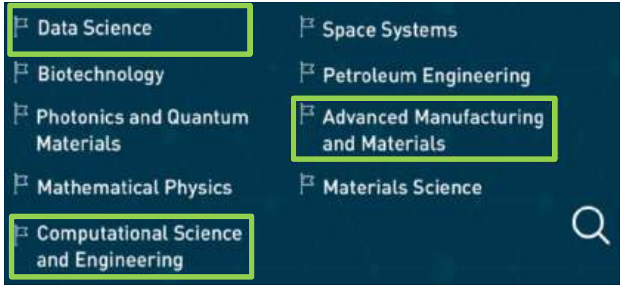
LABORATORY OF CYBER-PHYSICAL SYSTEMS

Skoltech

Skolkovo Institute of Science and Technology



- Data Science
- Biotechnology
- Photonics and Quantum Materials
- Mathematical Physics
- Computational Science and Engineering
- Space Systems
- Petroleum Engineering
- Advanced Manufacturing and Materials
- Materials Science

AGENDA

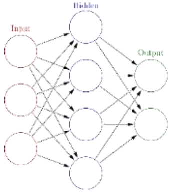
- About Skoltech Cyber-Physical Laboratory
- Project-oriented courses in Skoltech
- pSeven in industrial applications
- pSeven in educational applications
- pSeven in scientific – industrial applications

Digital twins of complex technical systems

Industrial AI for Design & Manufacturing

Prescriptive analytics and preventive maintenance

DIGITAL TWIN



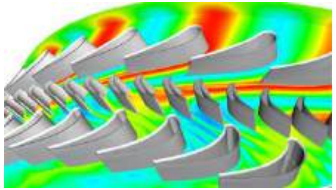
ML* models

- High speed
- Lack of data
- Non-physical models

Digital Twin

Physics-based models

- Low speed
- Physics-based



Use data to find the dependencies

- Decision trees
- Random forest
- Neural networks
- Kriging, etc.

Use dependencies to generate data

Numerical methods

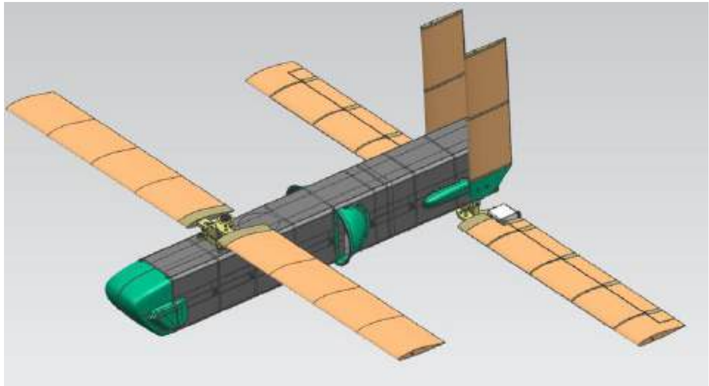
- Structural mechanics
- Fluid dynamics
- Heat and mass transfer
- System dynamics

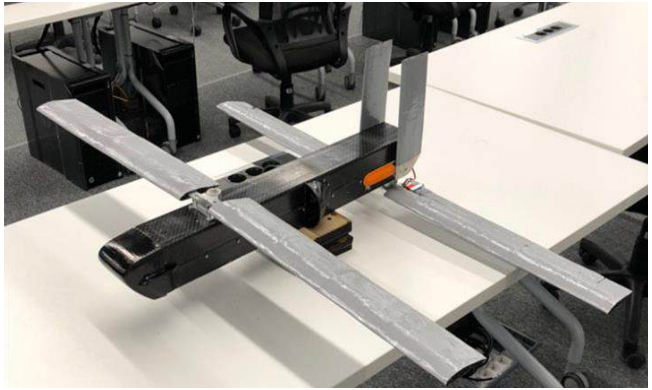
*machine learning

TECHNOLOGY STACK

EDUCATION BASED ON PROJECT ORIENTED COURSES

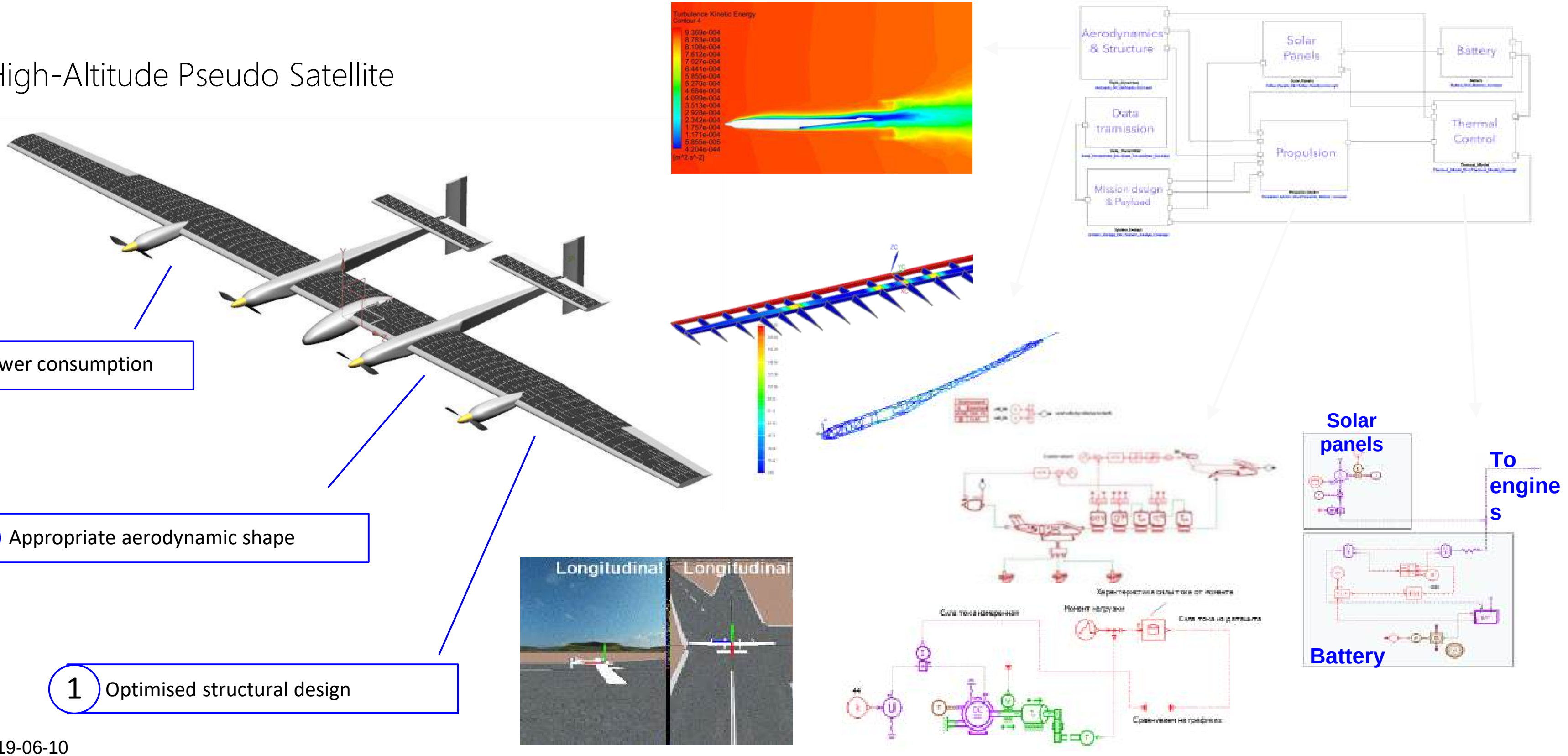
TUBE-LAUNCHED UAV DESIGN AND PROTOTYPE





PROJECT-BASED EDUCATION ON DIGITAL DESIGN. HAPS DESIGN

High-Altitude Pseudo Satellite



② Efficient power consumption

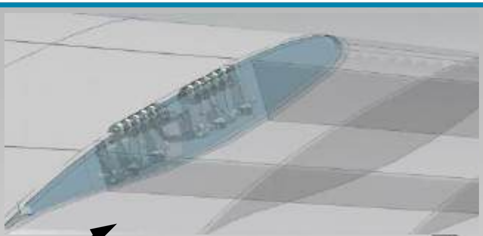
③ Appropriate aerodynamic shape

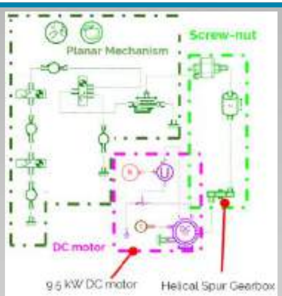
① Optimised structural design

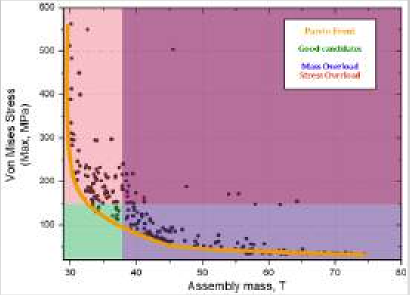
PROJECT-BASED EDUCATION ON DIGITAL DESIGN. TBW DESIGN

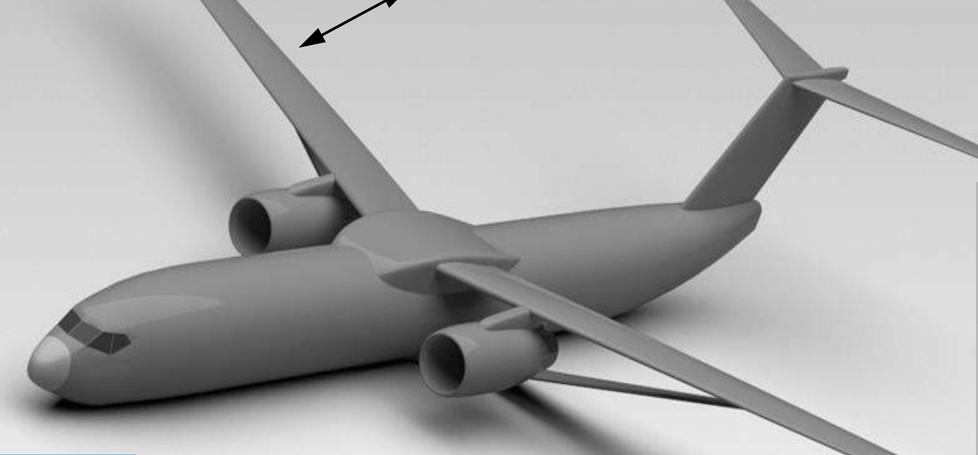
Flight distance: 5700 km

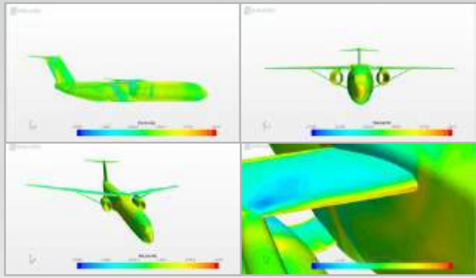
Wing span: 45 m
Hybrid turbofan
Thrust: 190 kN
Fuel consumption: 3400 kg/hour

