

OPTIMISATION OF COMPLEX GEOMETRY BUILDINGS BASED ON WIND LOAD ANALYSIS

P5 Presentation
Erron Estrado | 4716116

INTRODUCTION

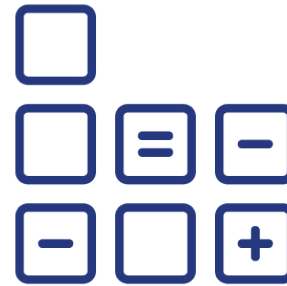
PROBLEM



More dangerous
and frequent
wind events



More complex
building shapes



Present
calculation
methods
insufficient



Calculations
done at late
stage

RESEARCH QUESTION

How can **computational methods** be used to accurately and efficiently calculate **wind load** on a **complex geometry** building and **optimise** the geometry to reduce wind responses in the **early design phase**?

SOLUTION

Parametric
Geometry + Computational
Fluid Dynamics
(CFD) + Finite Element
Analysis
(FEA) + Optimisation

Parametric
Geometry

+

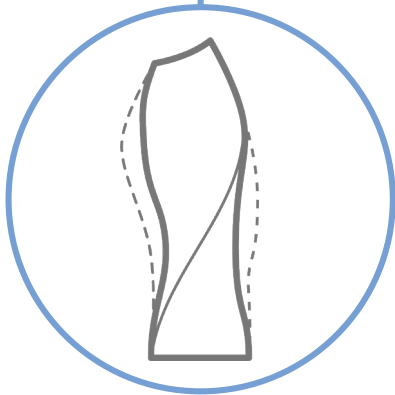
Computational
Fluid Dynamics
(CFD)

+

Finite Element
Analysis
(FEA)

+

Optimisation



Parametric
Geometry

+

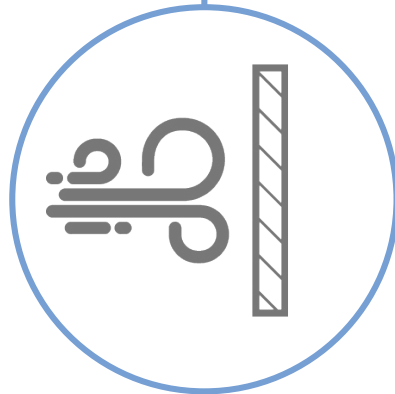
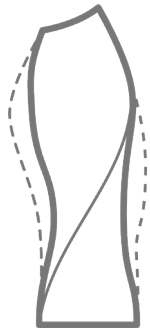
Computational
Fluid Dynamics
(CFD)

+

Finite Element
Analysis
(FEA)

+

Optimisation



Parametric
Geometry

+

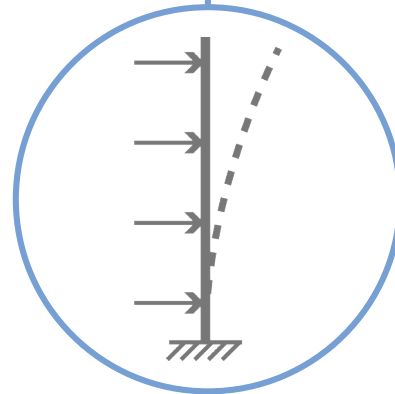
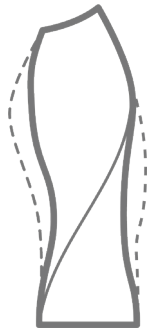
Computational
Fluid Dynamics
(CFD)

+

Finite Element
Analysis
(FEA)

+

Optimisation



Parametric
Geometry

+

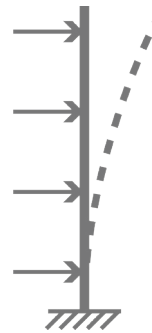
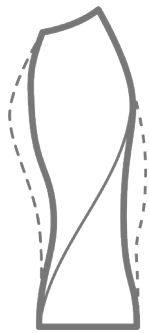
Computational
Fluid Dynamics
(CFD)

+

Finite Element
Analysis
(FEA)

+

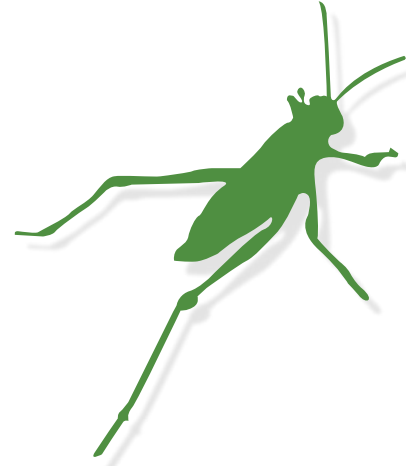
Optimisation



SOFTWARE USED



Rhinoceros 3D



Grasshopper

Well known to
architects/engineers

Parametric environment

Various plugins available

Custom coding/scripting

METHODOLOGY

RESEARCH

DEVELOP

VERIFY

RESEARCH

Wind flow in the environment

Wind actions on buildings

Calculation of wind loading

Computational Fluid Dynamics (CFD)

Fluid-Structure Interaction (FSI)

Optimisation methods

DEVELOP

Select case study buildings

CFD validation and sensitivity analysis

Couple CFD to FEA to create FSI procedure

Incorporate optimisation and test problems

VERIFY

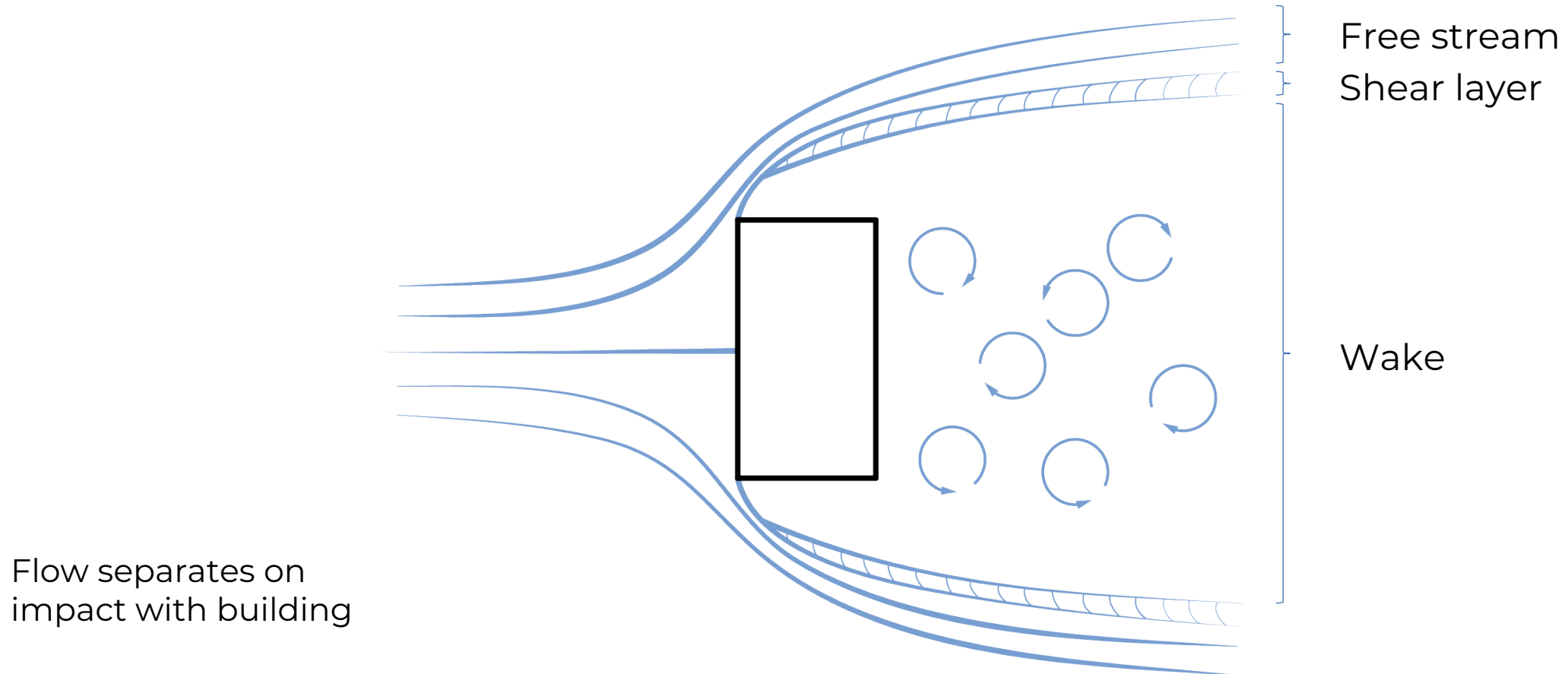
Calculate loading using FSI tool

Calculate loading using Eurocode

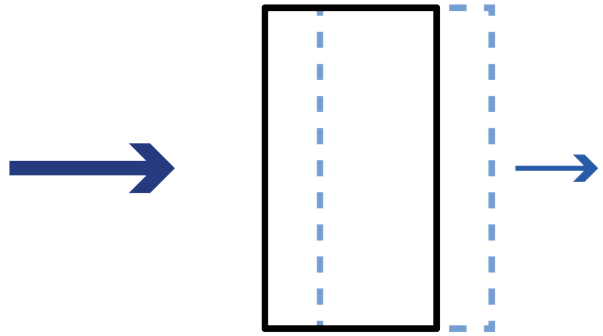
Compare results

RESEARCH

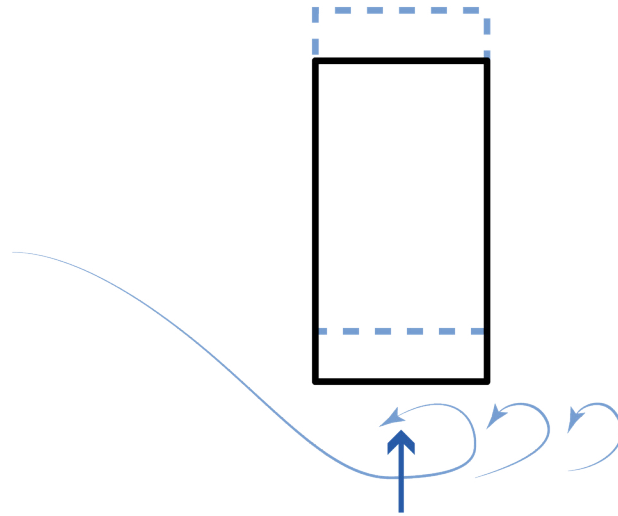
WIND FLOW AROUND A BUILDING



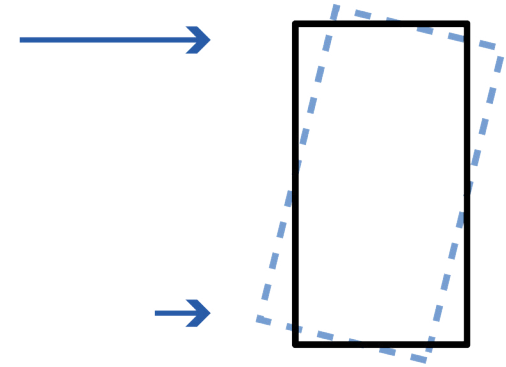
TYPES OF WIND LOADING



Along-wind

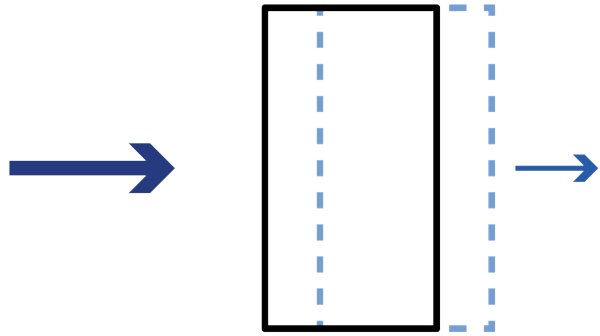


Cross-wind

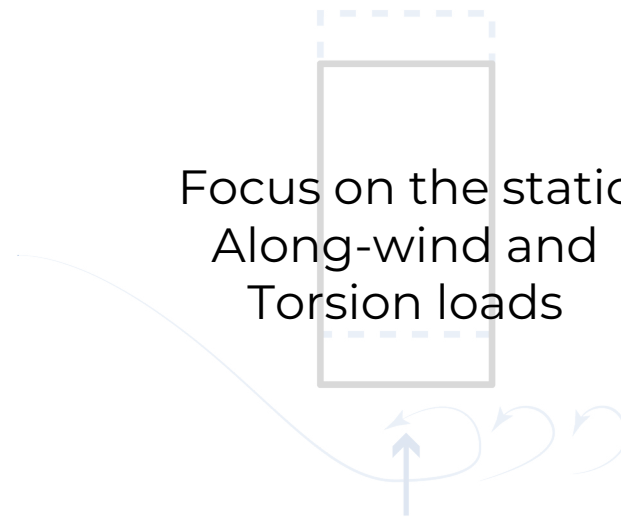


Torsion

TYPES OF WIND LOADING

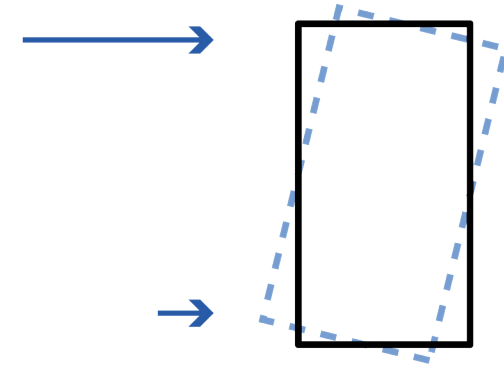


Along-wind



Focus on the static
Along-wind and
Torsion loads

Cross-wind



Torsion

STRATEGIES TO REDUCE WIND EFFECTS

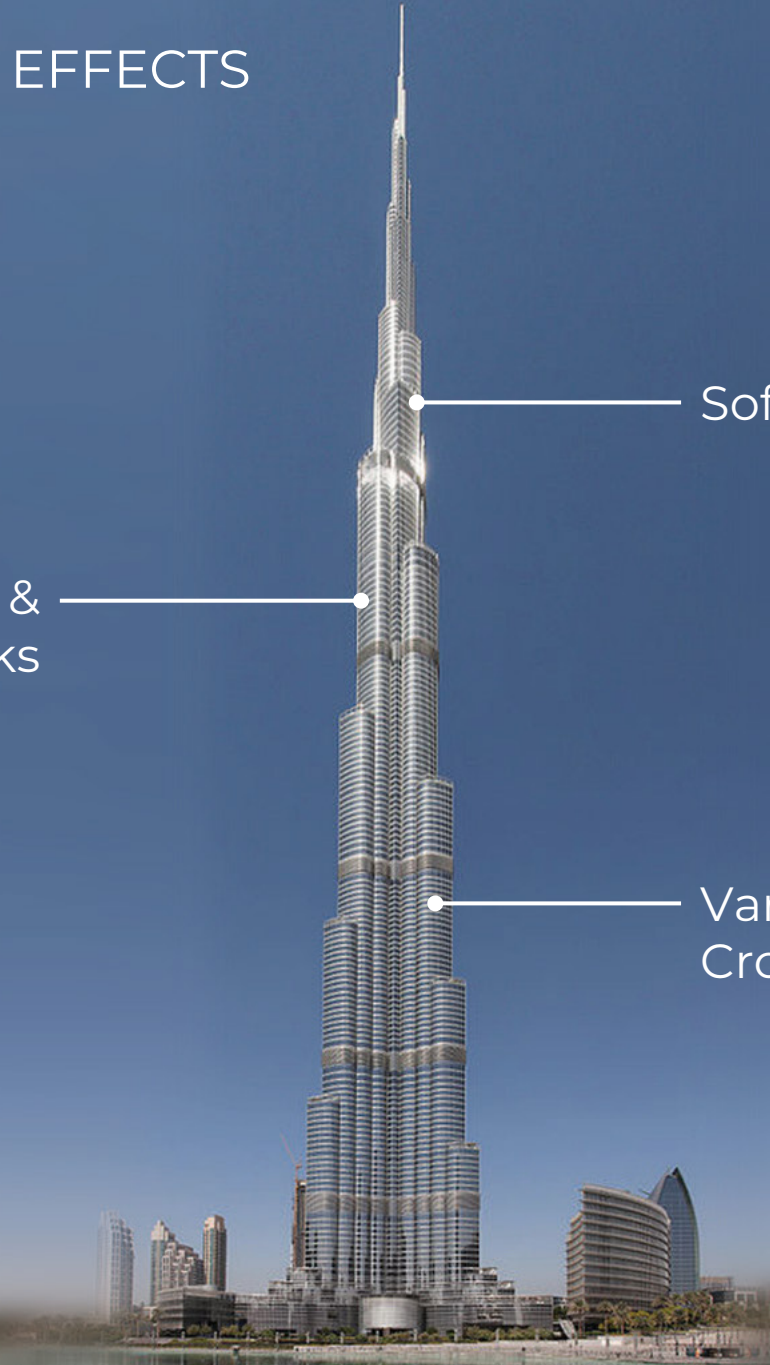
Burj Khalifa
by SOM

Tapering &
Setbacks

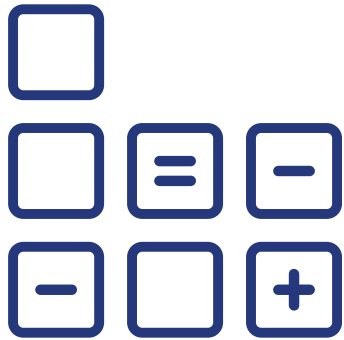
Softened Corners

Varying
Cross-section

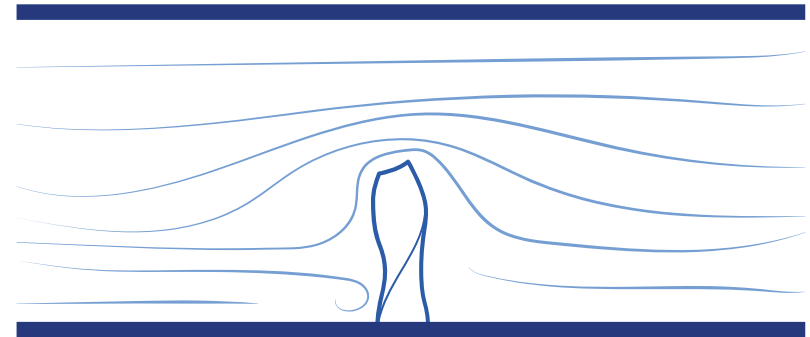
Based on
experience and
educated guessing



CALCULATION OF WIND LOADING



Eurocode calculations



Wind tunnel tests

EN1991-1-4:2005;
Eurocode 1: Actions on structures - Part 1-4:
General actions - Wind Actions



Applicable National Annex:

Netherlands National Annex to
EN1991-1-4:2005

Calculation of Wind Load

Wind force

Force coefficient

Reference area

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$$

Structural factor

Peak velocity pressure

The diagram illustrates the components of the wind load calculation equation. It features the equation $F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$ centered on the page. Above the equation, three labels are positioned: 'Wind force' above the first term, 'Force coefficient' above the second term, and 'Reference area' above the last term. Below the equation, two labels are positioned: 'Structural factor' below the third term and 'Peak velocity pressure' below the fourth term. Vertical blue lines connect each label to its corresponding term in the equation.

Calculation of Wind Load

$$c_s c_d = \frac{1 + 2 \cdot k_p \cdot I_v(z_s) \sqrt{B^2 + R^2}}{1 + 7 \cdot I_v(z_s)}$$

$$k_p = \sqrt{2 \cdot \ln(v \cdot T)} + \frac{0.6}{\sqrt{2 \cdot \ln(v \cdot T)}}$$

$$I_v(z) = \frac{k_I}{c_0(z) \cdot \ln\left(\frac{z}{z_0}\right)}$$

$$B^2 = \frac{1}{1 + \frac{3}{2} \cdot \sqrt{\left(\frac{b}{L(z_s)}\right)^2 + \left(\frac{h}{L(z_s)}\right)^2 + \left(\frac{b}{L(z_s)} \cdot \frac{h}{L(z_s)}\right)^2}}$$

$$L(z) = L_t \cdot \left(\frac{z}{z_t} \right)^\alpha$$

$$\alpha = 0.67 \cdot 0.05 \ln(z_0)$$

$$\delta = \delta_s + \delta_a + \delta_d$$

$$\phi_y = \frac{c_y \cdot b \cdot n}{v_m(z_s)}$$

$$K_S(n) = \frac{1}{1 + \sqrt{(G_y \cdot \phi_y)^2 + (G_z \cdot \phi_z)^2 + \left(\frac{2}{\pi} \cdot G_y \cdot \phi_y \cdot G_z \cdot \phi_z\right)^2}}$$

$$c_f = c_{f,0} \cdot \psi_\lambda$$

$$Re = \frac{b \cdot v(z_e)}{v}$$

$$f_L(z, n) = \frac{n \cdot L(z)}{v_m(z)}$$

$$q_p(z) = (1 + 7 \cdot I_v(z)) \cdot 1/2 \cdot \rho \cdot v_m^2(z)$$

$$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b$$

$$k_r = 0.19 \cdot \left(\frac{z_0}{0.05} \right)^{0.07}$$

$$c_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right)$$

$$v = n_{1,x} \sqrt{\frac{R^2}{B^2 + R^2}}$$

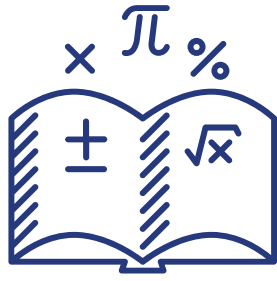
$$\delta_a = \frac{c_f \cdot \rho \cdot b \cdot v_m(z_s)}{2 \cdot n_1 \cdot m_e}$$

$$\phi_z = \frac{c_z \cdot h \cdot n}{v_m(z_s)}$$

$$R^2 = \frac{\pi^2}{2 \cdot \delta} \cdot S_L(z_s, n_{1,x}) \cdot K_S(n_{1,x})$$

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$$

EN1991-1-4:2005 + NA



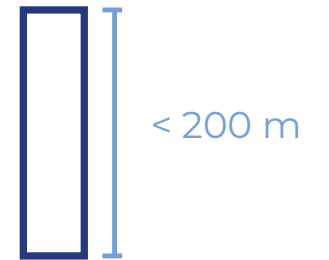
Complex
calculation



No visual
feedback



Only standard
shapes

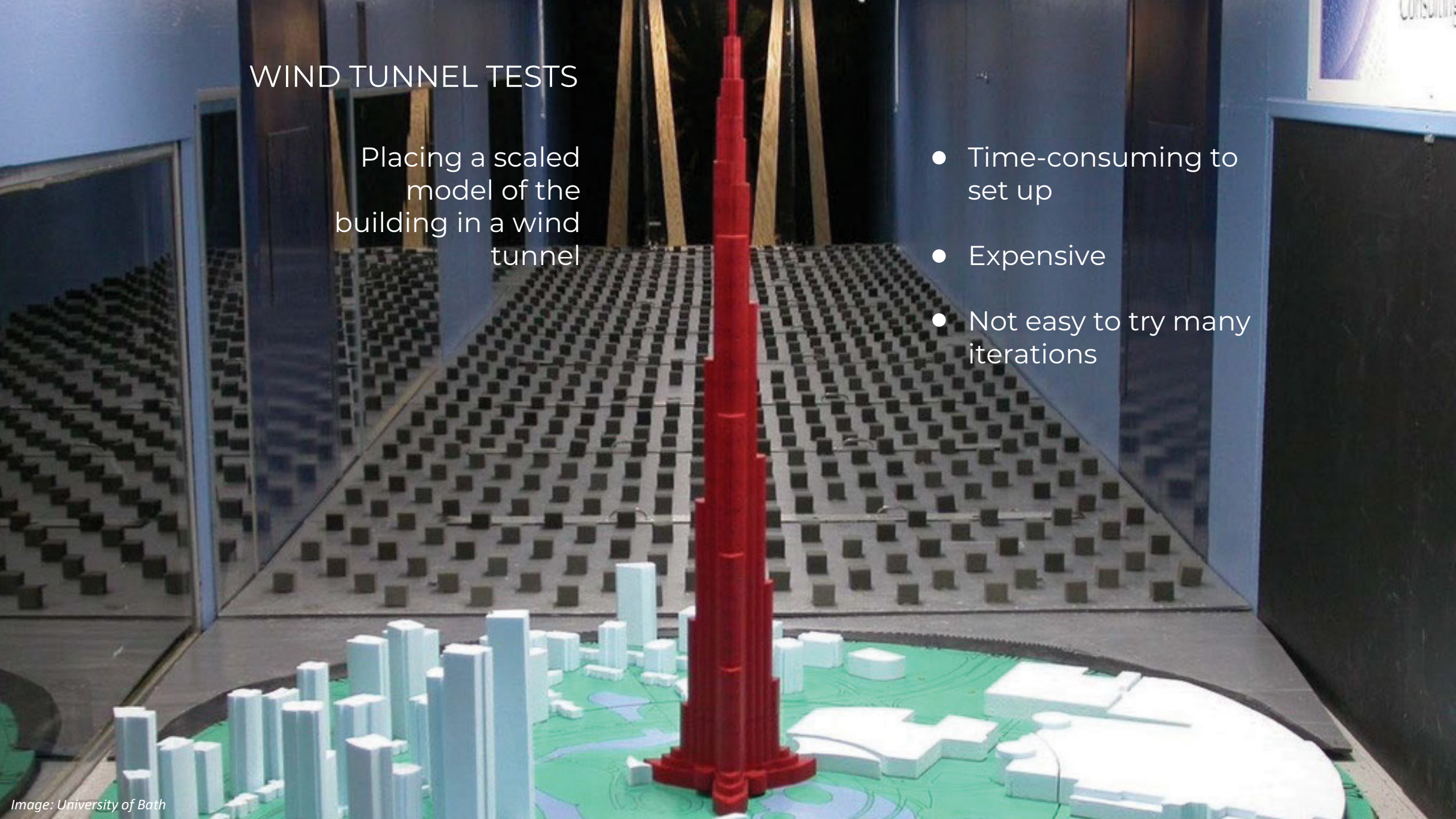


Max 200m height

WIND TUNNEL TESTS

Placing a scaled model of the building in a wind tunnel

- Time-consuming to set up
- Expensive
- Not easy to try many iterations



FLUID DYNAMICS

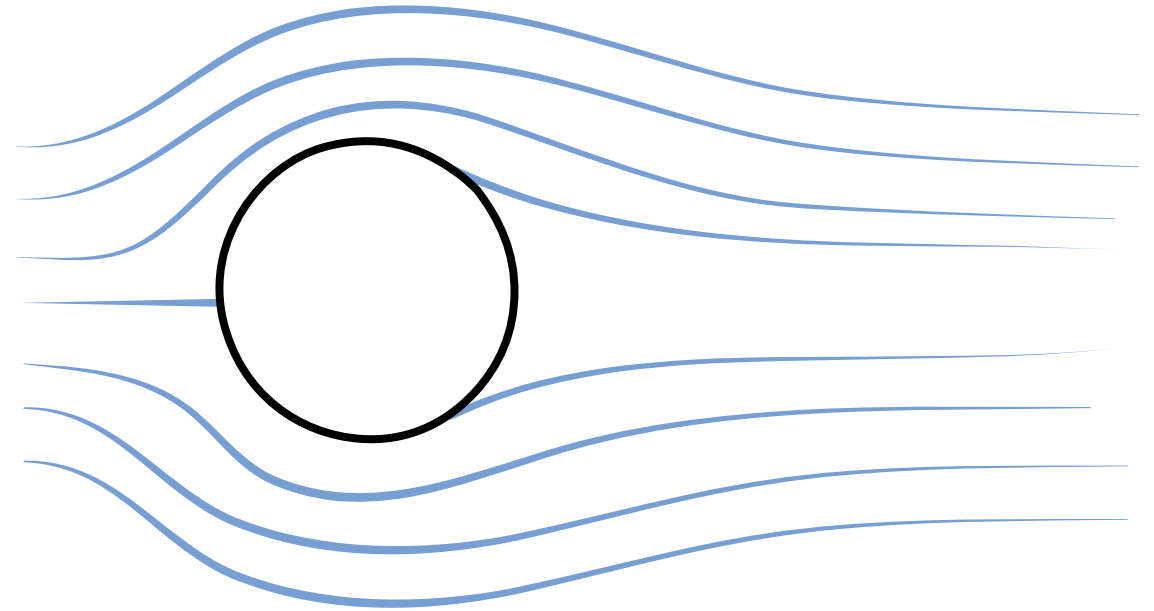
Study of the motion of fluids and the forces acting on them.

