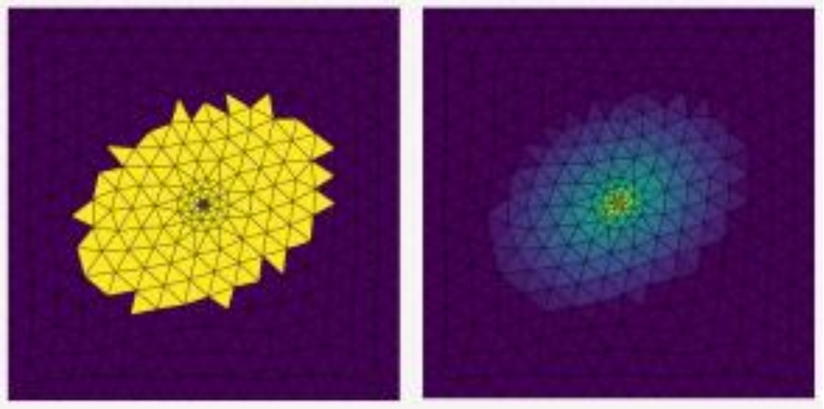
LCMsim basic training



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Aerospace Engineering / Fachhochschule Wiener Neustadt

Agenda

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- Discussion of installation issues (PrePoMax and LCMsim)
- Introduction to filling simulations

- Case 1: Workflow for RTM filling simulations of aerospace part
- Case 2: Rectilinear VARI simulation
- Case 3: VARI simulations with flow distribution medium
- Case 4: Complete workflow (STEP file of part mid-surface, Meshing with PrePoMax, Filling simulation with LCMsim)
- Case 5: Case 4 with own geometry
- Case 6: Simulation of permeameter experiments with different patches

LCM process

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In all Liquid Composite Molding (LCM) technologies dry fiber preforms are placed into a mold which is subsequently closed or sealed with a flexible bag by drawing a vacuum. Resin then enters into the mold until the preform is fully wetted with resin. As soon as the resin is cured the mold is opened and the part is extracted.

In Resin Transfer Molding (RTM) resin is injected into a matched mold under pressure which gives excellent surface finish on both sides and high fiber volume fractions (55-65%) can be obtained. The mold walls are considered rigid and the preform is stationary during injection.

In contrast to RTM, in Vacuum Assisted Resin Infusion (VARI) vacuum pulls resin through the preform on a single-sided mold with vacuum bagging.

LCM process

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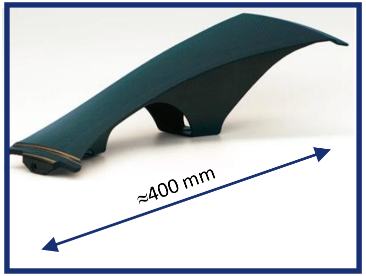
LCM manufacturing requires a mold and an injection strategy (placement of injection gates and vents).

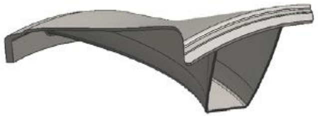
Let's consider two parts, the first manufactured with RTM and the second manufactured with VARI:

RTM part

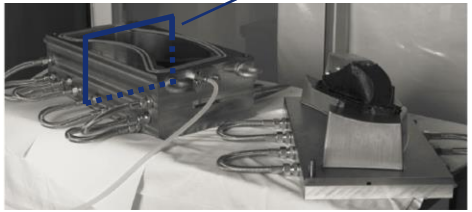
Large scale jet engines use annulus fillers to close the gap between the individual fan blades and to guarantee an appropriate airflow.

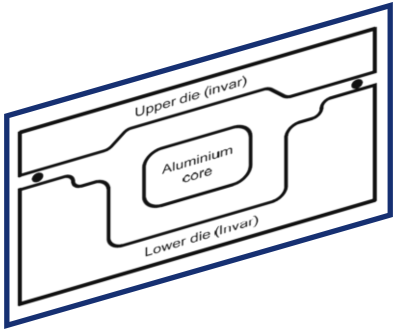


The hollow design of the filler consists of three individual preforms that are combined to form the moulded shape. Four plies are wrapped around the core, four plies are placed into the lower die, four plies are placed on the upper die.