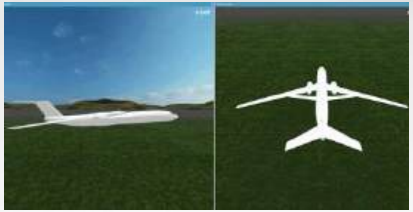






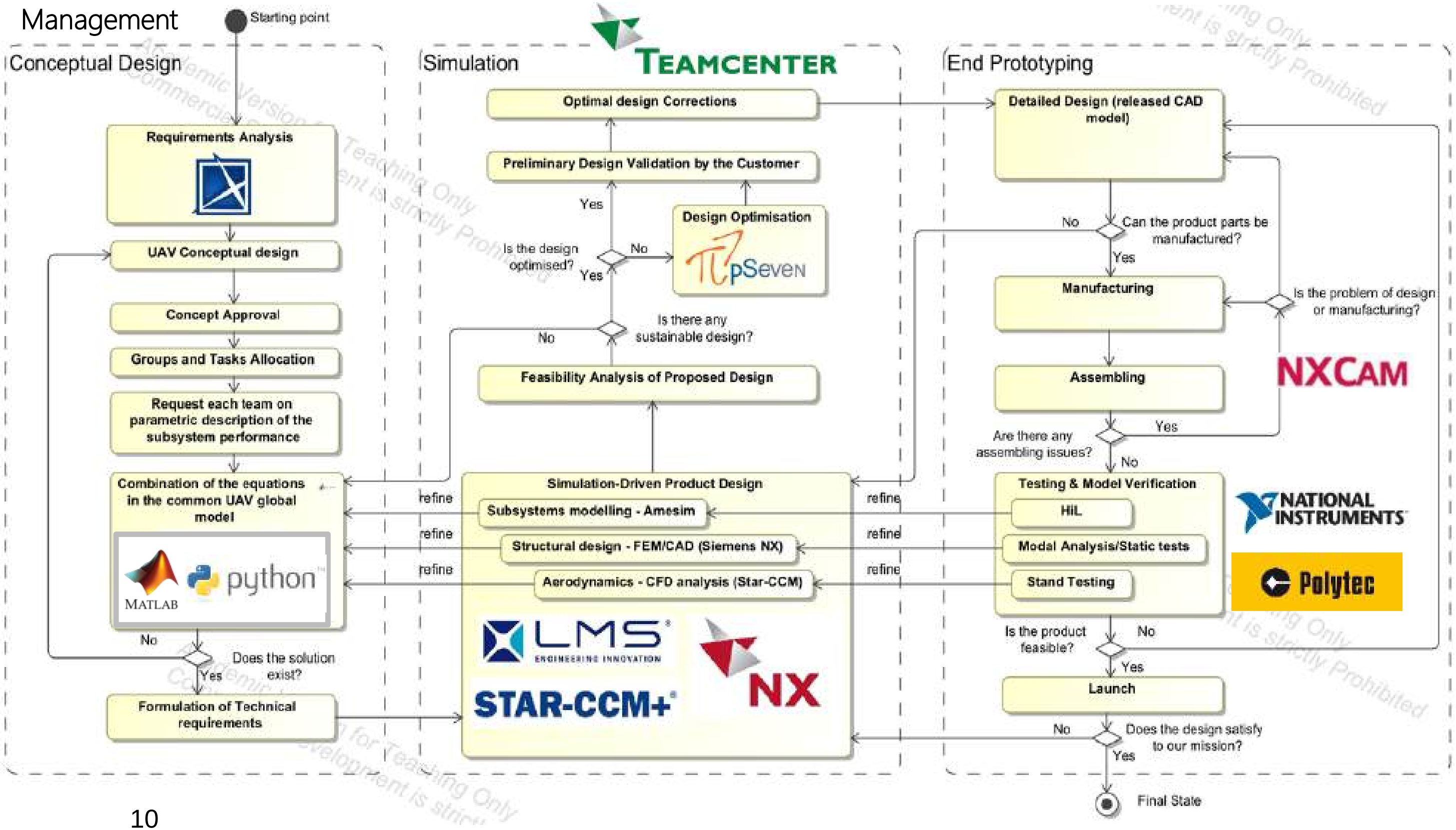






DIGITAL DESIGN WORKFLOW

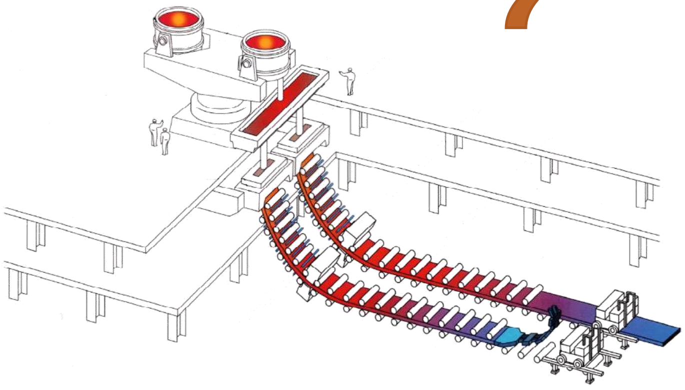
Data & Processes Management



CONTINUOUS CASTING OF A STEEL.
SECONDARY COLING ZONE OPTIMIZATION

DIGITAL TWIN IN METALLURGY INDUSTRY

Operated Equipment

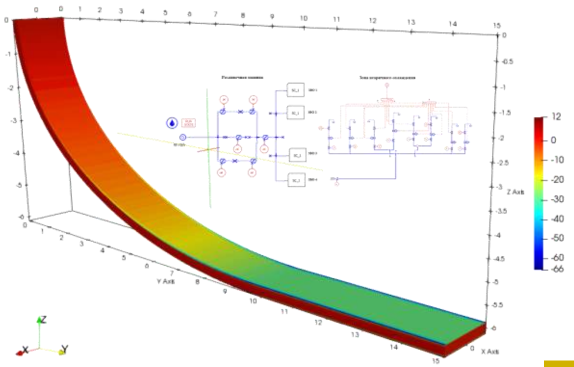


Caster, pumps, compressors, rollers, live rolls, etc.

Process Data

Optimization of the technological parameters

Digital twin

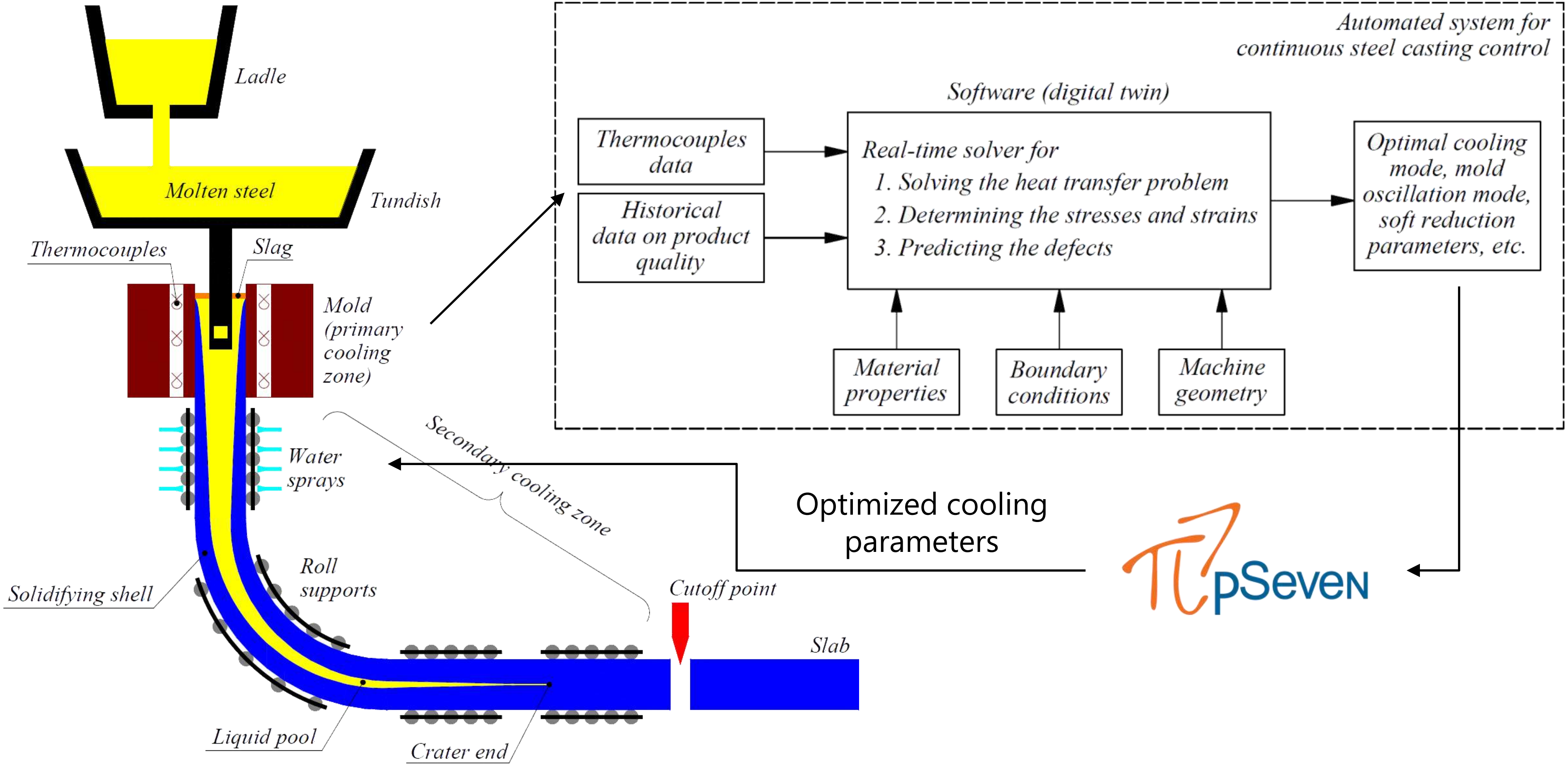


Physics-based models

Benefits

- Decrease in economic losses for operation and repair
- Optimization of the technological parameters
- For continuous casting machines, casting speed increase up to 10% with quality improvement

APPLICATION OF DIGITAL TWINS IN MODERN STEELMAKING



Automated system for continuous steel casting control

Software (digital twin)

Thermocouples data

Historical data on product quality

Real-time solver for
1. Solving the heat transfer problem
2. Determining the stresses and strains
3. Predicting the defects

Material properties

Boundary conditions

Machine geometry

Optimal cooling mode, mold oscillation mode, soft reduction parameters, etc.

Optimized cooling parameters

MODELS AND ALGORITHMS: HEAT TRANSFER PROBLEM

I. Fourier-Kirchhoff equation

$$\rho c\left(\frac{\partial T}{\partial t} + (\bar{v}\cdot\bar{\nabla})T\right) = \bar{\nabla}(k\,\bar{\nabla}\,T) + q_v$$

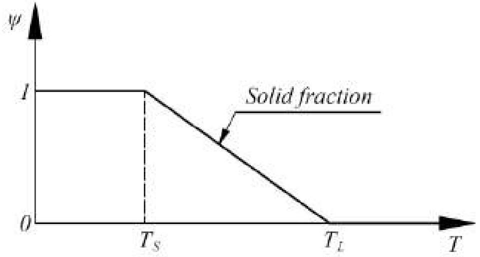
$$\downarrow$$

$$\chi(T) \triangleq \frac{\rho}{k}v\left(c + \frac{\lambda'}{T_L - T_S}\right)$$

$$\downarrow$$

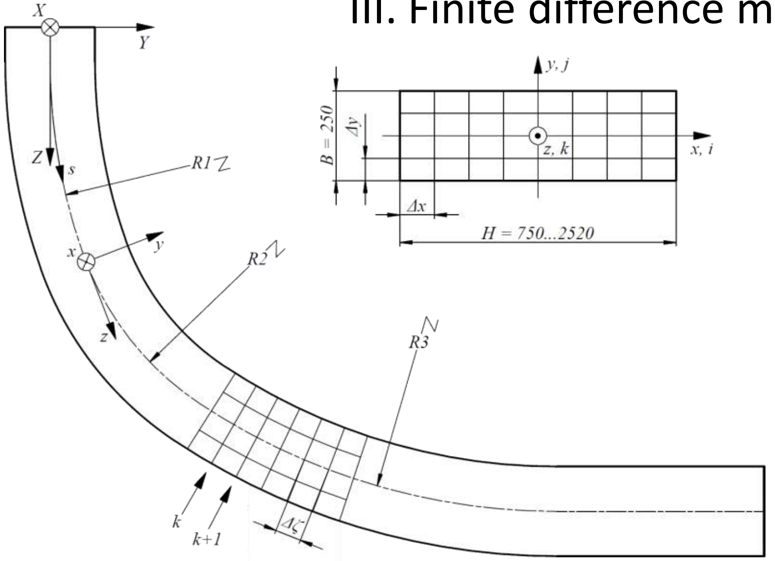
$$\chi\frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}$$

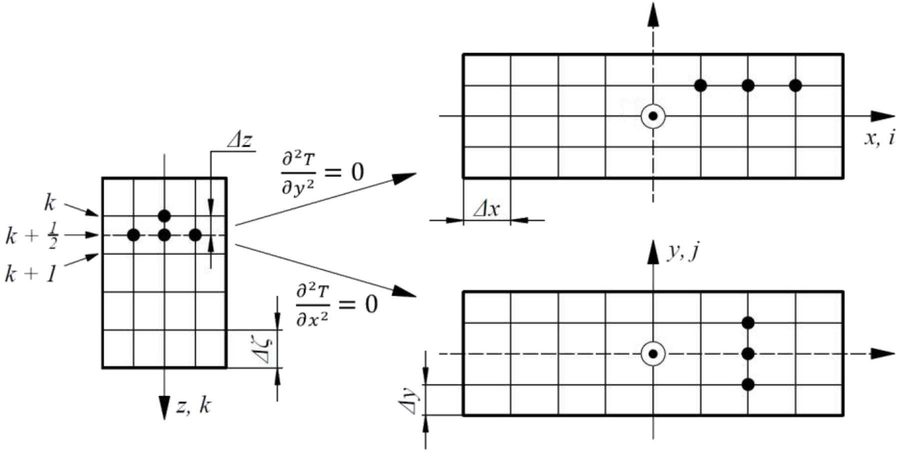
II. Considering the phase change



$$\rho = \psi\rho_S + (1-\psi)\rho_L$$

III. Finite difference method (FDM) scheme and stencils





MODELS AND ALGORITHMS: PREDICTION OF CRACKS

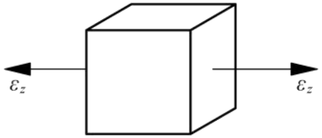
I. Considered components of strain

$$\varepsilon = \varepsilon_z = \varepsilon_0 - æy = \varepsilon^e + \varepsilon^t + \varepsilon^c$$

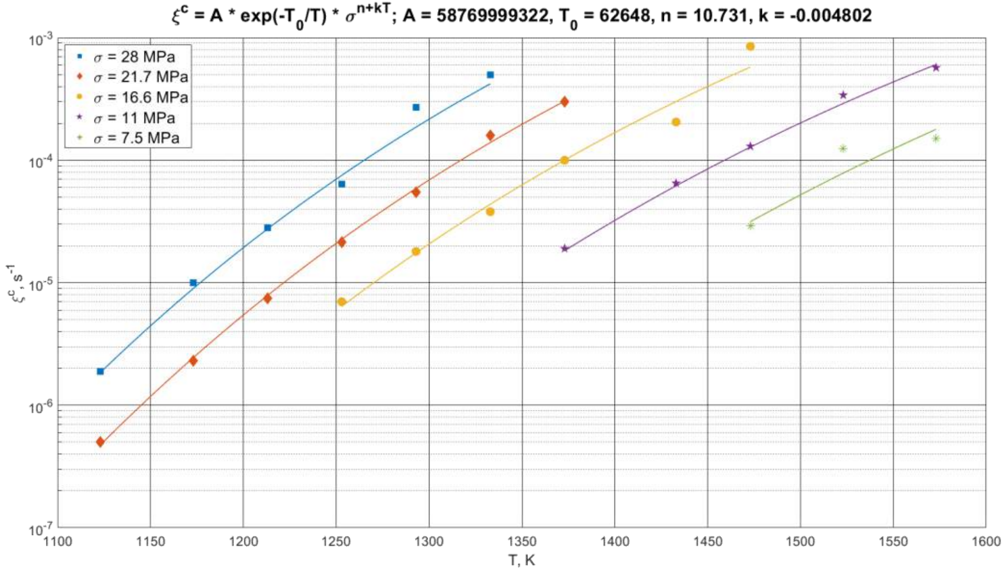
Elastic strain → $\varepsilon^e = \dfrac{\sigma}{E}$

Thermal strain → $\varepsilon^t = \alpha \Delta T$

Creep strain → $\varepsilon^c = \int \xi^c dt$



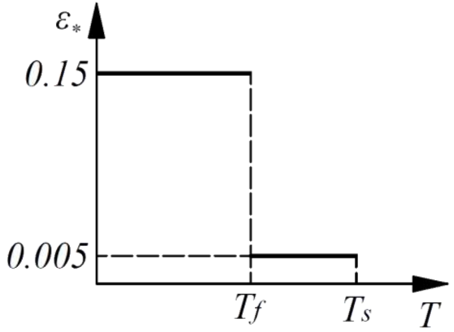
II. Creep strain rate formula


ξ^c = A * exp(-T_0/T) * σ^{n+kT}; A = 58769999322, T_0 = 62648, n = 10.731, k = -0.004802