Described by:

Navier-Stokes equations

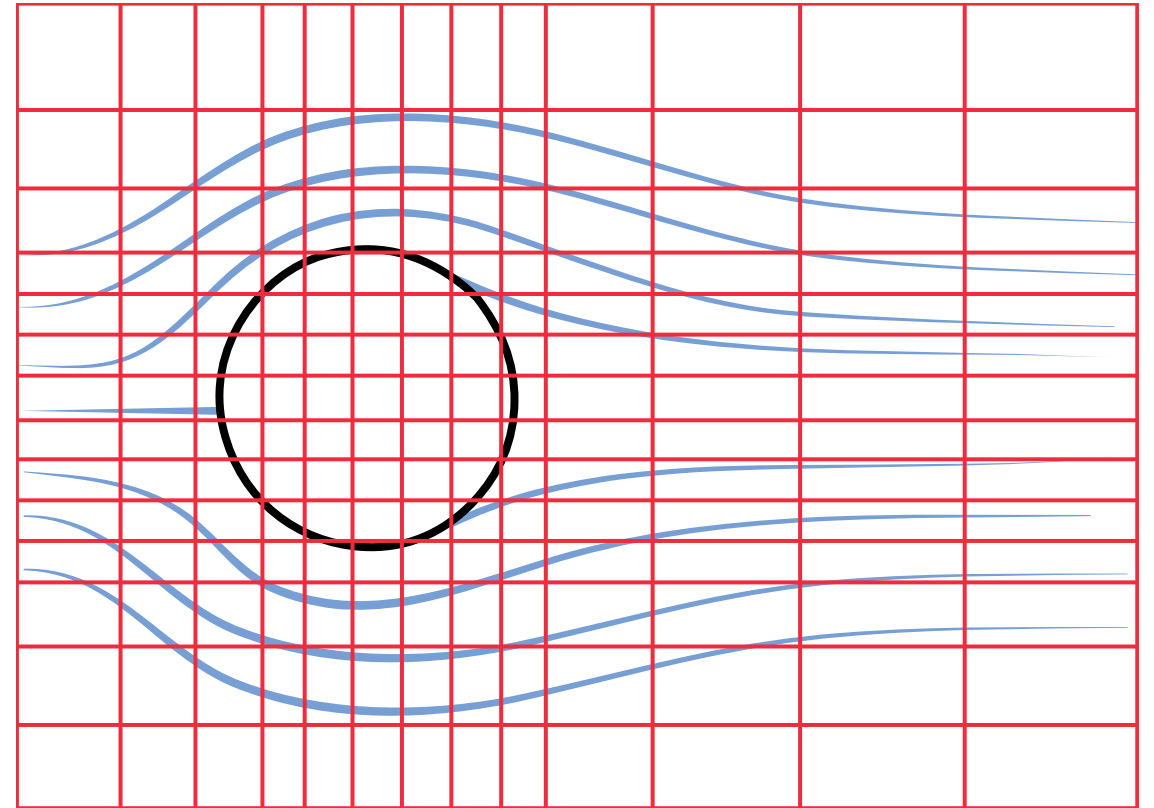
$$\frac{\partial u}{\partial t} + u \cdot \nabla u = \frac{\nabla P}{\rho} + \nu \nabla^2 u$$

Partial differentials which cannot be solved implicitly



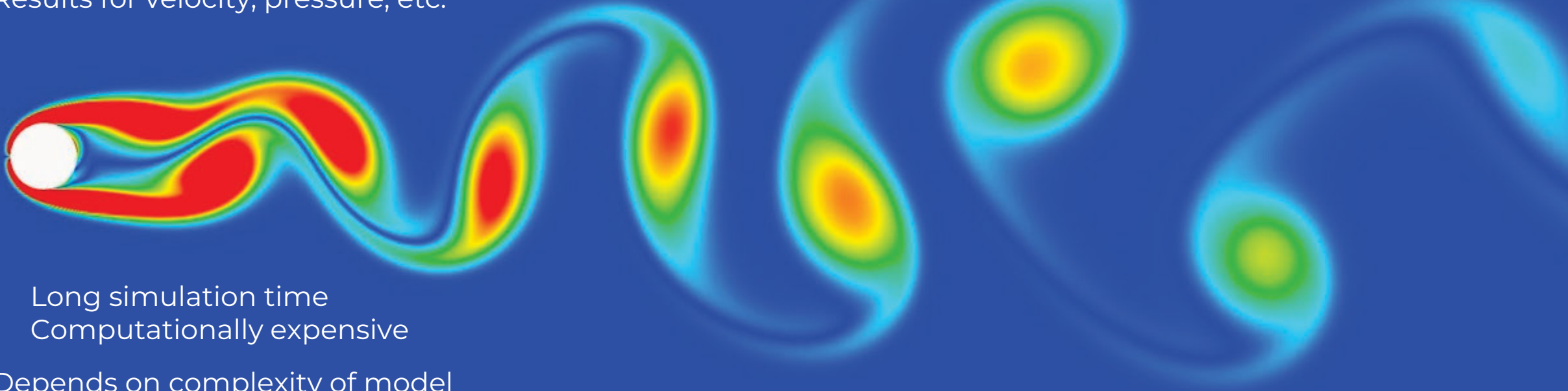
COMPUTATIONAL FLUID DYNAMICS (CFD)

The use of numerical methods to discretise and solve the Navier-Stokes equations per cell.



COMPUTATIONAL FLUID DYNAMICS (CFD)

Visual representation of fluid flow
Results for velocity, pressure, etc.



- Long simulation time
- Computationally expensive

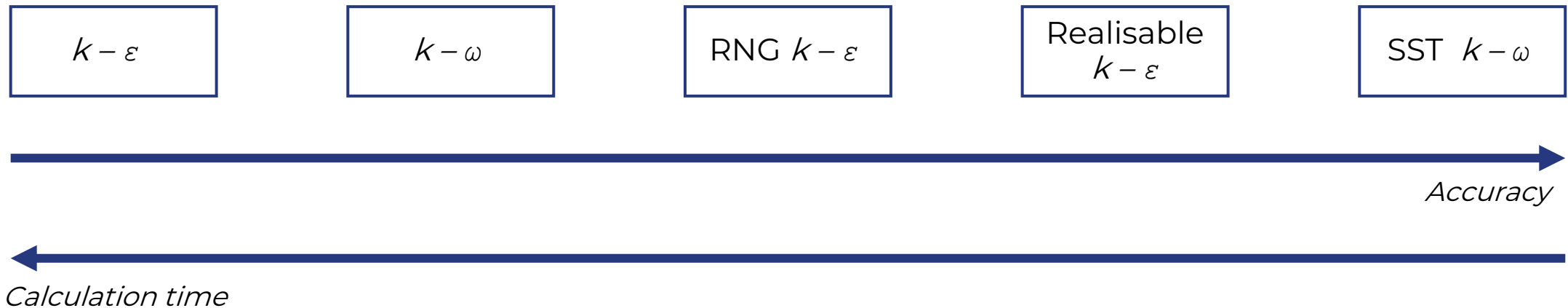
Depends on complexity of model
and settings used

TURBULENCE MODELS

Models the effects of small eddies of the flow instead of fully calculating them

RANS

Reynolds Averaged Navier-Stokes

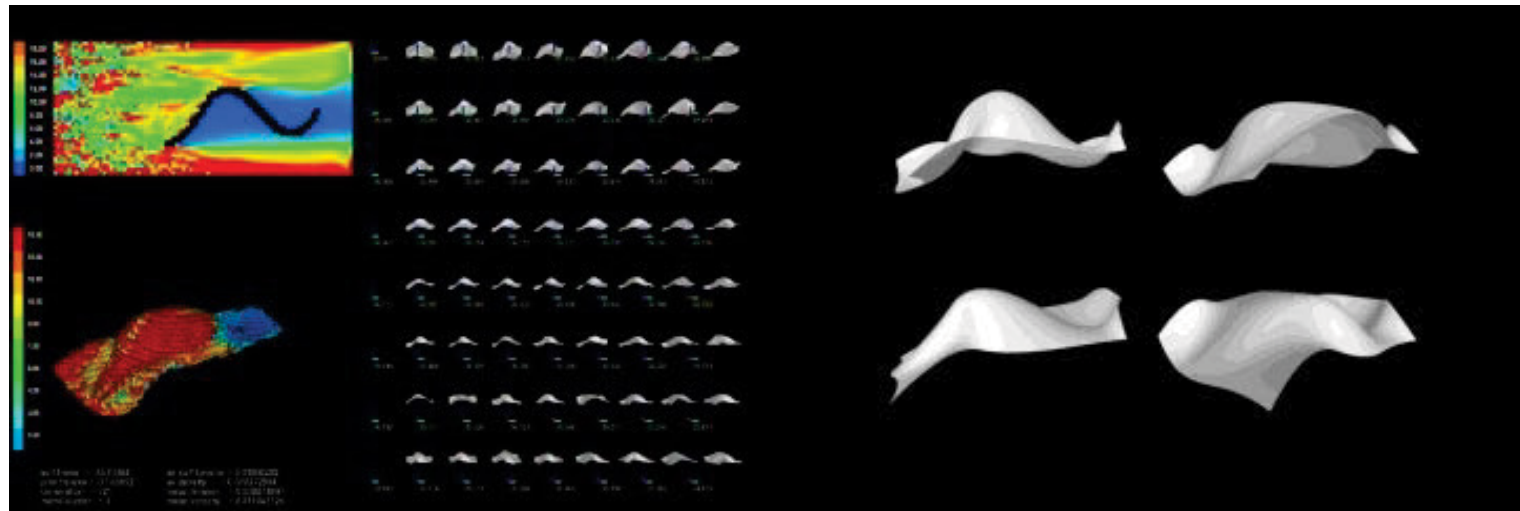


FAST FLUID DYNAMICS (FFD)

Developed for quicker CFD simulations in game design
Being explored for building problems

FASTER

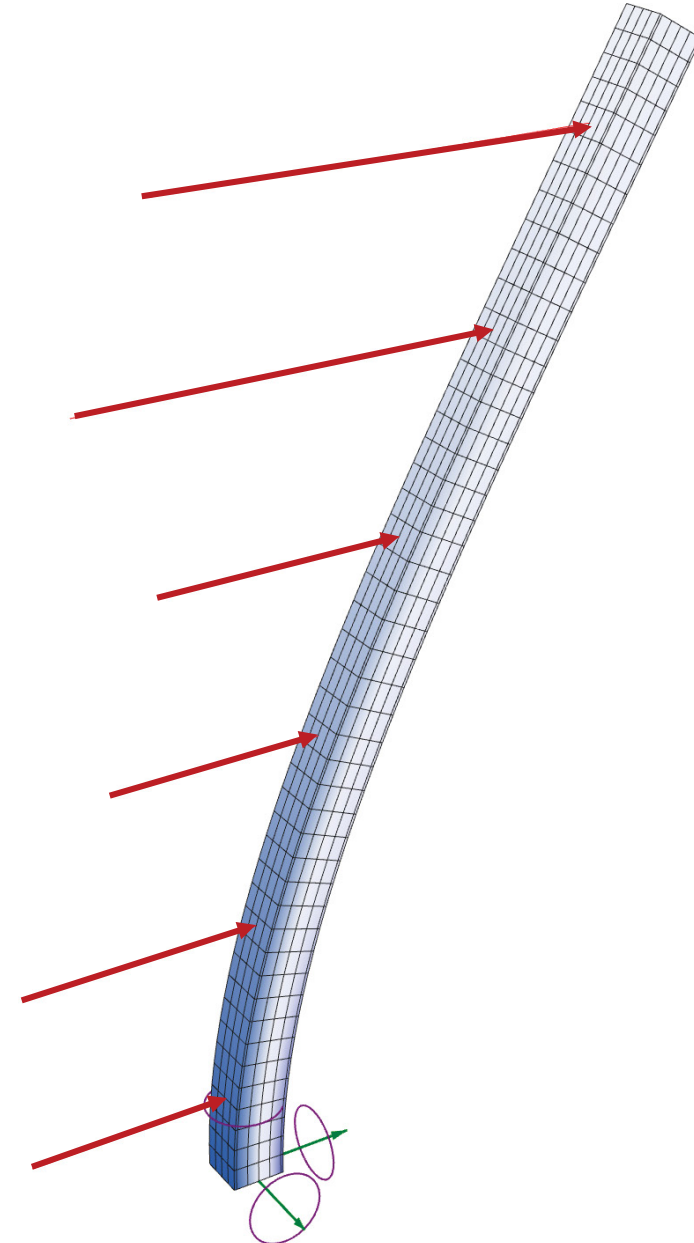
LESS ACCURATE



FINITE ELEMENT ANALYSIS (FEA)

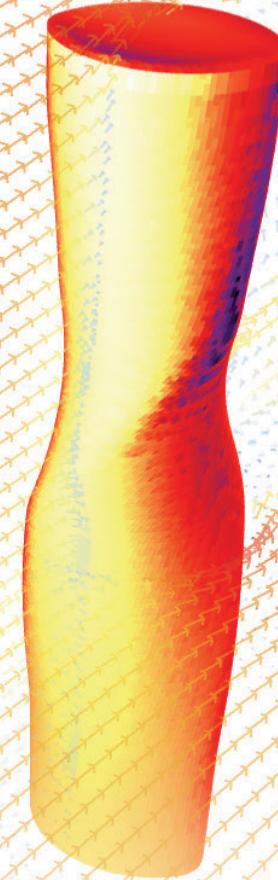
Algorithm to analyse the effect of forces on an object.
Discretizes object into a elements.

- Deflections
- Reaction forces
- Stresses

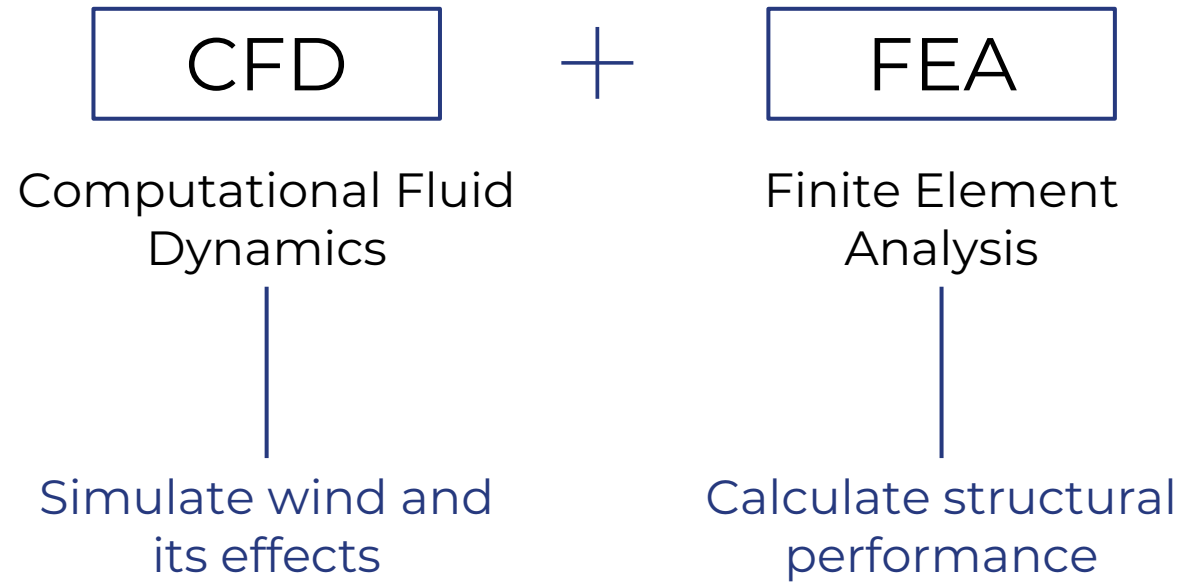


FLUID-STRUCTURE INTERACTION (FSI)

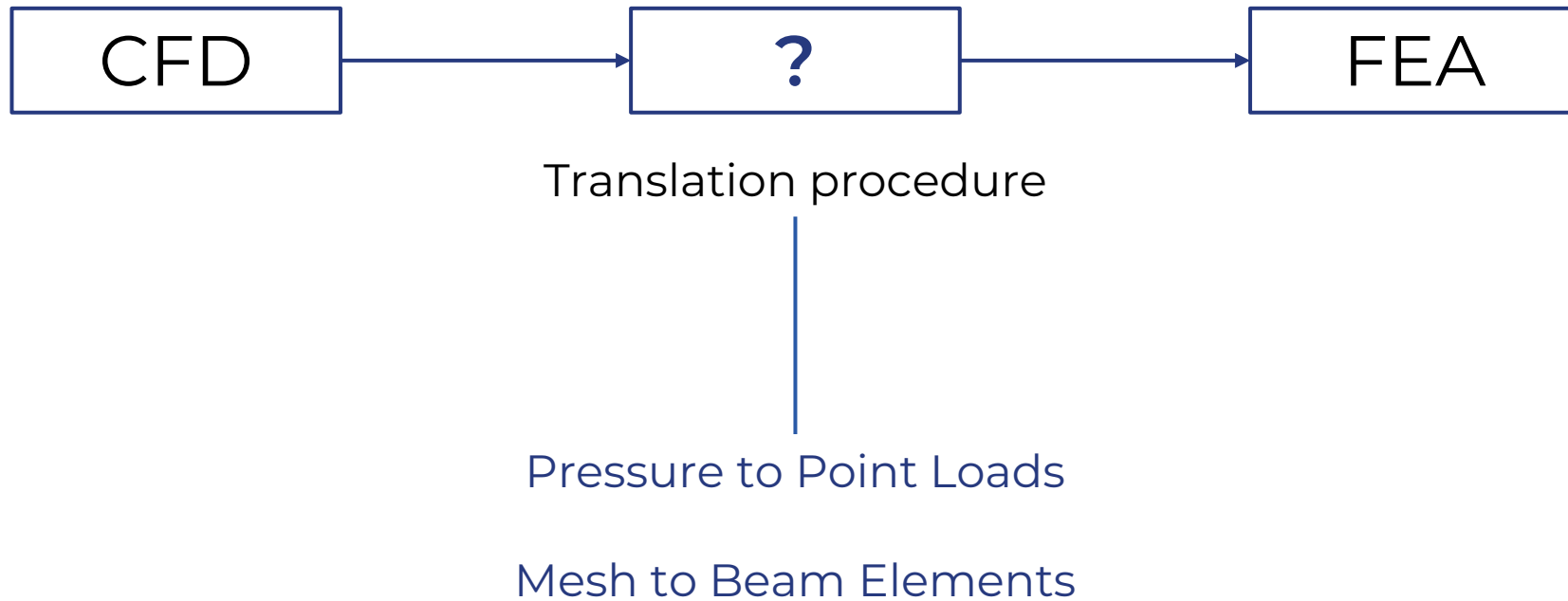
The analysis of the forces, deformations, and dynamic motions imposed on a body in a fluid flow



PARTITIONED FSI

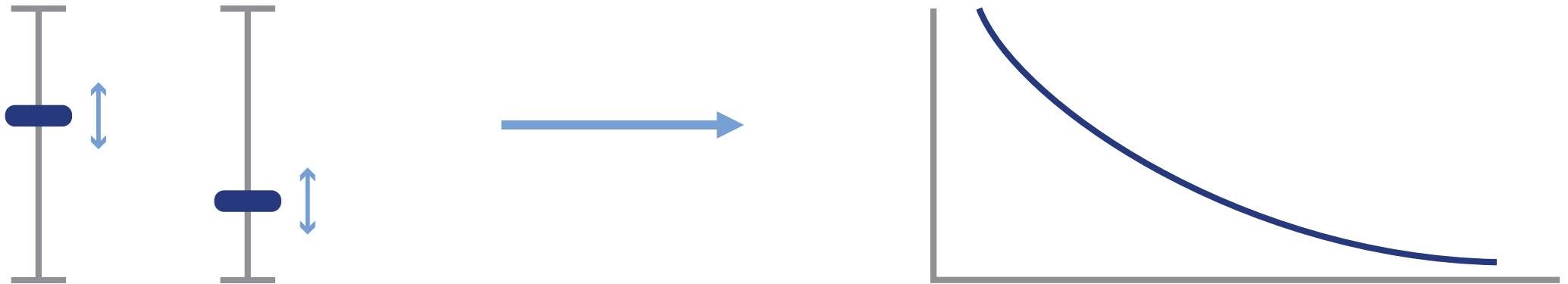


PARTITIONED FSI



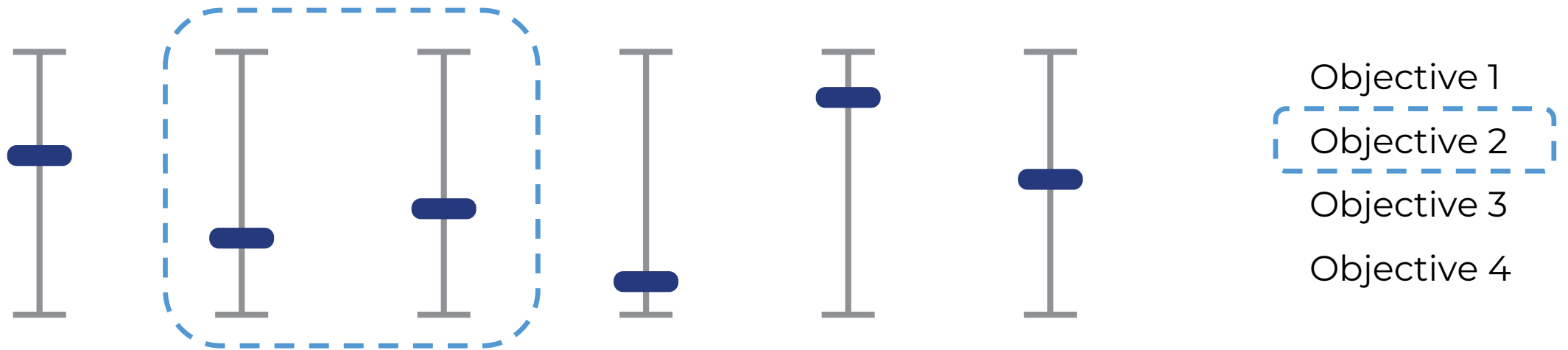
OPTIMISATION

The manipulating of input variables in order to minimise (or maximise) a certain output objective



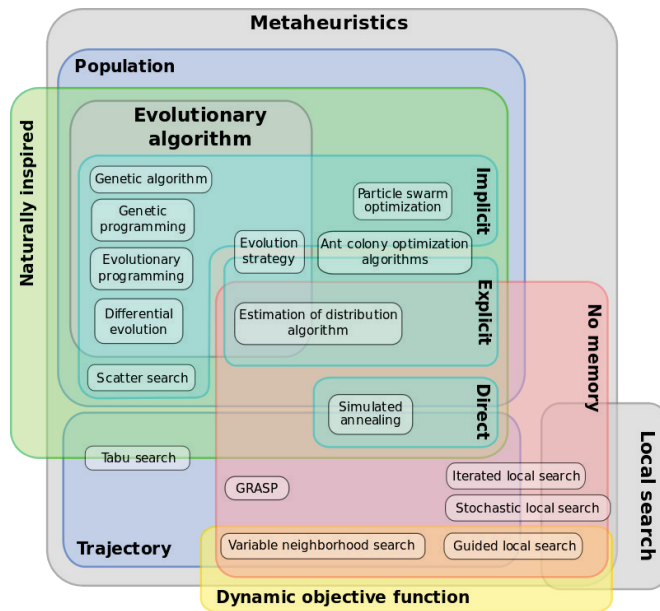
OPTIMISATION PROBLEM FORMULATION

It is important to choose the right combination of input variables and objective to ensure a meaningful optimisation



