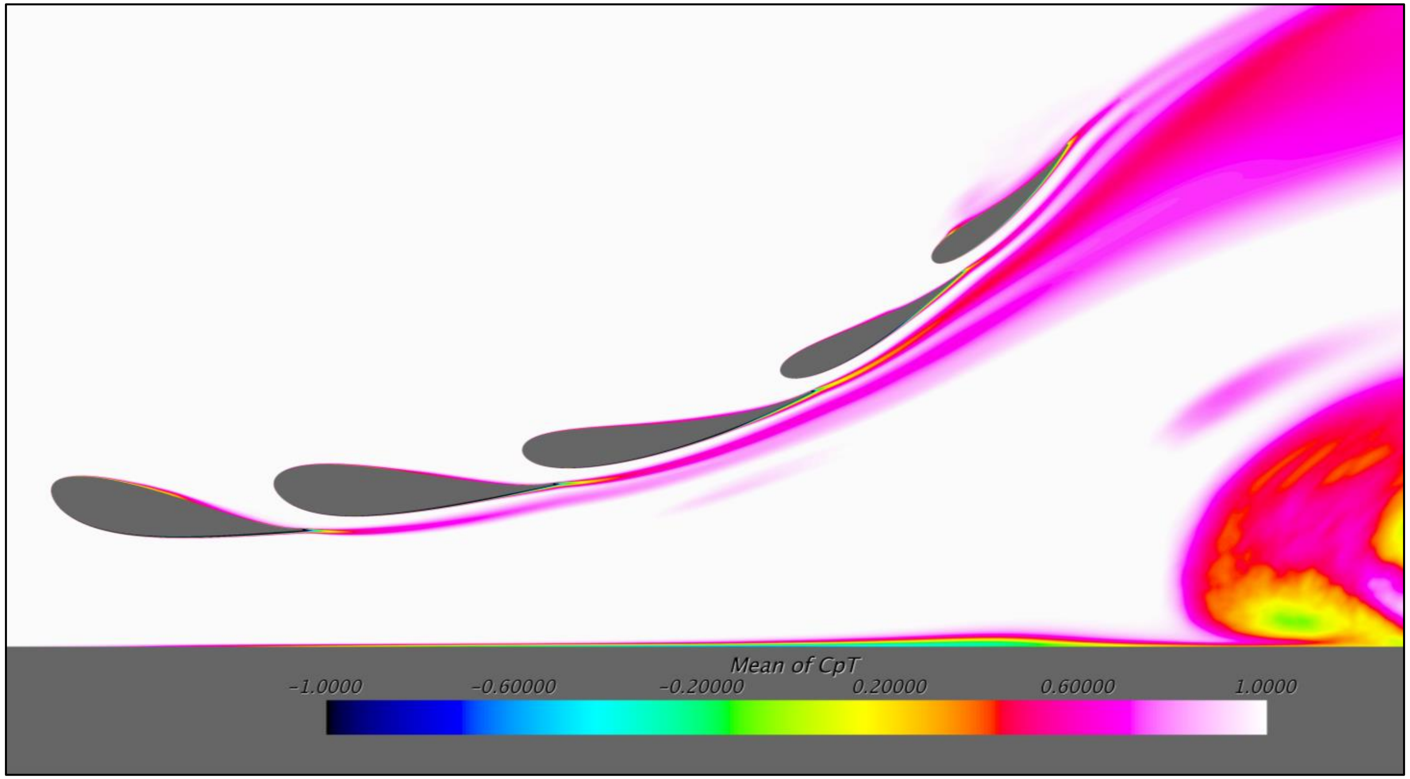
- More load
- Less lossy departing flow
- Easier to develop
- Lighter



MULTI ELEMENT WING CASCADES

Slot gaps

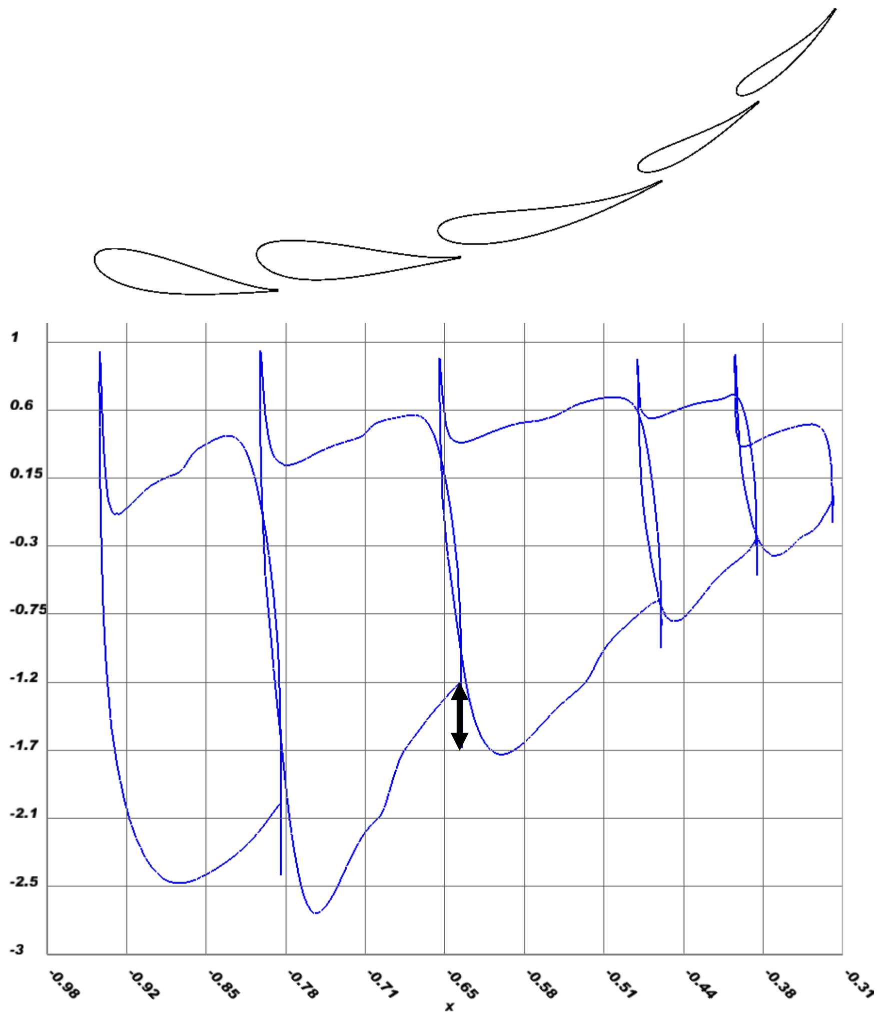
- Allow high energy flow from pressure side to suction side
- Decrease slot gap size to
  - Support upstream profile
  - Increase overall load
- Increase slot gap size to
  - Allow more air going through
  - Support downstream profile



MULTI ELEMENT WING CASCADES

Curvature

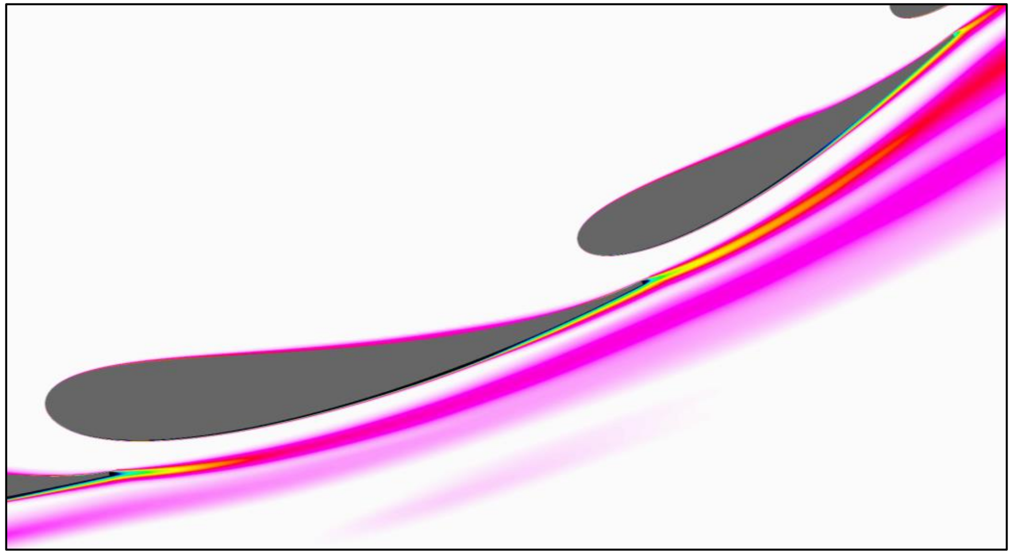
- Avoid large Cp jumps between elements
- Move curvature forward to support upstream element
- Supported elements can have significant amount of trailing edge curvature