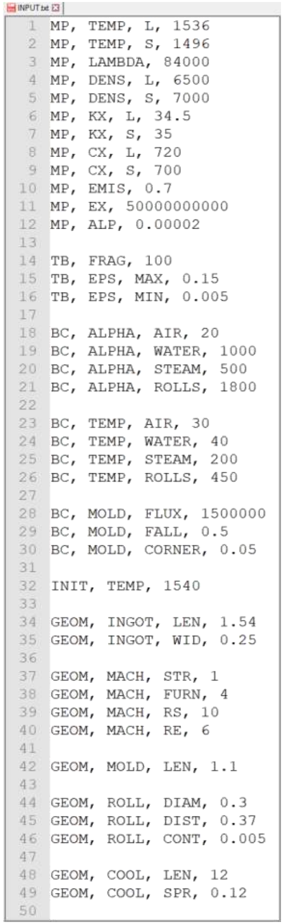
III. Damage accumulation

$$\Delta\omega = \frac{\Delta t}{t_f}$$

$$t_f = \frac{\varepsilon_*(T)}{\xi^c}$$



PRELIMINARY RESULTS: SOFTWARE



```
MP, TEMP, L, 1536
MP, TEMP, S, 1496
MP, LAMBDA, 84000
MP, DENS, L, 6500
MP, DENS, S, 7000
MP, KX, L, 34.5
MP, KX, S, 35
MP, CX, L, 720
MP, CX, S, 700
MP, EMIS, 0.7
MP, EX, 50000000000
MP, ALP, 0.00002

TB, FRAG, 100
TB, EPS, MAX, 0.15
TB, EPS, MIN, 0.005

BC, ALPHA, AIR, 20
BC, ALPHA, WATER, 1000
BC, ALPHA, STEAM, 500
BC, ALPHA, ROLLS, 1800

BC, TEMP, AIR, 30
BC, TEMP, WATER, 40
BC, TEMP, STEAM, 200
BC, TEMP, ROLLS, 450

BC, MOLD, FLUX, 1500000
BC, MOLD, FALL, 0.5
BC, MOLD, CORNER, 0.05

INIT, TEMP, 1540

GEOM, INGOT, LEN, 1.54
GEOM, INGOT, WID, 0.25

GEOM, MACH, STR, 1
GEOM, MACH, FURN, 4
GEOM, MACH, RS, 10
GEOM, MACH, RE, 6

GEOM, MOLD, LEN, 1.1

GEOM, ROLL, DIAM, 0.3
GEOM, ROLL, DIST, 0.37
GEOM, ROLL, CONT, 0.005

GEOM, COOL, LEN, 12
GEOM, COOL, SPR, 0.12

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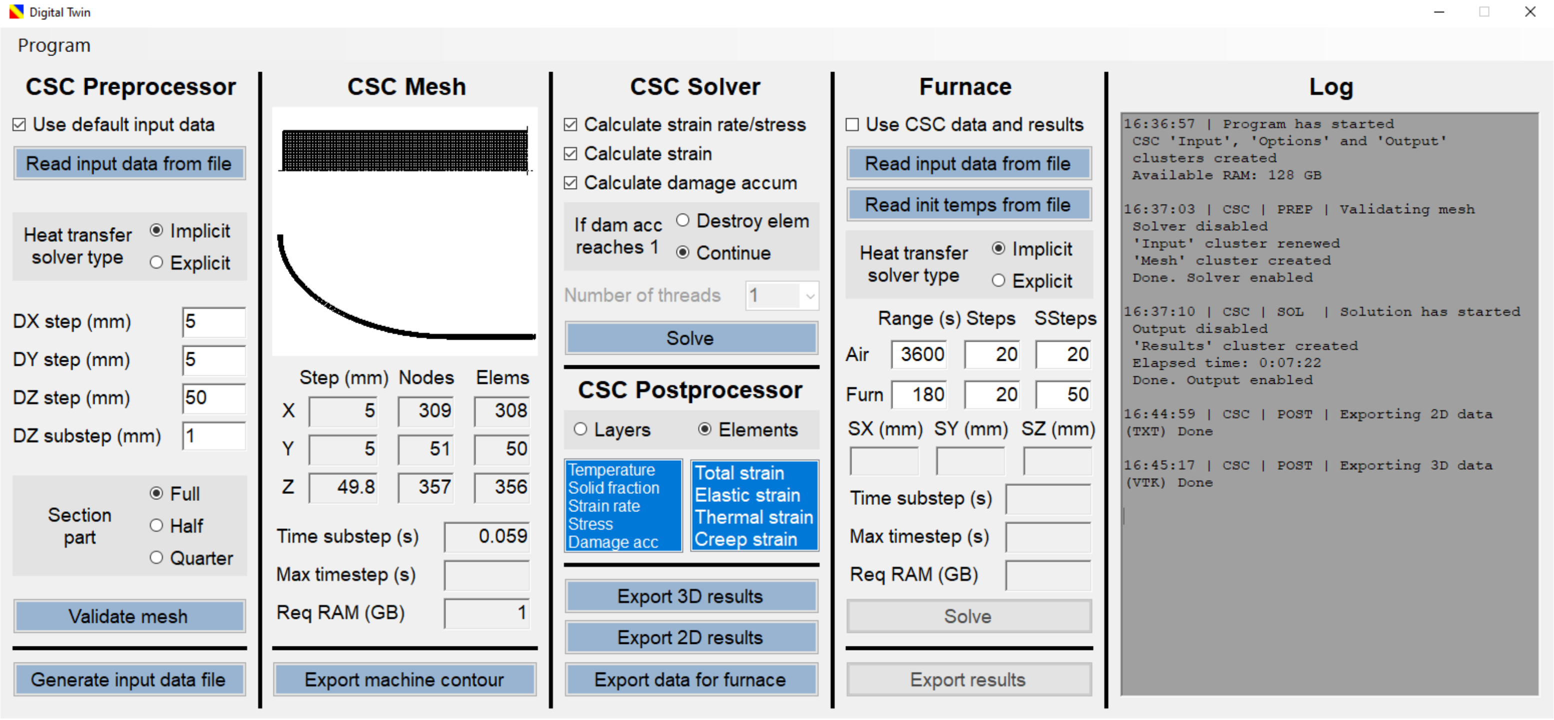


CSC Preprocessor

☑ Use default input data

Heat transfer solver type: ● Implicit ○ Explicit

DX step (mm): 5

DY step (mm): 5

DZ step (mm): 50

DZ substep (mm): 1

Section part: ● Full ○ Half ○ Quarter

CSC Mesh

	Step (mm)	Nodes	Elems
X	5	309	308
Y	5	51	50
Z	49.8	357	356

Time substep (s): 0.059

Max timestep (s):

Req RAM (GB): 1

CSC Solver

☑ Calculate strain rate/stress

☑ Calculate strain

☑ Calculate damage accum

If dam acc reaches 1: ○ Destroy elem ● Continue

Number of threads: 1

CSC Postprocessor

○ Layers ● Elements

Temperature
Solid fraction
Strain rate
Stress
Damage acc

Total strain
Elastic strain
Thermal strain
Creep strain

Furnace

☐ Use CSC data and results

Heat transfer solver type: ● Implicit ○ Explicit

	Range (s)	Steps	SSteps
Air	3600	20	20
Furn	180	20	50

SX (mm) SY (mm) SZ (mm)

Time substep (s):

Max timestep (s):

Req RAM (GB):

Log

```
16:36:57 | Program has started
 CSC 'Input', 'Options' and 'Output'
 clusters created
 Available RAM: 128 GB

16:37:03 | CSC | PREP | Validating mesh
 Solver disabled
 'Input' cluster renewed
 'Mesh' cluster created
 Done. Solver enabled

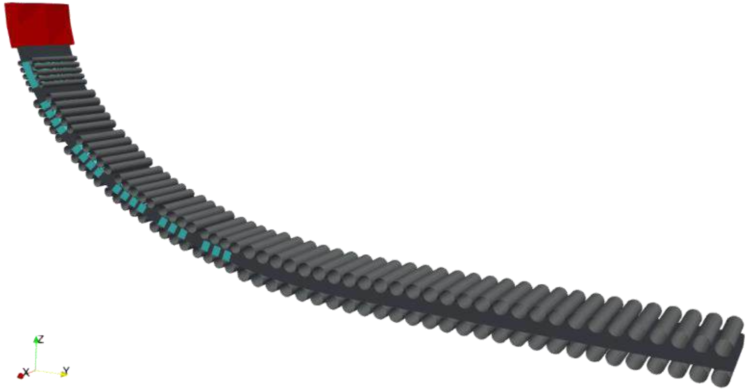
16:37:10 | CSC | SOL  | Solution has started
 Output disabled
 'Results' cluster created
 Elapsed time: 0:07:22
 Done. Output enabled