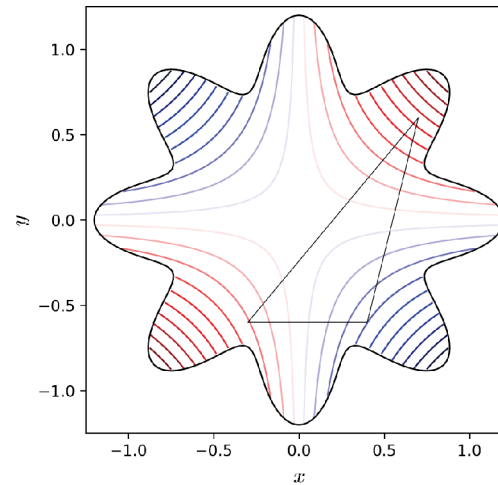
OPTIMISATION ALGORITHMS

Metaheuristics



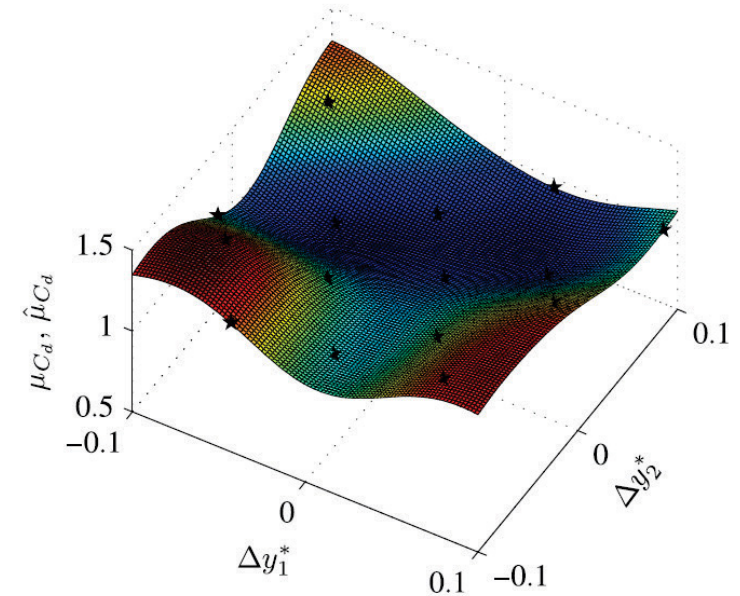
Based on natural processes

Direct Search



Successive explorations in a design space

Model-based



Uses machine learning or statistical methods

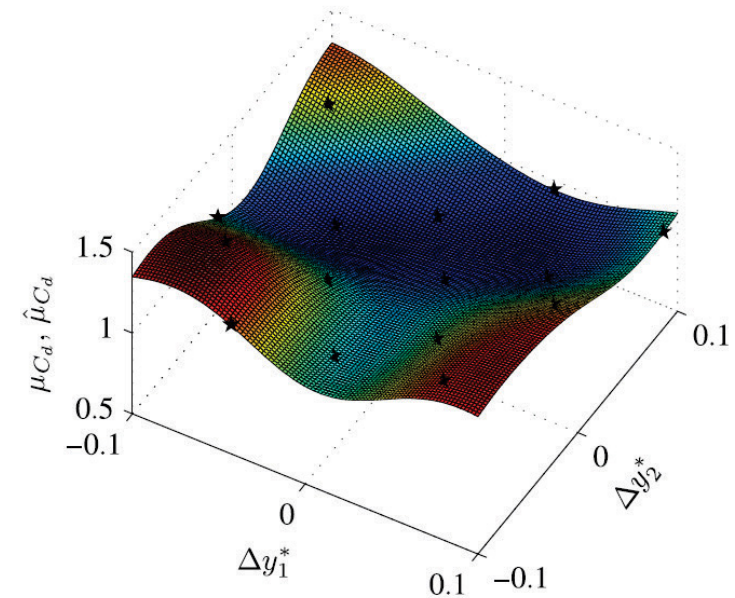
OPTIMISATION ALGORITHMS

Ideal for intensive
simulations such as
CFD

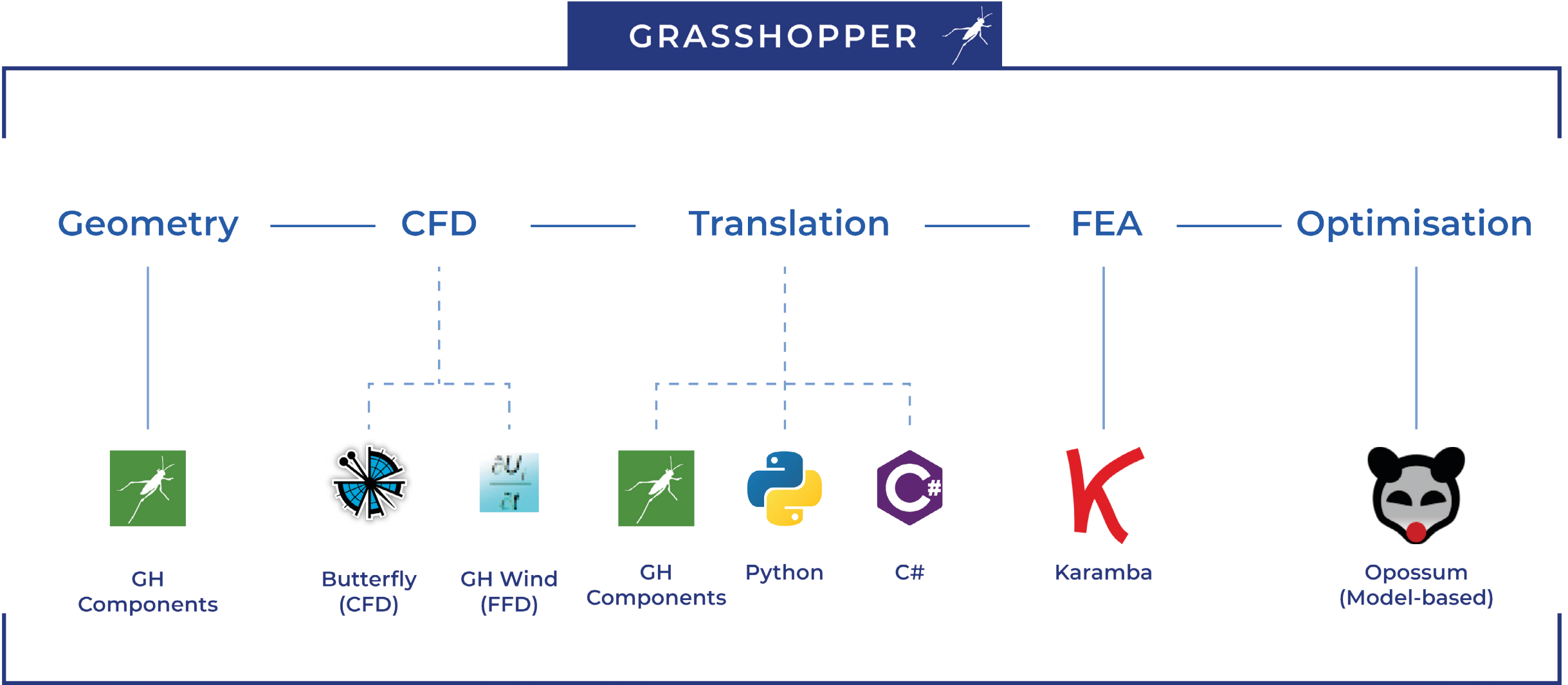
Converge in a low
number of iterations

Robust performance

Model-based



Uses machine learning or
statistical methods



DEVELOP

CASE STUDY BUILDINGS



A rendering of the Absolute Towers in Vancouver, showing two tall, curved skyscrapers with a blue glass facade and horizontal bands of windows. The towers are set against a cloudy sky, with a city street and other buildings visible in the background.

Absolute Towers
MAD Architects
© Iwan Baan



A rendering of the Jiangxi Nanchang Greenland Central Plaza, featuring two tall, curved skyscrapers with a blue glass facade. The buildings are set against a sunset sky, with a mountain visible in the background. The foreground shows a city street with cars and pedestrians.

Jiangxi Nanchang Greenland Central Plaza
SOM
© SOM



A rendering of the Ardmore Residence, showing a tall, white, curved skyscraper with a unique, sculptural facade. The building is set against a blue sky, with other city buildings visible in the background. The foreground shows a city street with cars and pedestrians.

Ardmore Residence
UN Studio
© Iwan Baan

CFD DEVELOPMENT PROCEDURE

SCRIPT SETUP

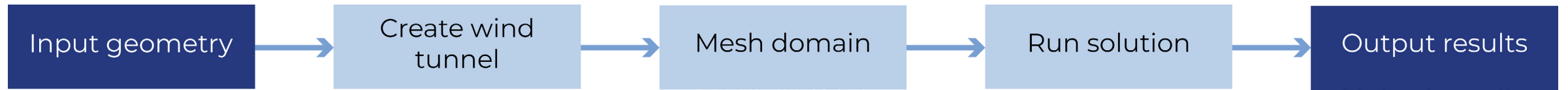


VALIDATION



SENSITIVITY
ANALYSIS

CFD WORKFLOW



AVAILABLE PLUGINS

**Butterfly**

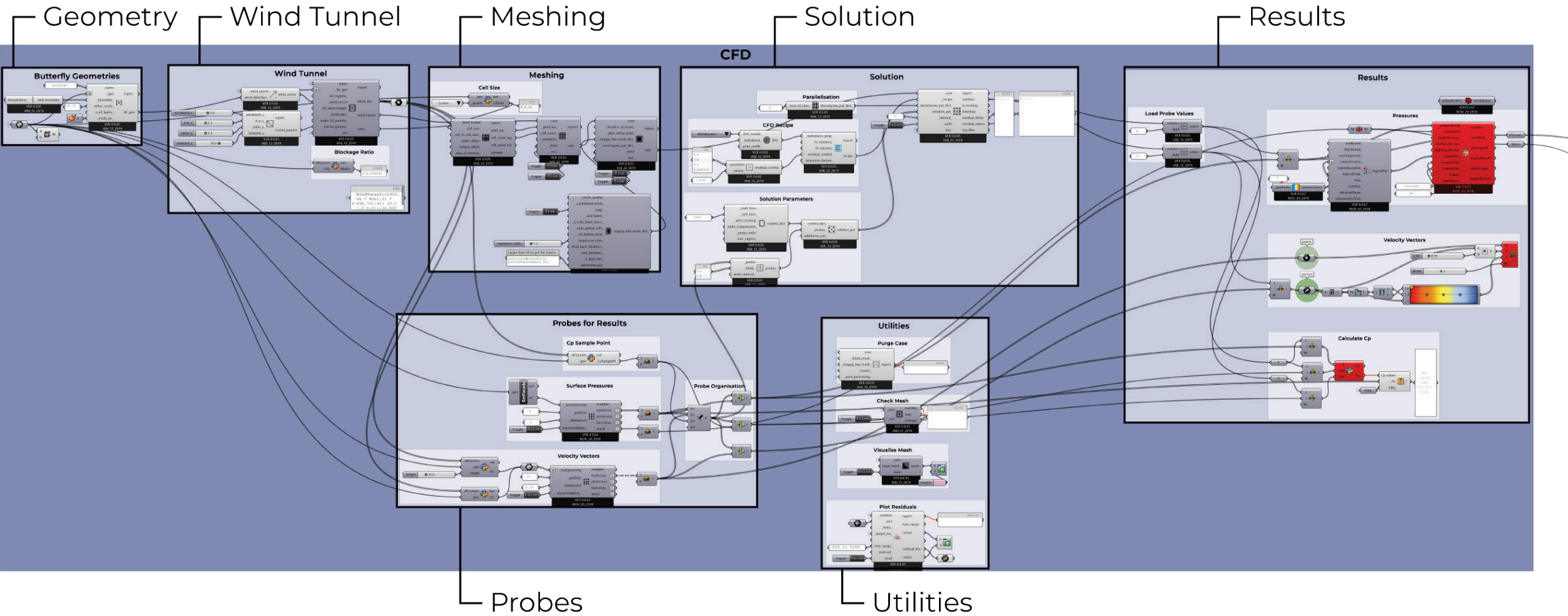
- Based on OpenFOAM widely used and validated
- Many settings for mesh and turbulence model
- Open source with active online community
- × Can be difficult to install and use

GH Wind

- Fast Fluid Dynamics in parametric Grasshopper environment
- Open source
- Easy to use
- × Fairly new and not widely used

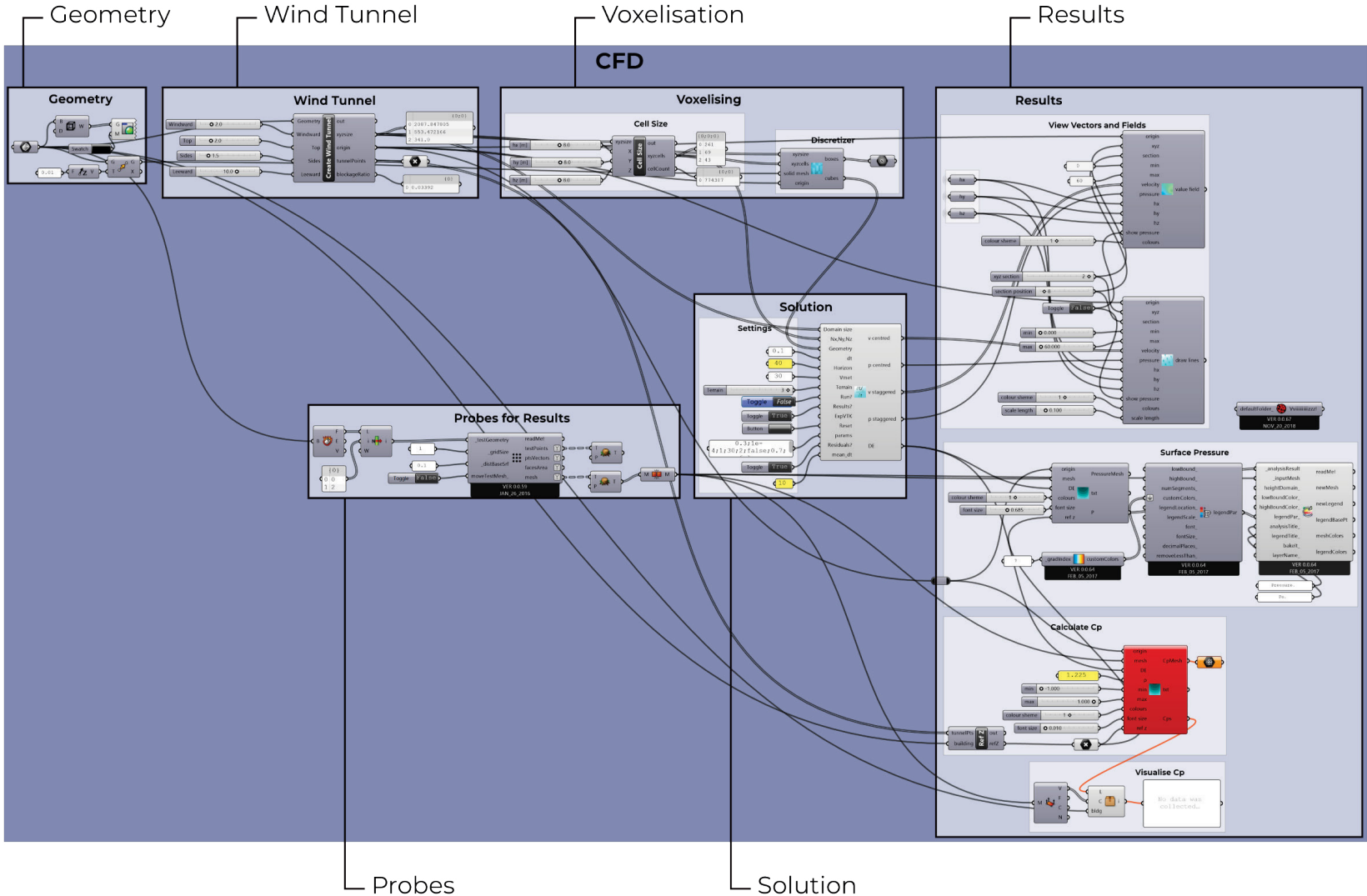


BUTTERFLY



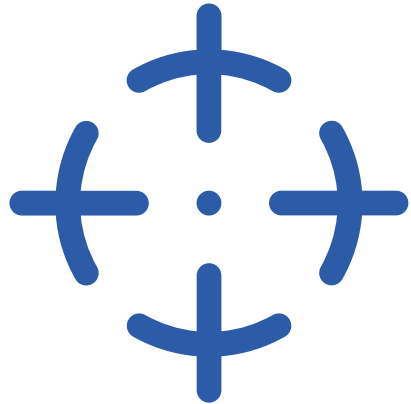
CFD Script Setup

GH WIND



CFD VALIDATION

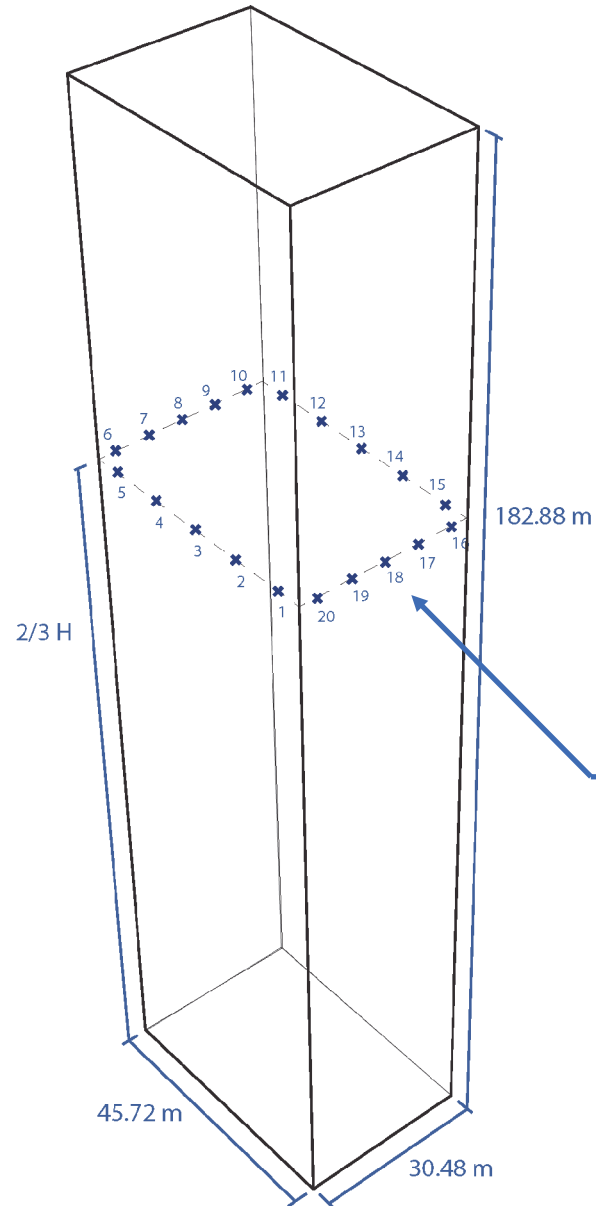
Compare CFD solvers to
physical wind tunnel tests to
evaluate:



Accuracy &
precision



Time



CAARC MODEL

- Standard high-rise model with wind tunnel results
- Compare pressure coefficient, C_p at 20 points

$$C_{p,i} = \frac{P_i - P_0}{0.5\rho U_0^2}$$

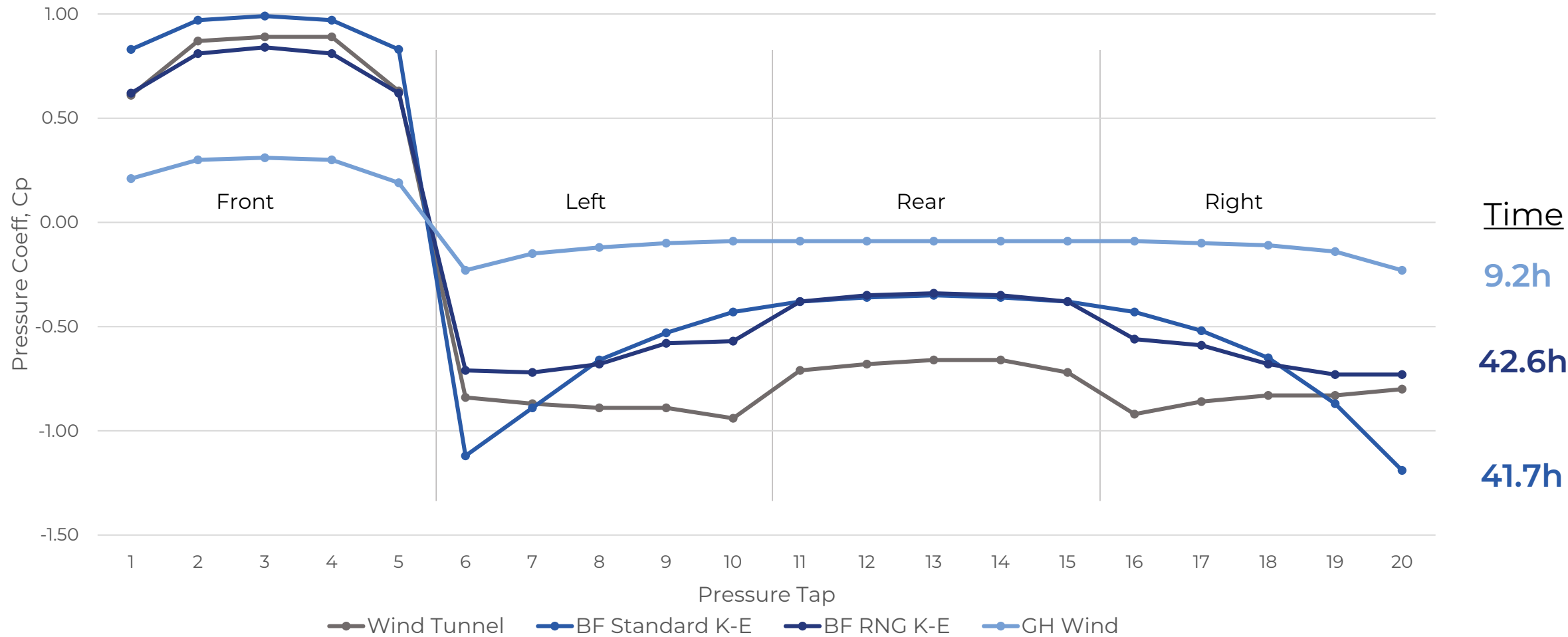
Pressure tap locations

TO BE COMPARED

- Butterfly with Standard $k - \varepsilon$ turbulence model
- Butterfly with RNG $k - \varepsilon$ turbulence model
- GH Wind (no turbulence model)
- Physical Wind Tunnel Test Results

RESULTS

CP AT PRESSURE TAPS



CONCLUSIONS



- BF with RNG $k - \varepsilon$
Accurate but
time-consuming.

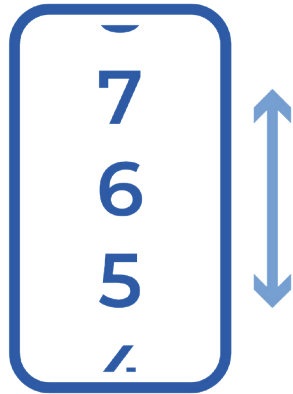
GH Wind is fastest •
but not very
accurate.

$$\frac{\partial U_i}{\partial t}$$

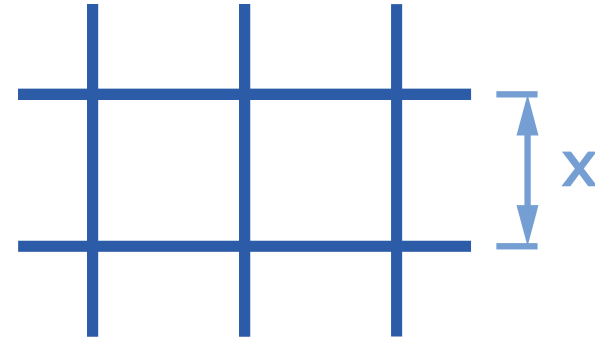
SENSITIVITY ANALYSIS

Manipulating a parameter while keeping others constant to determine how much calculation time can be reduced while maintaining accuracy

Parameters to test:



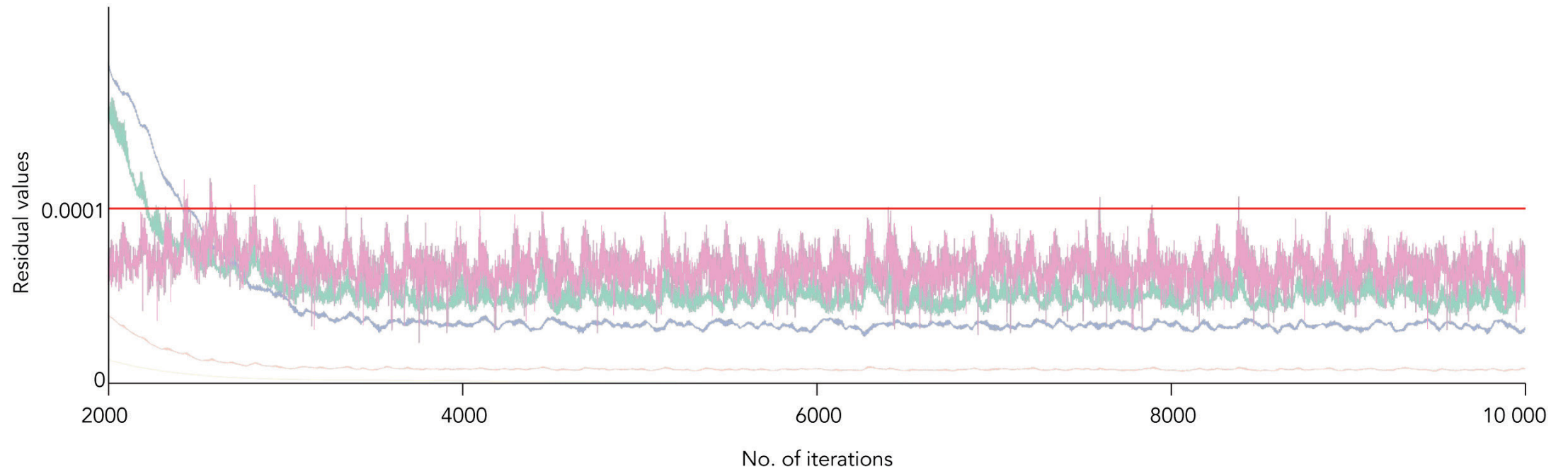
Number of
iterations



Mesh cell size

NO. OF ITERATIONS

Butterfly



Residual values are below threshold at 10 000 iterations

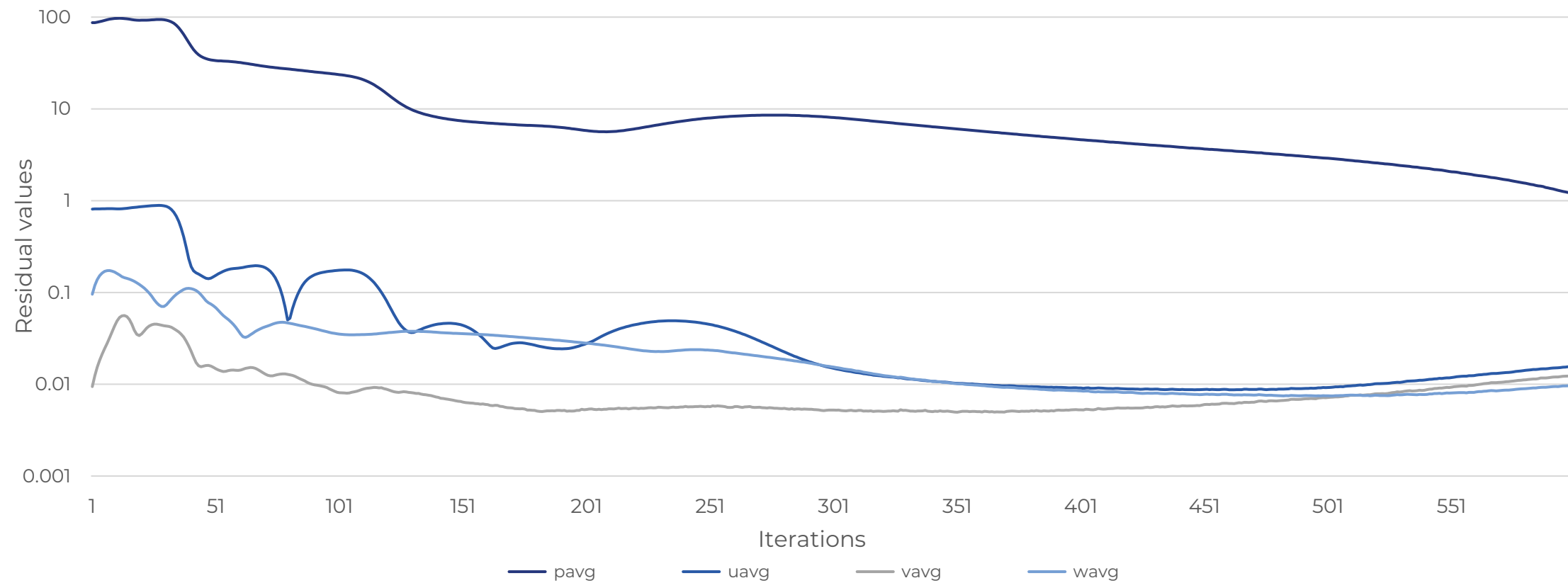
NO. OF ITERATIONS

Butterfly

Test	Turbulence model	Cell size (m)	no. of cells	Time	Iterations
RNG_30k	RNGkEpsilon	0.987552	615 120	42.6h	30000
RNG_10k	RNGkEpsilon	0.987552	615 120	15.7 h	10000
RNG_5k	RNGkEpsilon	0.987552	615 120	6.95h	5000