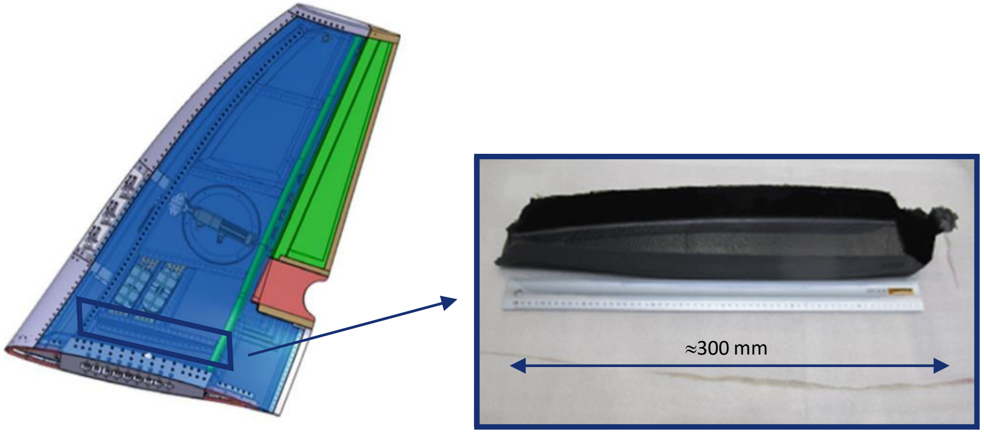
Since the manufacturung process is Resin transfer moulding (RTM), the preforms is not yet saturated with resin. The resin is injected with overpressure into the closed mould.

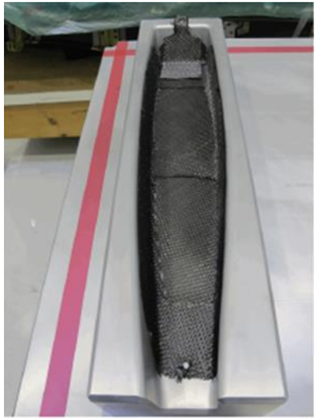




After demoulding the filler is machined:

VARI part






Filling simulations

During mold design, filling simulations can study different manufacturing concepts (i.e. placement of injection gates and vents) to

- guarantee complete filling of the part (flow front must not reach vents before the complete part is filled),
- avoid air entrapment where flow fronts converge
- predict the filling time

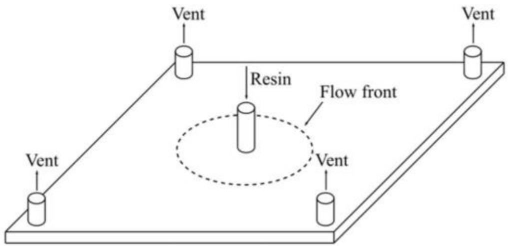
Filling simulations

Different software packages for performing filling simulations:

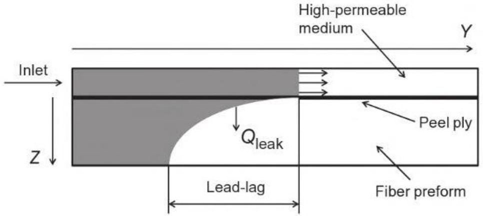
+ user-friendly GUI
+ extensive documentation
+ large number of industrial case studies
- limitation in customizability
- expensive

Commercial		Non-commercial	
Ansys Fluent	General purpose CFD software packages	OpenFOAM	- without GUI and mesher - requires both CFD and programming knowledge
PAM-RTM RTM-Worx LIMS	Software packages which are tailored for the simulation of the LCM processes	myRTM	+ easy-to-use - only RTM, no VARI - only isotropic preform - predicted filling pattern correct, predicted filling time differs considerably
		LCMsim	+ easy-of-use for the mold engineer and maximum flexibility for the researcher + complete workflow withPrePoMax as mesher - still under development

Filling simulations



- The thickness of the part is much smaller than the overall dimensions.
- All packages describe the flow on a macroscopic level. The physical quantities porosity and permeability are used to describe resin flow through the fibrous media.
- For RTM flow (and VARI flow without flow distribution medium) transverse flow is neglected and the flow is modeled as two-dimensional in-plane flow.
- For VARI, in-plane flow in flow distribution medium and transverse flow into actual preform.