16:44:59 | CSC | POST | Exporting 2D data
(TXT) Done

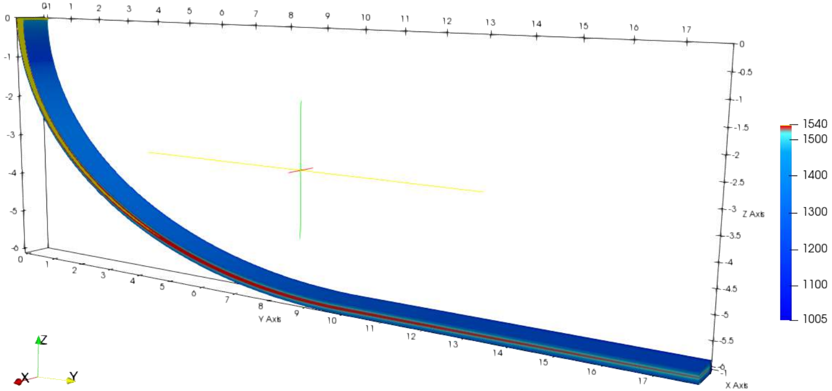
16:45:17 | CSC | POST | Exporting 3D data
(VTK) Done
```

CALCULATION RESULTS

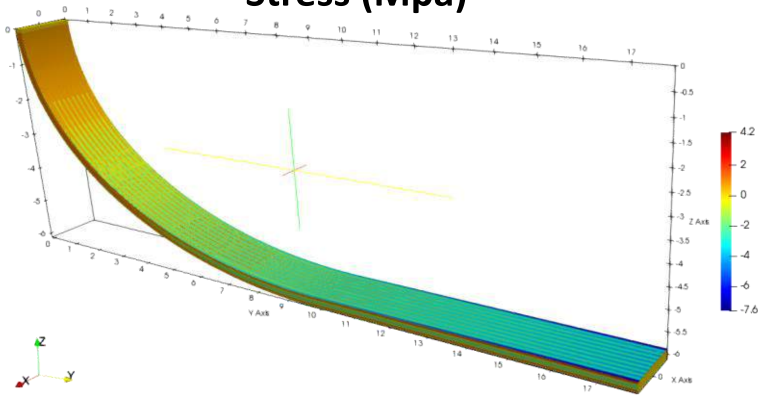
Continuous casting machine with rollers



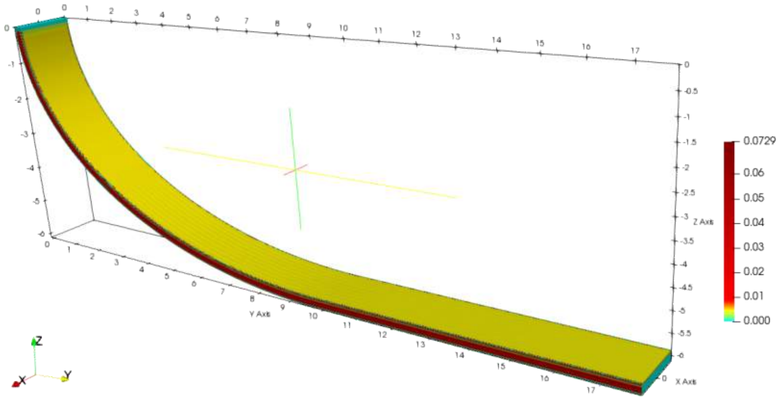
Temperature distribution (C)



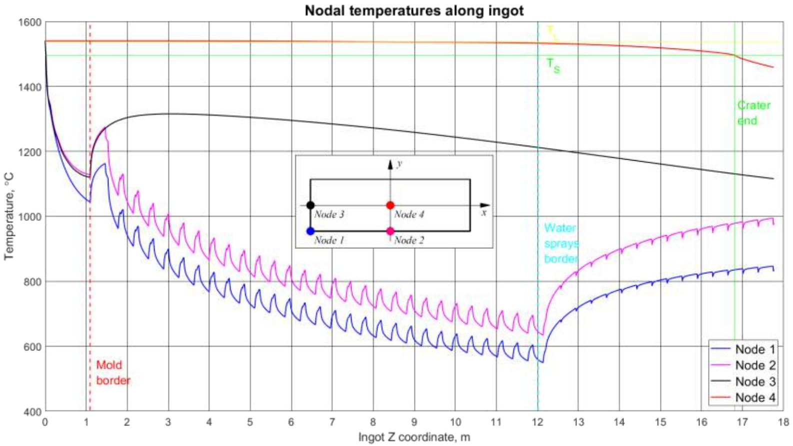
Stress (Mpa)

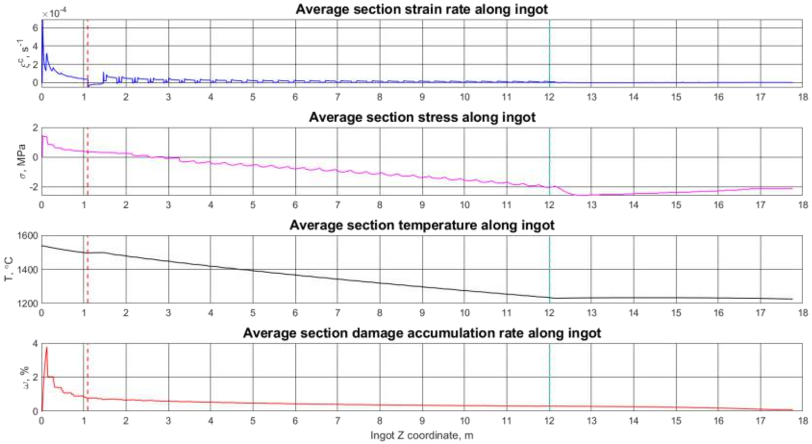


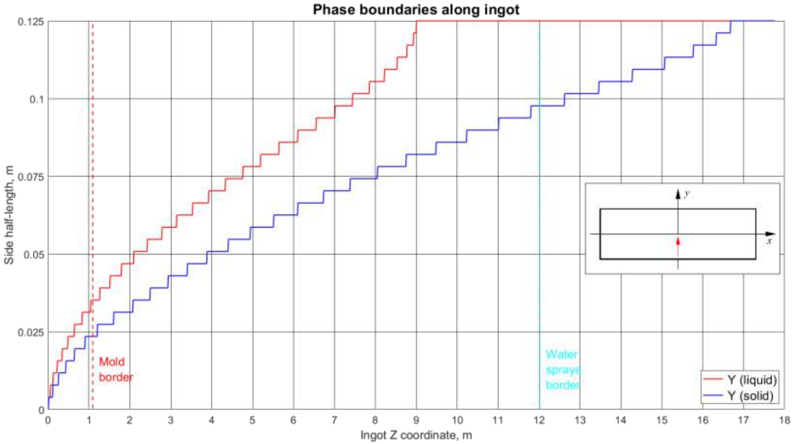
Damage range

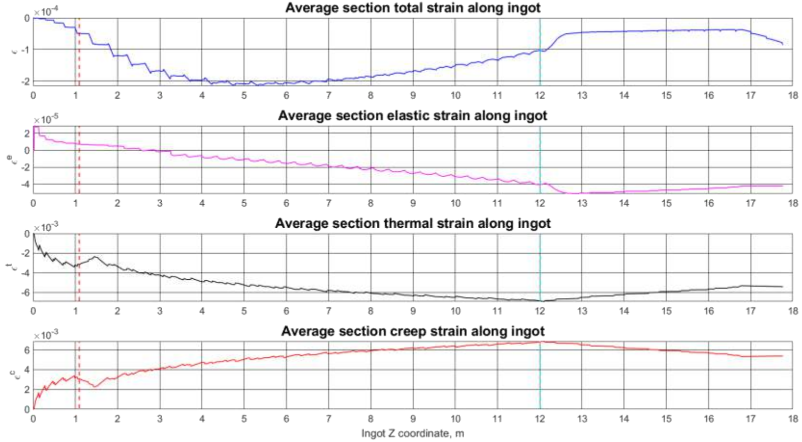


PRELIMINARY RESULTS: 2D PLOTS



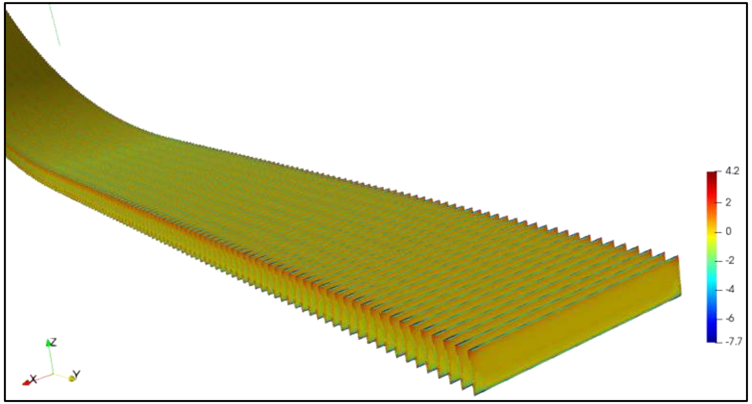




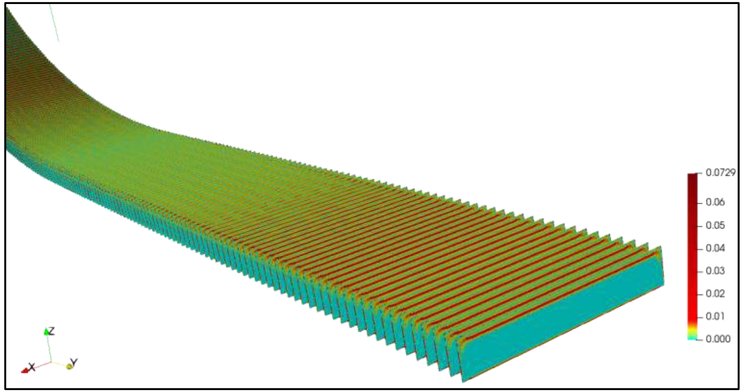


CALCULATION RESULTS

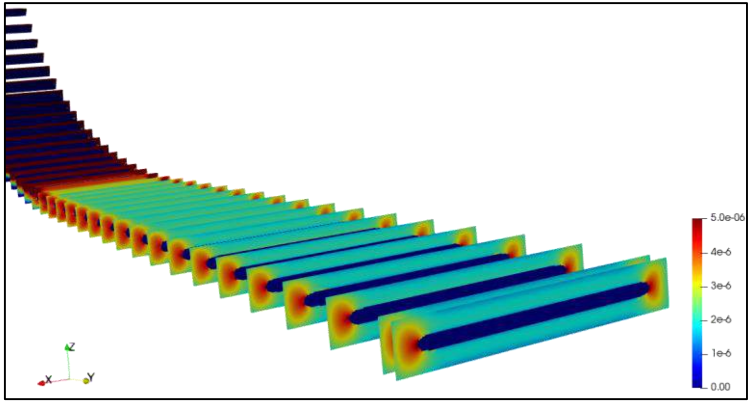
Stress in section (MPa)



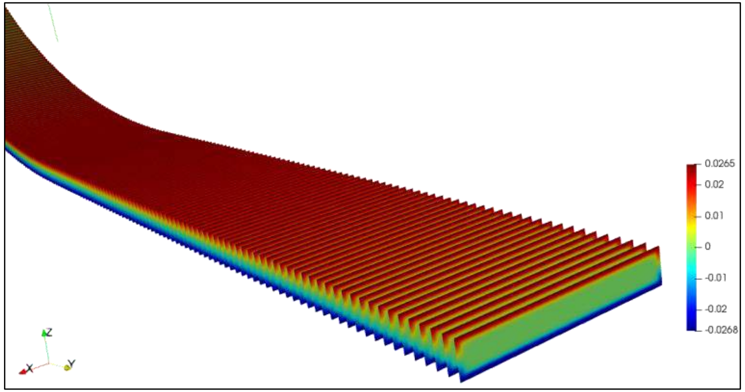
Damage



Strain rate (sec^{-1})



Full strain



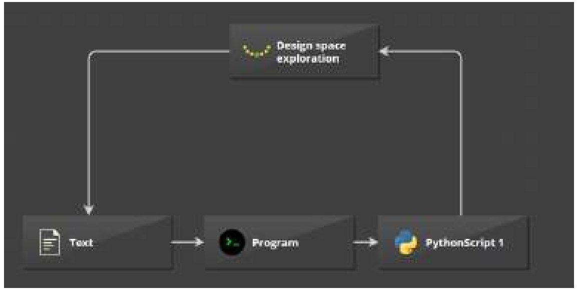
OPTIMIZATION RESULTS

Calculation of the optimal heat removal mode in the SCZ for a casting speed of 1 m / min:

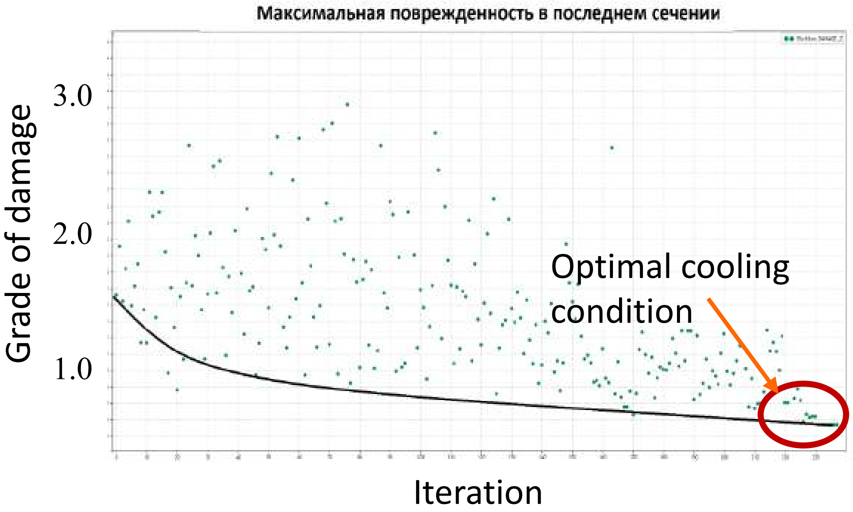
- The starting point is the data of water consumption in the SCZ for casting speeds of 0.6 - 1.0 m / min;
- Specific steel.

Results:

- Potential of optimization.
- Improving quality from **1.5 to 1** grade of damage



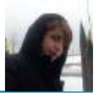
Simple Workflow



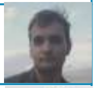
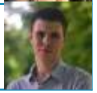
Maximum damage in the last section

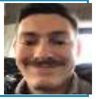
TRUSS BRACED WING AIRCRAFT STUDENT PROJECT

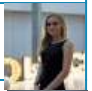
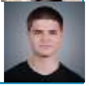
Team of Introduction to PLM 2019

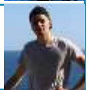
MBSE team	
Hekmat Taheri Nejad	
Yana Brovar	
Hamed Jafarzadeh	
Fahimeh Shiravani	

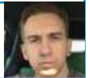
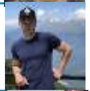
Wing structure team	
Ishwarchandra Gulgule	
Kirill Minchenkov	
Eugene Statnik	
Bogdan Tonanaiskii	

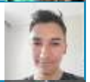
SDPM team	
Guillaume Debaille	
Karolina Latserus	
Alexander Matkov	
Vitaly Petrov	

Production system team	
Arzu Kurgan	
Artur Kolesnikov	
Svetlana Okoyomova	
Mikhail Pustovgarov	

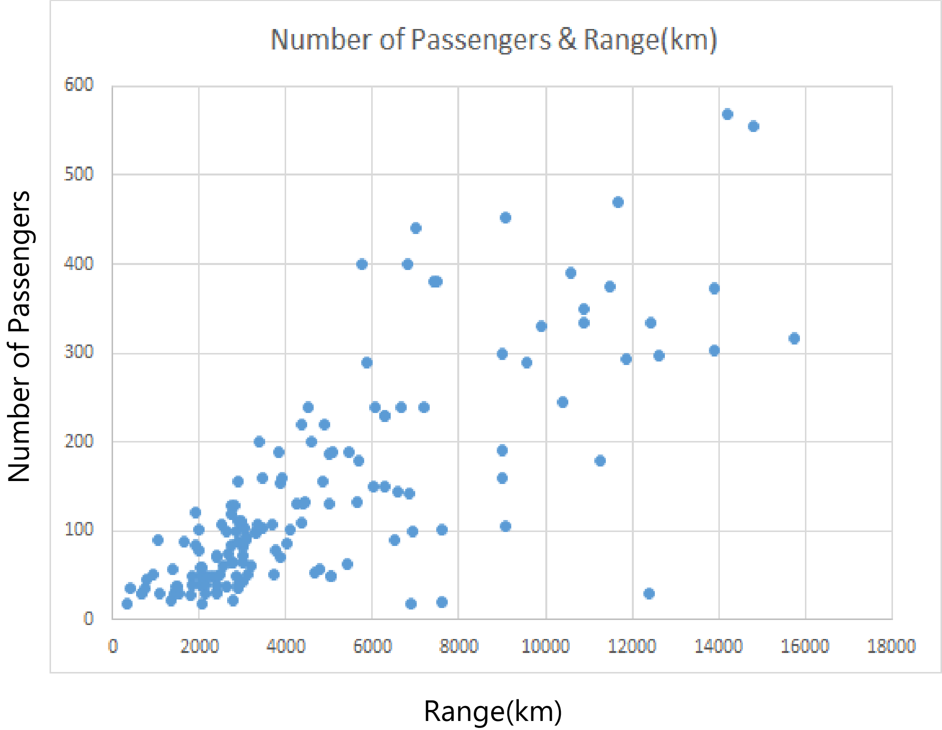
Aerodynamics team	
Ekaterina Isachenko	
Yaroslav Nasonov	

Flight Dynamics team	
Aleksandr Filimonov	
Vadim Leshchev	
Artem Yakimchuk	

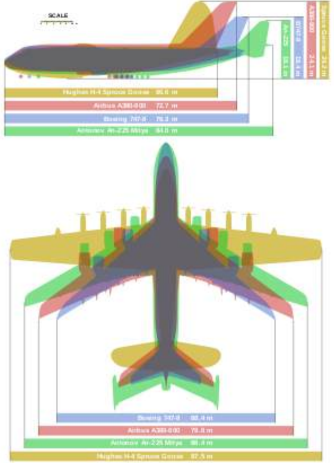
Folding team	
Denis Galagan	
Vladislav Solovyev	
Denis Sopichev	

Propulsion team	
Igor Usachev	
Igor Yatsenko	
Andrey Zogov	
Mikhail Raevskiy	

MBSE(Comparative study)



Boeing SUGAR Truss-Braced Wing (TBW) Aircraft Concept *



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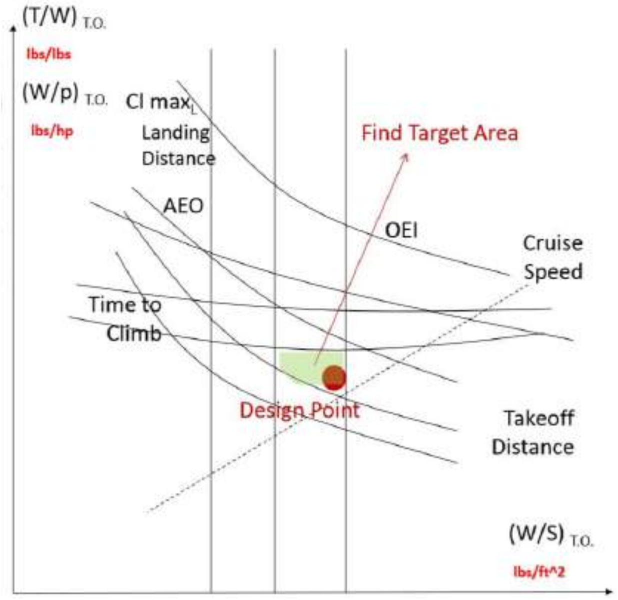
* Ting, Eric, et al. "Aerodynamic Analysis of the Truss-Braced Wing Aircraft Using Vortex-Lattice Superposition Approach." *32nd AIAA Applied Aerodynamics Conference*. 2014.