NO. OF ITERATIONS

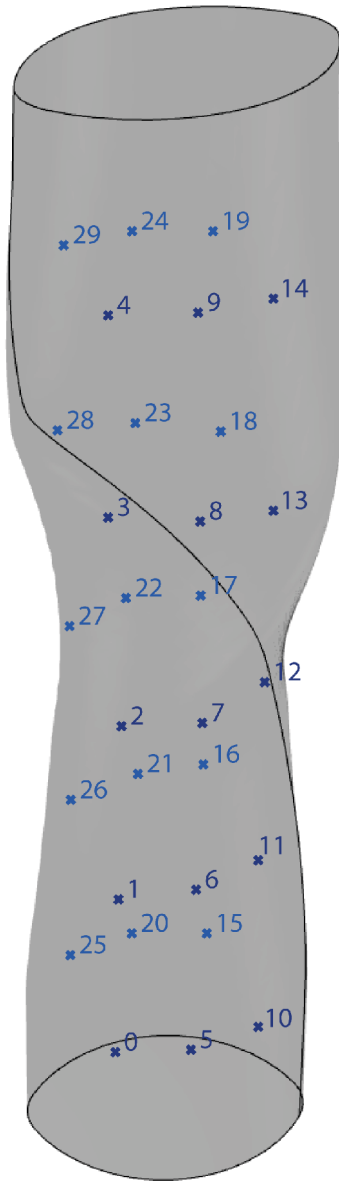
GH Wind



NO. OF ITERATIONS

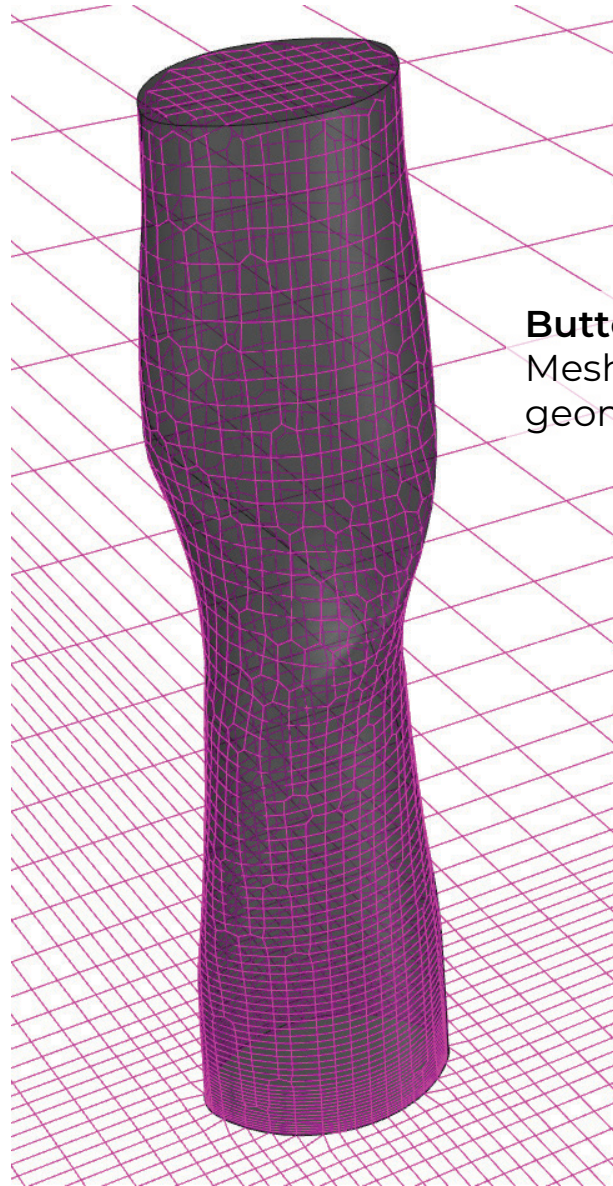
GH Wind

Test	Turbulence model	Cell size (m)	no. of cells	Time	Iterations
FFD_600	$\nu = 0.1$	5	1 728 000	9.2h	600
FFD_400	$\nu = 0.1$	5	1 728 000	5.7h	400



CELL SIZE

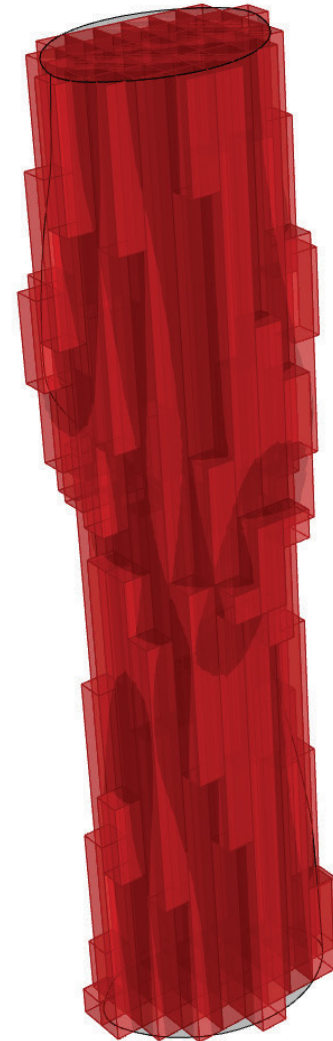
- Absolute Tower model
- Compare C_p at 30 points on front and rear
- Wind speed = 30m/s (108 km/h, Beaufort 11, violent storm)



Butterfly
Mesh snaps to
geometry

CELL SIZE

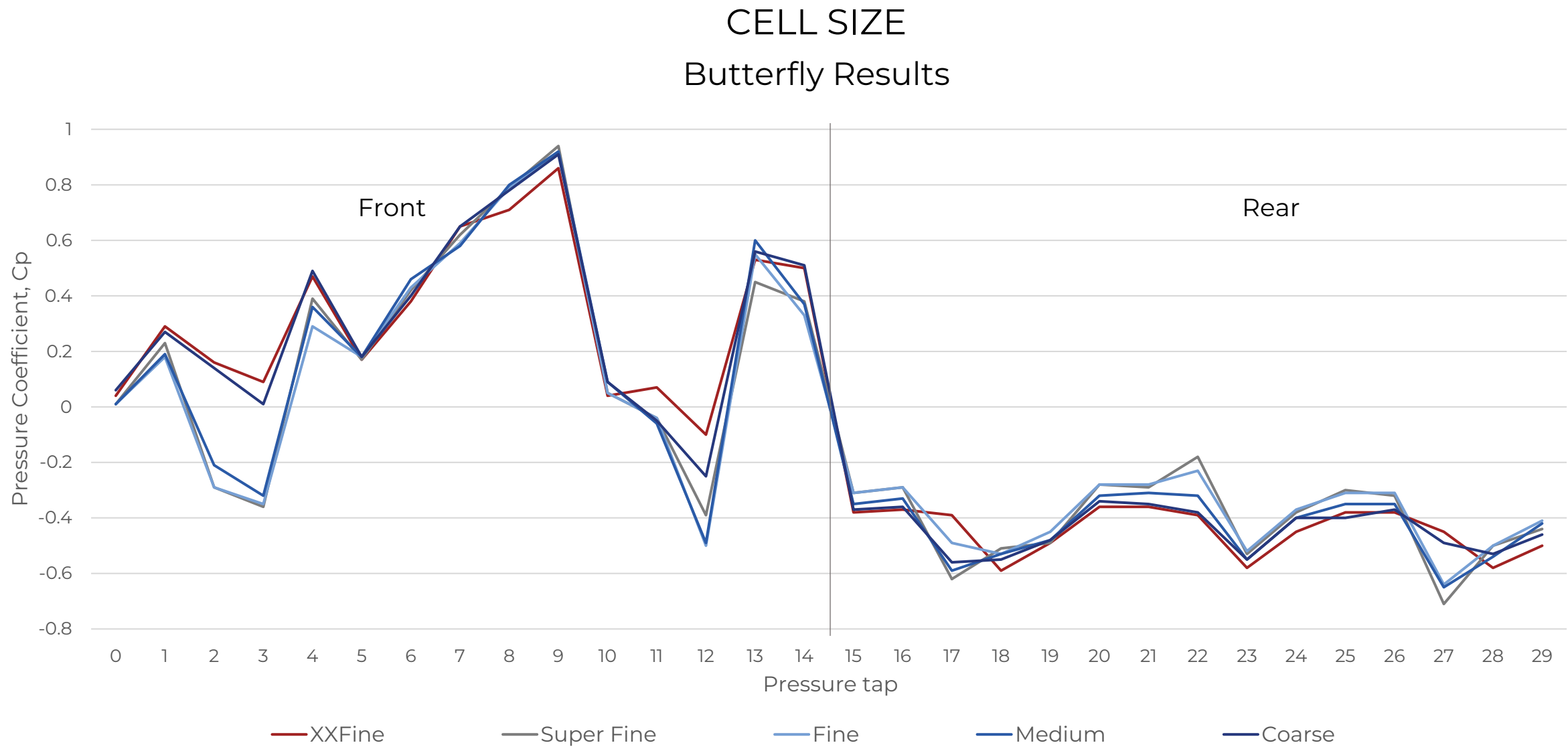
GH Wind
Voxels approximate
geometry



CELL SIZE
Butterfly Results

Test	MAD_1	MAD_2	MAD_3	MAD_4	MAD_5
Turbulence model	RNGkEpsilon	RNGkEpsilon	RNGkEpsilon	RNGkEpsilon	RNGkEpsilon
Resolution	Coarse	Medium	Fine	Super Fine	XXFine
Cell size (m)	4.18	2.96	2.09	1.48	1.08
no. of cells	176545	236050	346647	525640	732422
Time	5.7h	6.3h	8.6h	14.5h	20.3h
Iterations	10000	10000	10000	10000	10000

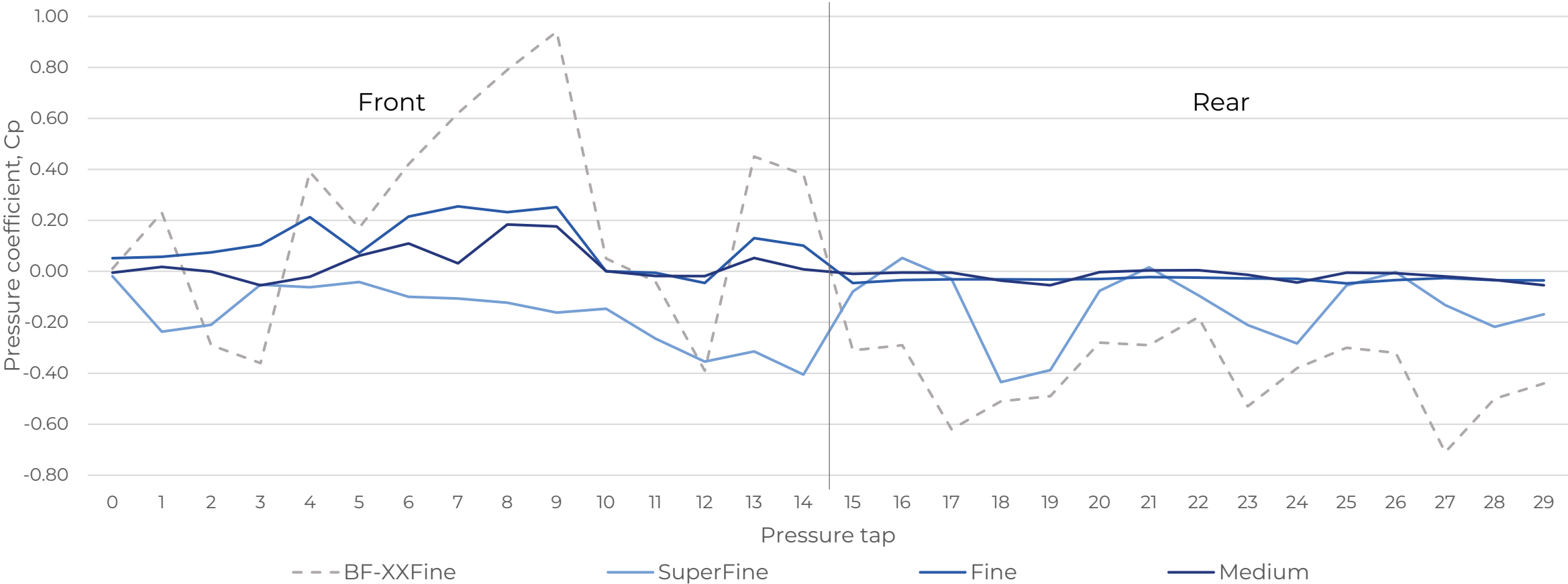
Sensitivity Analysis



CELL SIZE
GH Wind Results

Test	MAD_5	MAD_6	MAD_7
Turbulence model	FFD	FFD	FFD
Resolution	Medium	Fine	SuperFine
Cell size [m]	10	8	6
no. of cells	390830	774387	1824912
Time	3.4h	7.1h	11.8h
Iterations	400	400	400

CELL SIZE
GH Wind Results



CONCLUSIONS



**BUTTERFLY +
RNG $k - \varepsilon$**



FLUID-STRUCTURE INTERACTION (FSI)

Partitioned approach
(couple CFD and FEA solvers)

CFD

Butterfly

+

?