⇒ Consider RTM flow with quasi-isotropic layup first: Annulus filler

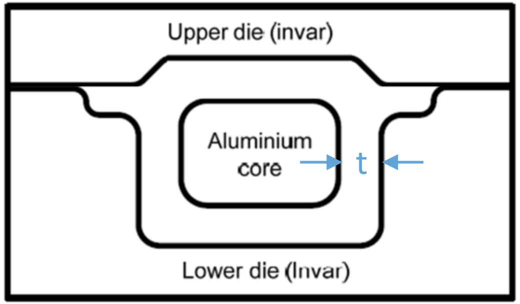
Case 1

Constant cavity thickness inside mould: t=3 mm

Everywhere filled with 8 plies, quasi-isotropic layup: porosity ε=1-FVF=0.45

Flow front propagation:

- pressure equal zero in region which is not yet filled
- pressure decrease between injection gate and flow front position
- flow front propagation is proportional to the pressure gradient $\mathbf{u} = (k/\mu)\,\nabla p$



Isotropic permeability must be determined with permeameter experiment.

Fluid: dynamic viscosity μ=0.07 Pas, mass density ρ=960 kg/m^3

Process: initial cavity pressure 1e5 Pa, injection pressure 1.9e5 Pa

Case 1

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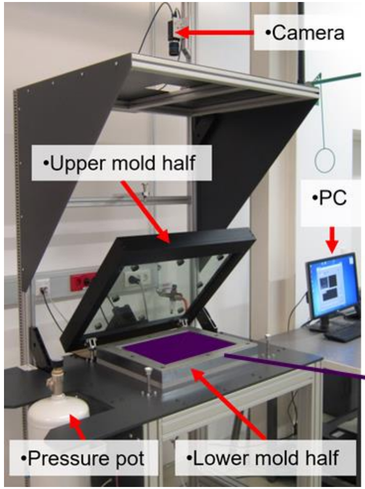
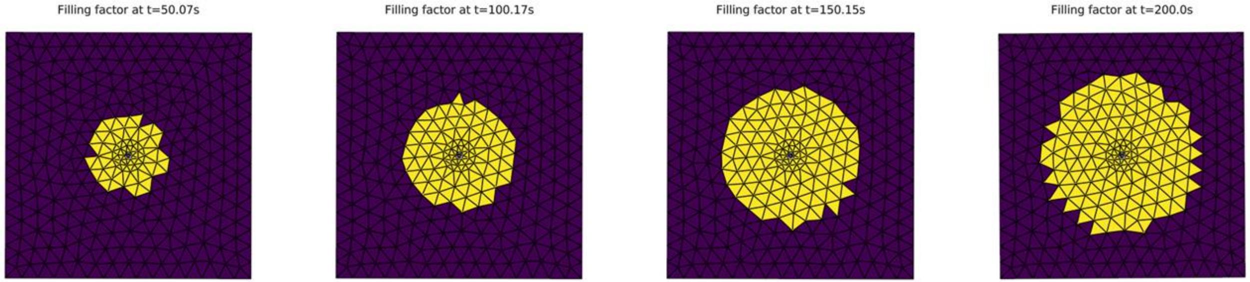
The preform must characterized beforehand in an (optical) permeameter
$\Rightarrow$ Isotropic permeability k=20e-12 m²





Case 1

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Sim 1.1: Use software LCMsim to simulate the flow front propagation in the optical permeameter.