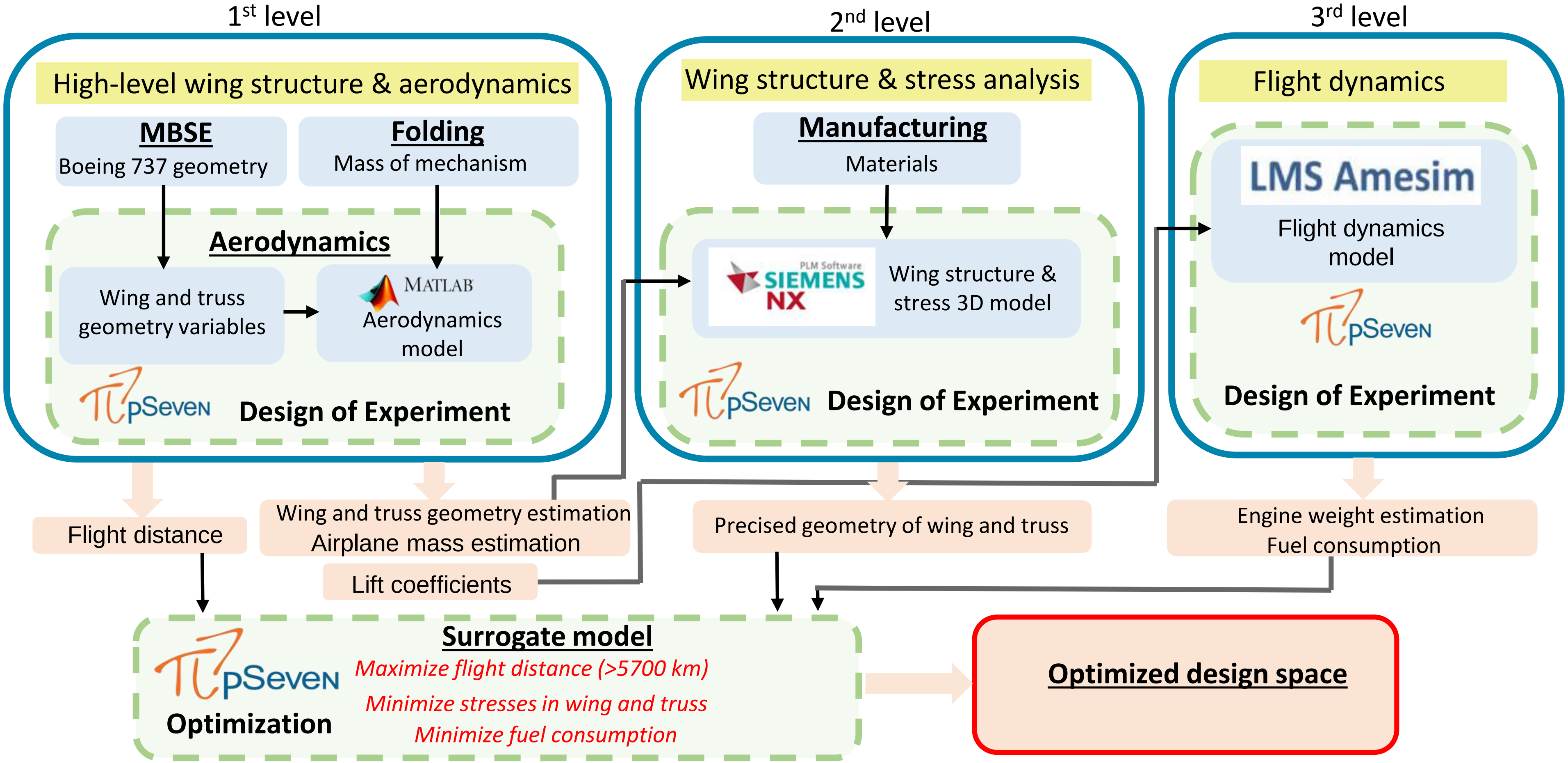
MBSE (Preliminary sizing)

W_TO	77110 kg
Range	5700 km
W/S	456 kg/m^2 ~ 94 lb/m^2
T/W	0.4
CD0	0.0132
Wing Span	51.8 m
Wing area	111.5 m^2



Thrust over weight ratio vs. Wing loading

SPDM - Simulation and optimization framework



1st level

High-level wing structure & aerodynamics

MBSE
Boeing 737 geometry

Folding
Mass of mechanism

Aerodynamics

Wing and truss geometry variables

MATLAB
Aerodynamics model

pSeven **Design of Experiment**

2nd level

Wing structure & stress analysis

Manufacturing
Materials

SIEMENS NX
Wing structure & stress 3D model

pSeven **Design of Experiment**

3rd level

Flight dynamics

LMS Amesim
Flight dynamics model

pSeven

Design of Experiment

Flight distance

Wing and truss geometry estimation
Airplane mass estimation

Lift coefficients

Precised geometry of wing and truss

Engine weight estimation
Fuel consumption

Surrogate model

pSeven
Optimization

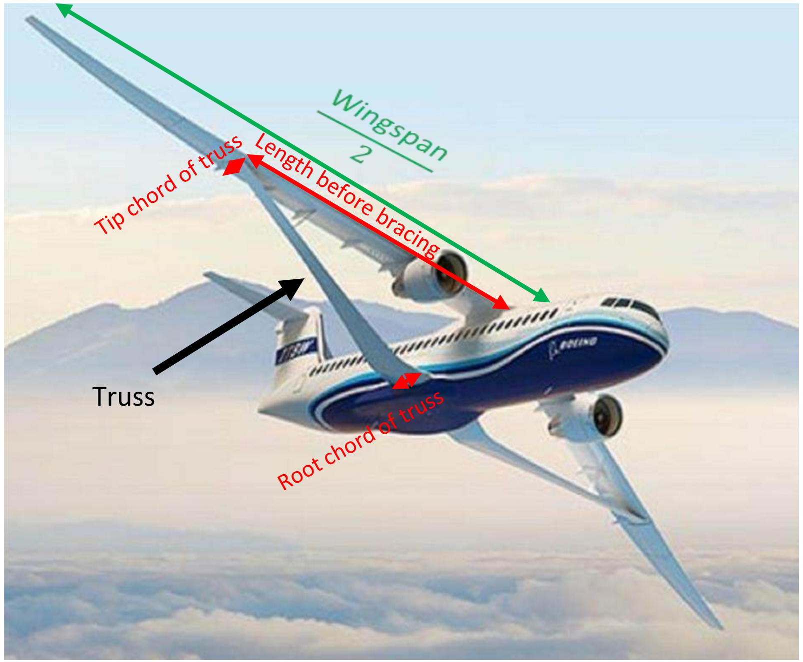
Maximize flight distance (>5700 km)

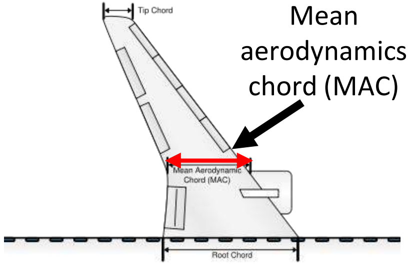
Minimize stresses in wing and truss

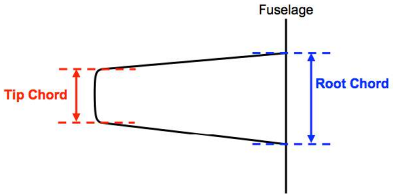
Minimize fuel consumption

Optimized design space

SPDM - 1st level optimization: general idea




Mean aerodynamics chord (MAC)



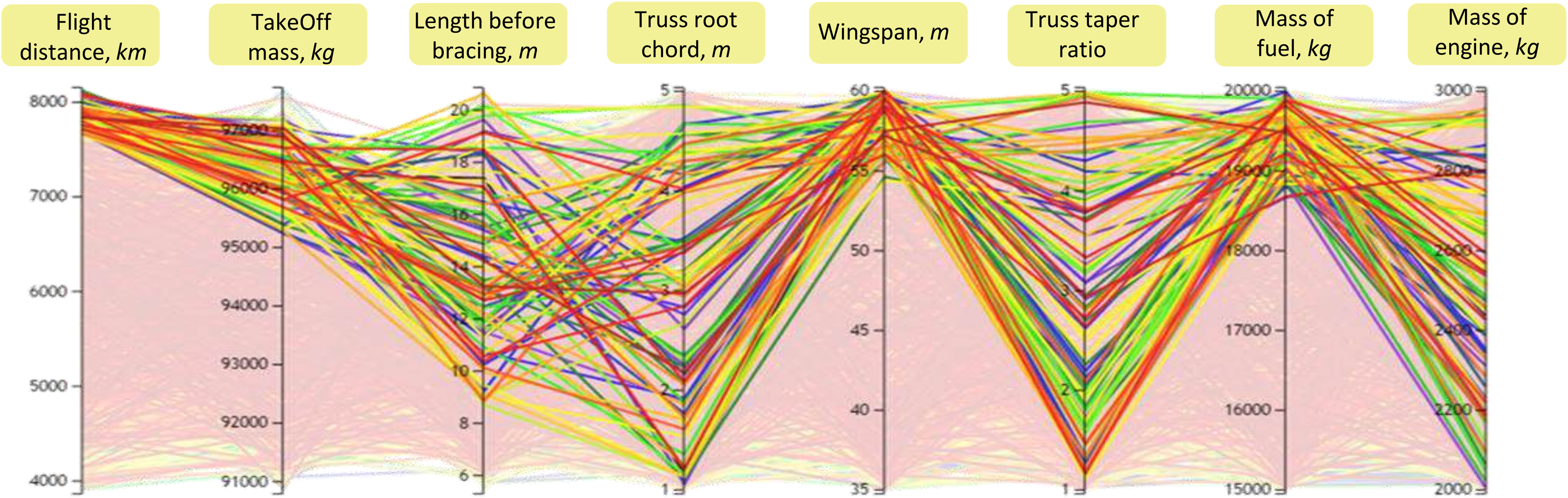
$$\text{Truss taper ratio} = \frac{Root\ chord\ of\ truss}{Tip\ chord\ of\ truss}$$

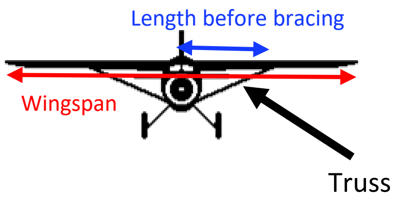
Parameter	Interval of variation
Truss taper ratio	[1; 5]
Length before bracing, m	[9; 14]
Wing span, m	[35; 60]
Truss root chord, m	[1; 5]

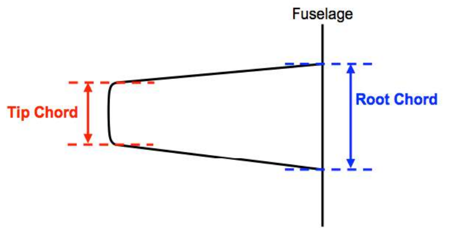
Our goal is ***to maximize the flight distance*** (to fit the requirement of flight distance ≥ 5700 km) and to ***minimize the total mass of aircraft***

SPDM - 1st level optimization: results

Parallel plots on optimized parameters



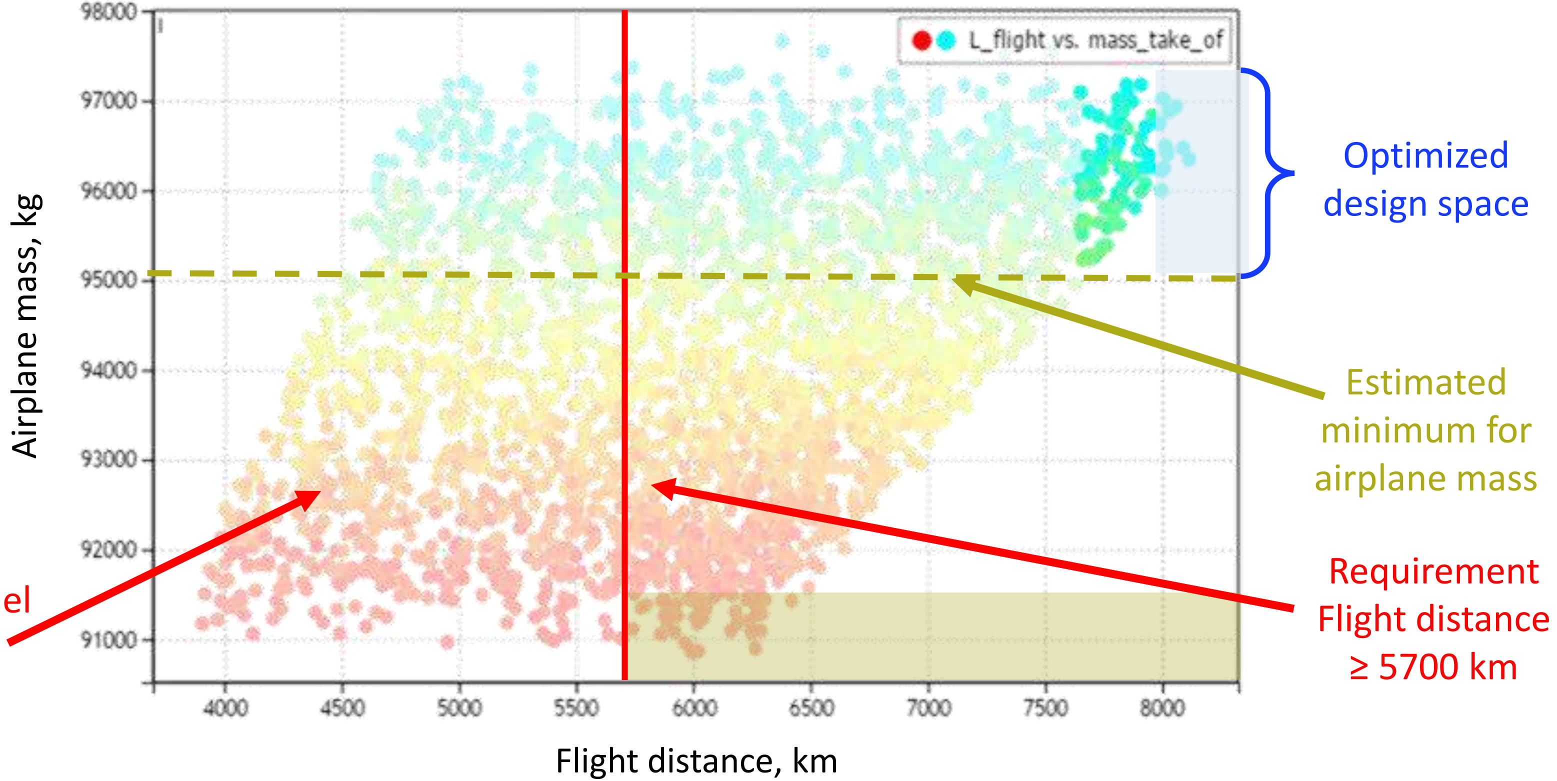




$$\text{Truss taper ratio} = \frac{\textit{Root chord of truss}}{\textit{Tip chord of truss}}$$

SPDM - 1st level optimization: results

Dependency of airplane mass on flight distance



Optimized design space

Estimated minimum for airplane mass

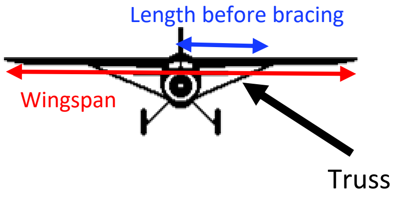
Requirement Flight distance ≥ 5700 km

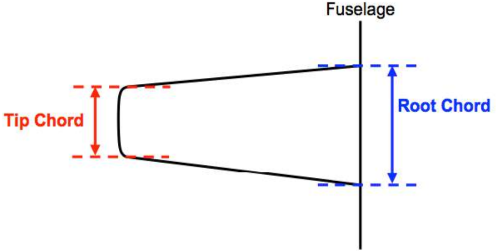
Color is fuel mass

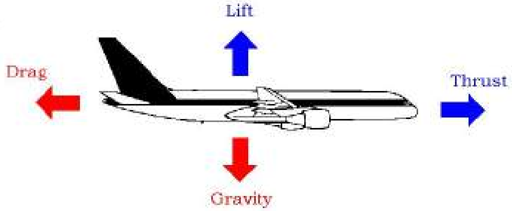
SPDM - 1st level optimization: results

Optimized parameter from the high level model

Length of flight, km	Take-Off Mass, kg	Length before bracing, m	Truss root chord, m	Truss taper ratio	Wingspan, m	Mass of fuel, kg	Mass of engine, kg
8114	96343	15.0	4.10	1.83	59.9	19905	2391
8057	96934	10.6	2.84	3.69	59.0	19813	2568
8088	96469	17.0	1.21	2.62	59.5	19871	2593

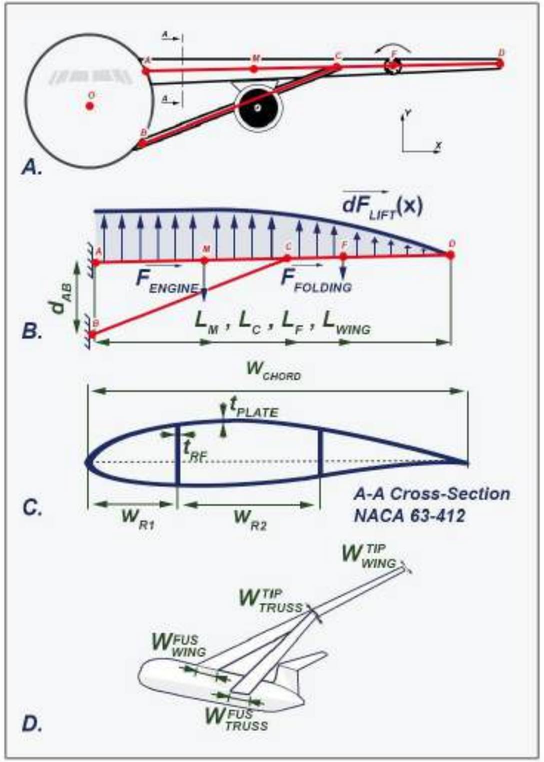