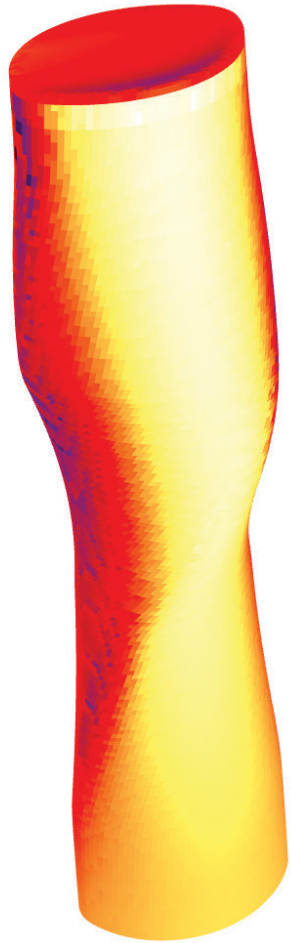
Translation
procedure

+

FEA

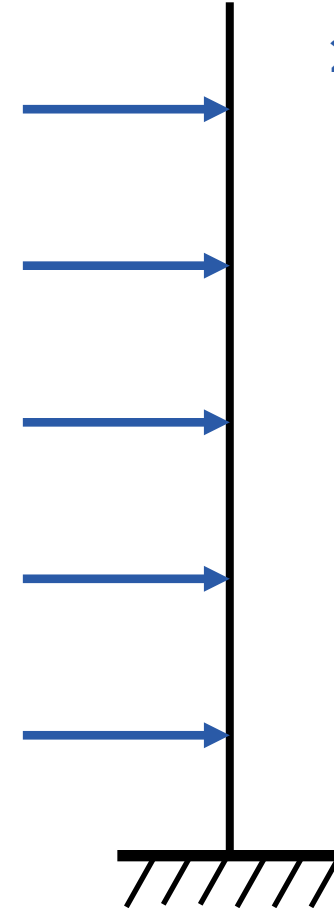
Karamba3D

TRANSLATION



3D MESH

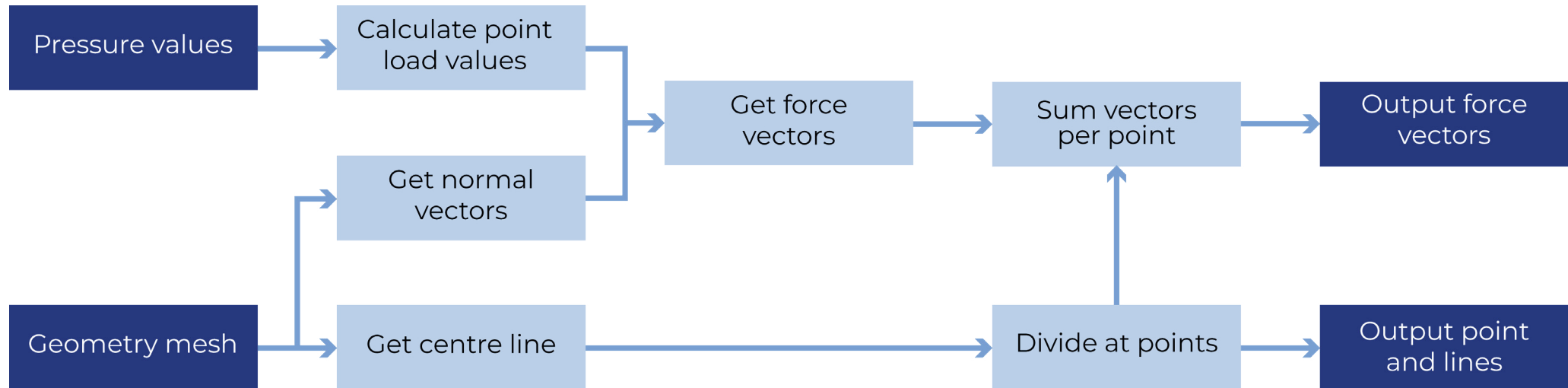
Area loads
 N/m^2



2D BEAM

Point loads
kN

TRANSLATION



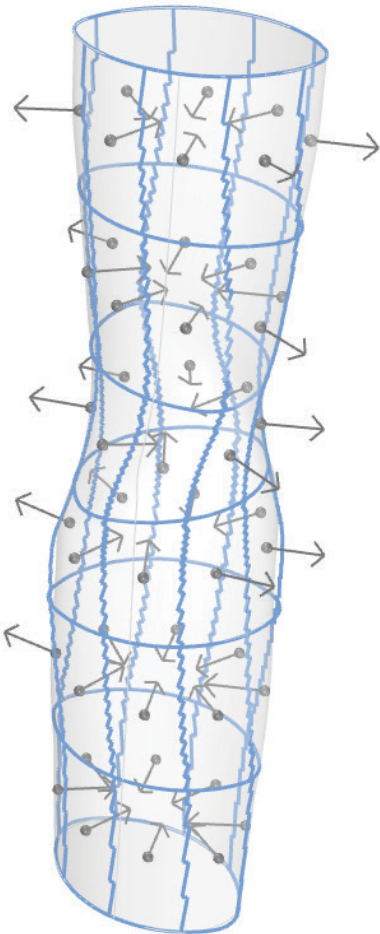
TRANSLATION



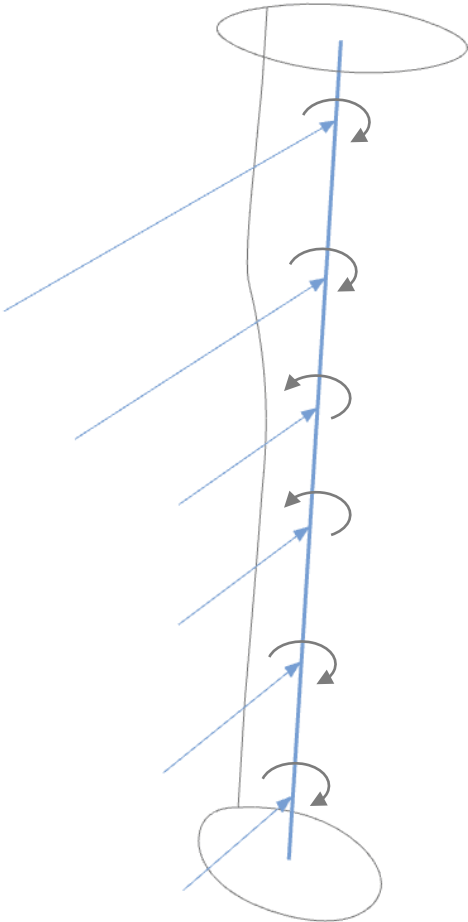
Mesh with face pressures



Divide mesh

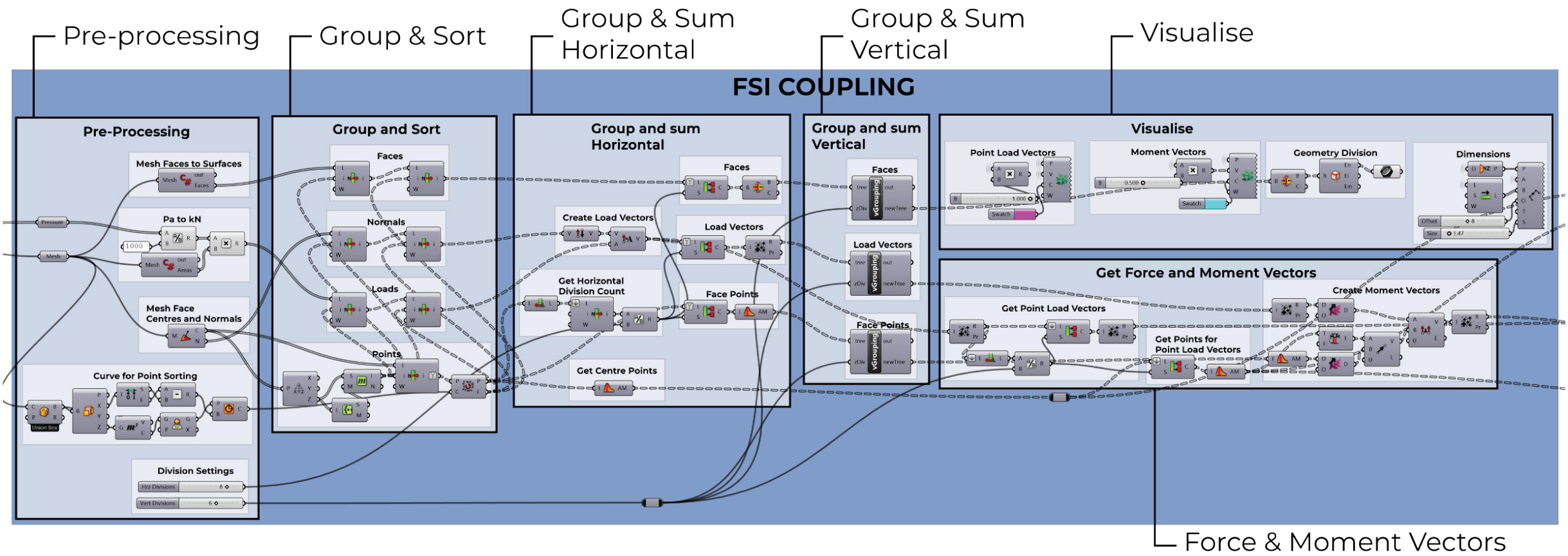


Sum force vectors per section

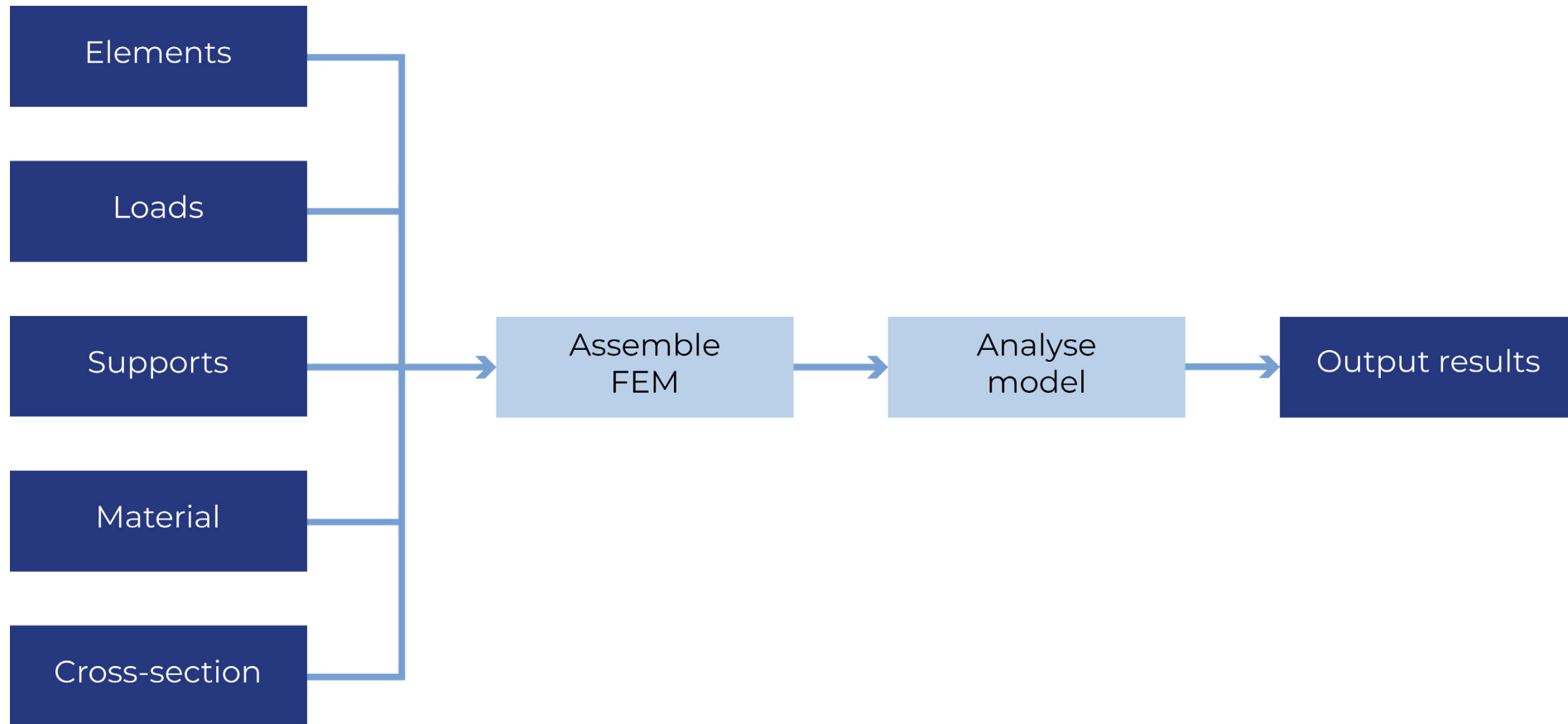


Sum vectors and apply to core

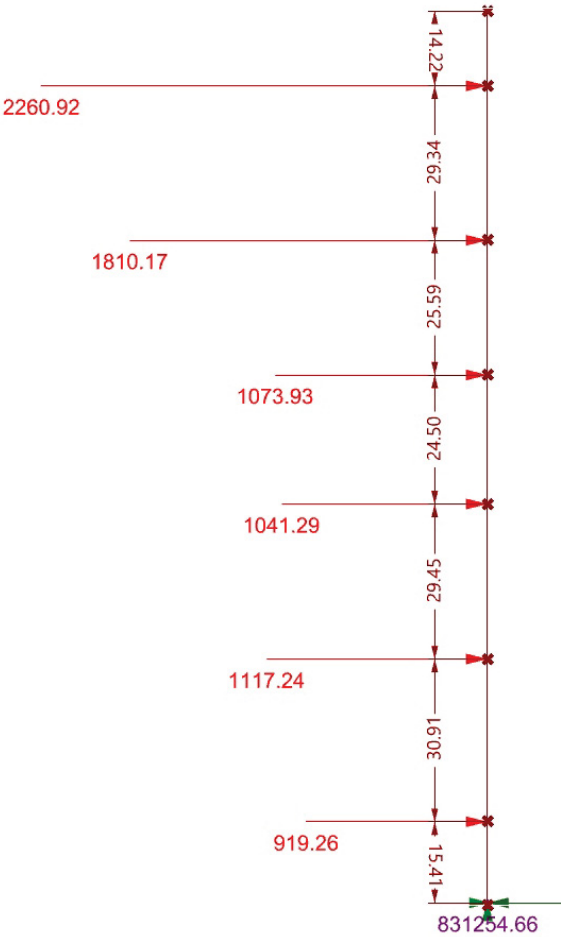
FSI TRANSLATION SCRIPT



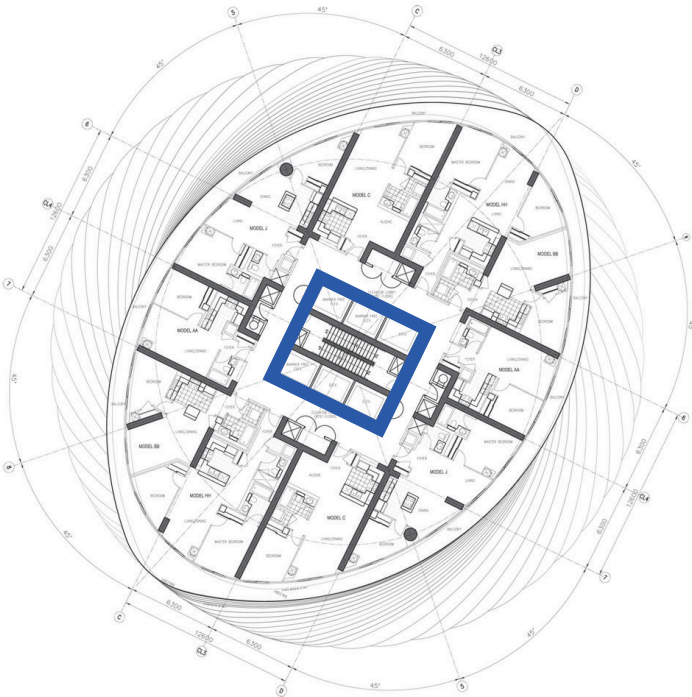
FINITE ELEMENT ANALYSIS



ELEMENTS & LOADS

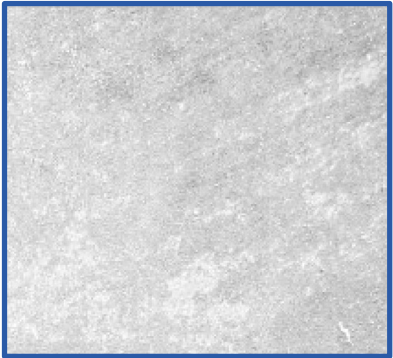


CROSS-SECTION



8.0m x 8.6m x 0.40m (L x W x t)

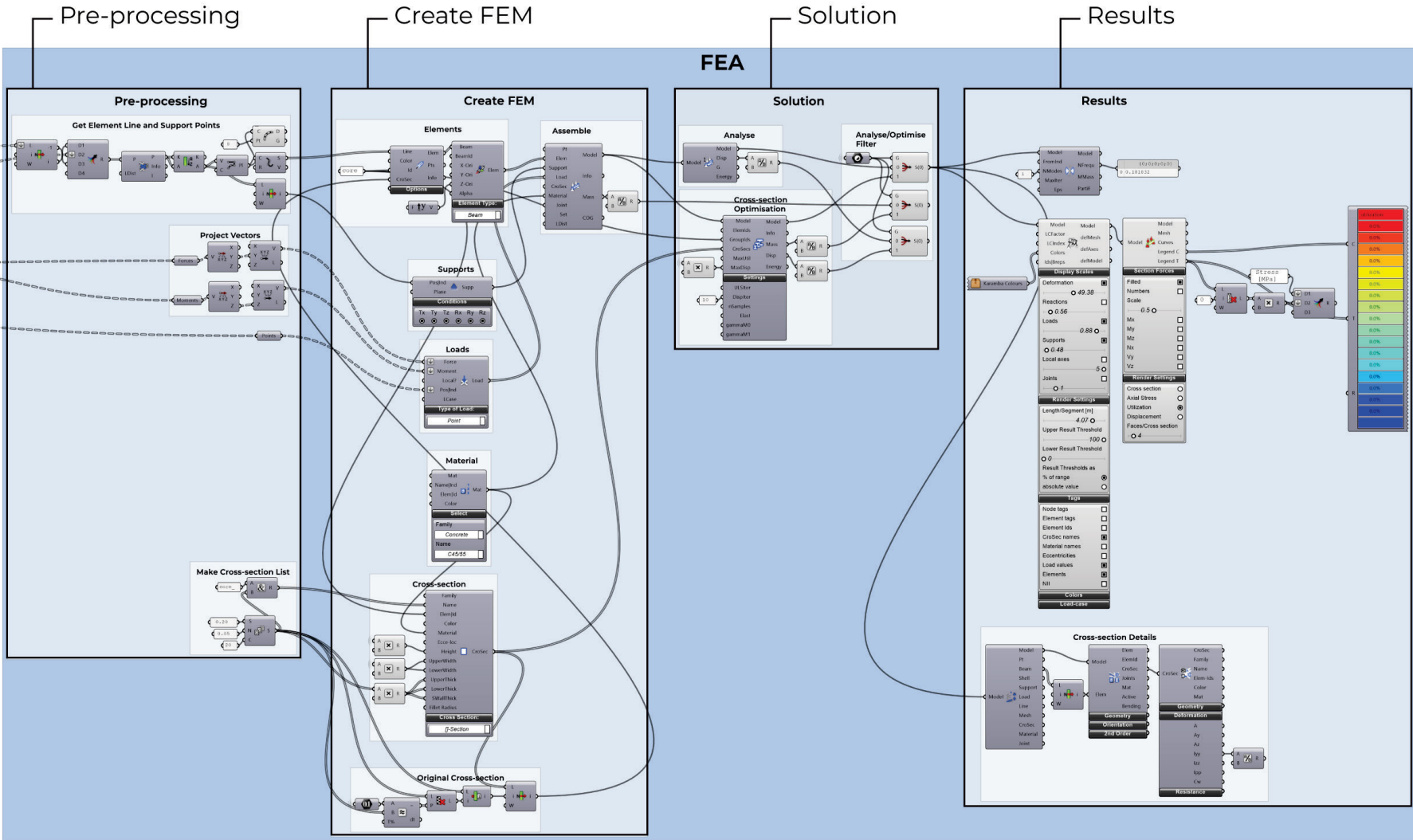
MATERIAL



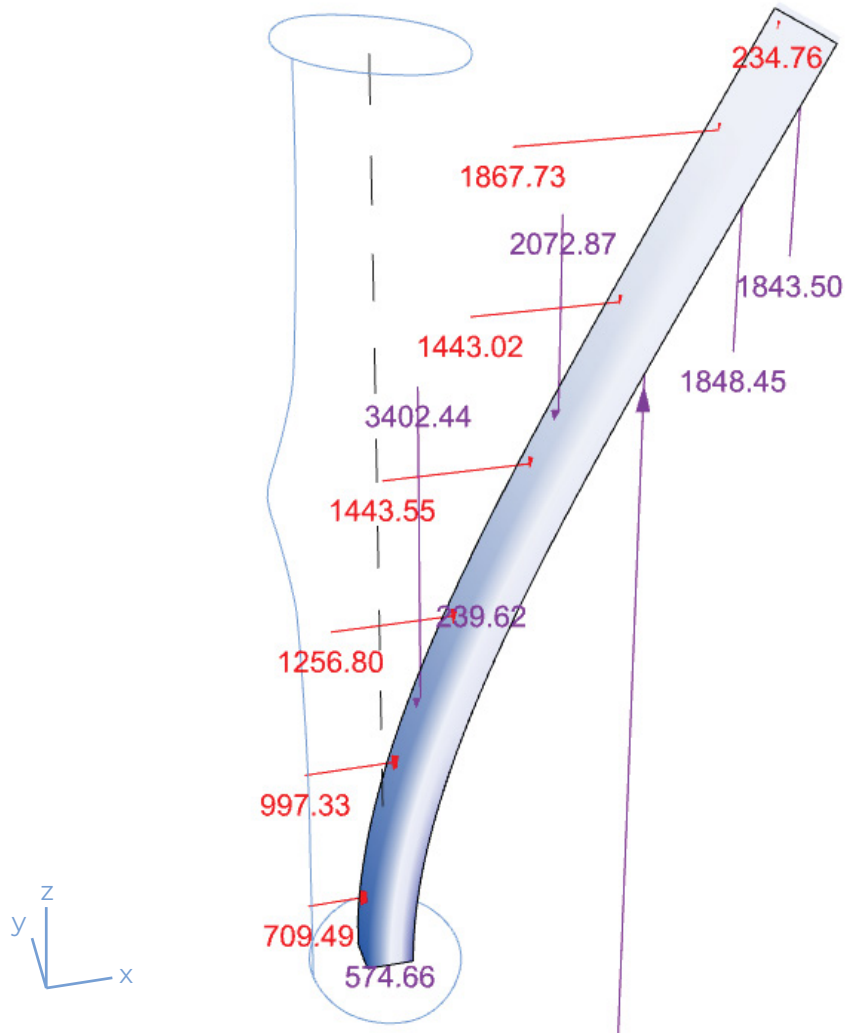
C45/55 Concrete

Finite Element Analysis (FEA)

FEA SCRIPT



RESULTS



Deflection = 1.28 m

$M_y = 831\,254 \text{ kNm}$

$M_z = 3717 \text{ kNm}$

Max stress = 25.7 MPa

Mass = 5353.8 Tons

Karamba 3D
parametric engineering

CONCLUSIONS

FSI

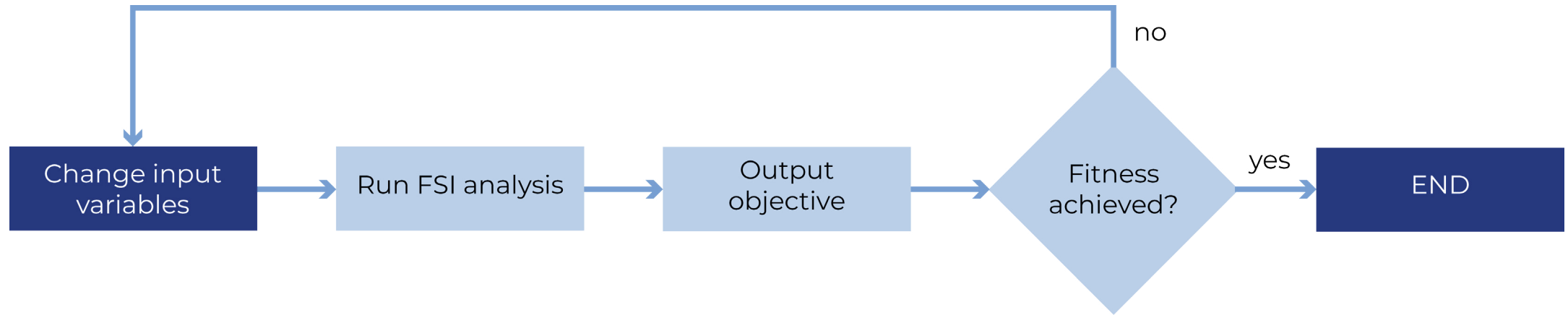
CFD + FEA

- Translation algorithm successful
- FEA can output many results to be optimised

- Deflections larger than SLS limit
- Compare relative results rather than to absolute limits for optimisation



OPTIMISATION

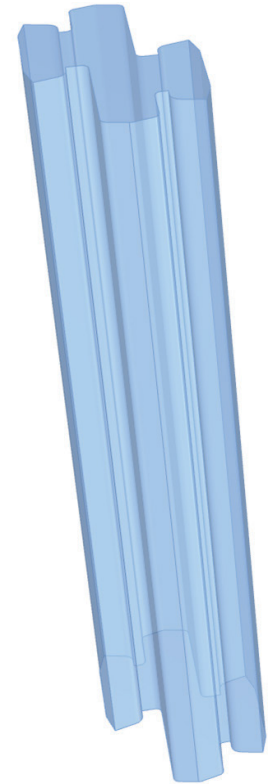




Absolute Tower



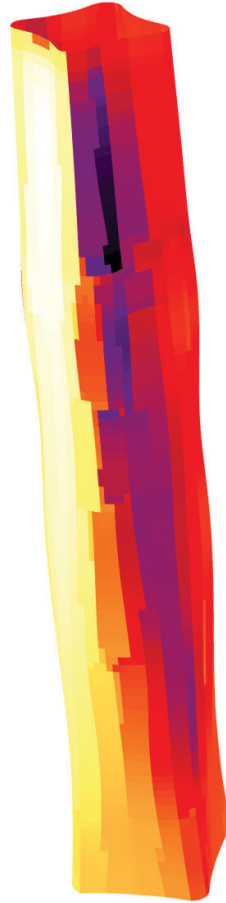
Nanchang Tower



Ardmore Residence



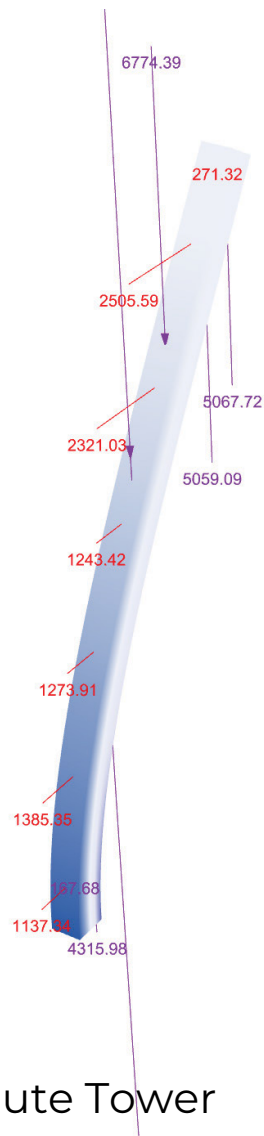
Absolute Tower



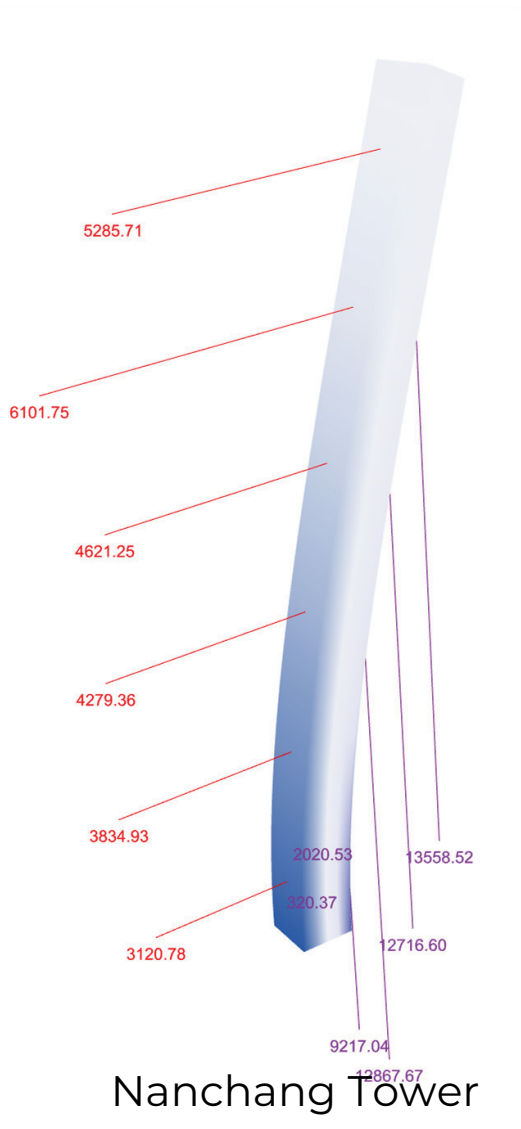
Nanchang Tower



Ardmore Residence



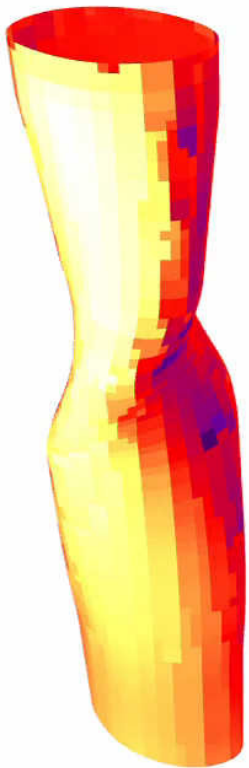
Absolute Tower



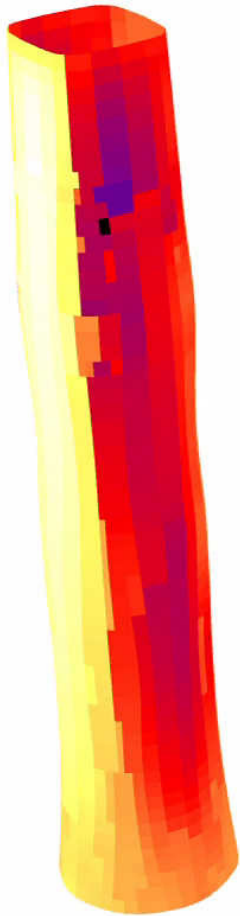
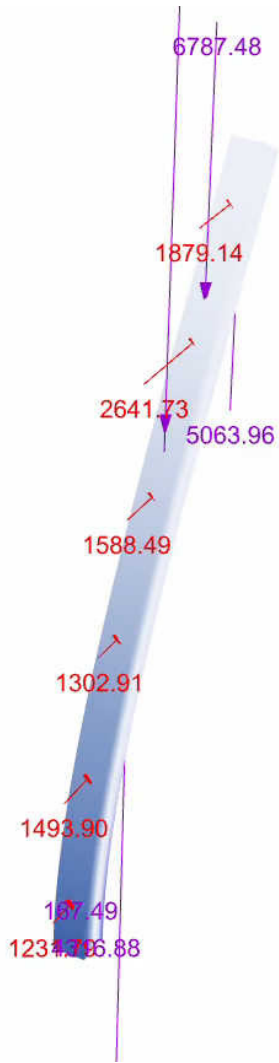
Nanchang Tower



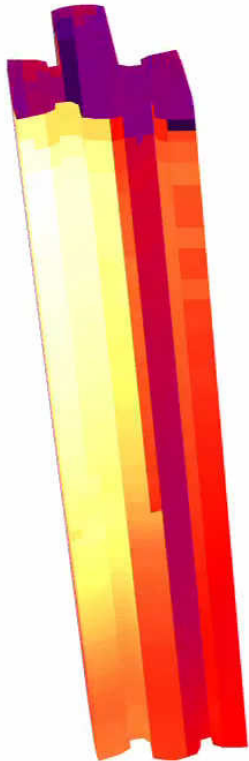
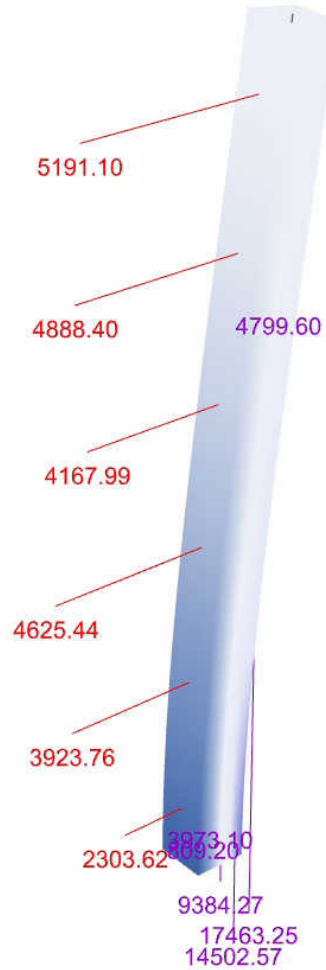
Ardmore Residence



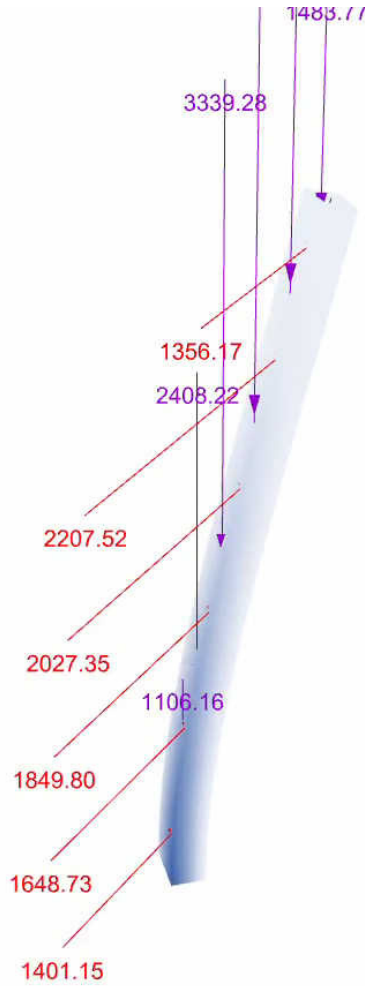
Absolute Tower



Manxman Tower



Ardmore Residence



OPTIMISATION TESTS

OPT 1

OPT 2

OPT 3

OPT 4

OPT 5

CONSTANT:

Opossum:
RBFOpt algorithm

CFD:
Coarse mesh
2000 iterations
Domain size

EVALUATED:

Geometry:
Inputs & ranges

FEA:
Objective outputs

Optimisation:
No. of iterations

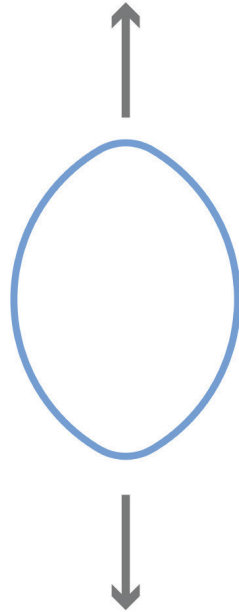


Image: © Iwan Baan

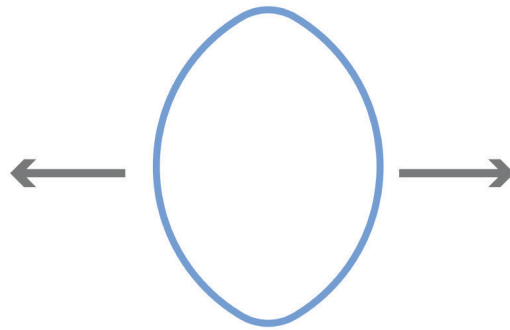
OPTIMISATION 1

Model	Absolute Tower		
Max iterations	60		
Variables	Base length	Base width	Twist
Ranges	$13.0 < x < 15.0$	$13.0 < x < 15.0$	$0.5 < x < 1.5$
Objective	Deflection		