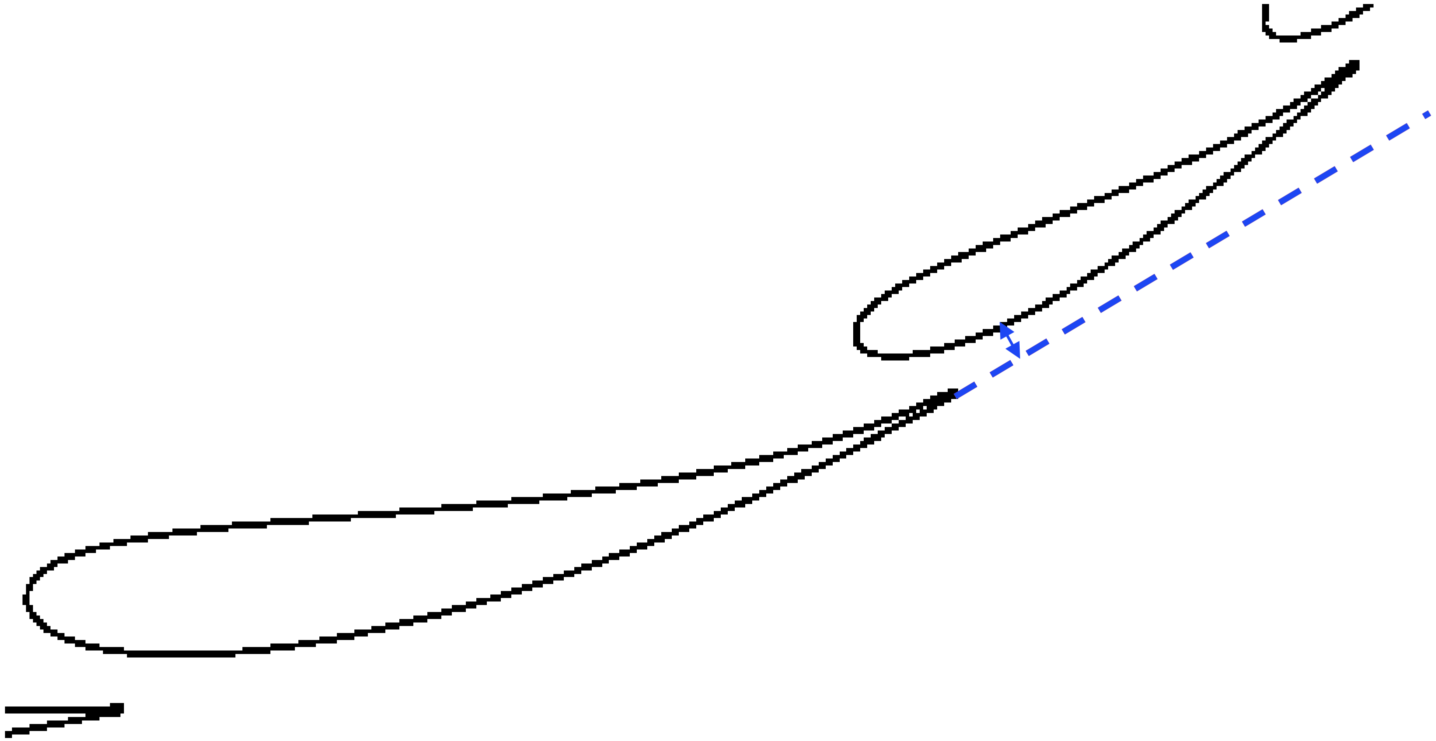


MULTI ELEMENT WING CASCADES

Departure angle

- Leave space for flow through slot gap

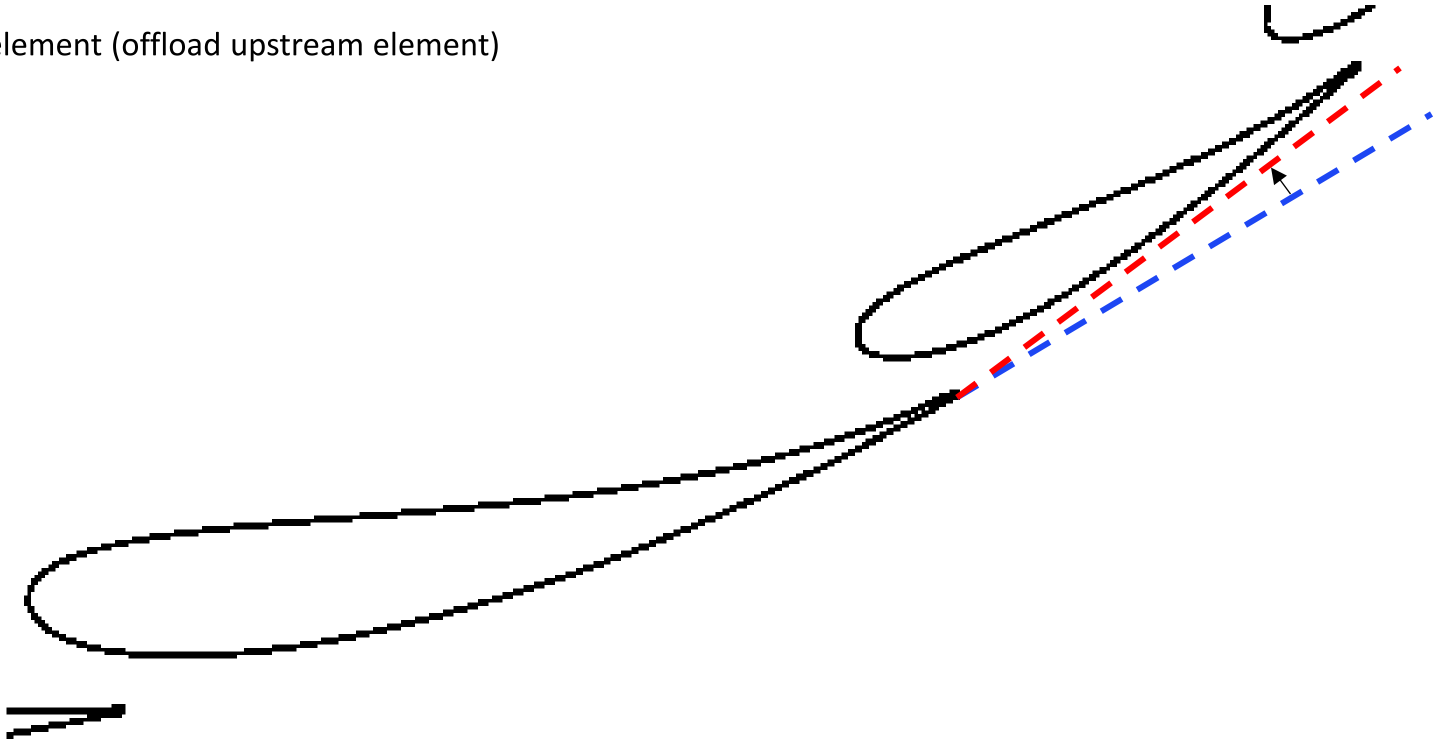




MULTI ELEMENT WING CASCADES

Departure angle

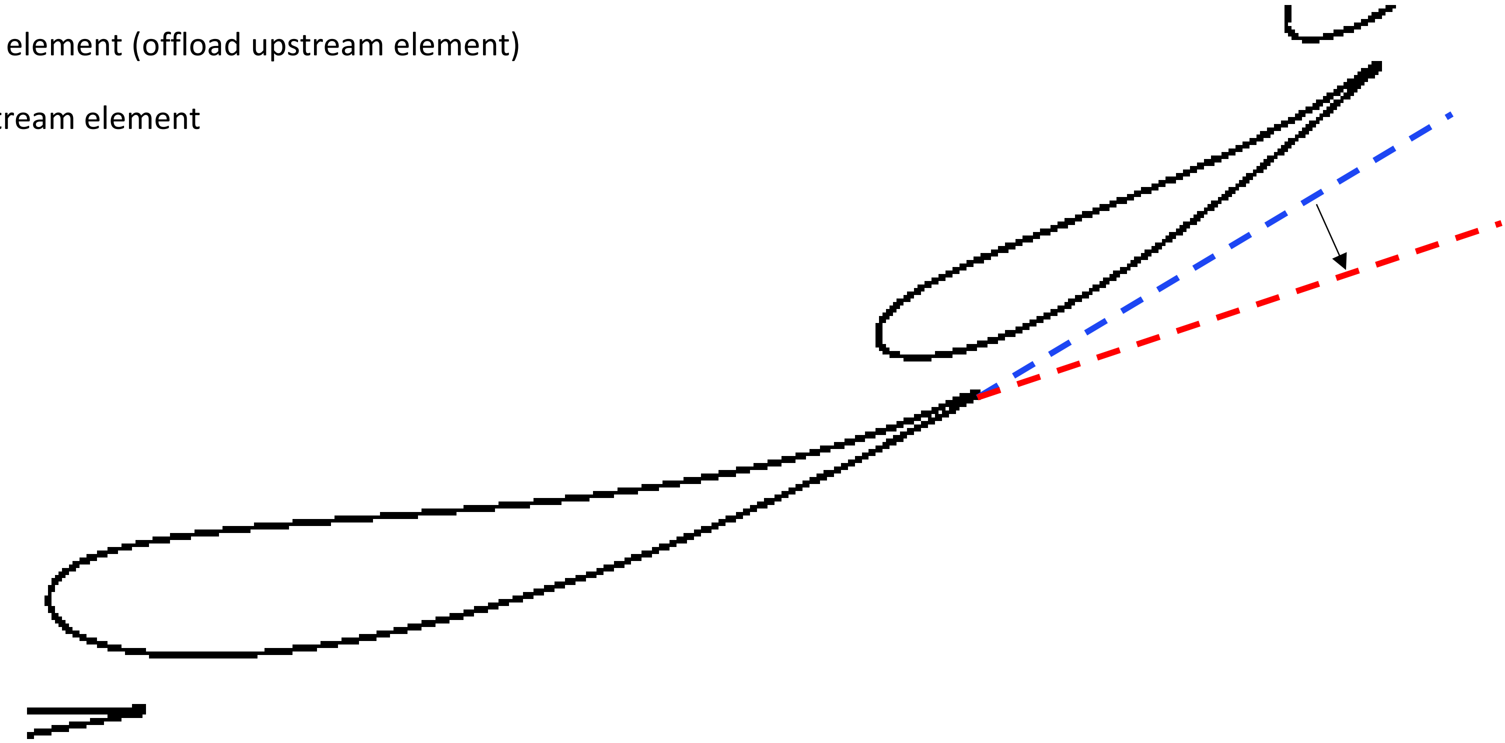
- Leave space for flow through slot gap
- Increase departure angle to transfer load to forward element (offload upstream element)