Simulation input:

- All parameters in SI units
- Existing permeameter mesh mesh_permeameter1.bdf
- Preform paramters: $t=0.003$ m, $\varepsilon=0.45$, $k=20e-12$ m² (no need to specify k_1, $k_2=\alpha \cdot k_1$ and primary direction vector; no need to specify additional input for VARI)
- Fluid parameters: $\mu=0.07$ Pas, $\rho=960$ kg/m³
- Process parameters: initial cavity pressure 1e5 Pa, injection pressure 1.9e5 Pa

Case 1

> Dieser PC > Data (D:) > work > LCMsim_v2_20240204 > LCMsim-1.0.4

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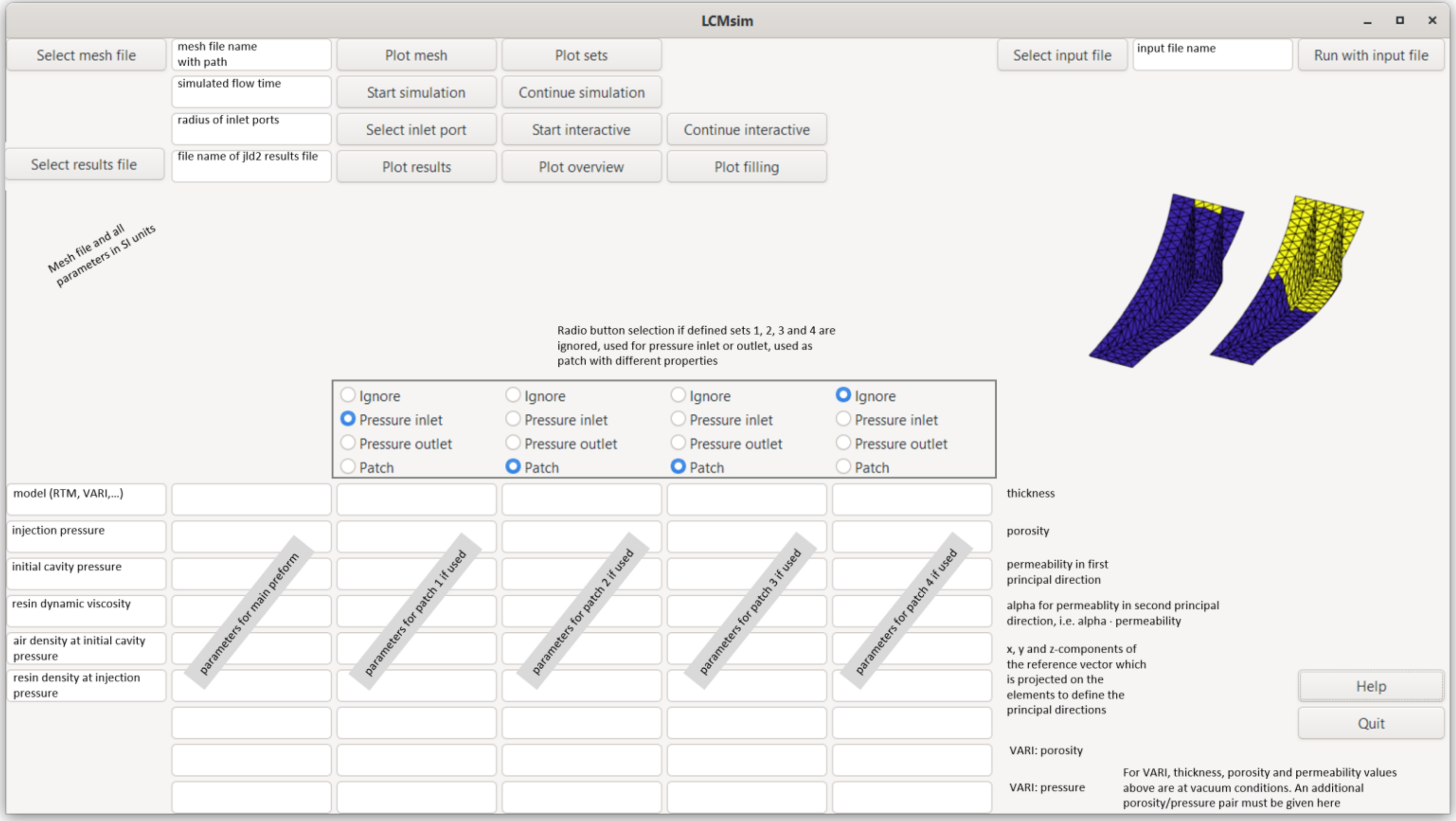
figures	02.04.2024 13:29	Dateiordner	
inputfiles	02.04.2024 13:29	Dateiordner	
meshfiles	02.04.2024 13:29	Dateiordner	
lcmsim.jl	09.01.2024 15:22	JL-Datei	148 KB
lcmsim_GUI.jl	09.01.2024 15:22	JL-Datei	32 KB
LICENSE	09.01.2024 15:22	Datei	18 KB
README	09.01.2024 15:22	Markdown-Quelldatei	27 KB
run_lcmsim_GUI	09.01.2024 15:22	Windows-Batchdatei	1 KB