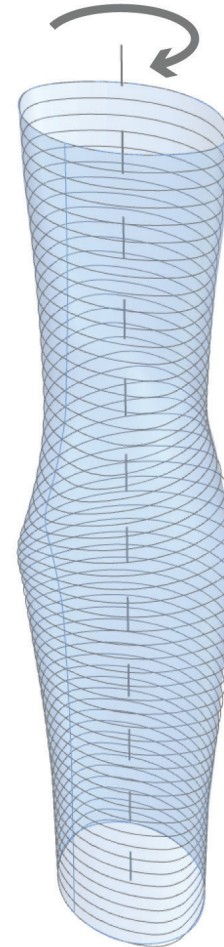
GEOMETRY DEFINITION



Base length

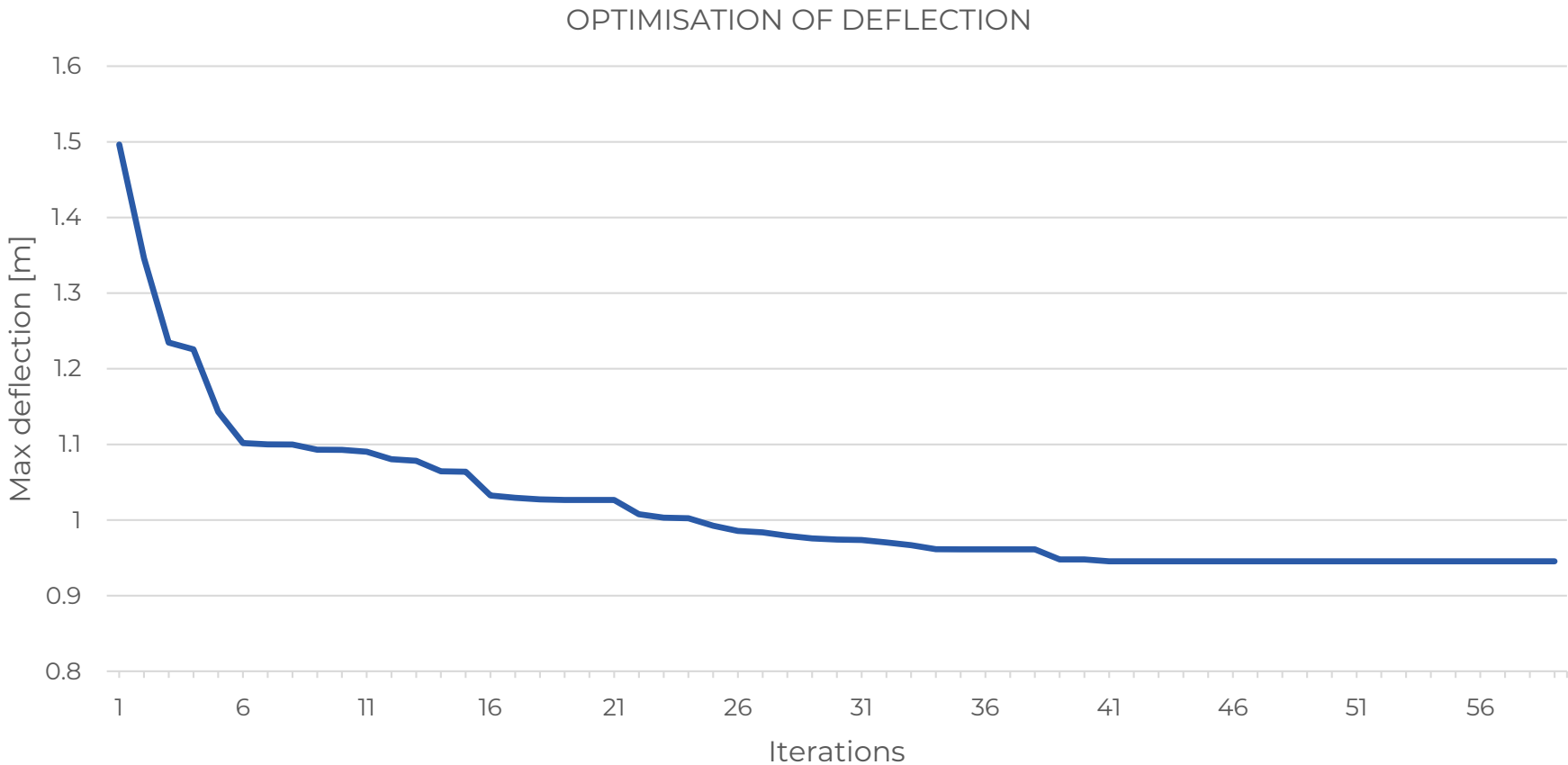


Base width



Twist angle

RESULTS

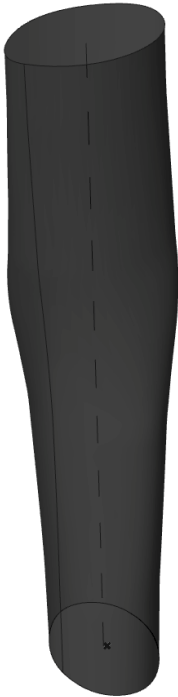


Original = 1.54 m
Optimised = 0.95 m

38% Reduction



Original



Optimised

Geometry

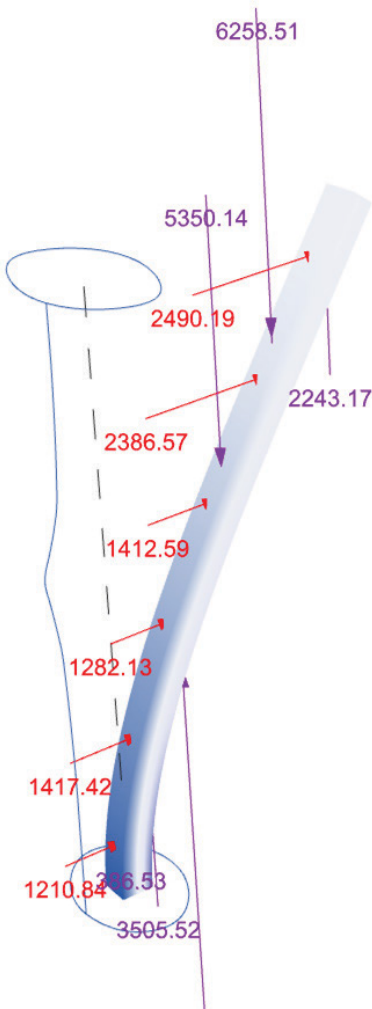


Original

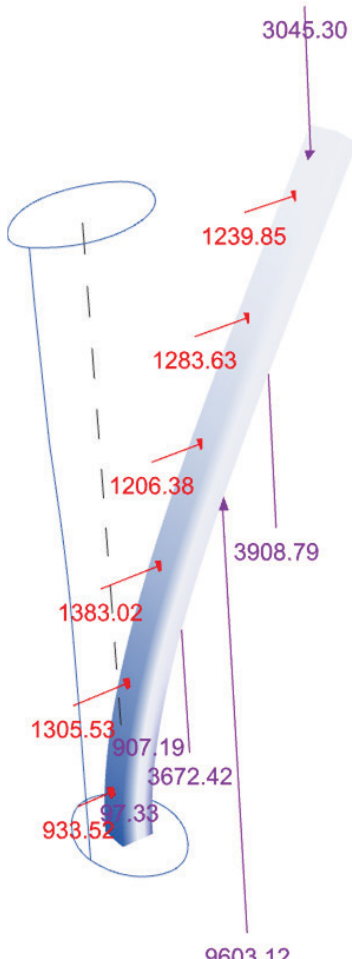


Optimised

Pressure



Original



Optimised

FEA



Image: © Iwan Baan

OPTIMISATION 2

Model	Absolute Tower		
Max iterations	60		
Variables	Base length	Base width	Twist
Ranges	$12.0 < x < 16.0$	$12.0 < x < 16.0$	$-1.0 < x < 2.0$
Objective	Material mass		
CS Settings	0.10m to 0.80m in 0.05m increments		

KARAMBA CROSS-SECTION OPTIMISATION (CSO)

In order to vary material mass

Input list of
cross-sections



Analyse model



Pick lightest cross-section
that fulfils requirements

Thickness from
0.10m to 0.80m in
0.05m intervals

Deflection limit
= 1.54 m

Output mass of
structure

RESULTS

OPTIMISATION OF MATERIAL USE



Properties	Original	Optimised
Material mass [T]	5984.924	4068.394
Core thickness [m]	0.40	0.30
Deflection [m]	1.544	1.073

32% Reduction



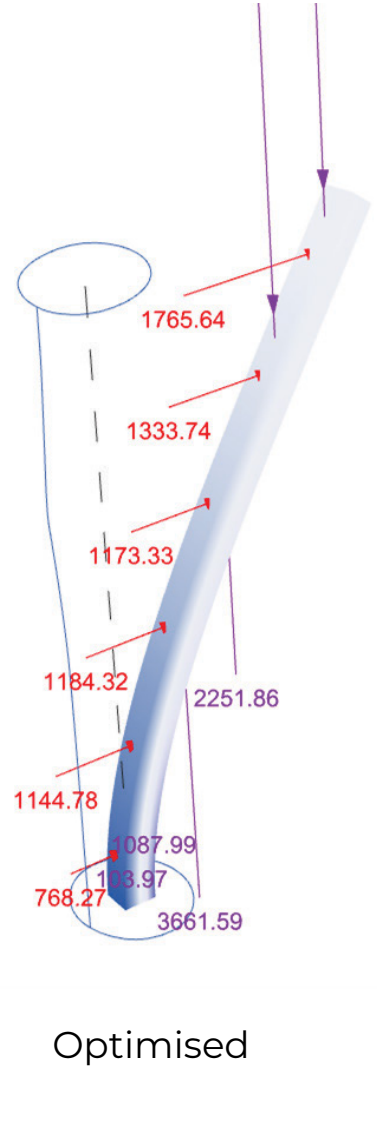
Optimised

Geometry



Optimised

Pressure



Optimised

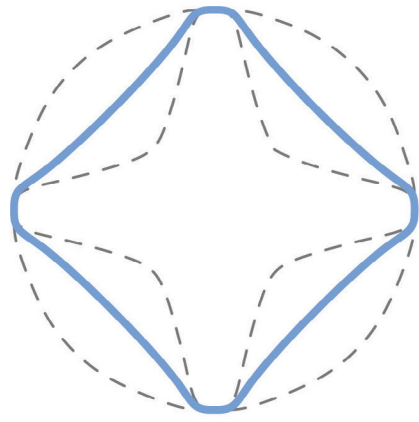
FEA



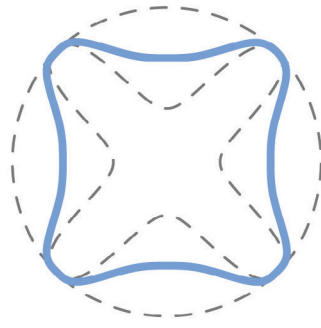
OPTIMISATION 3

Model	Nanchang Tower	
Max iterations	60	
Variables	Top curves	Bot curves
Ranges	$-1.000 < x < 1.000$	$-1.000 < x < 1.000$
Objective	Material mass	
CS Settings	0.20m to 1.15m in 0.05m increments	

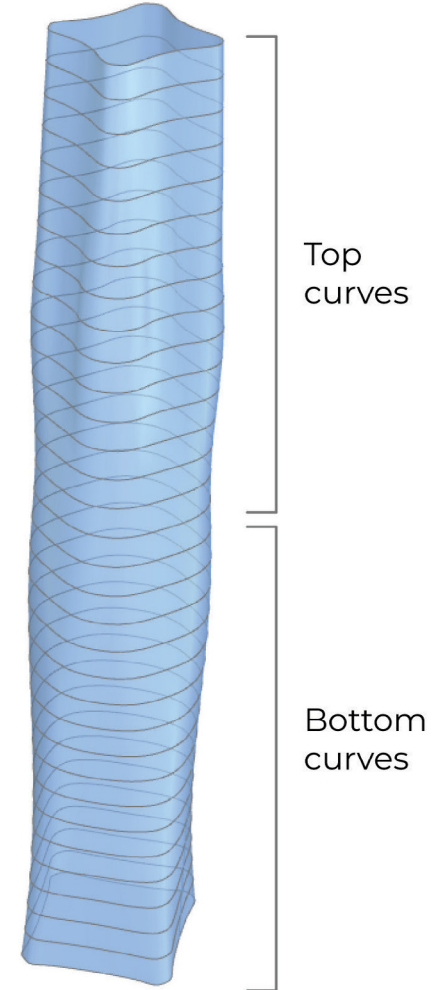
GEOMETRY DEFINITION



Bottom curve

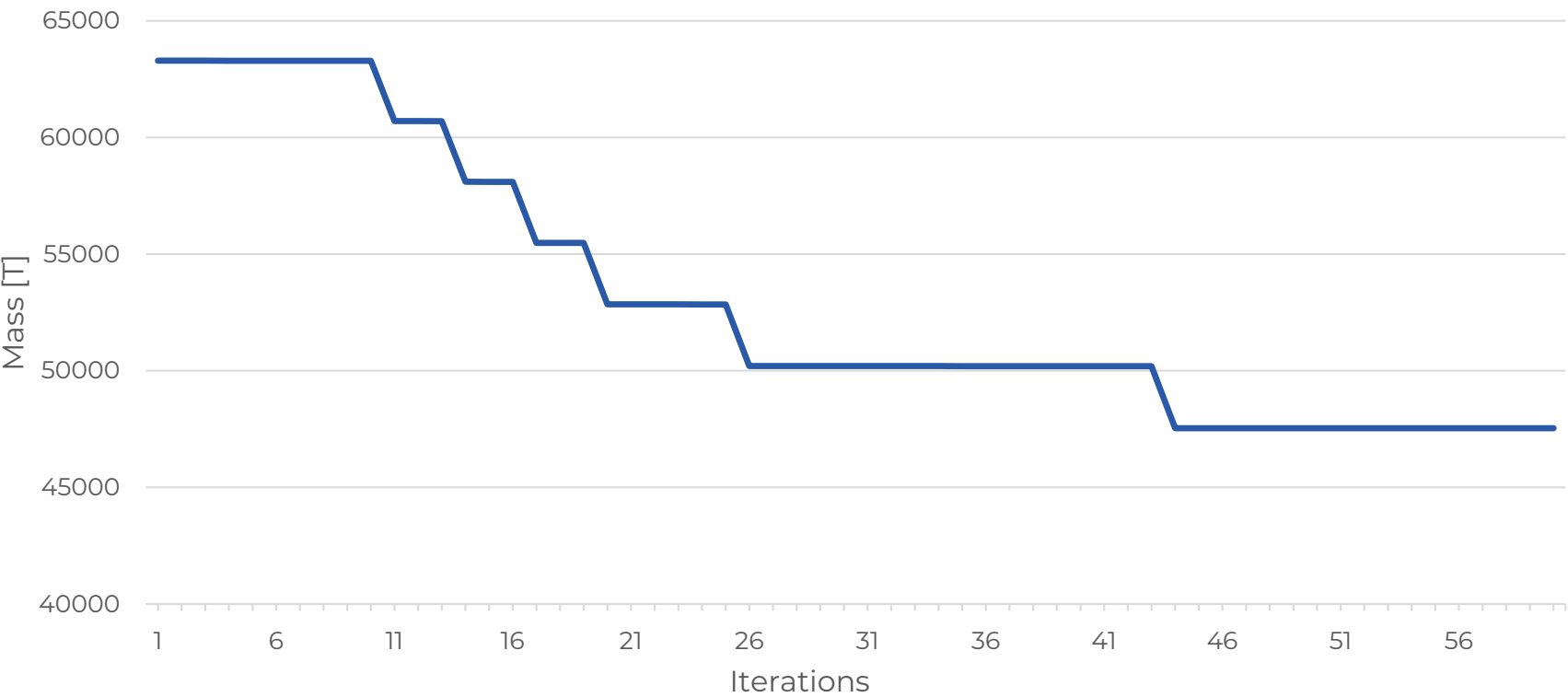


Top curve



RESULTS

OPTIMISATION OF MATERIAL USE



Properties	Original	Optimised
Material mass [T]	56240.466	47533.016
Core thickness [m]	1.00	0.85
Deflection [m]	0.6836	0.66132

15% Reduction



Original



Optimised

Geometry

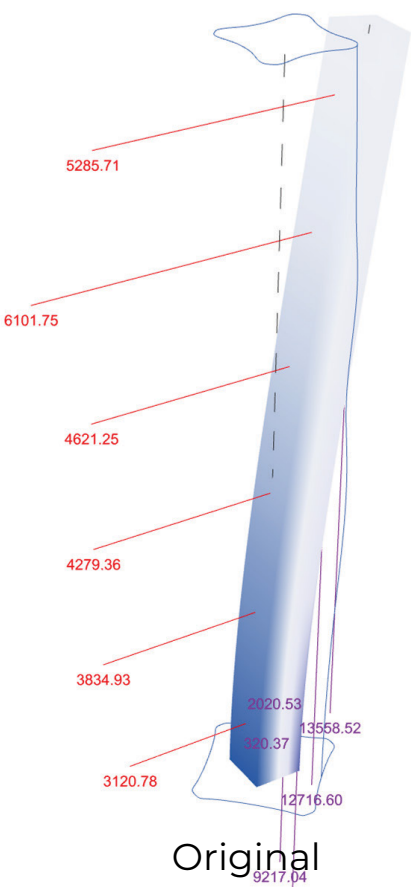


Original

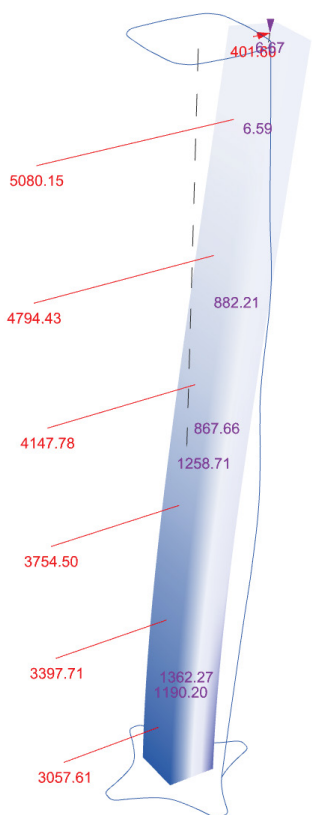


Optimised

Pressure



Original



Optimised

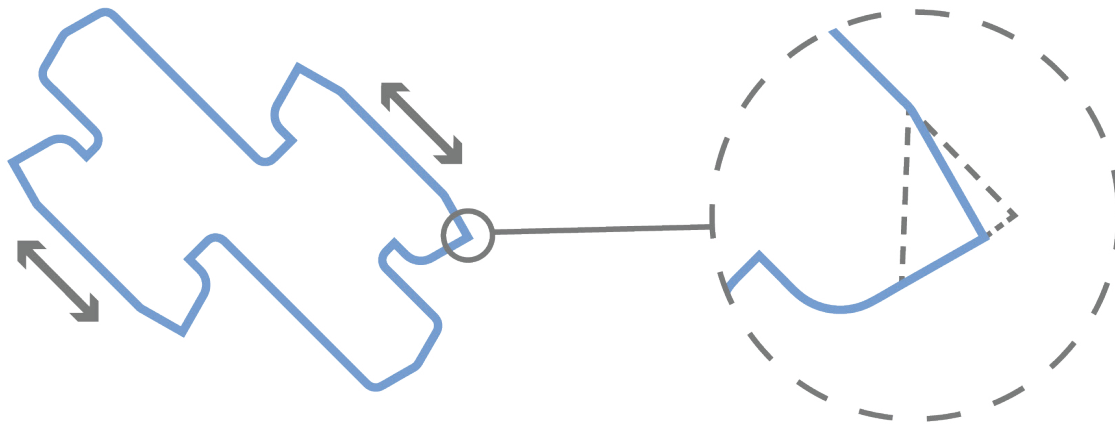
FEA



OPTIMISATION 4

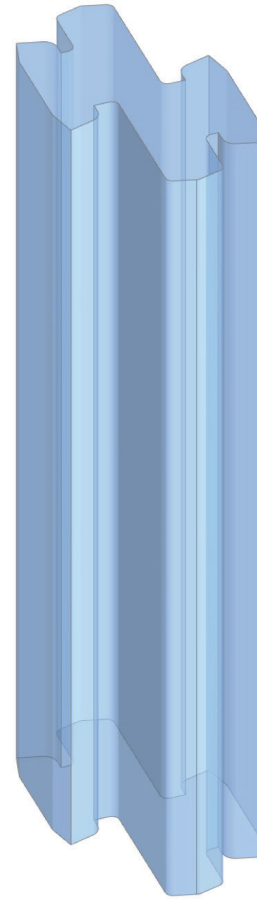
Model	Ardmore Residence		
Max iterations	100		
Variables	Top position	Bot position	Edge angle
Ranges	$-15.00 < x < 5.00$	$-5.00 < x < 15.00$	$-2.00 < x < 1.00$
Objective	Material mass		
CS Settings	0.10m to 0.59m in 0.01m increments		

GEOMETRY DEFINITION



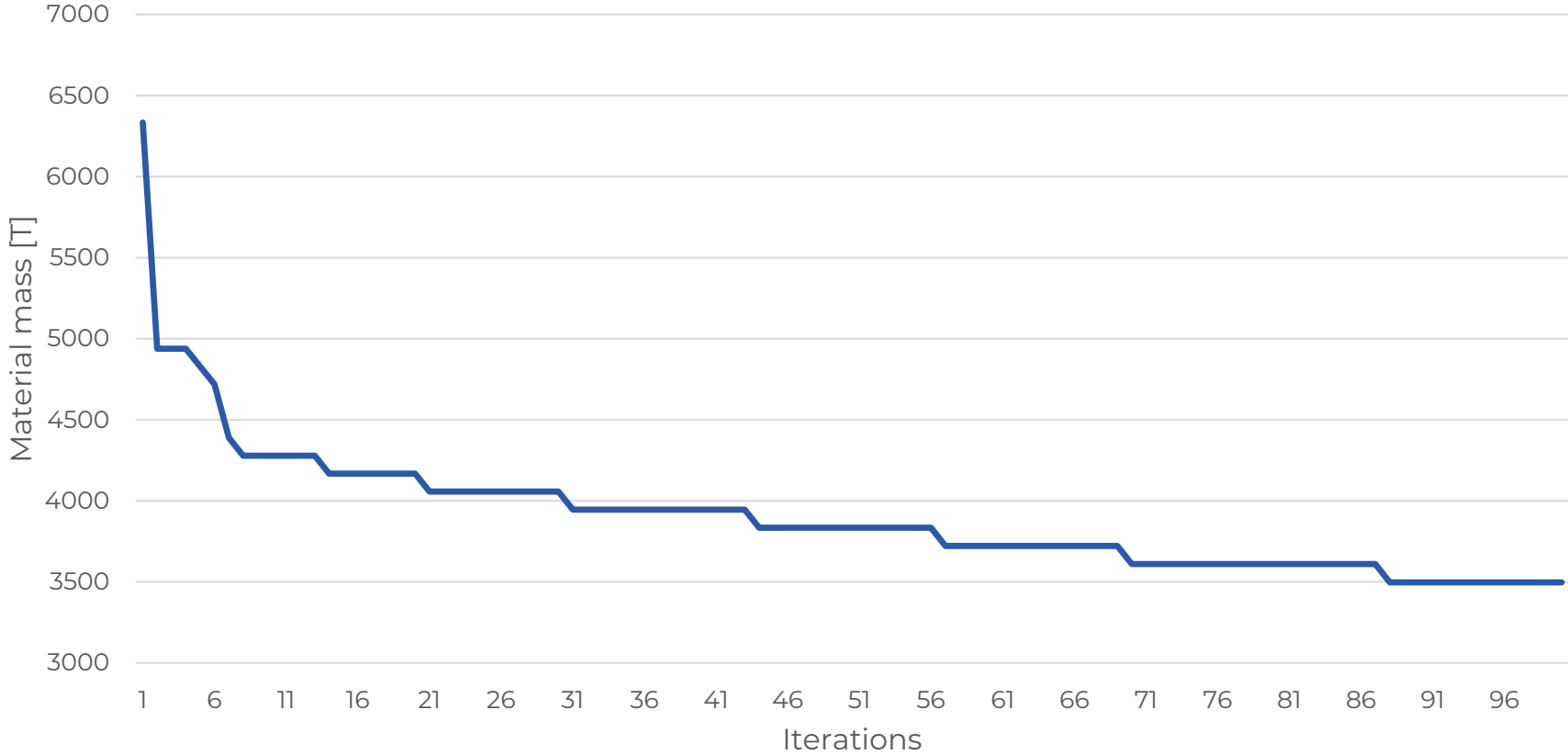
Wing position

Edge position



RESULTS

OPTIMISATION OF MATERIAL USE



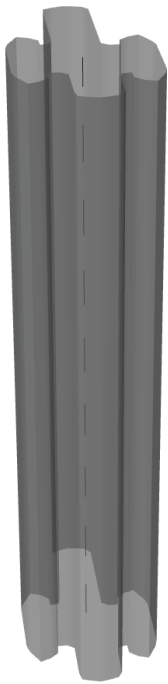
Properties	Original	Optimised
Material mass [T]	4609.59	3497.39
Core thickness [m]	0.40	0.30
Deflection [m]	0.66	0.66