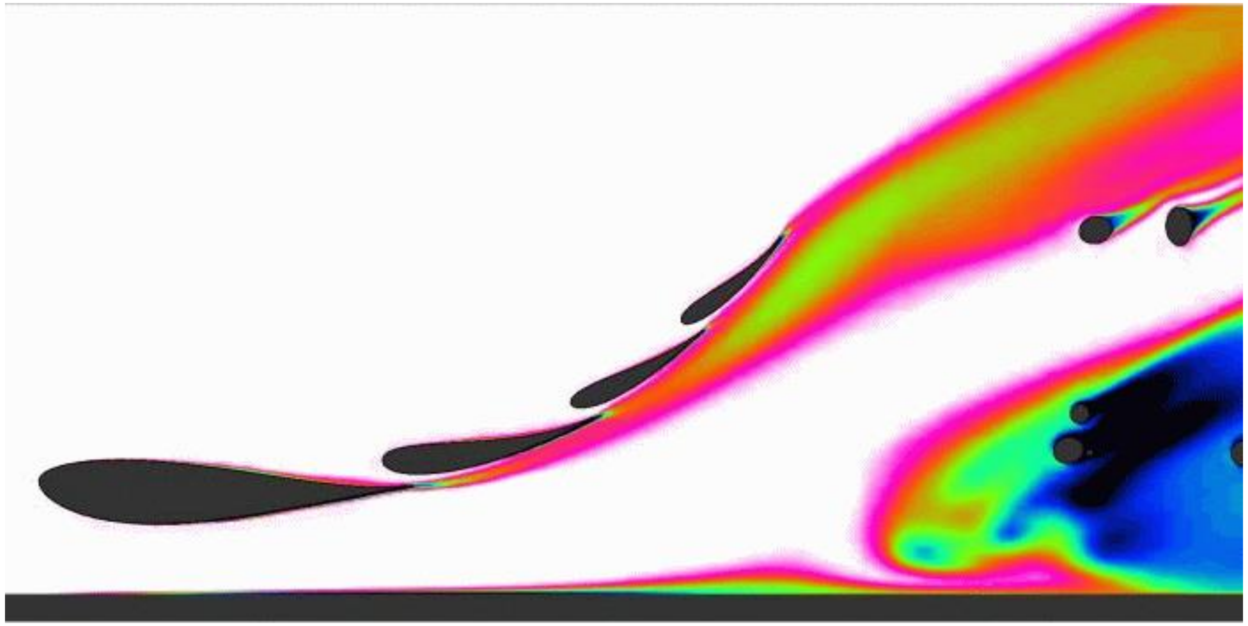


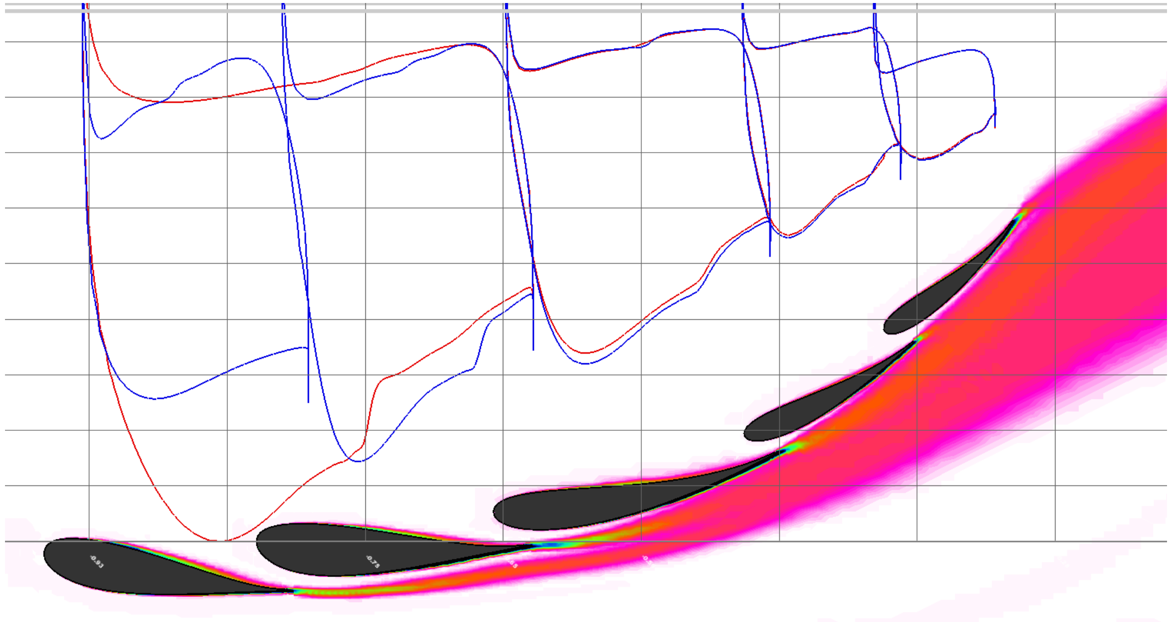
MULTI ELEMENT WING CASCADES

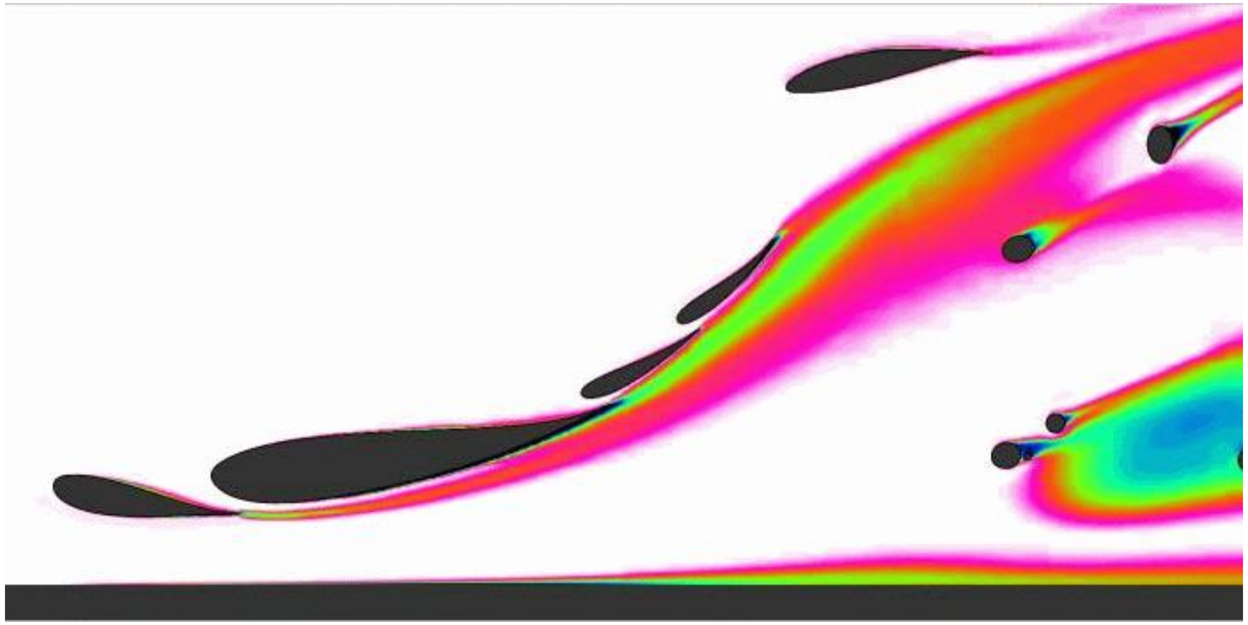
Departure angle

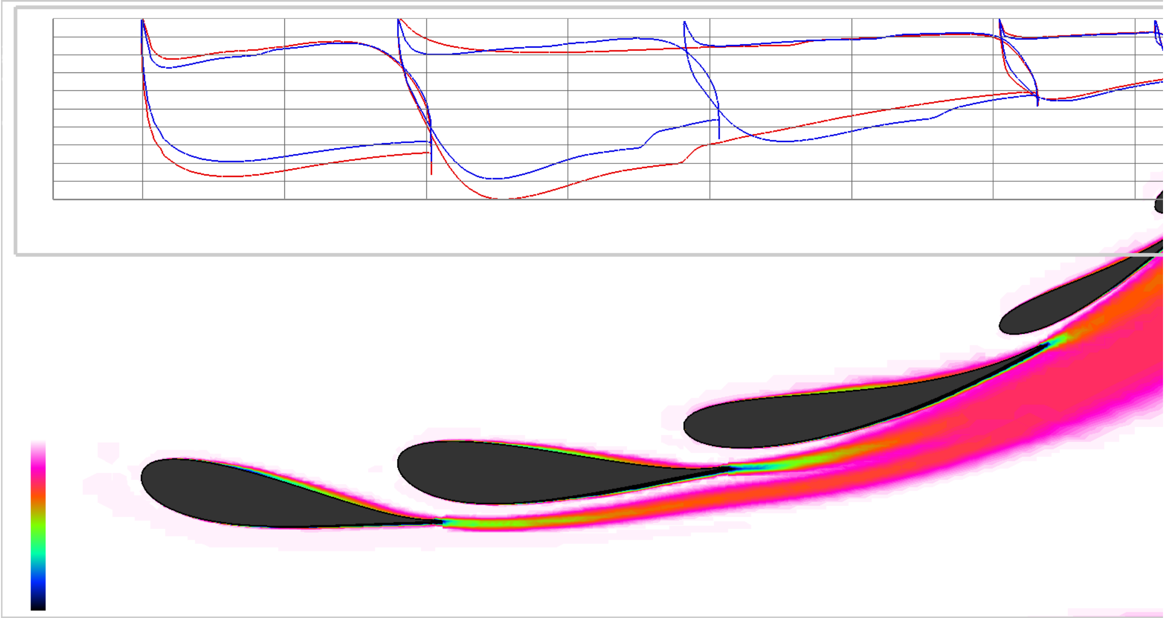
- Leave space for flow through slot gap
- Increase departure angle to transfer load to forward element (offload upstream element)
- Decrease departure angle to transfer load to downstream element