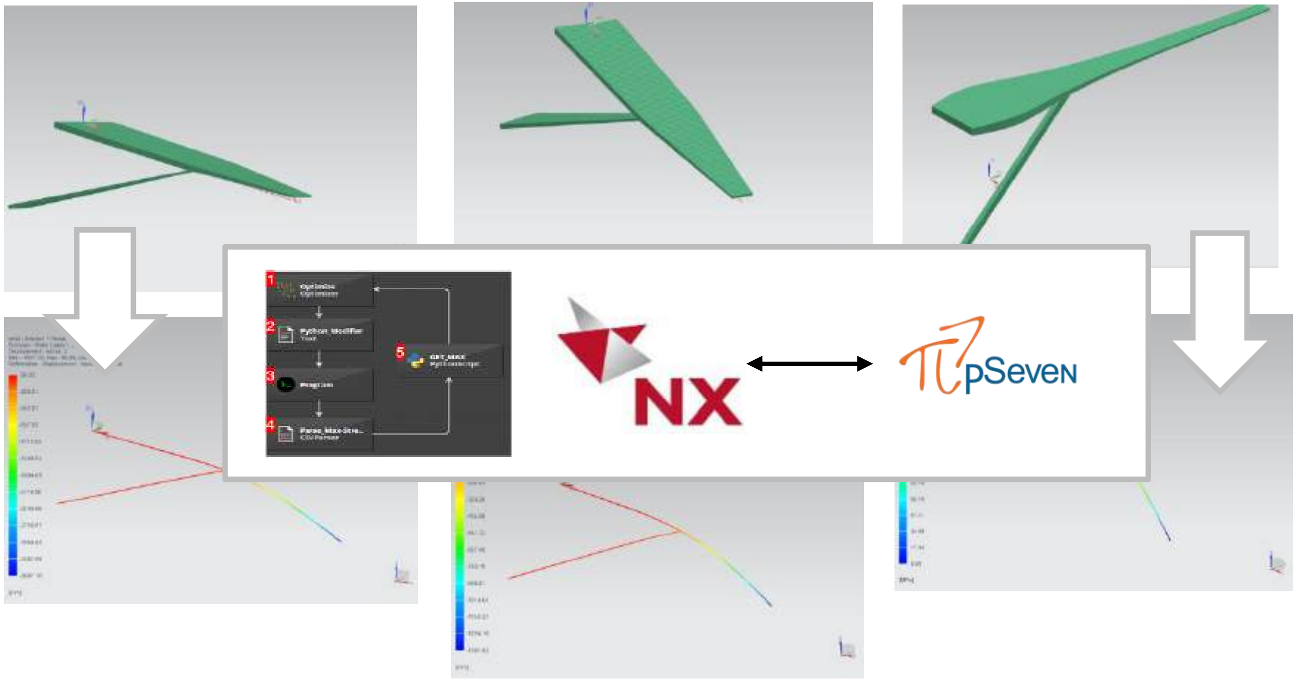




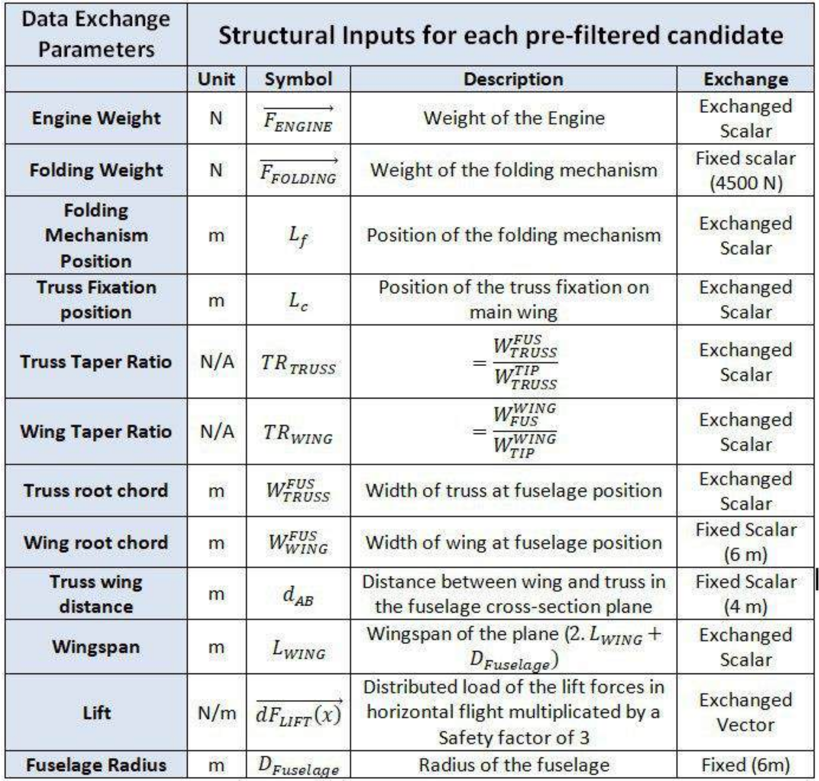
$$\text{Truss taper ratio} = \frac{Root\ chord\ of\ truss}{Tip\ chord\ of\ truss}$$

SPDM - 2rd level optimization: generative algorithm for structure

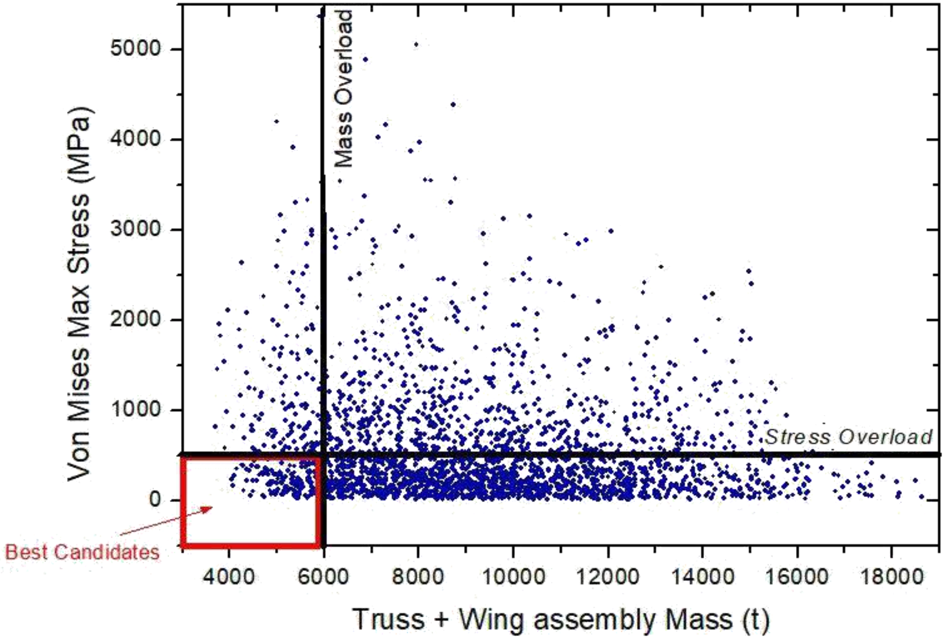




SPDM - 2rd level optimization: generative algorithm for structure



Data Exchange Parameters	Structural Inputs for each pre-filtered candidate			
	Unit	Symbol	Description	Exchange
Engine Weight	N	$\overrightarrow{F_{ENGINE}}$	Weight of the Engine	Exchanged Scalar
Folding Weight	N	$\overrightarrow{F_{FOLDING}}$	Weight of the folding mechanism	Fixed scalar (4500 N)
Folding Mechanism Position	m	L_f	Position of the folding mechanism	Exchanged Scalar
Truss Fixation position	m	L_c	Position of the truss fixation on main wing	Exchanged Scalar
Truss Taper Ratio	N/A	TR_{TRUSS}	$= \frac{W_{TRUSS}^{FUS}}{W_{TRUSS}^{TIP}}$	Exchanged Scalar
Wing Taper Ratio	N/A	TR_{WING}	$= \frac{W_{FUS}^{WING}}{W_{TIP}^{WING}}$	Exchanged Scalar
Truss root chord	m	W_{TRUSS}^{FUS}	Width of truss at fuselage position	Exchanged Scalar
Wing root chord	m	W_{WING}^{FUS}	Width of wing at fuselage position	Fixed Scalar (6 m)
Truss wing distance	m	d_{AB}	Distance between wing and truss in the fuselage cross-section plane	Fixed Scalar (4 m)
Wingspan	m	L_{WING}	Wingspan of the plane ($2.L_{WING} + D_{Fuselage}$)	Exchanged Scalar
Lift	N/m	$\overrightarrow{dF_{LIFT}(x)}$	Distributed load of the lift forces in horizontal flight multiplicated by a Safety factor of 3	Exchanged Vector
Fuselage Radius	m	$D_{Fuselage}$	Radius of the fuselage	Fixed (6m)

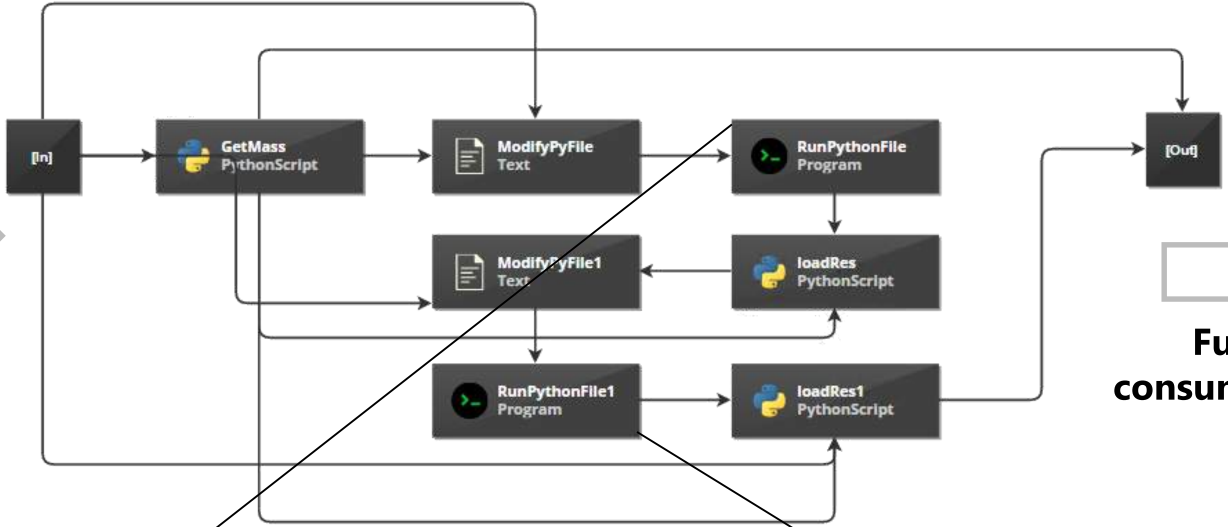


SPDM - 3nd level optimization: workflow

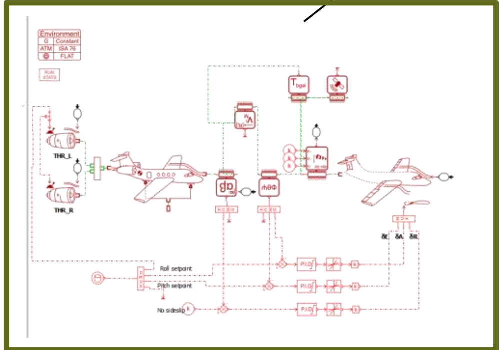
Skolkovo Institute of Science and Technology

Initial parameters from high level model

massFull
cx0
lift
dc
Sref
ChordRef

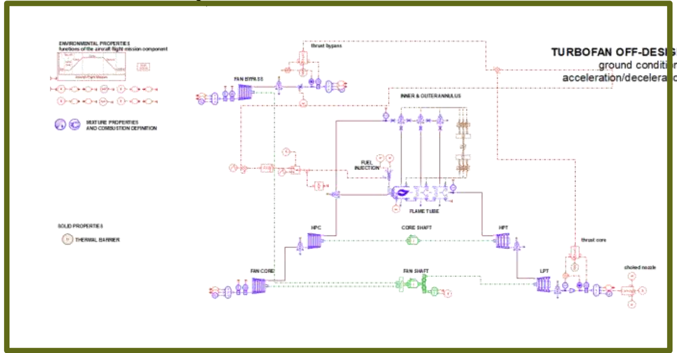


Fuel consumption



Amesim Model of Flight Dynamics

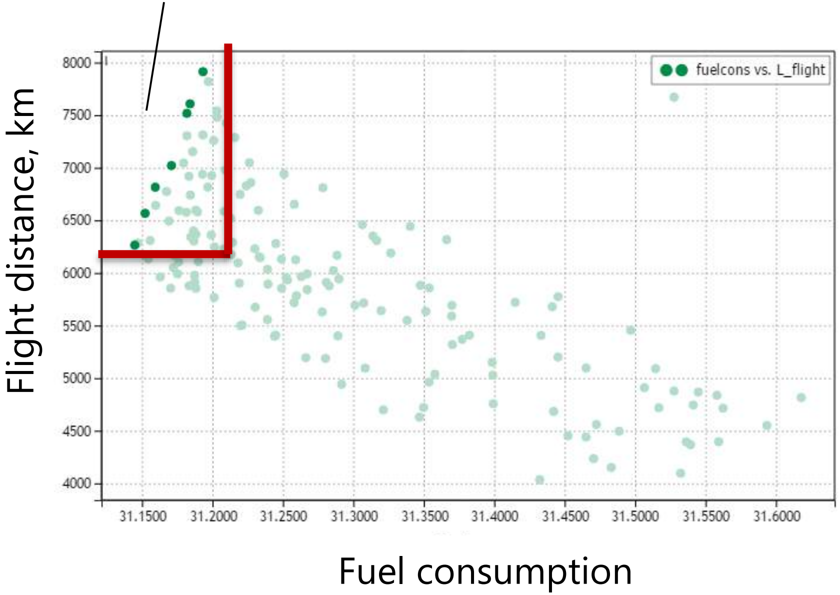
Required thrust force

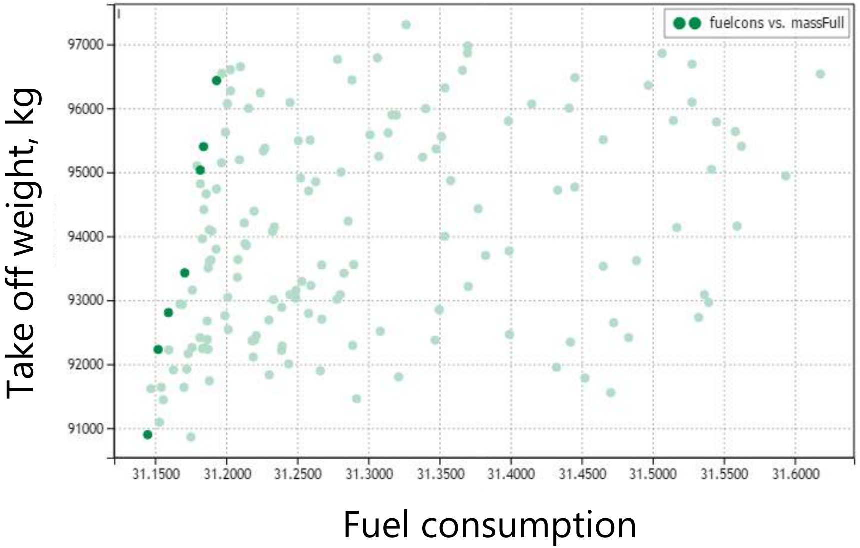


Amesim Model of Engine

Results of optimization

- Results are based on the DOE with initial sample evaluation


Optimal zone



Best design: flight distance = 7912 km ToM = 96433 kg

Optimized on 38 %

NUMERICAL SIMULATION OF CRACKING DURING PULTRUSION OF LARGESIZE PROFILES

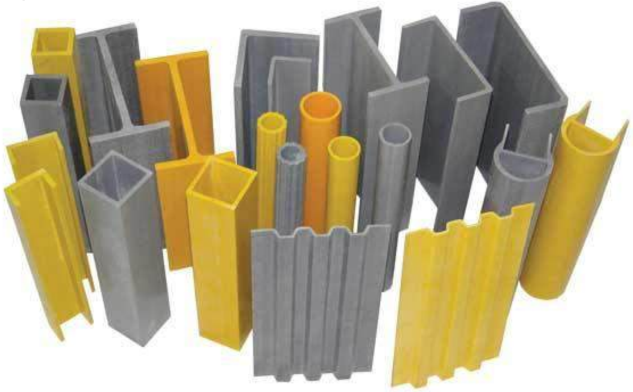
Numerical simulation of cracking during pultrusion of largesize profiles

Alexander Safonov, Mikhail Gusev, Anton Saratov, Iskander Akhatov

Center for Design, Manufacturing and Materials,
Skolkovo Institute of Science and Technology, Moscow, Russia

22nd International Conference on Composite Structures and
1st Chinese Conference on Composite Structures
Wuhan, China
02 Nov 2019

Applications & Main challenges



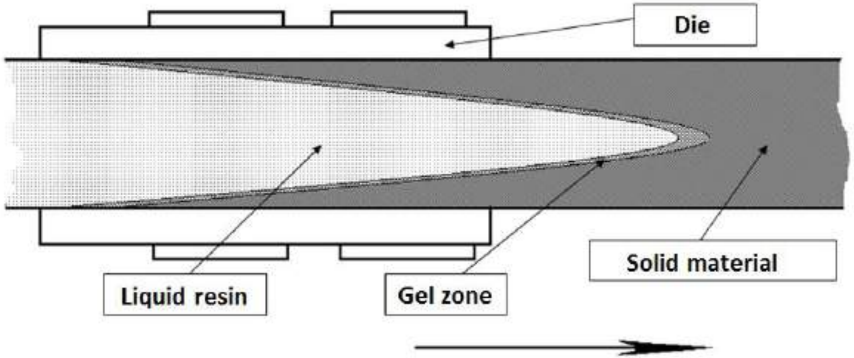