24% Reduction

Optimisation 4



Original



Optimised

Geometry

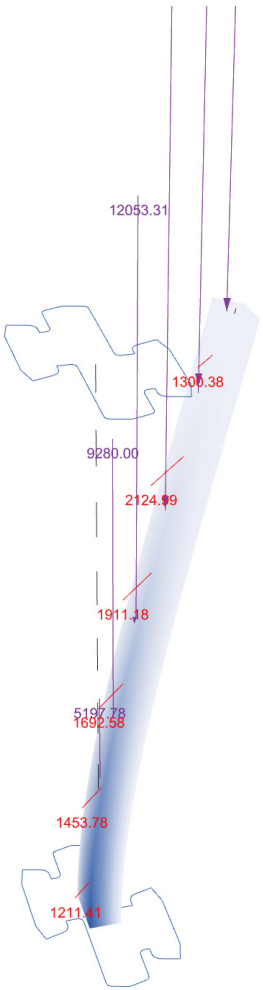


Original

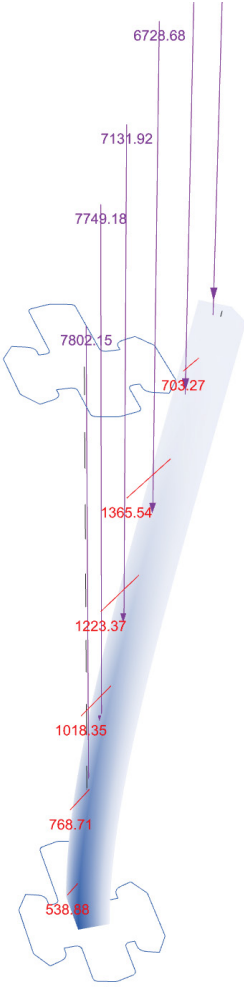


Optimised

Pressure



Original



Optimised

FEA

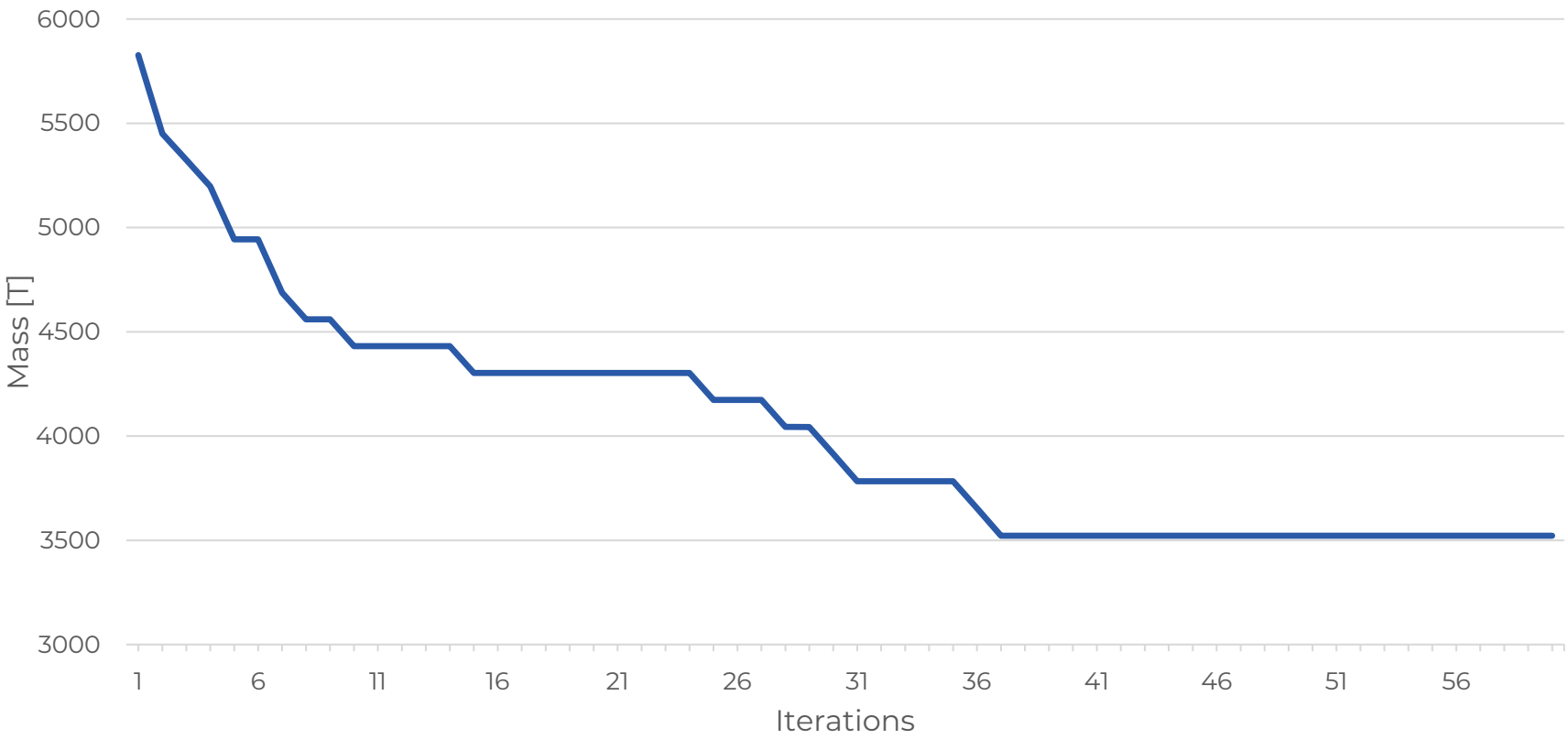


OPTIMISATION 5

Model	Absolute Tower		
Max iterations	60		
Variables	Base length	Base width	Twist
Ranges	$12.0 < x < 16.0$	$12.0 < x < 16.0$	$-1.0 < x < 2.0$
Objective	Material mass		
CS Settings	0.10m to 0.59m in 0.01m increments		

RESULTS

OPTIMISATION OF MATERIAL USE



Properties	Original	Optimised
Material mass [T]	5984.924	3522.112
Core thickness [m]	0.40	0.26
Deflection [m]	1.544	1.420

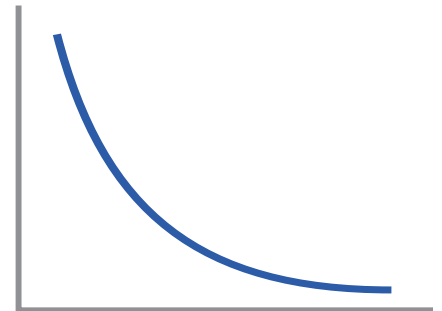
41% Reduction

CONCLUSIONS

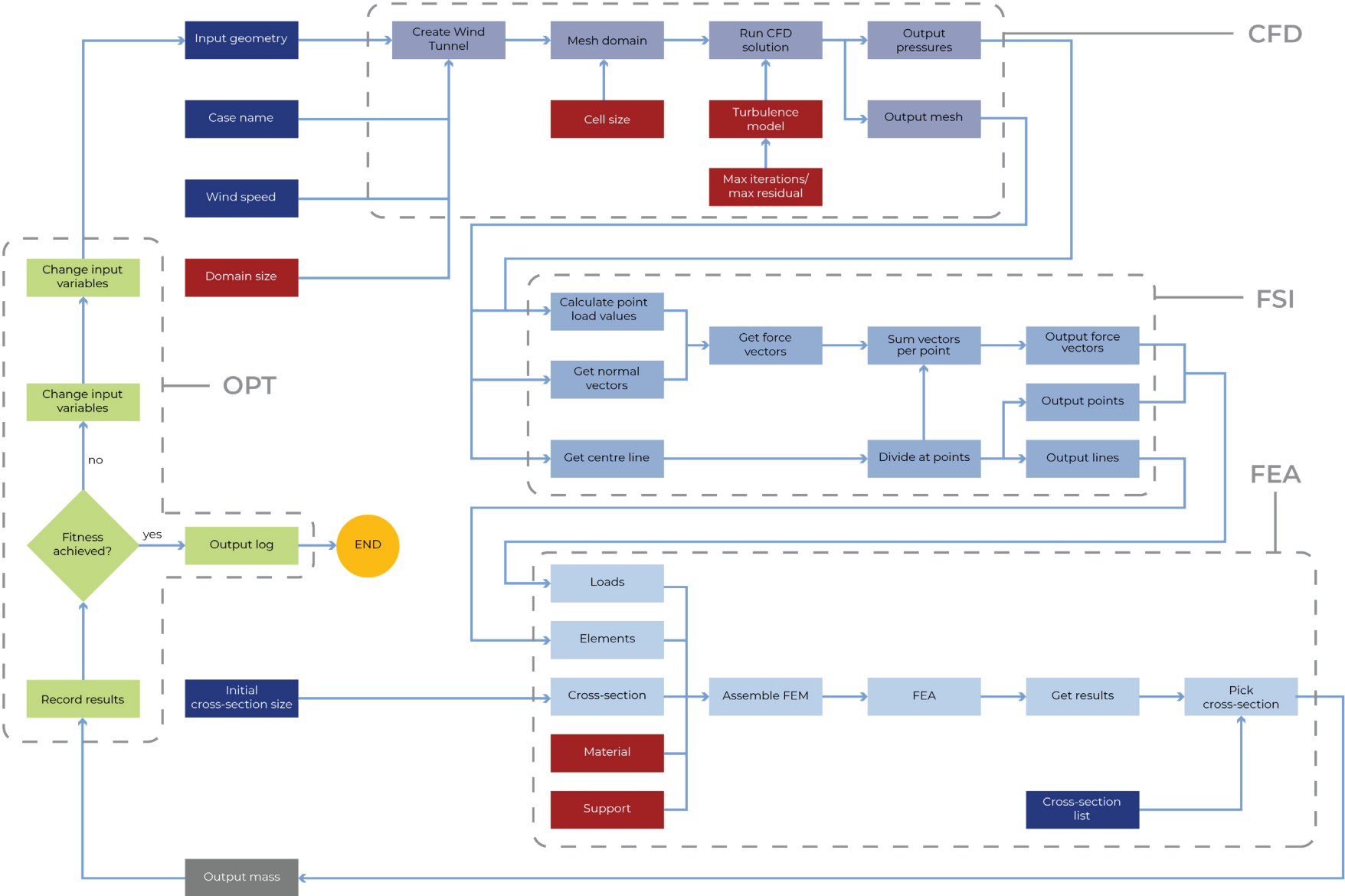


- Model-based RBFOpt algorithm can converge in relatively short time
- CFD: approx. 2 hours per sim, optimisation: 2-3 days

- Material mass is a useful objective
- Cross-section list should be sufficiently incremented

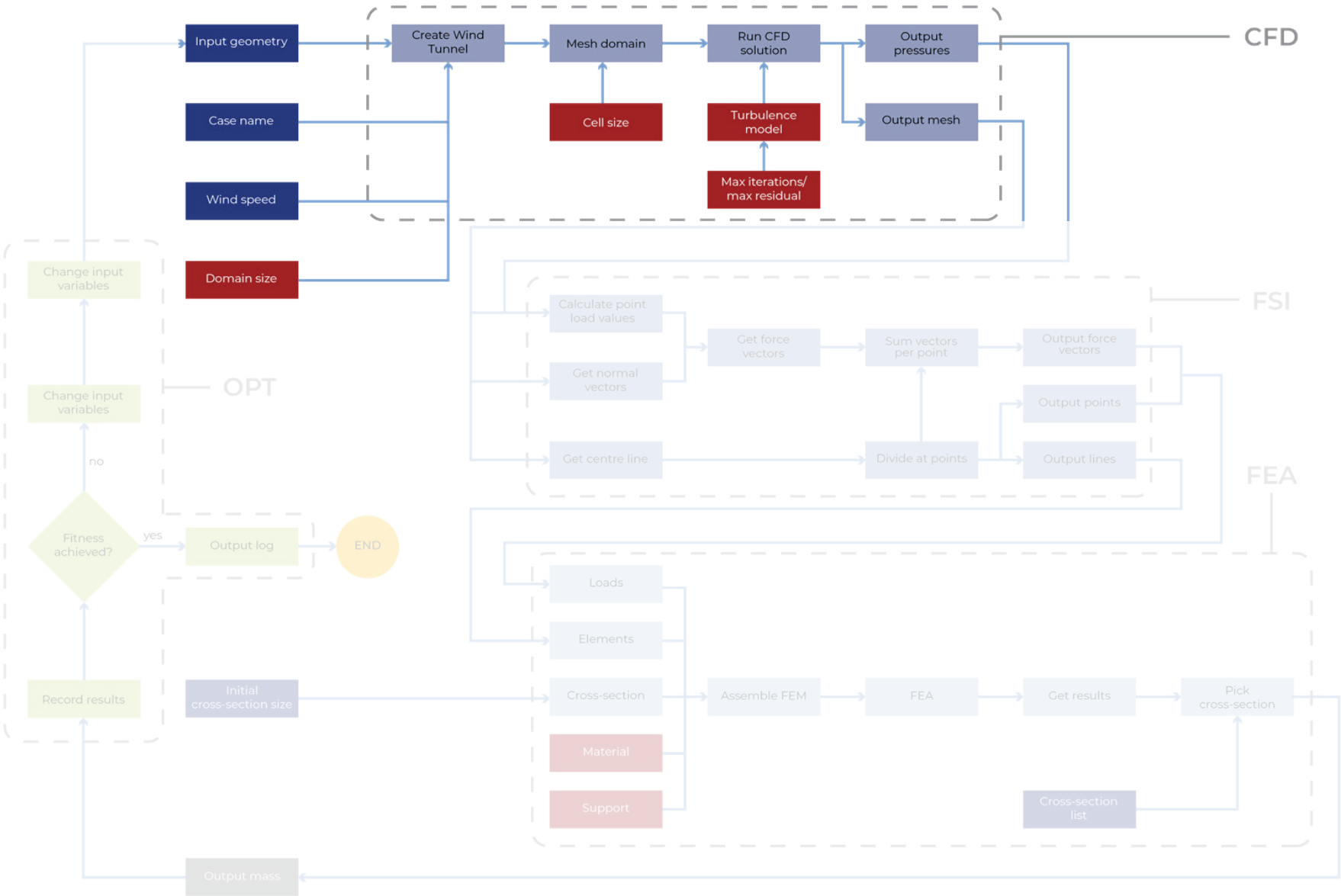


FSIO
Fluid-Structure
Interaction based
Optimisation (FSIO)



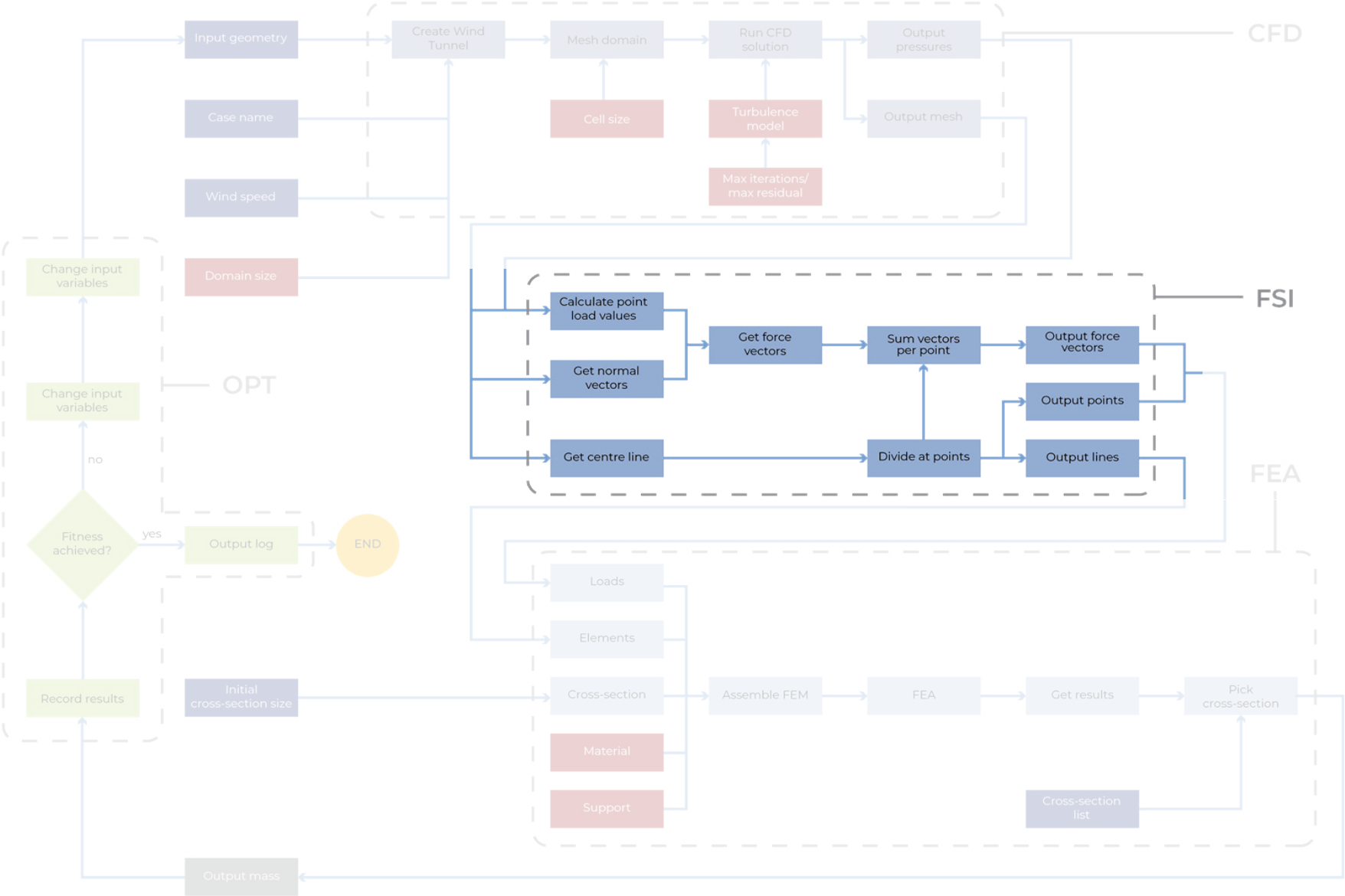
Final Method

CFD
Simulate wind and pressure

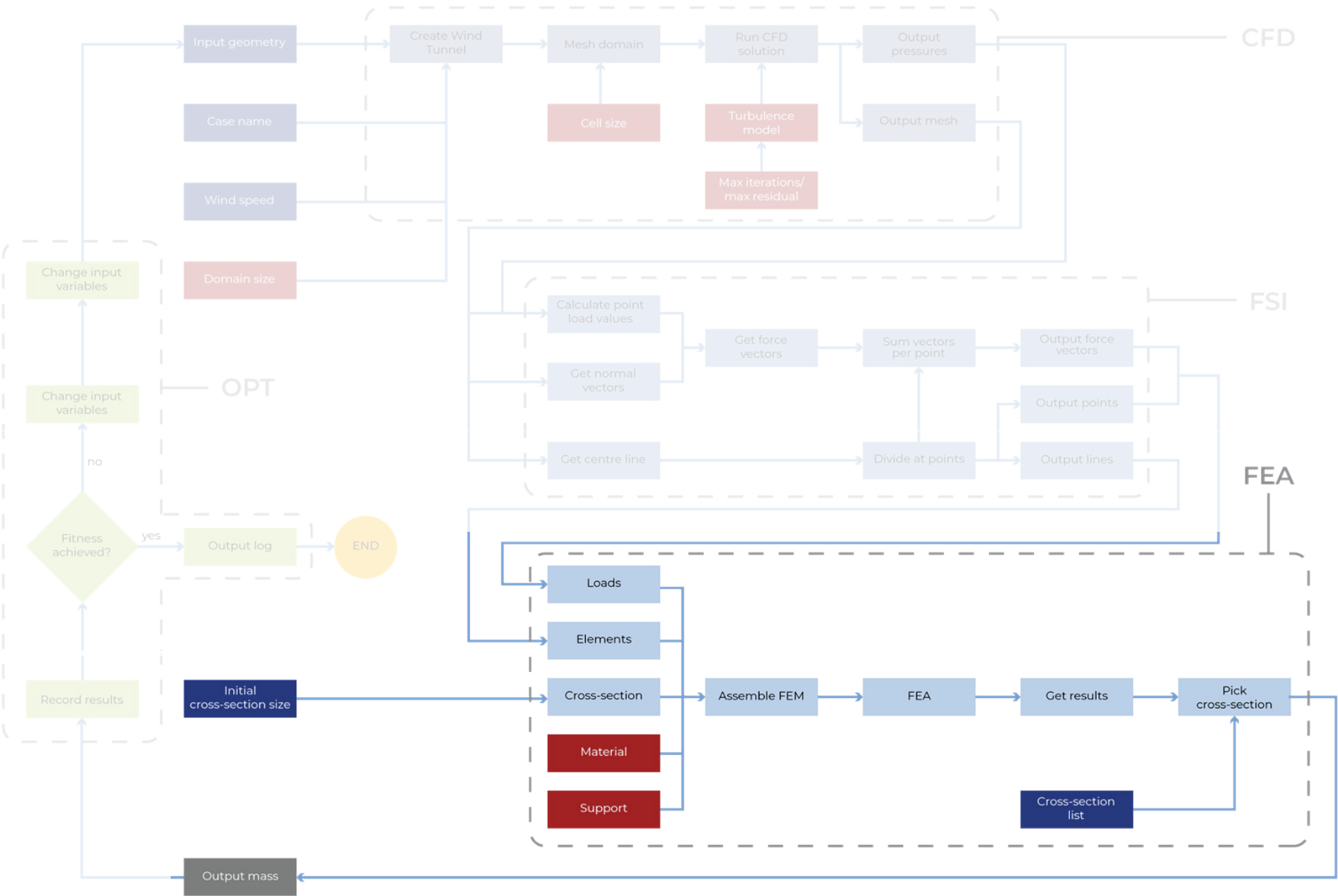


Final Method

FSI
Translate CFD output
to FEM

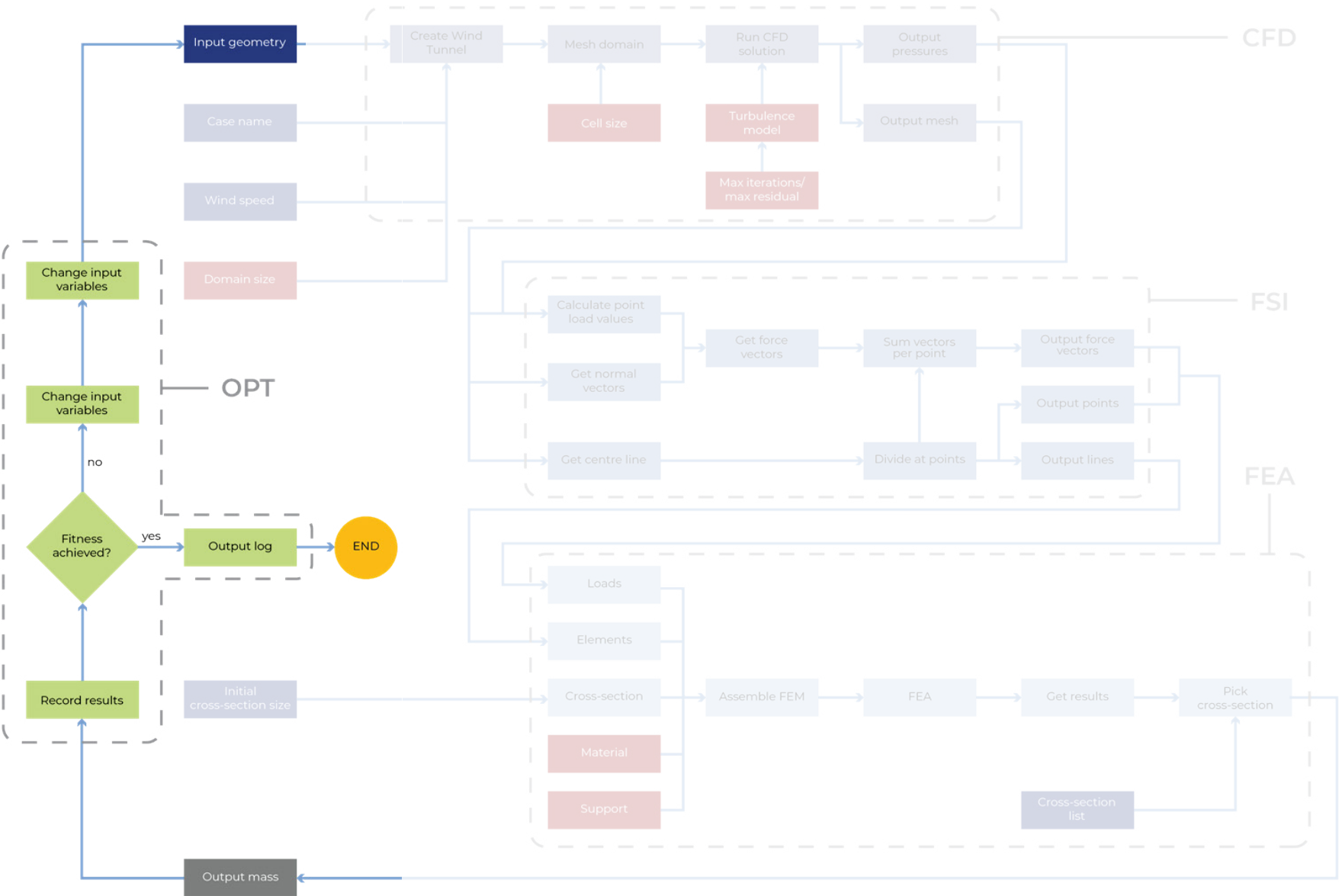


FEA
Analyse structural
reactions

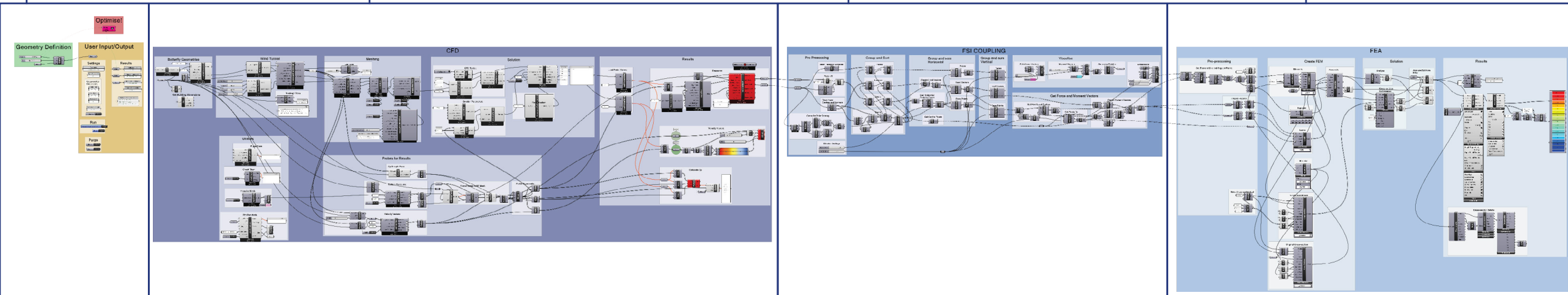


Final Method

OPT
Manipulate inputs to
minimize output.
Record results.