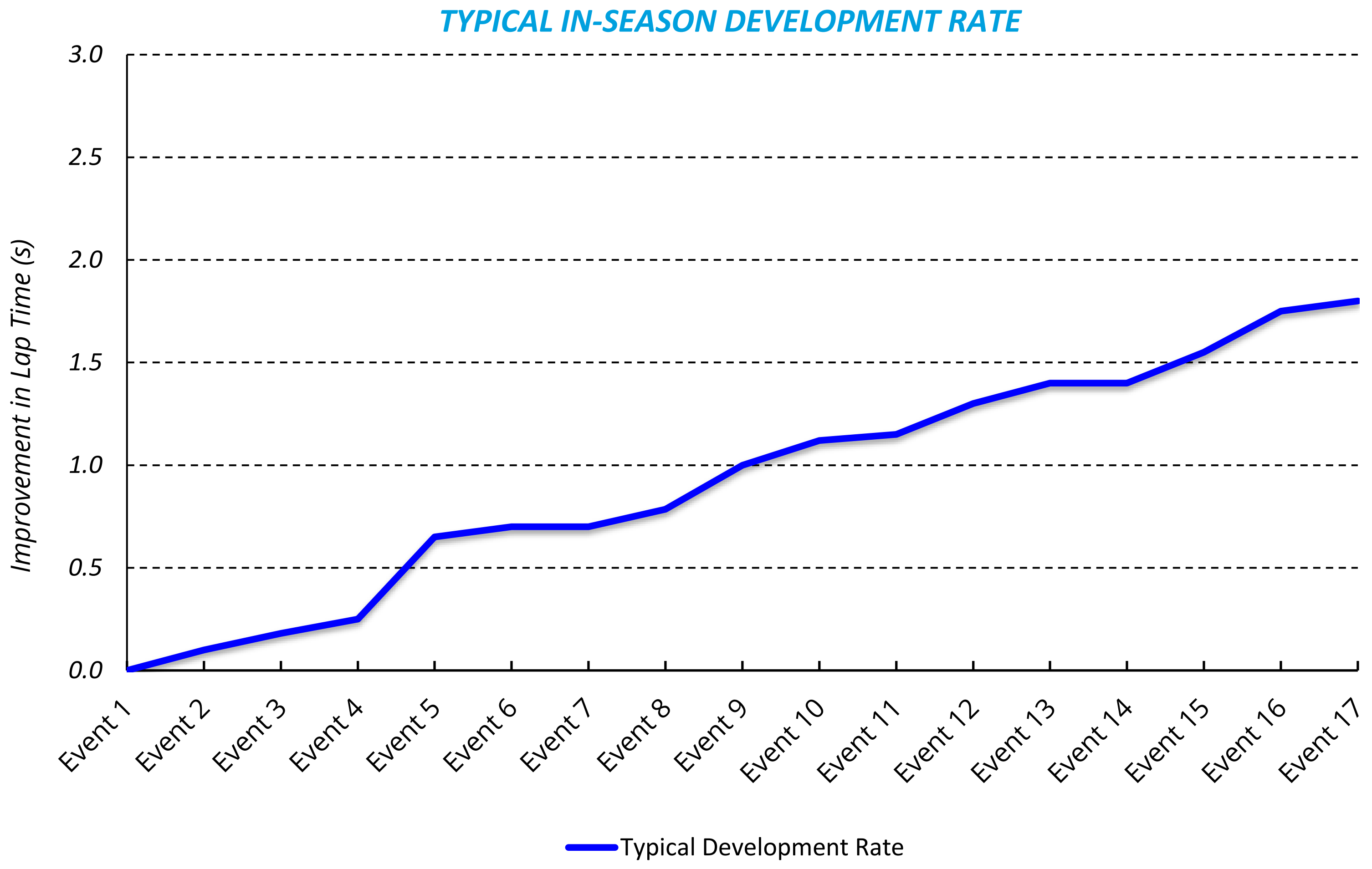








OPTIMIZING THE CFD PROCESS

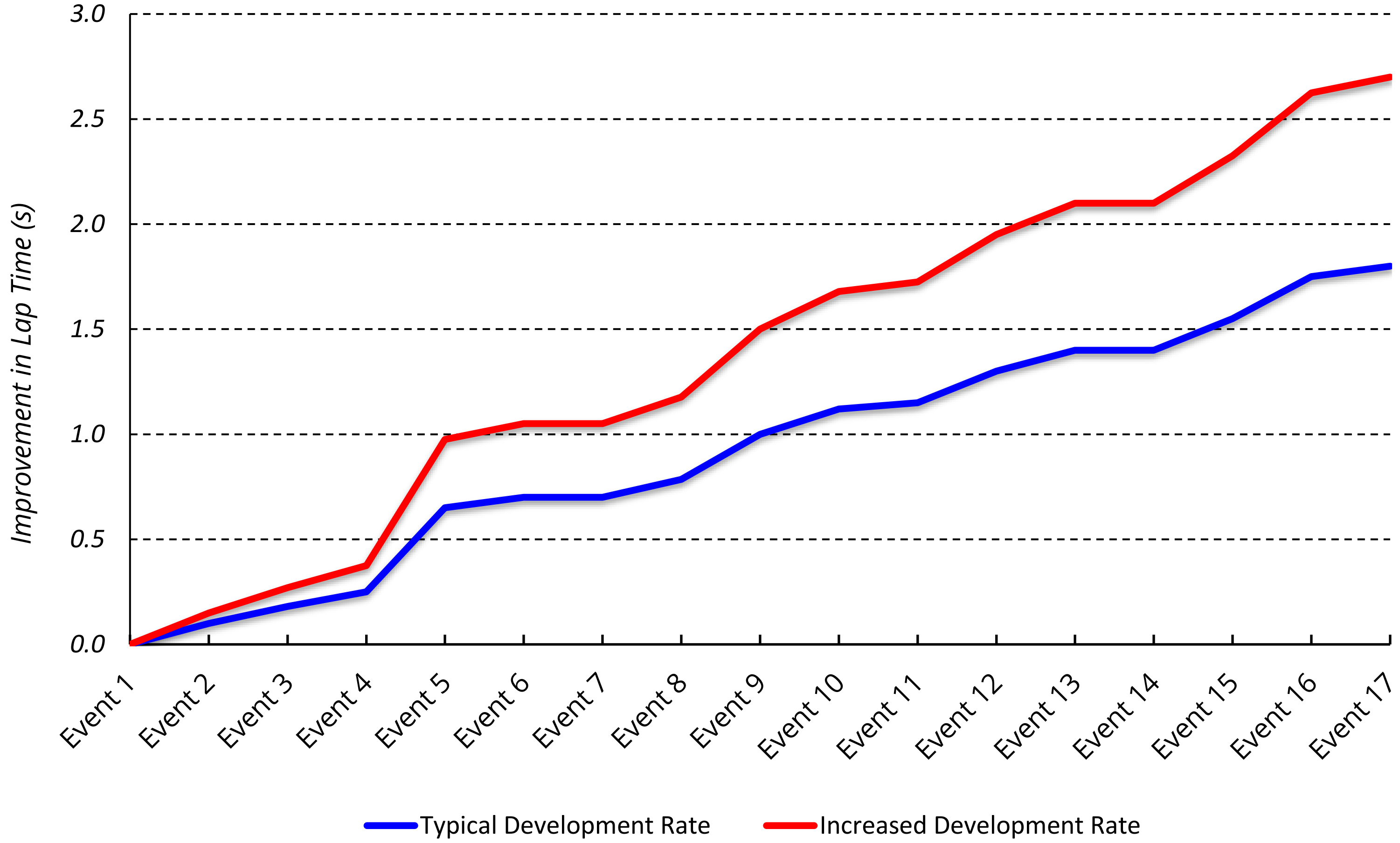


OPTIMIZING THE CFD PROCESS

Improving the Tool Kit

- Improved simulation accuracy
- Better utilisation of data
- Quicker turnaround times