Industry
- *Construction*
- *Corrosion resistance*
- *Electrical applications*
- *Marine*
- *Transportation*
- *Sport and Leisure*

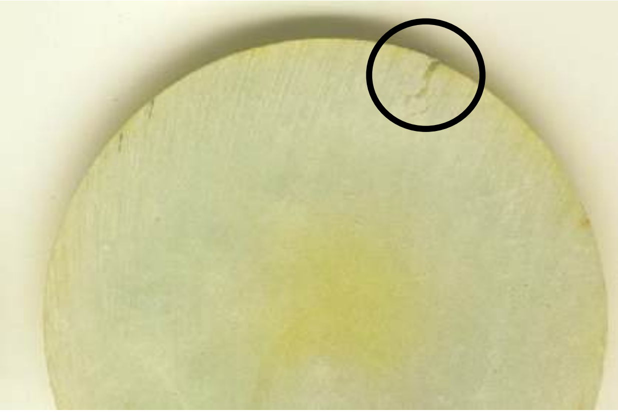
Advantages
- Light weight
- High strength
- Fatigue resistance
- Ease of installation
- Corrosion resistance
- Fire performance
- Easy maintenance
- Insulating properties

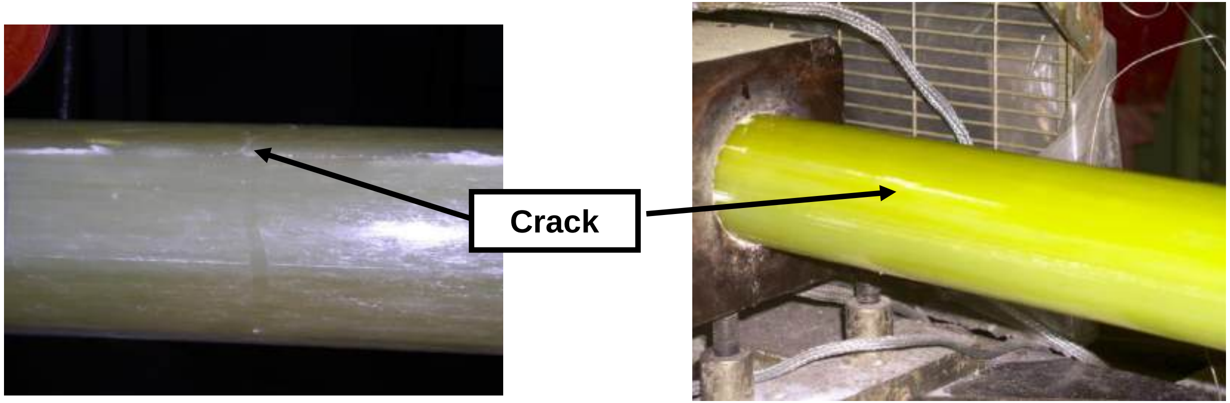
Challenges, Main reasons, Physics involved
- Peak temperature and degree of cure evolution
- Exothermic chemical reaction during curing
- Heater configurations
- Type of resin matrix system
- Geometry of the die
- Geometry of the resin injection chamber
- Phase transformations
- Anisotropic permeability of the fibre reinforcement
- Residual stresses and shape distortions
- Crack & void formations
- Pulling force
- Fibre misalignment

Safonov AA, Carlone P, Akhatov I. Mathematical simulation of pultrusion processes: A review. Composite Structures 2018;184. doi:10.1016/j.compstruct.2017.09.093

Pultrusion of large diameter rods (80 mm)







Pulling speed – 5 cm/min

Process simulation

- Heat transfer

$$\rho_c C_{pc}(T,\alpha)\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} + q,$$

- Curing of resin

$$\frac{d\alpha}{dt} = A_0 \exp\left(-\frac{E_a}{RT}\right)(1-\alpha)^n$$

- Stress-strain distribution

Cure-hardening/instantaneously linear elastic (CHILE) approach

$$E_m(T^*) = \begin{cases} E_m^0, & T^* < T_{C1} \\ E_m^0 + \dfrac{T^* - T_{C1}}{T_{C2} - T_{C1}}(E_m^\infty - E_m^0), & T_{C1} \le T^* \le T_{C2}, \\ E_m^\infty, & T^* > T_{C2} \end{cases}$$

$T^* = T_g - T$, T_g – glass transition temperature depending on degree of cure

$$T_g(\alpha) = T_{g0} + \left(T_{g\infty} - T_{g0}\right)\frac{\lambda\alpha}{1-(1-\lambda)\alpha}$$

The model is implemented in ABAQUS using the user-subroutines: HETVAL, UEXPAN, UMAT, FILM, URDFIL, UFIELD, UEXTERNALDB

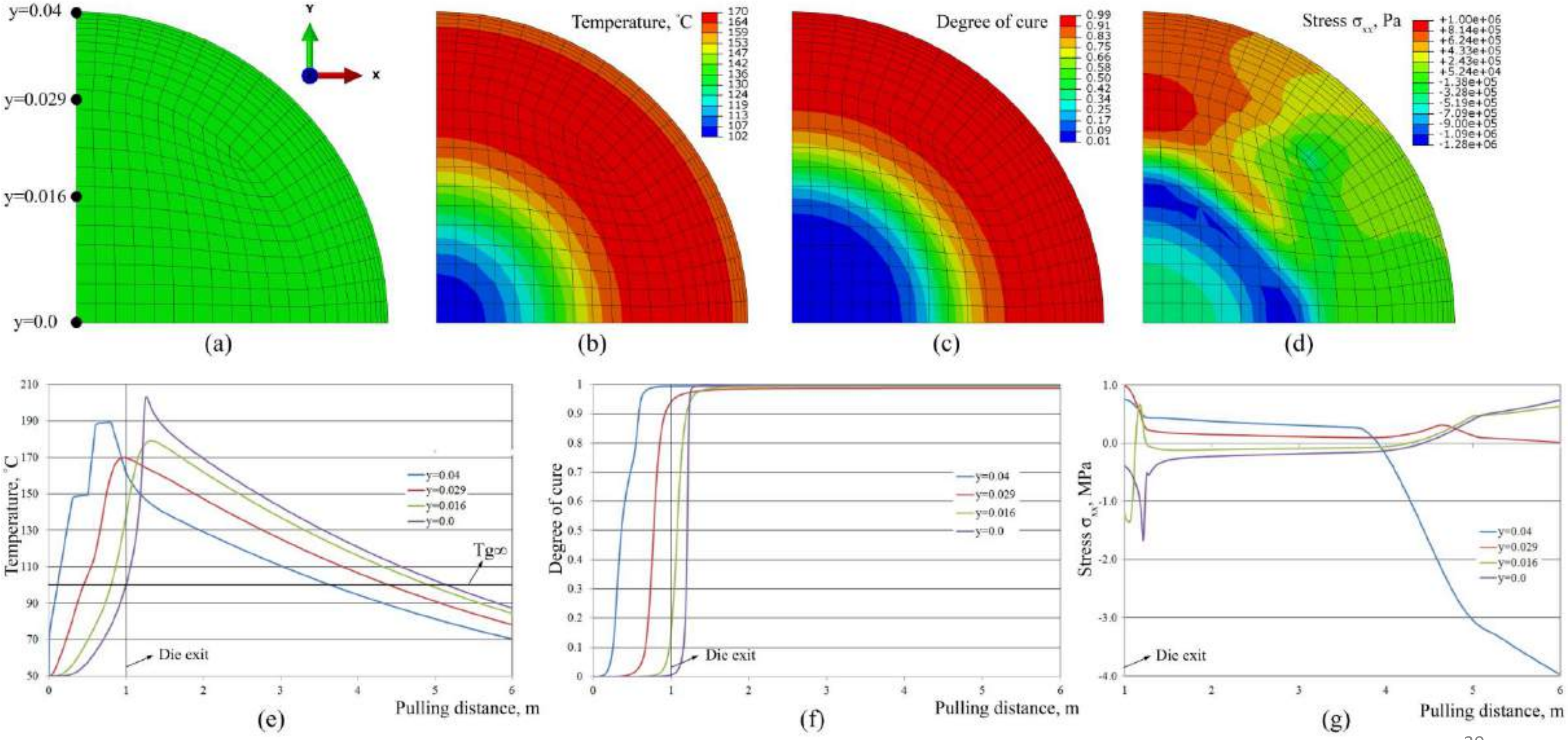
2D transient heat equation in the Lagrangian frame

G.L. Batch, C.W. Mocosko. Heat transfer and cure in pultrusion: model and experimental verification, *AIChE Journal*, 39, 7, 1993, pp. 1228-1241

2D plane strain model

I. Baran, C.C. Tutum, M.W. Nielsen, J.H. Hattel, Process induced residual stresses and distortions in pultrusion, *Composites Part B: Engineering*, 51, 2013, pp. 148-161

Simulation results in section after die exit

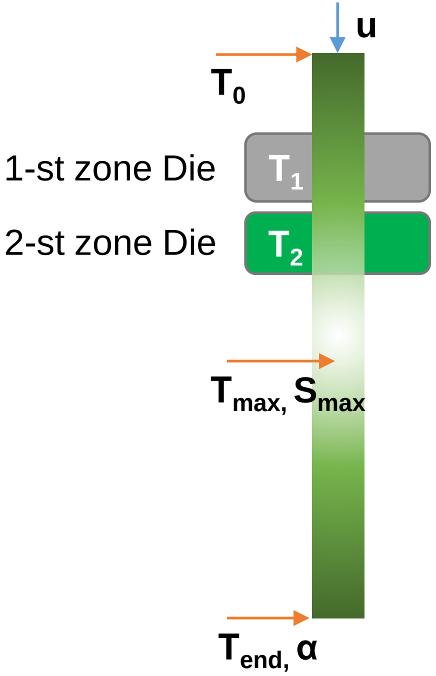


Optimization. Problem statement

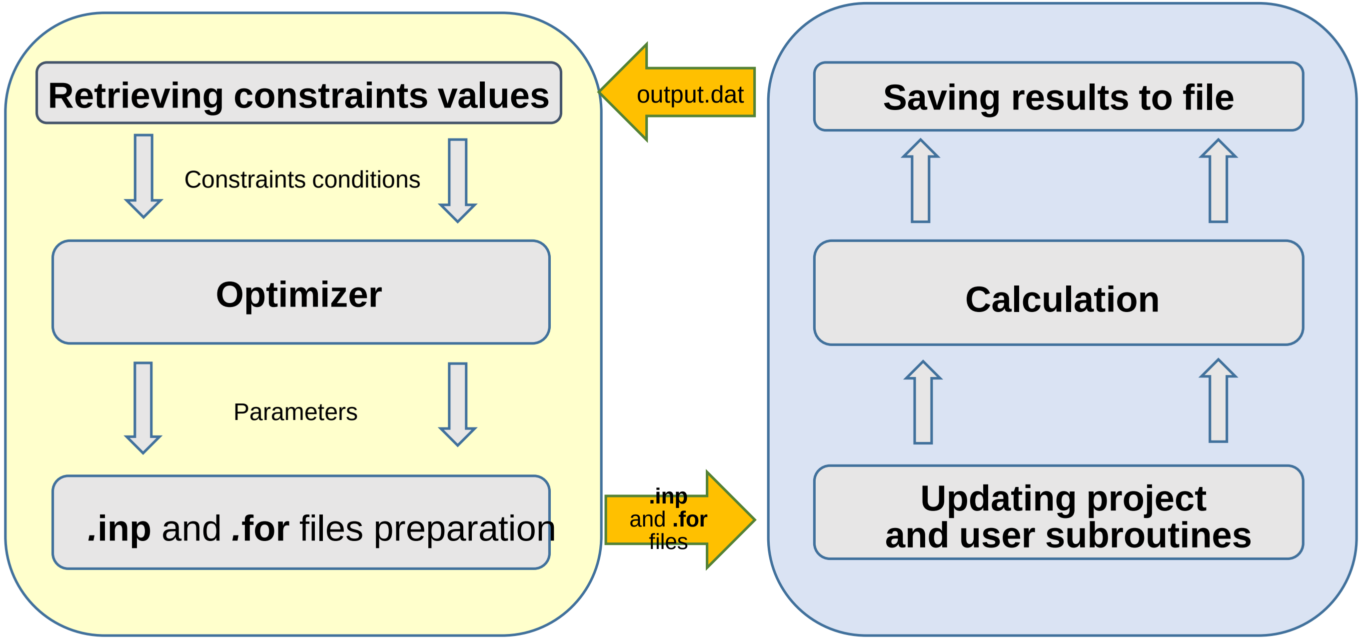
Optimization parameters:
- Initial temperature of mixture, $\mathbf{T_0}$
- Die 1-st zone temperature, $\mathbf{T_1}$
- Die 2-nd zone temperature, $\mathbf{T_2}$
- Pulling speed, **u**

Objective function of one criterion optimization:
- Pulling speed **u** → **max**

Constraints:
- Transverse stress in pultruded rod, $\mathbf{S_{max}}$