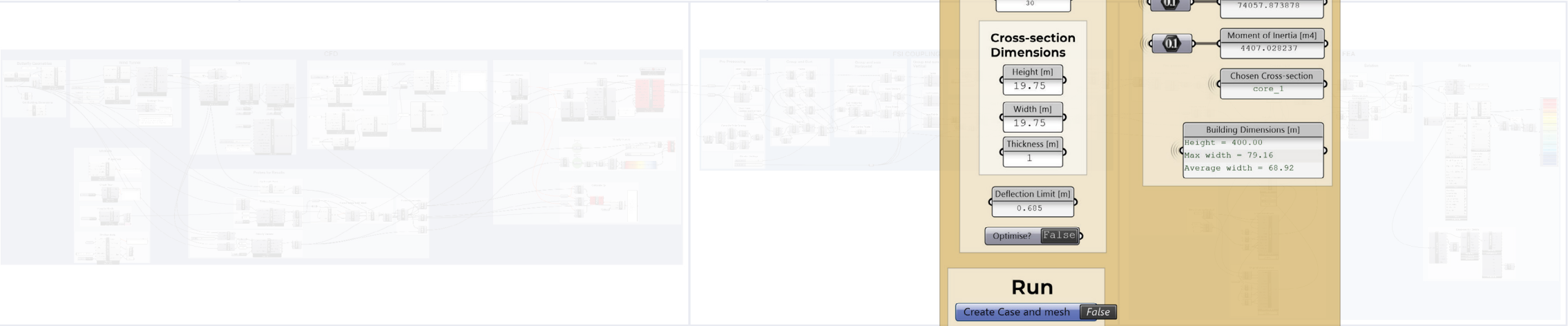
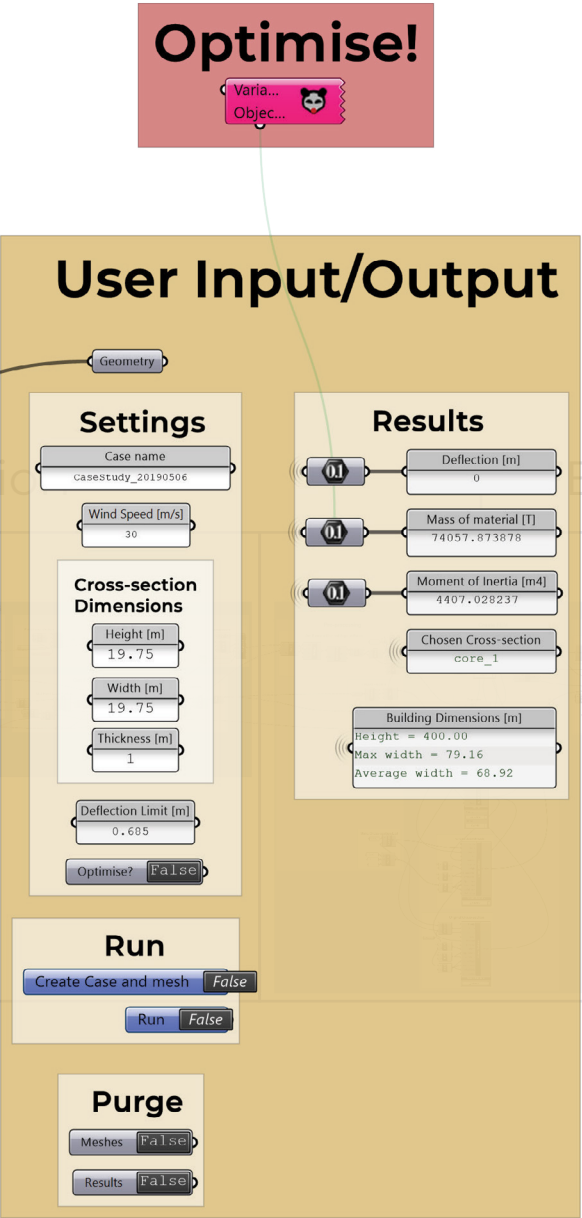
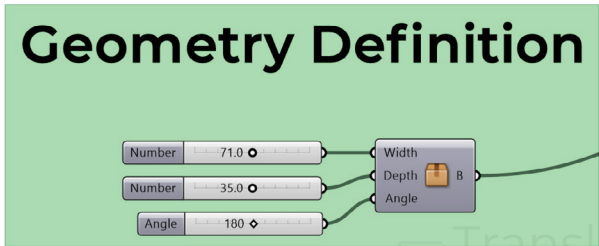
FINAL FSIO GH SCRIPT



USER INPUT AREA

Aid ease of use.
Clear inputs and outputs.
No need to interact with backend.

UI



Optimise!



Geometry Definition



User Input/Output

Settings

Save Settings

Load Settings

Reset Settings

Export Settings

Import Settings

Advanced Settings

Advanced Settings

Run

Run

Stop

Purge

Purge

Purge

Results

Results

Results

Results

Results

Results

Results

Results

Results

Results

Results

Results

Results

Results

Results

Results

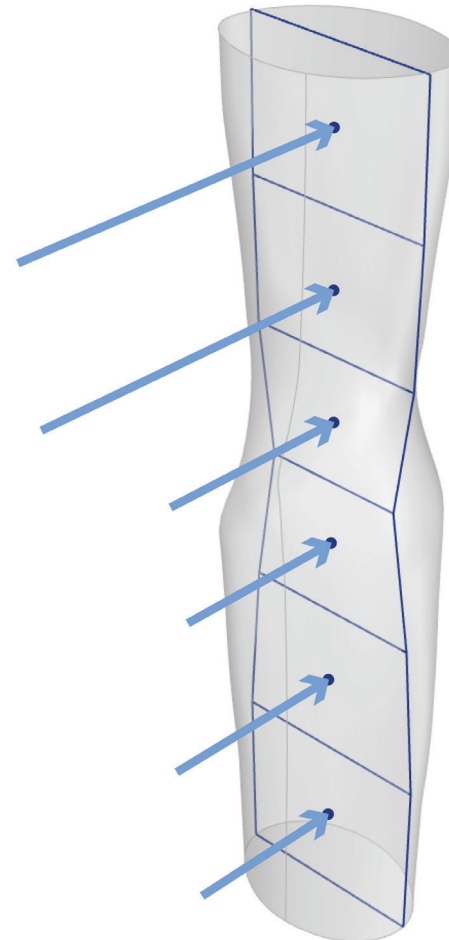
Results

VERIFY

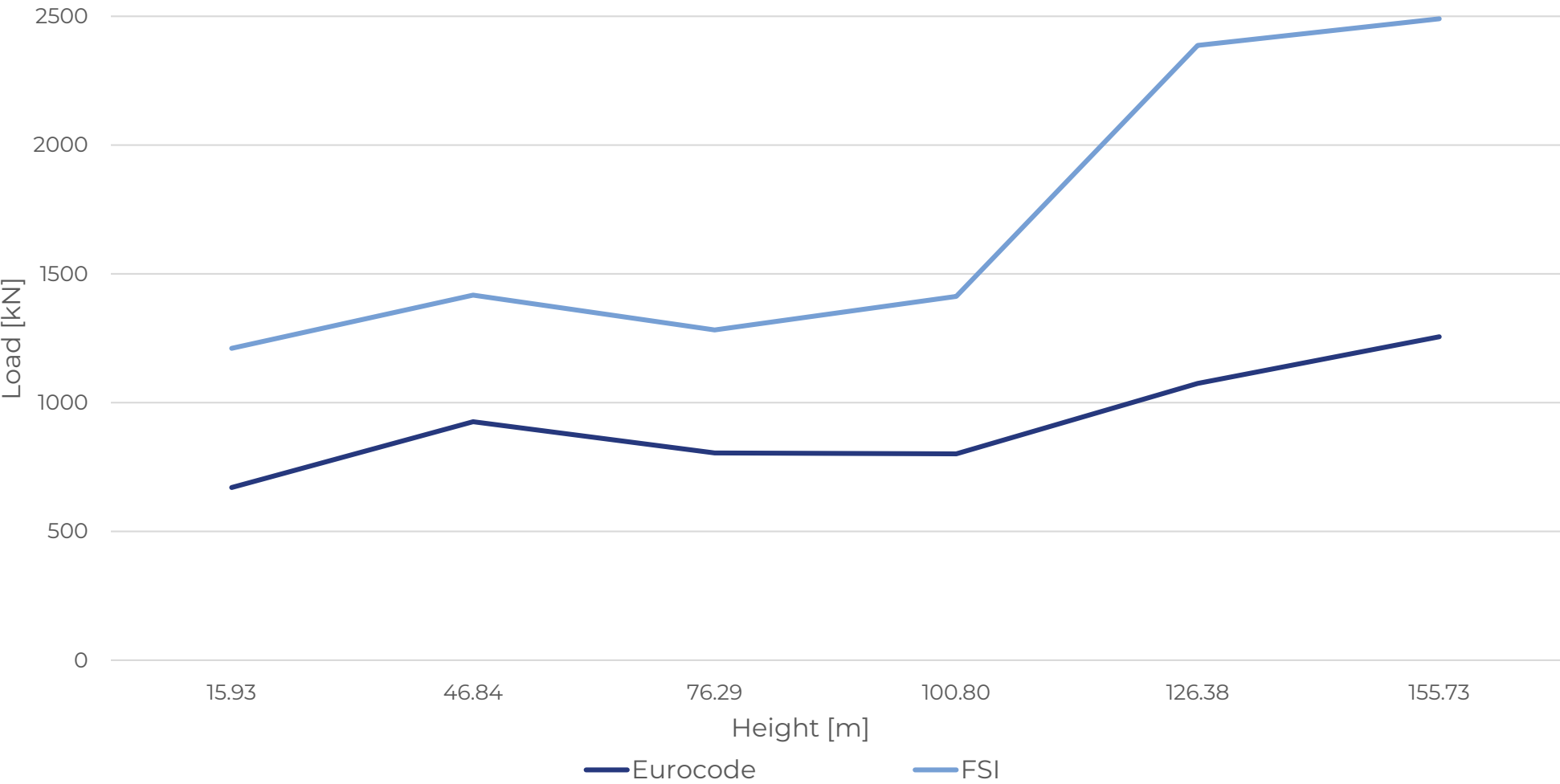
COMPARE FSI RESULTS TO EUROCODE

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$$

- Calculated at 6 heights as in FSI tool
- A_{ref} = areas around load points
- Wind speed = 30 m/s
- EN values for cylindrical geometry taken



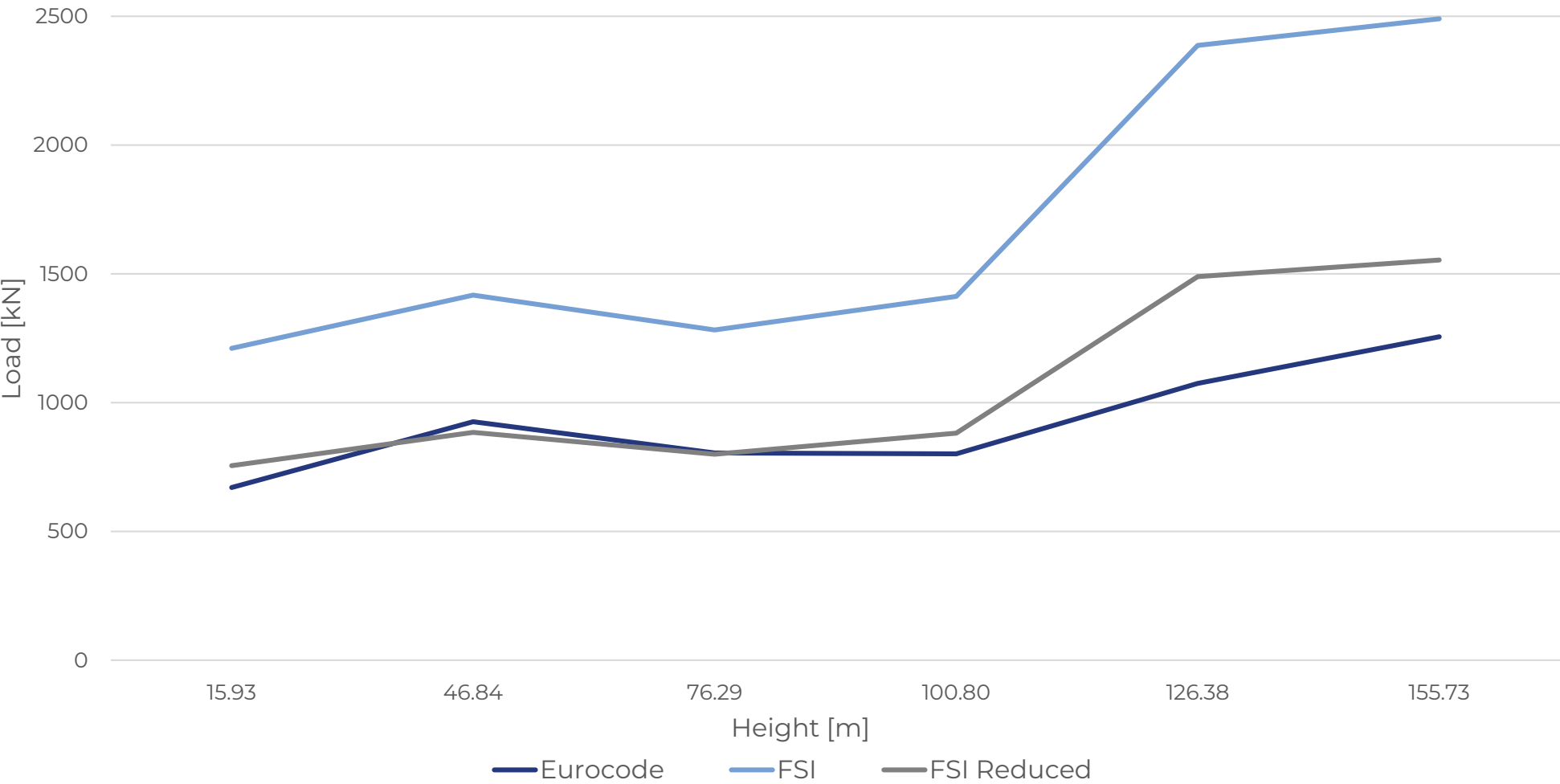
RESULTS – ABSOLUTE TOWER



FSI results much higher than EN

Likely because CFD calculates peak pressures

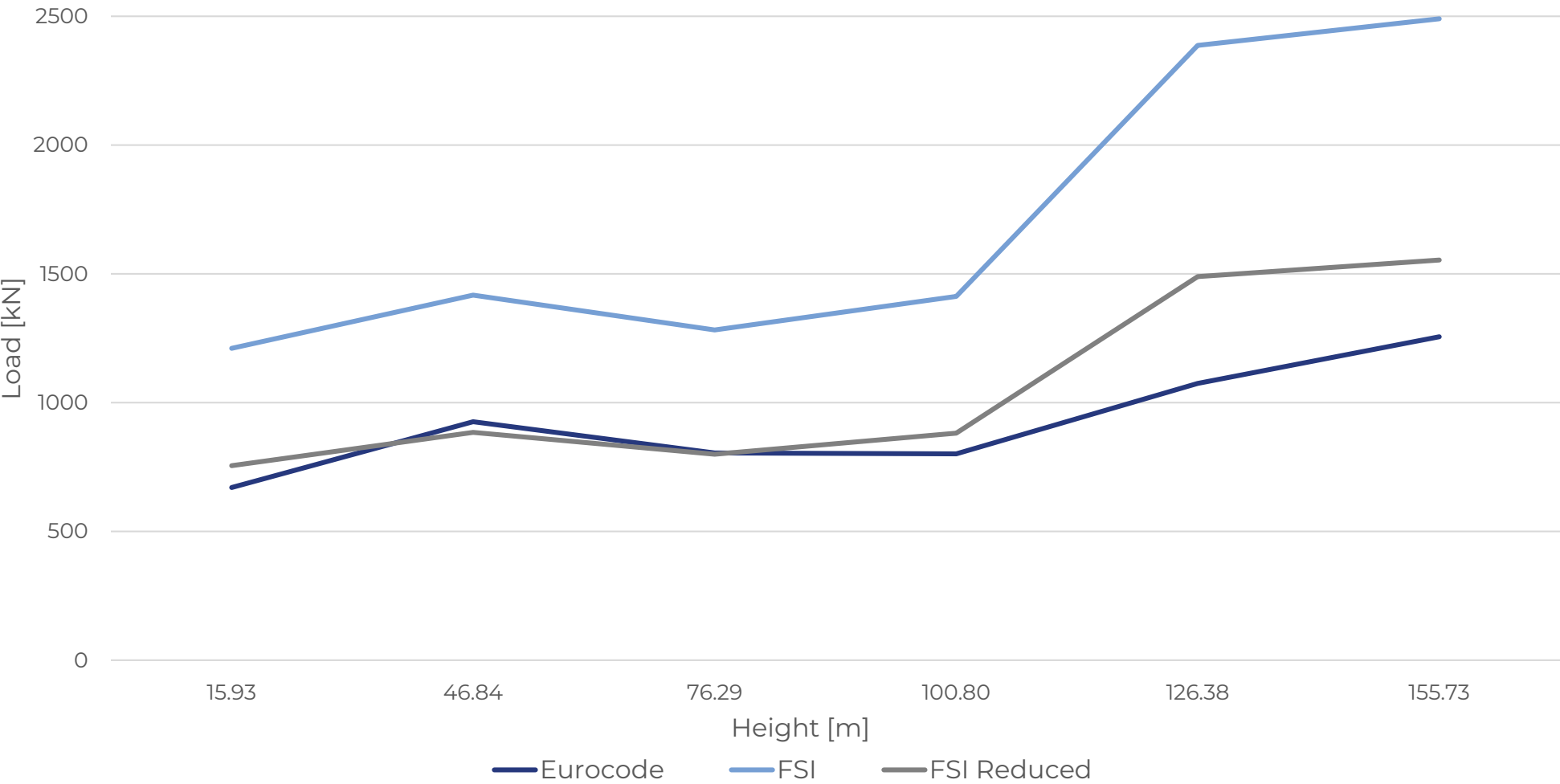
RESULTS – ABSOLUTE TOWER



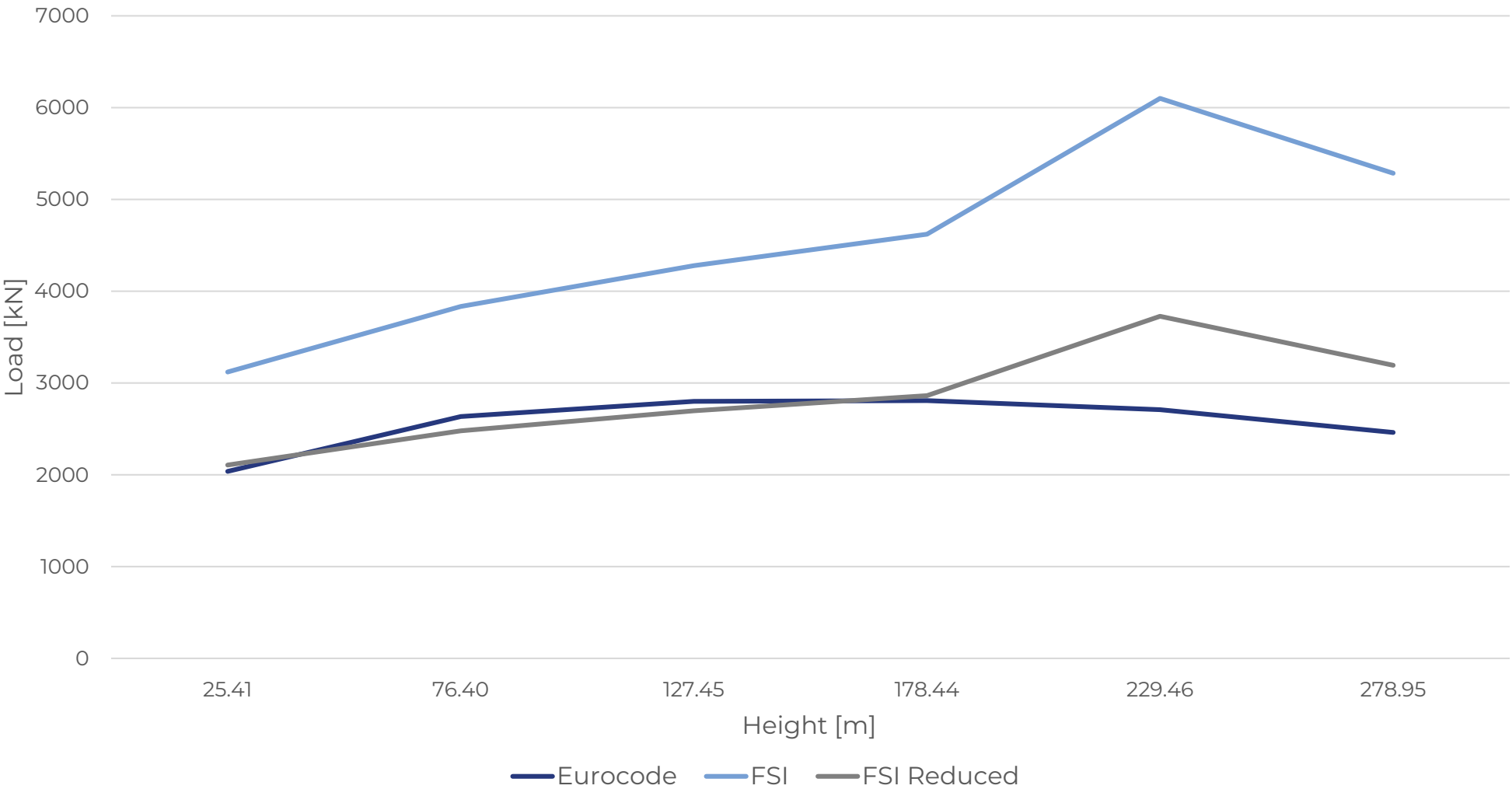
FSI reduced = $F_{W,FSI} \times c_s c_d \times c_f$

Accounts for non-simultaneous occurrence of peak pressures

RESULTS – ABSOLUTE TOWER



RESULTS – NANCHANG TOWER

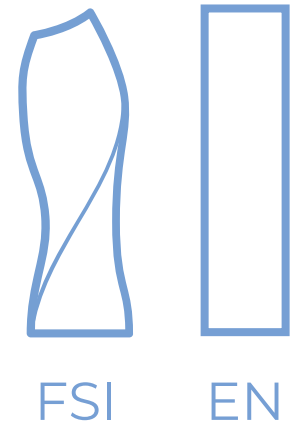


CONCLUSIONS

FSI $\approx$ EN

- FSI method with factors give close results to EN
- Values were expected to be lower than EN. Possibly due to coarse CFD settings.

Deviations show FSI method's ability to capture effects of geometry



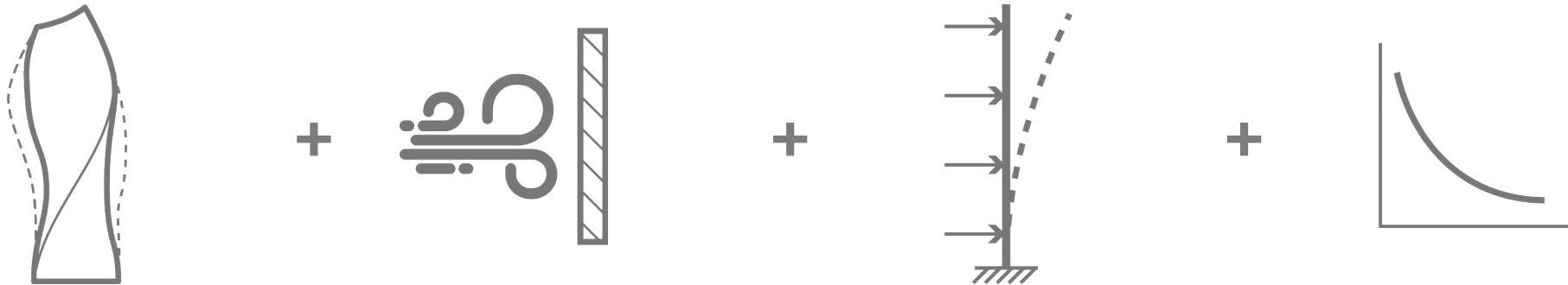
CONCLUSIONS

RESEARCH QUESTION

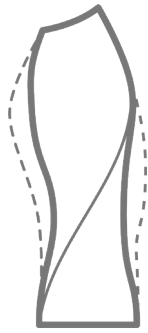
How can **computational methods** be used to accurately and efficiently calculate **wind load** on a **complex geometry** building and **optimise** the geometry to reduce wind responses in the **early design phase**?

ANSWER TO RESEARCH QUESTION

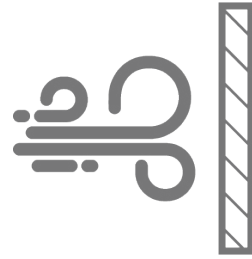
Fluid-Structure Interaction based Optimisation (FSIO) method



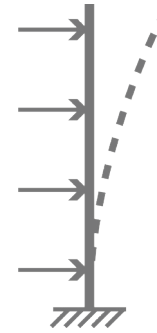
RECOMMENDATIONS FOR AN FSIO METHOD



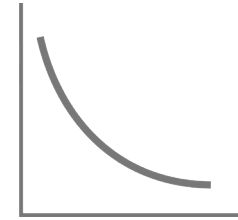
+



+



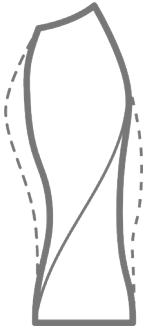
+



Maintain
design intent

Wide enough
input range

RECOMMENDATIONS FOR AN FSIO METHOD



Maintain
design intent

Wide enough
input range

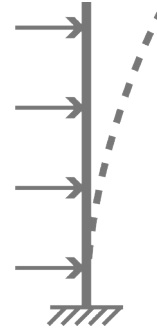
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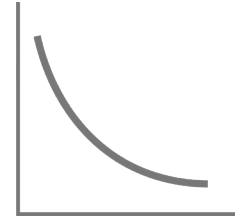
RNG $k - \varepsilon$
accuracy and
time

Coarse mesh
with minimal
iterations

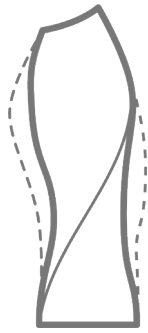
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+



RECOMMENDATIONS FOR AN FSIO METHOD



Maintain
design intent

Wide enough
input range

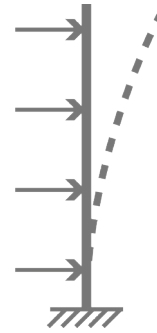
+



RNG $k-\epsilon$
accuracy and
time

Coarse mesh
with minimal
iterations

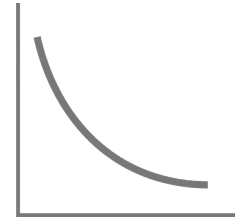
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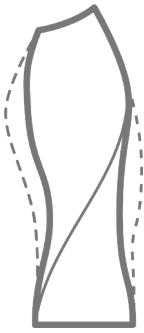
Material mass
useful objective

Thorough list of
cross-sections

+



RECOMMENDATIONS FOR AN FSIO METHOD



Maintain
design intent

Wide enough
input range

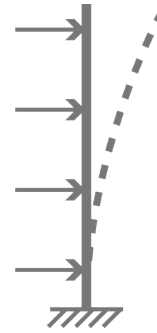
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RNG $k - \varepsilon$
accuracy and
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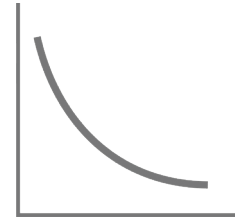
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Material mass
useful objective

Thorough list of
cross-sections

+



Model-based
optimisation
algorithm

List of results
rather than
single optimum

THANK YOU

FURTHER IMPROVEMENTS

A method for analysing and optimising dynamic cross-wind loading could be implemented

Analyse multiple wind directions

Further validation with wind tunnel tests from a complex geometry building could be done

Evaluation of different optimisation algorithms to determine if model-based is truly the best option