TYPICAL IN-SEASON DEVELOPMENT RATE



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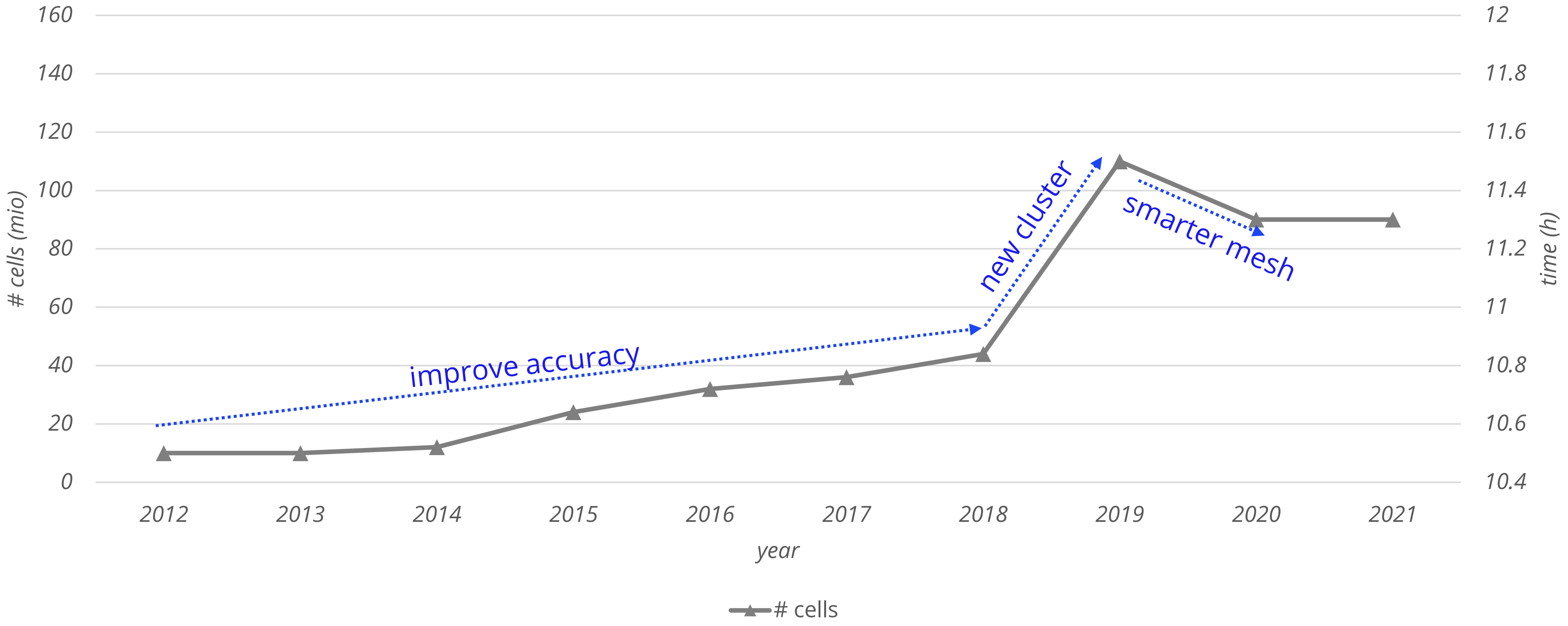

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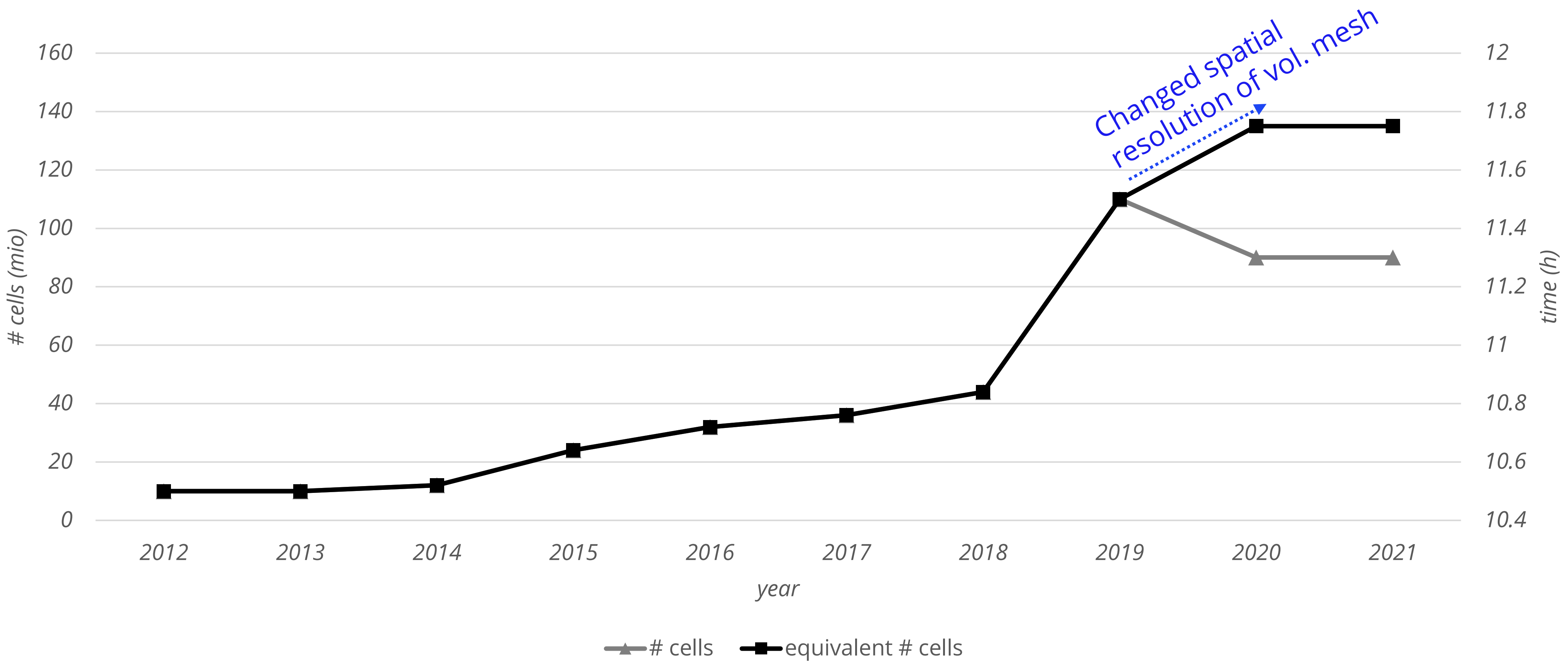

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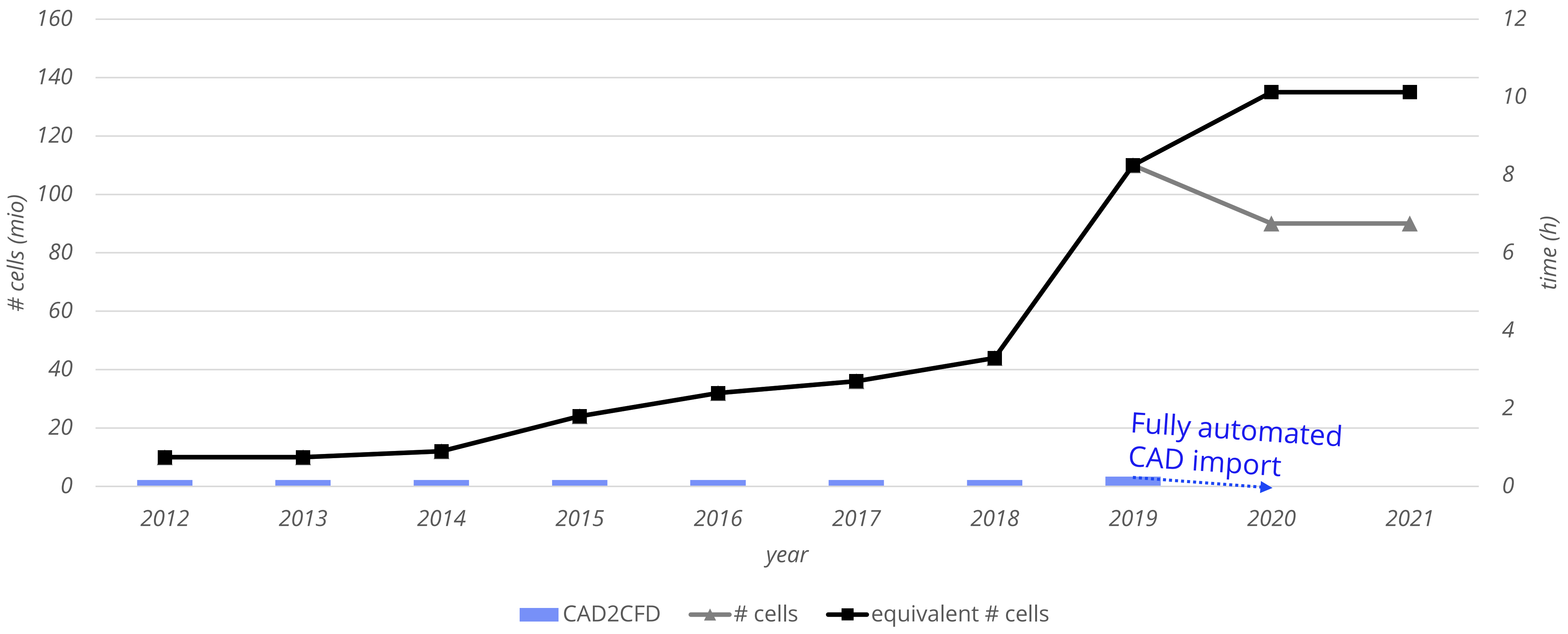