Double click to launch the GUI

Case 1



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Case 1

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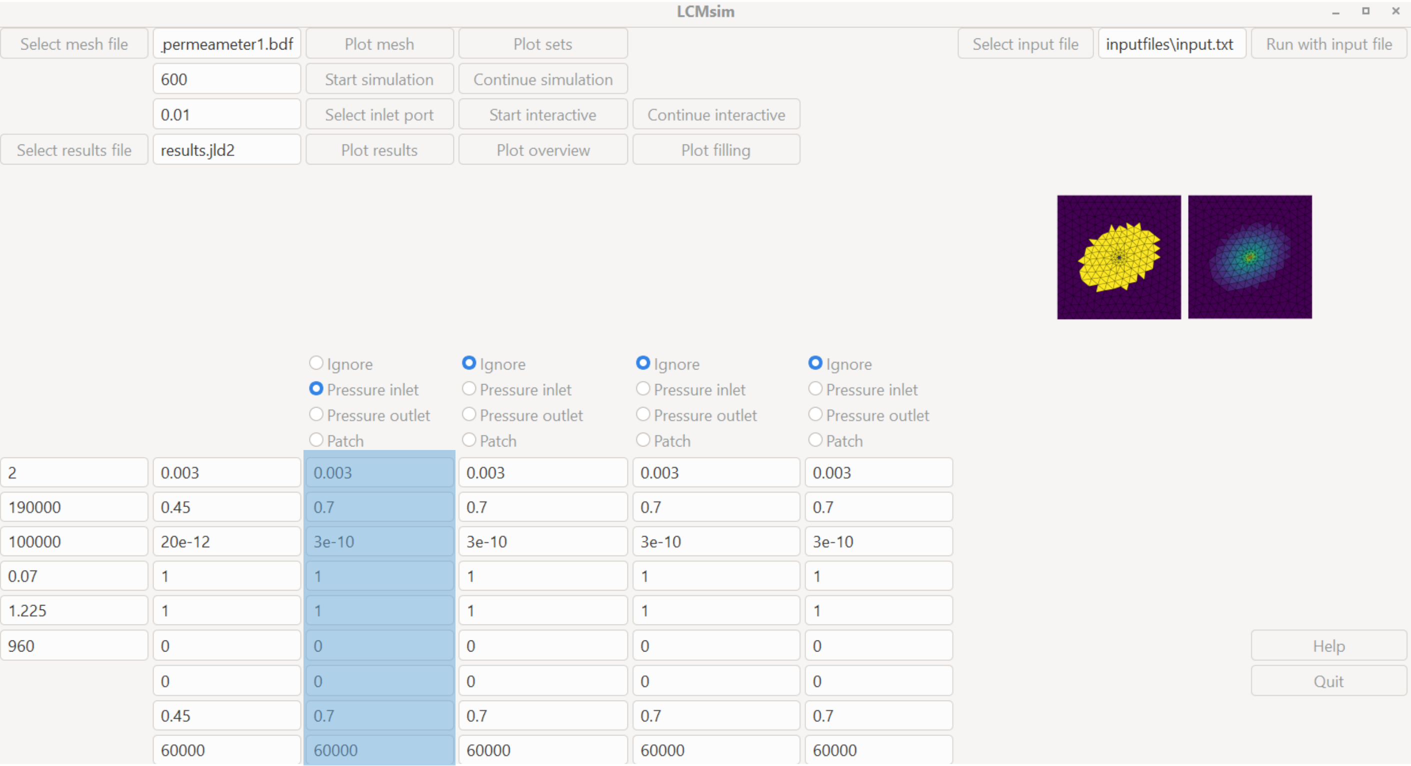
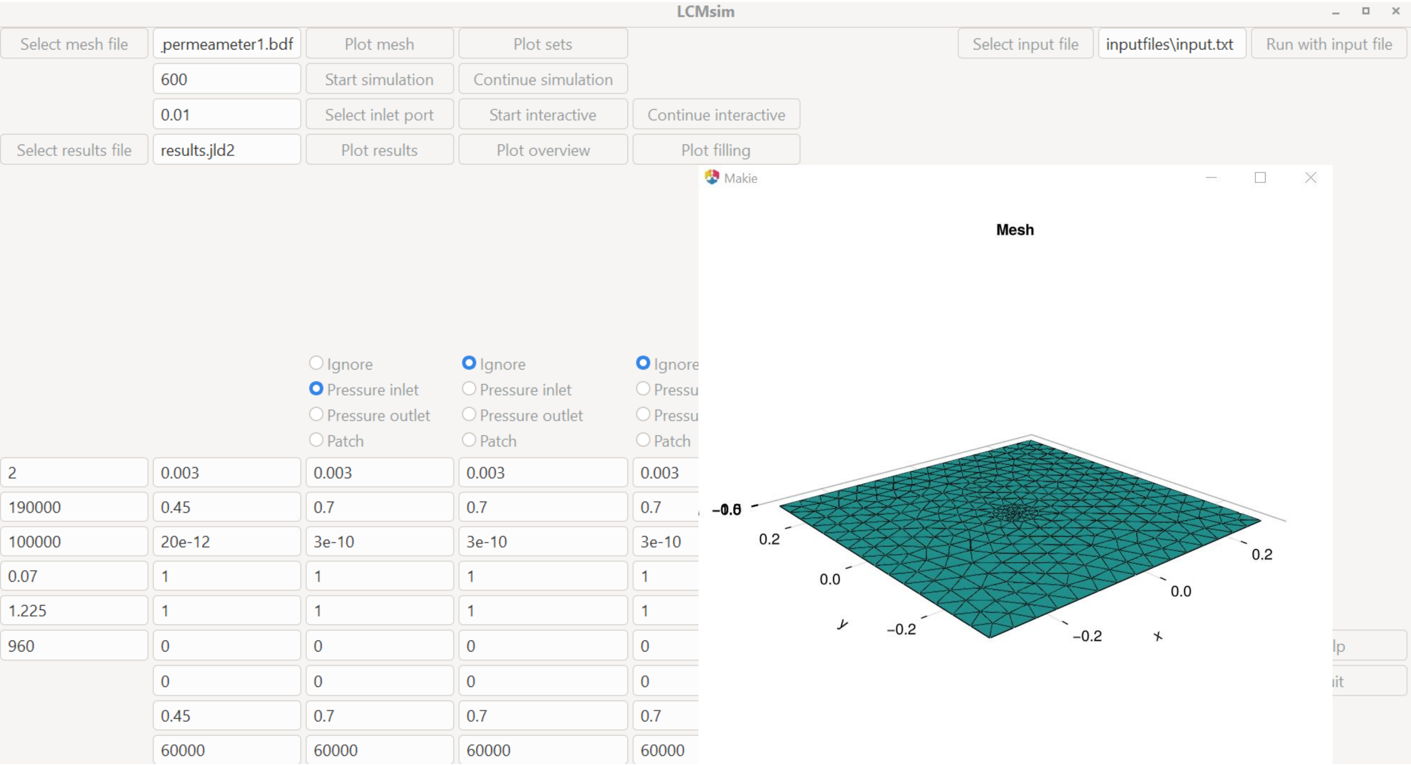