- Maximum temperature of material, $\mathbf{T_{max}}$
- Maximum temperature at the end section, $\mathbf{T_{end}}$
- Degree of polymerization at the end section, **α**



General Workflow



pSeven

SIMULIA ABAQUS

Retrieving constraints values

Constraints conditions

Optimizer

Parameters

.inp and **.for** files preparation

output.dat

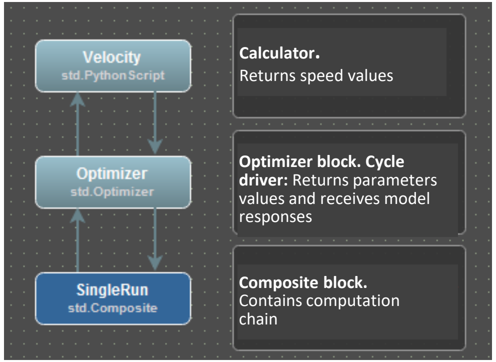
.inp
and **.for**
files

Saving results to file

Calculation

Updating project
and user subroutines

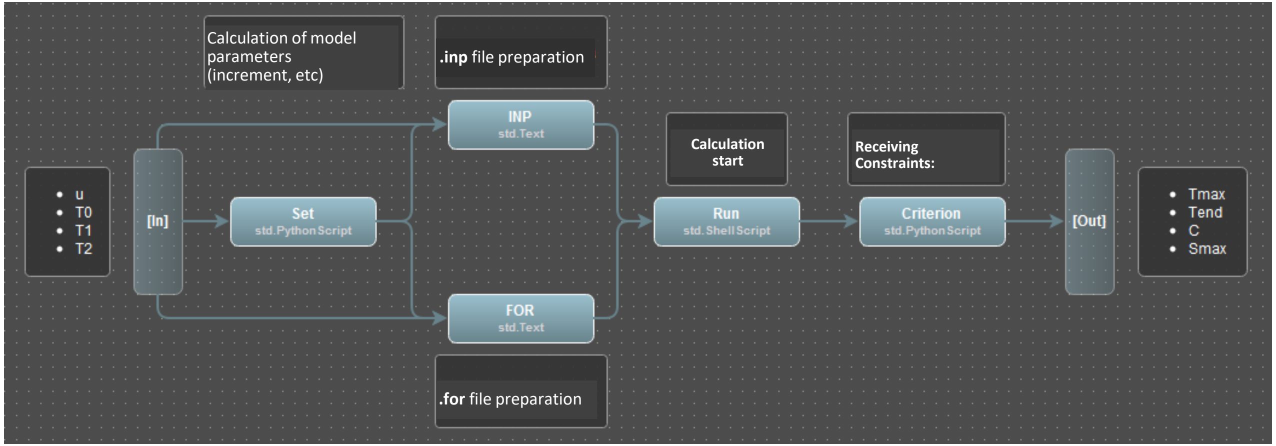
pSeven. Workflow



Calculator.
Returns speed values

Optimizer block. Cycle driver: Returns parameters values and receives model responses

Composite block.
Contains computation chain



- u
- T0
- T1
- T2

Calculation of model parameters (increment, etc)

.inp file preparation

.for file preparation

Calculation start

Receiving Constraints:

- Tmax
- Tend
- C
- Smax

- Single-criterion optimization problem: **SBO** (surrogate-based optimization) method
- Four constraints

Best point

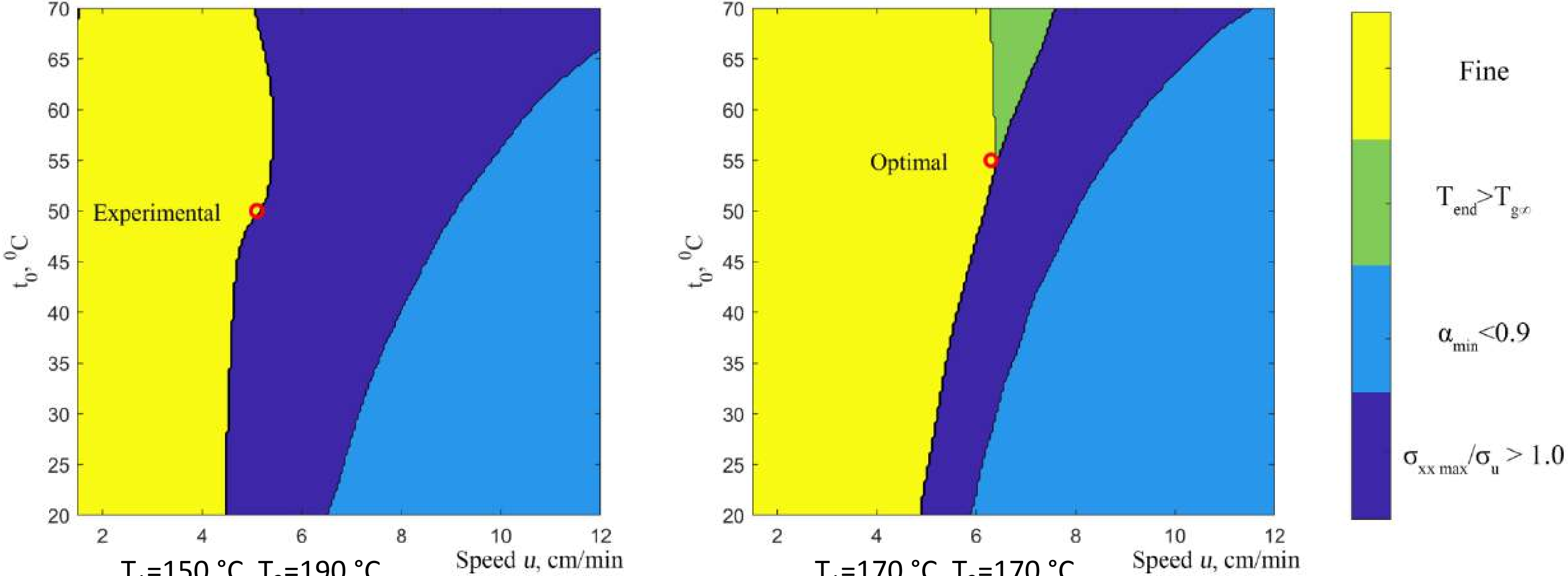
Initial vs **Optimum** configuration comparison

	Parameters				Constraints			
	u, cm/min	T_0, °C	T_1, °C	T_2, °C	T_{end}, °C	T_{max}, °C	α_{min}	$\sigma_{xx_{max}}/\sigma_u$
Boundaries	-	20-70	120-170	150-200	<101.5	<210.0	>0.90	<1.0
Initial	5.0	50	150	190	87.6	202.9	0.99	0.99
Optimum	**6.0**	55	170	170	101.4	203.0	0.97	0.95

Achieved **20%** of increasing the pulling speed

Computation results. Approximation model

Contour plot with boundary restrictions for Initial and Optimal area based on Surrogate Model



T_1=150 °C, T_2=190 °C

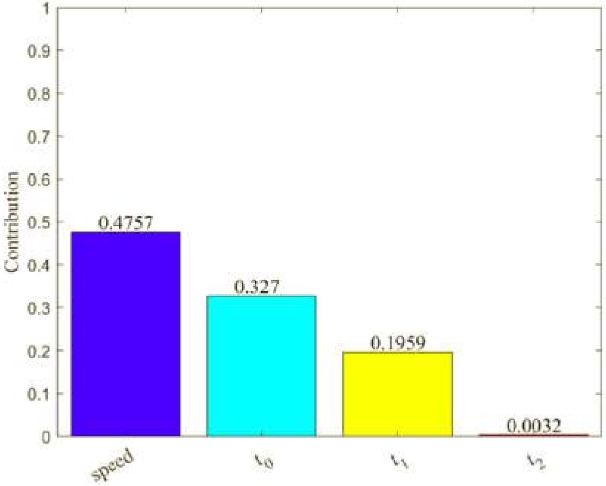
Initial area

T_1=170 °C, T_2=170 °C

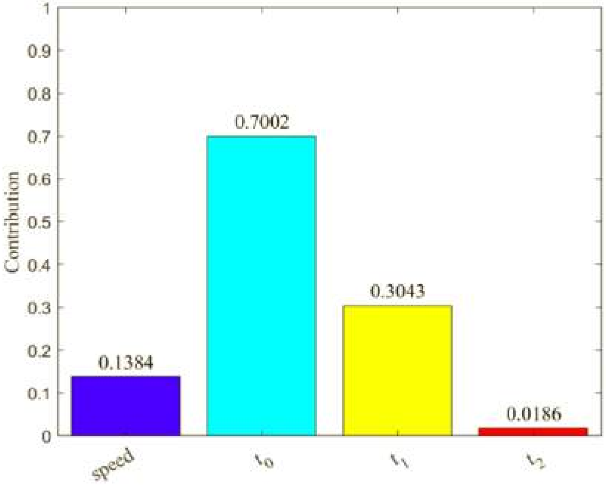
Optimal area

Sensitivity Analysis. Process parameters

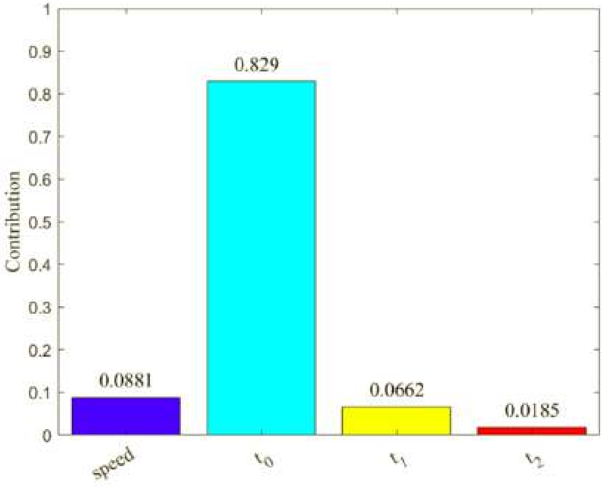
The analysis of numerical model: how input parameters are influence on the output Maximum Temperature, degree of cure and Transversal Stress



Maximum Temperature



Final degree of cure



Transversal Stresses

Laboratory of Composite Materials and Structures at Center for Design, Manufacturing, and Materials (CDMM)

- Shape distortions
- Technological defects
- Effect of process parameters
- Numerical simulation of process
- Thermoplastic pultrusion
- Process optimization

Pultrusion machine: Pultrex Px500-6T

- Pulling force: 60kN
- Pulling speed: 0.04÷5 m/min

SUMMARY

- Optimization and Surrogate Modeling in pSeven for scientific projects
- Results of application pSeven in industry oriented projects
- Design space exploration in pSeven for research – education - student projects
- Easy to connect pSeven to the numerical model in various software
- Numerical simulation of various complex problems

M.Gusev@skoltech.ru
Mikhail Gusev, PhD, research scientist