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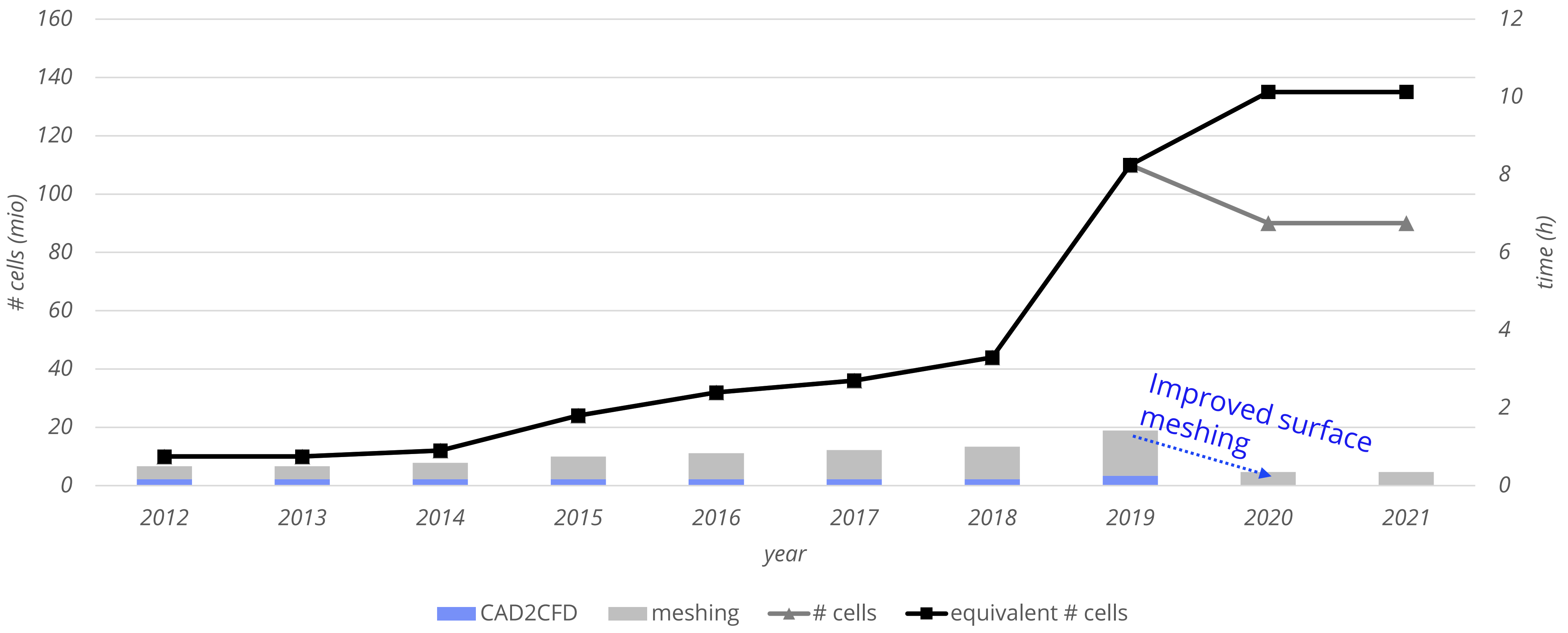

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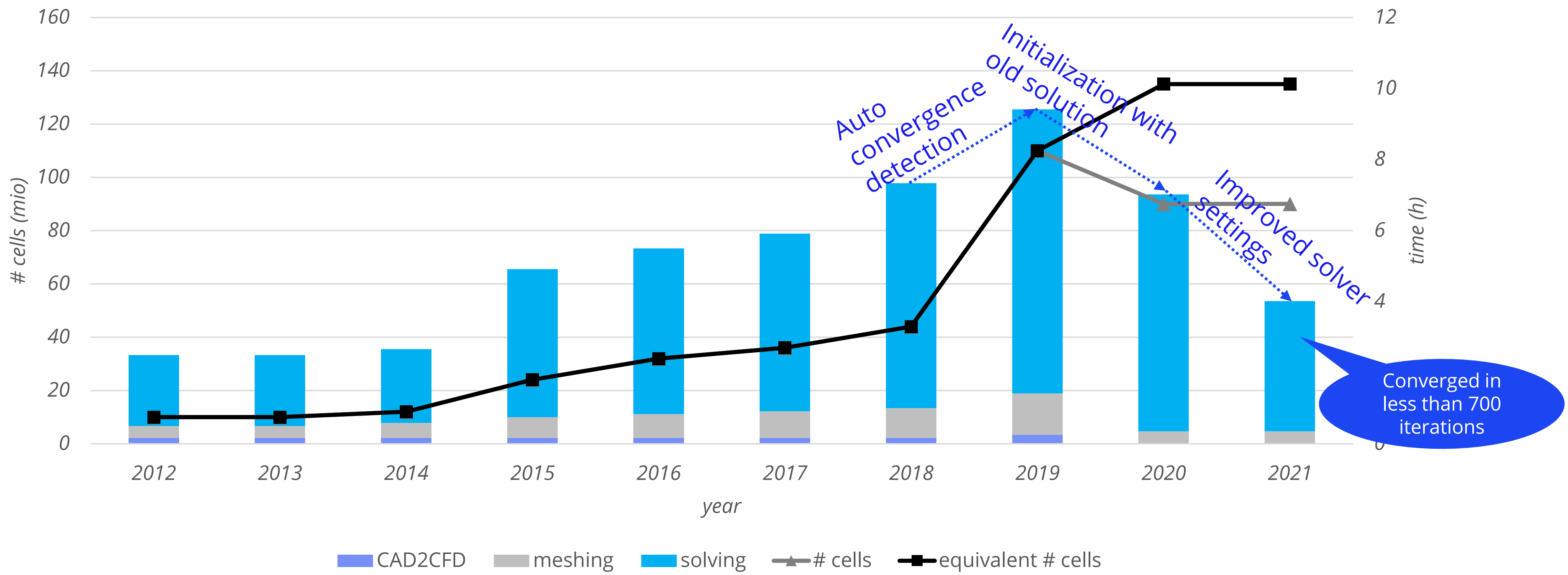

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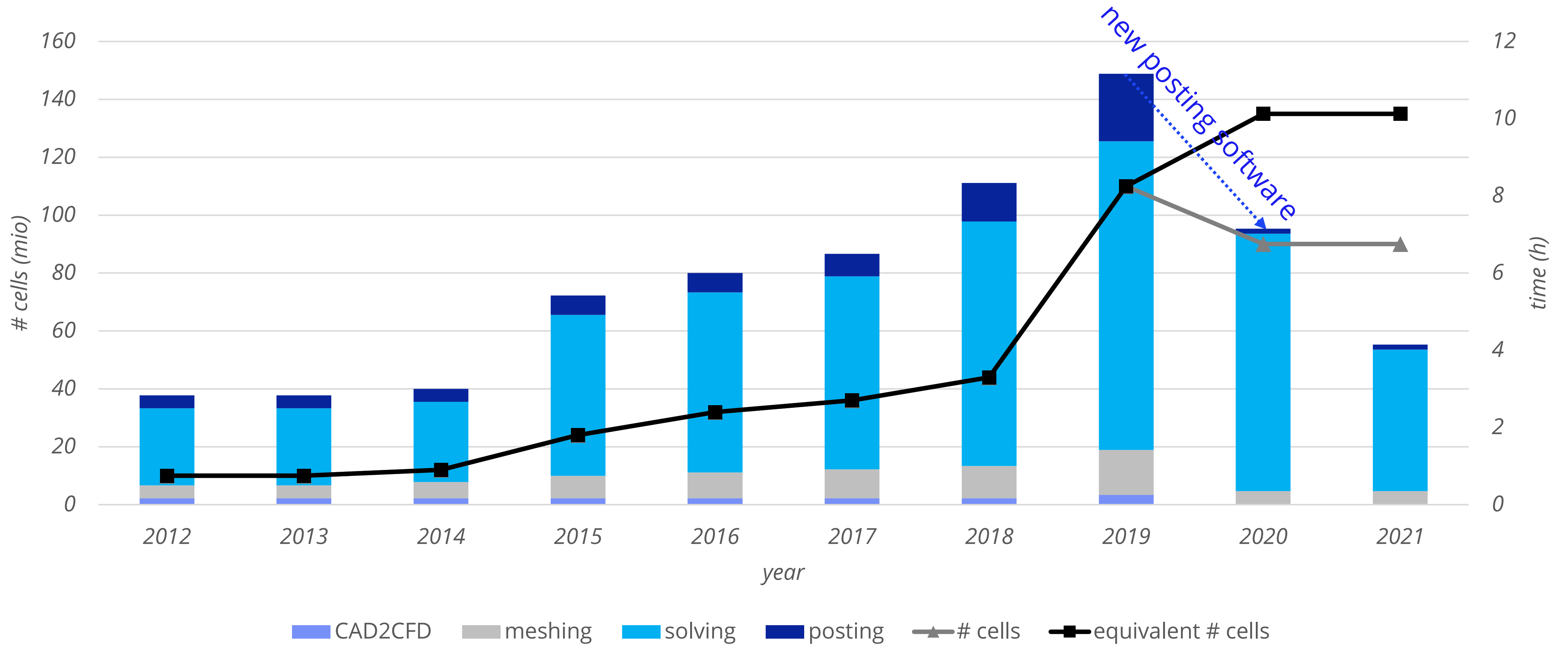
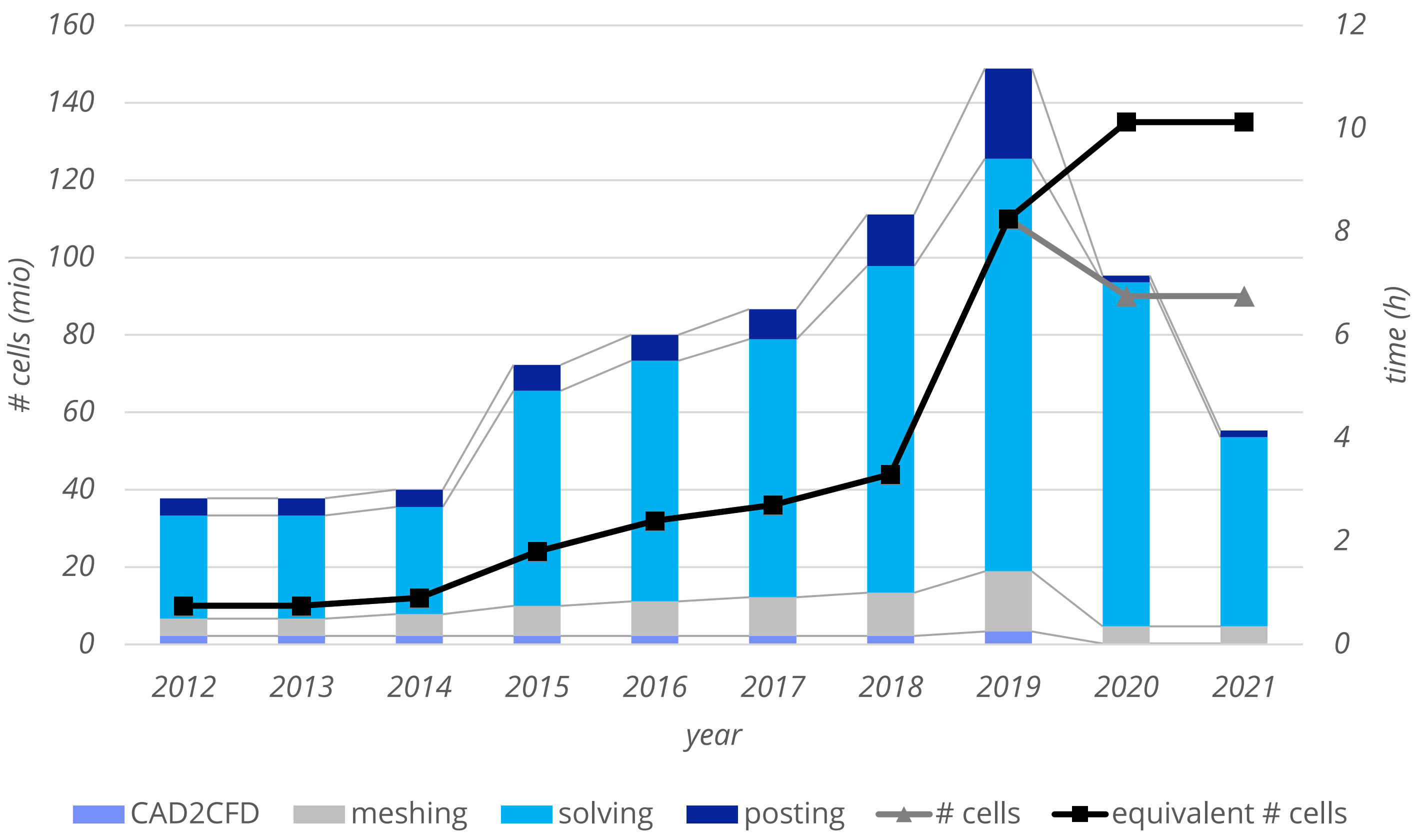


OPTIMIZING THE CFD PROCESS

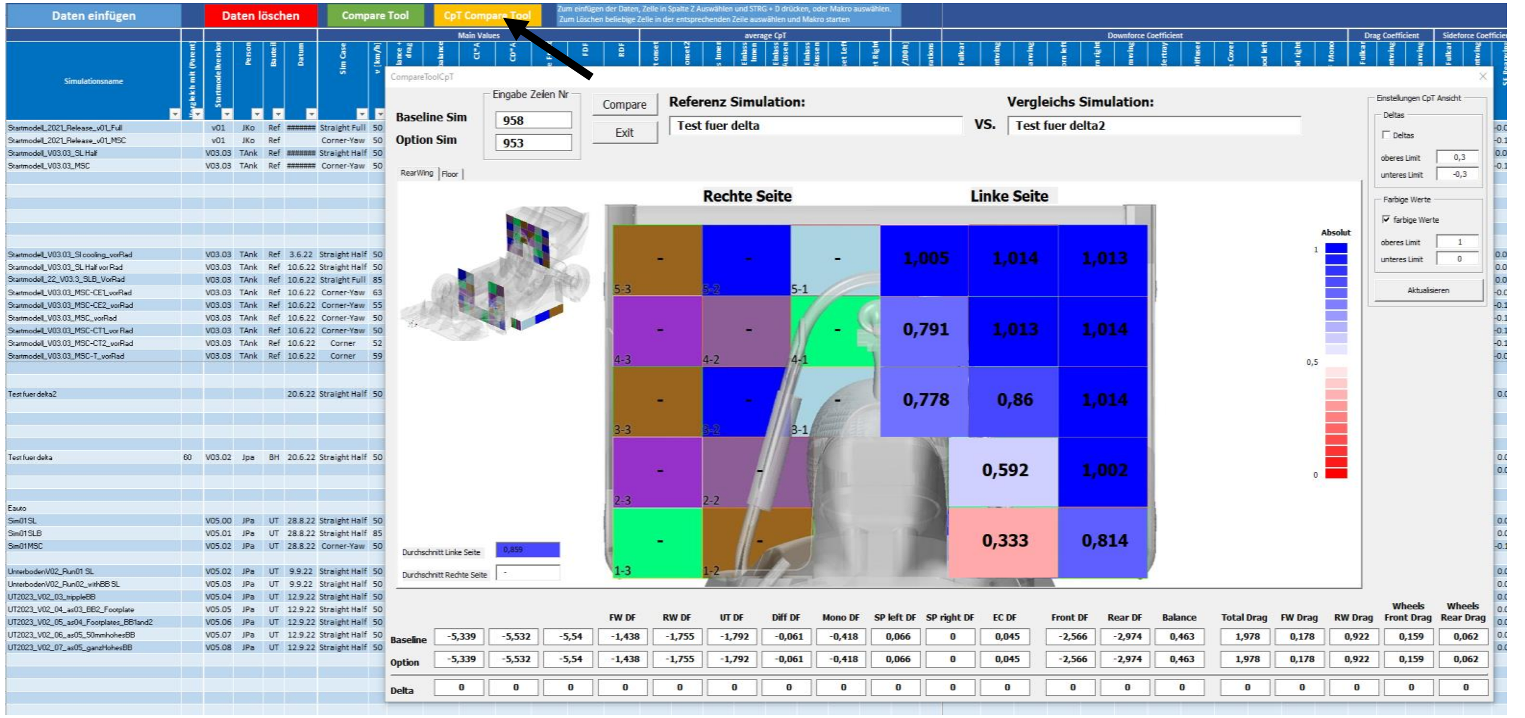
Improving the Tool Kit

- Focus on where you can improve the most
- Invest time & assign members to the process
- Make things easy for future generations



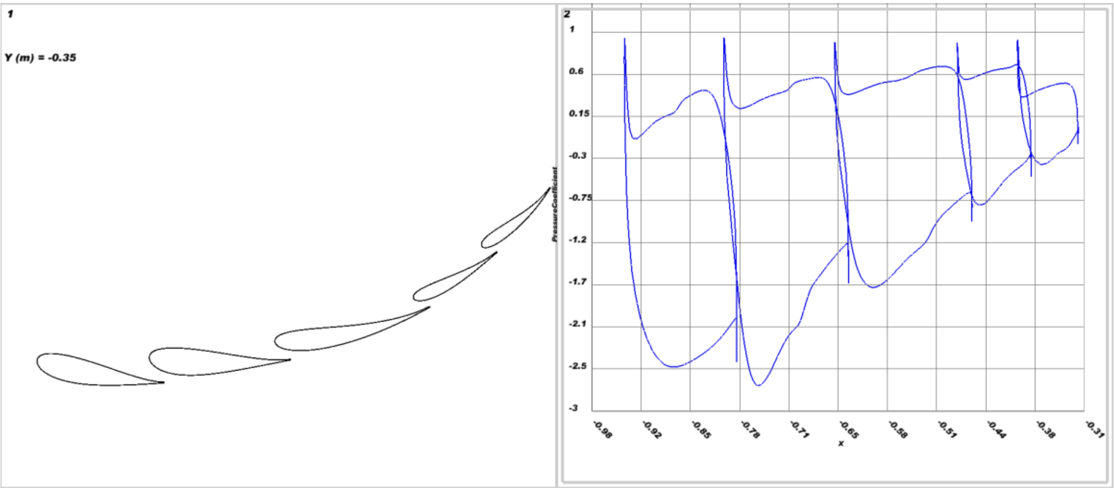
OPTIMIZING THE CFD VISUALIZATION

- Report the simulations and compare them
- Use simple techniques to allow a first conclusion



OPTIMIZING THE CFD VISUALIZATION

- Report the simulations and compare them
- Use simple techniques to allow a first conclusion
- Use delta plots to highlight flow field and pressure deltas
- Slice geometry and plot Cp distribution



OPTIMIZING THE CFD VISUALIZATION

Off-surface data:

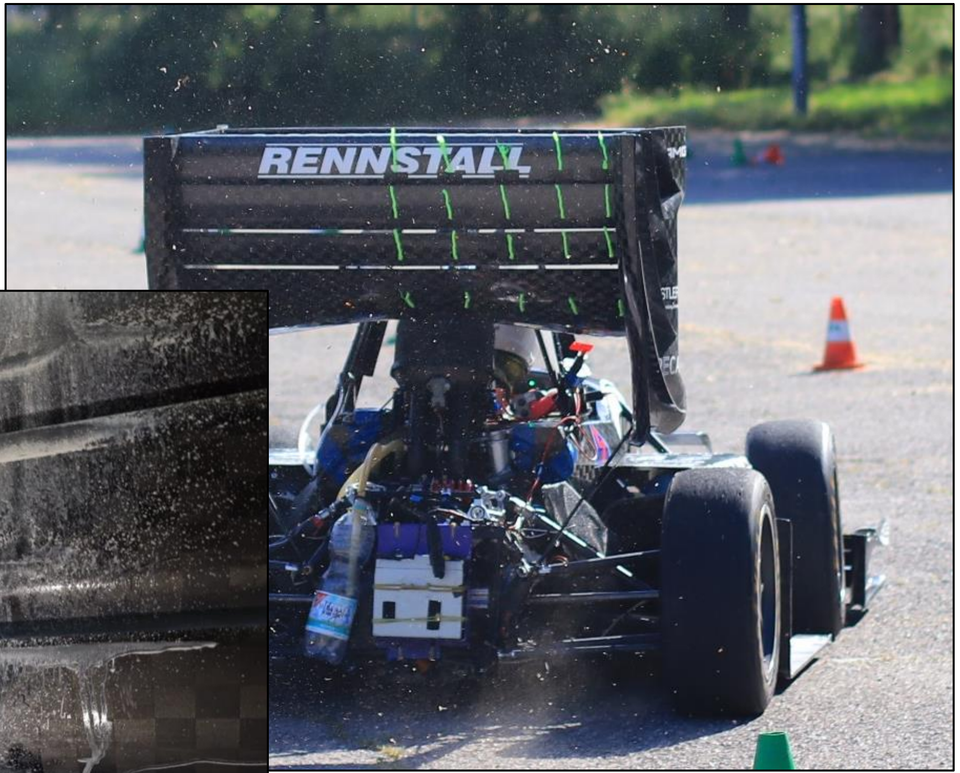
- Focus on energy content of air (total pressure → CpT)
- Use mainly x-slices to understand the flow field
- Additionally use static pressure (Cp) and vortex visualization (~~vorticity~~, Q-criterion, Lambda2-criterion, Rotex, …)
- Velocity vectors

Surface data:

- Static pressure
- Streamlines
- Wall shear stress

TESTING & VALIDATION

- Wool Tufts
- Flow Vis paint
- Spring travel → downforce
- Coasting test → drag
- Pressure Tapping
- Rake



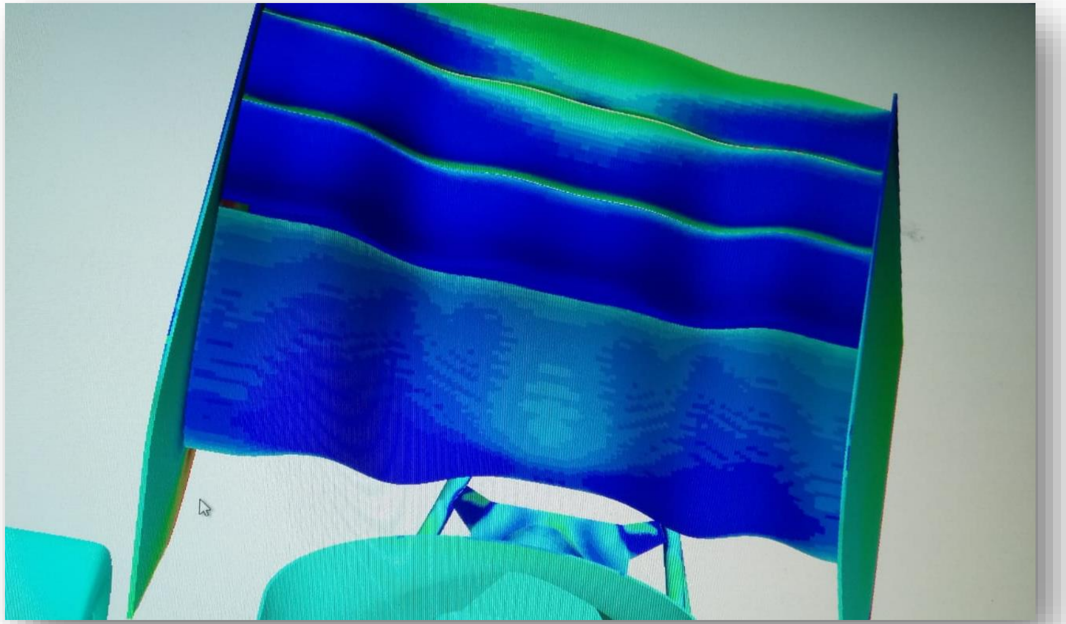
Greenteam Uni Stuttgart

COMMON FORMULA STUDENT MISTAKES

COMMON FORMULA STUDENT MISTAKES

CFD

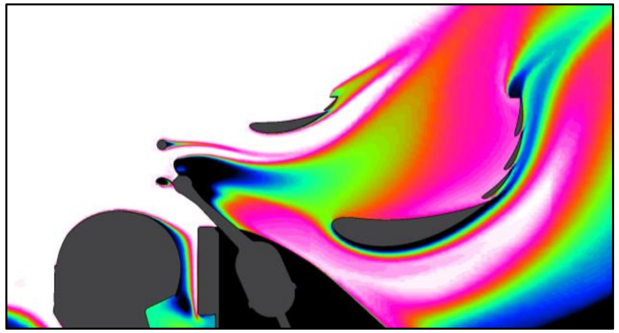
- High wall y^+ for the whole car
  - → Use high Reynolds approach where you don’t need to fully resolve the boundary layers
  - → Low Reynolds approach only where you really need it (suction surfaces of wings etc.)
- low quality CFD simulations (< 20 mio cells for fullcar simulation)
  - → Be aware of possible issues, do not assume you get the right solution
  - → Perform a mesh study
  - → Compare your results with a better resolved flow field
  - → Only refine where it is really necessary
  - → Can you use different mesh settings for developing different areas on the car?
- 2D simulations
  - → A race car is 3D!
  - → You can not even develop a front wing profile in clean flow in 2D
  - → You can use 2D to understand fundamentals of airfoils etc. but not to develop components for your car
- Transient simulations (RANS)
  - → Focus on improving your steady-state simulation first
  - → Transient simulations should use at least DES approach
  - → Use a finer mesh for DES. This still does not give you the real flow field



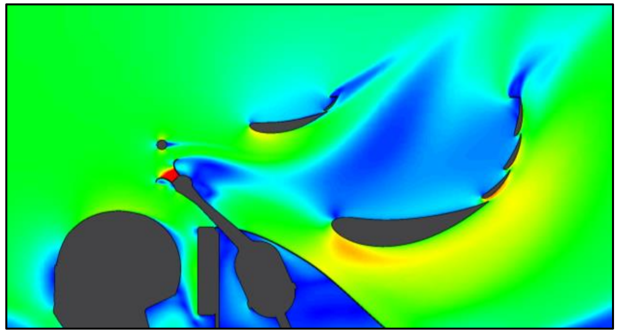
COMMON FORMULA STUDENT MISTAKES

CFD

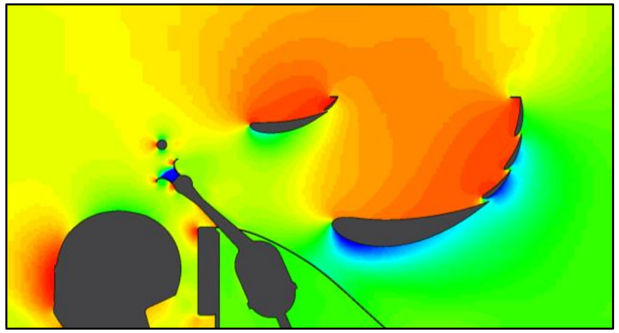
- Validate the simulations
  - → Use at least wool tufts to make sure your wings don't separate
  - → Wool tufts and flow viz on pressure sides is useless
  - → Validation is not something you only do for the engineering design event
- Make the most out of your CFD results
  - → Use the right flow variables for the visualization
  - → Are y-sections always the best?



Total Cp



Velocity

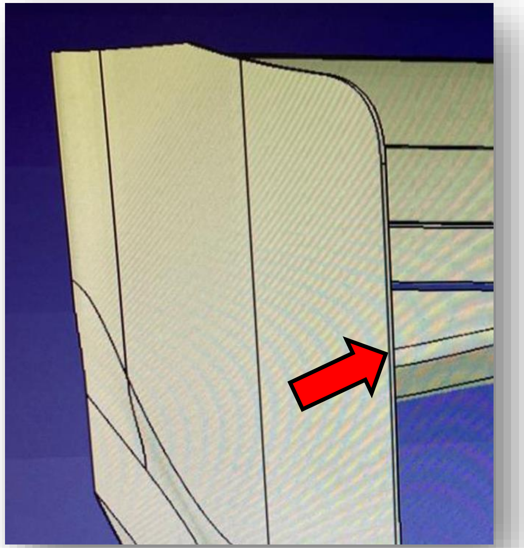


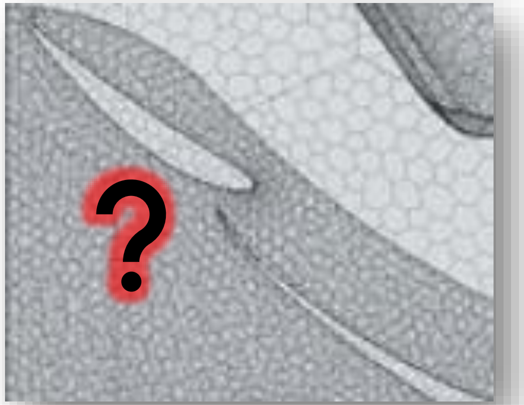
Cp

COMMON FORMULA STUDENT MISTAKES

Aero concept

- Define your design goals appropriately
  - → Lift/drag target
  - → Aero balance target
  - → Use lap time simulations or experience from previous years
  - → How much do you benefit from your aero?
  - → Do not copy from F1
- Do not design the car for straight ahead only
  - → imagine what will happen under yaw if you can not run cornering or yaw simulations
  - → Use wing profiles at leading edges of endplates
- Use the right wing profiles
  - → (high lift) airfoils from a online database are not designed for running in a multi element config or in close proximity to the ground
- Design your wing cascades properly
  - → Make sure there is a good reason to use more than one element
  - → Pay attention to the slot gaps. While designing them but also in manufacturing
- Integrate cooling into the aero package
  - → It is not something for the powertrain or battery guys
  - → Optimize your onset flow and manage the departing flow





THANK YOU!