Ignored for
injection gate

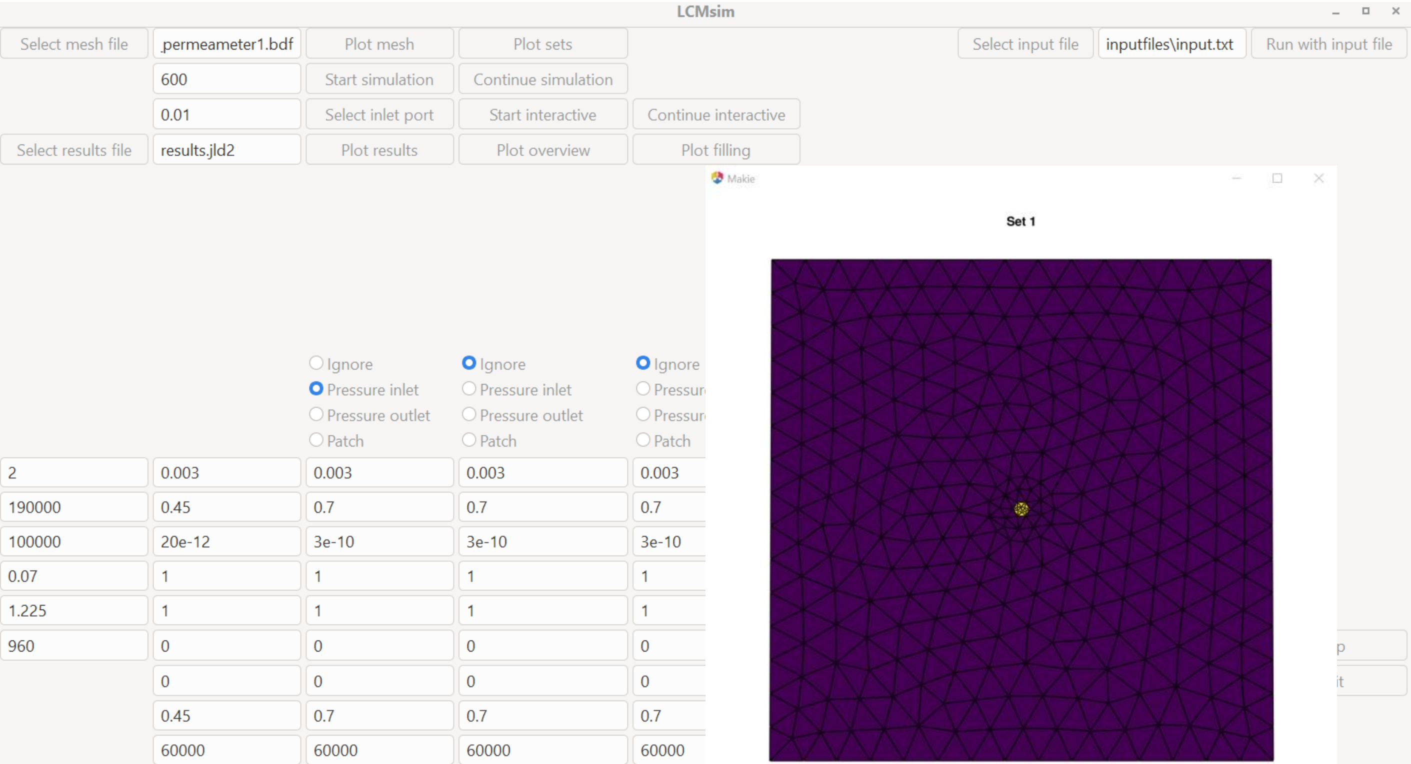
- Plot mesh
- Plot sets
- Start simulation
- Plot overview
- Plot results

Case 1



- Plot mesh
- Plot sets
- Start simulation
- Plot overview
- Plot results

Case 1



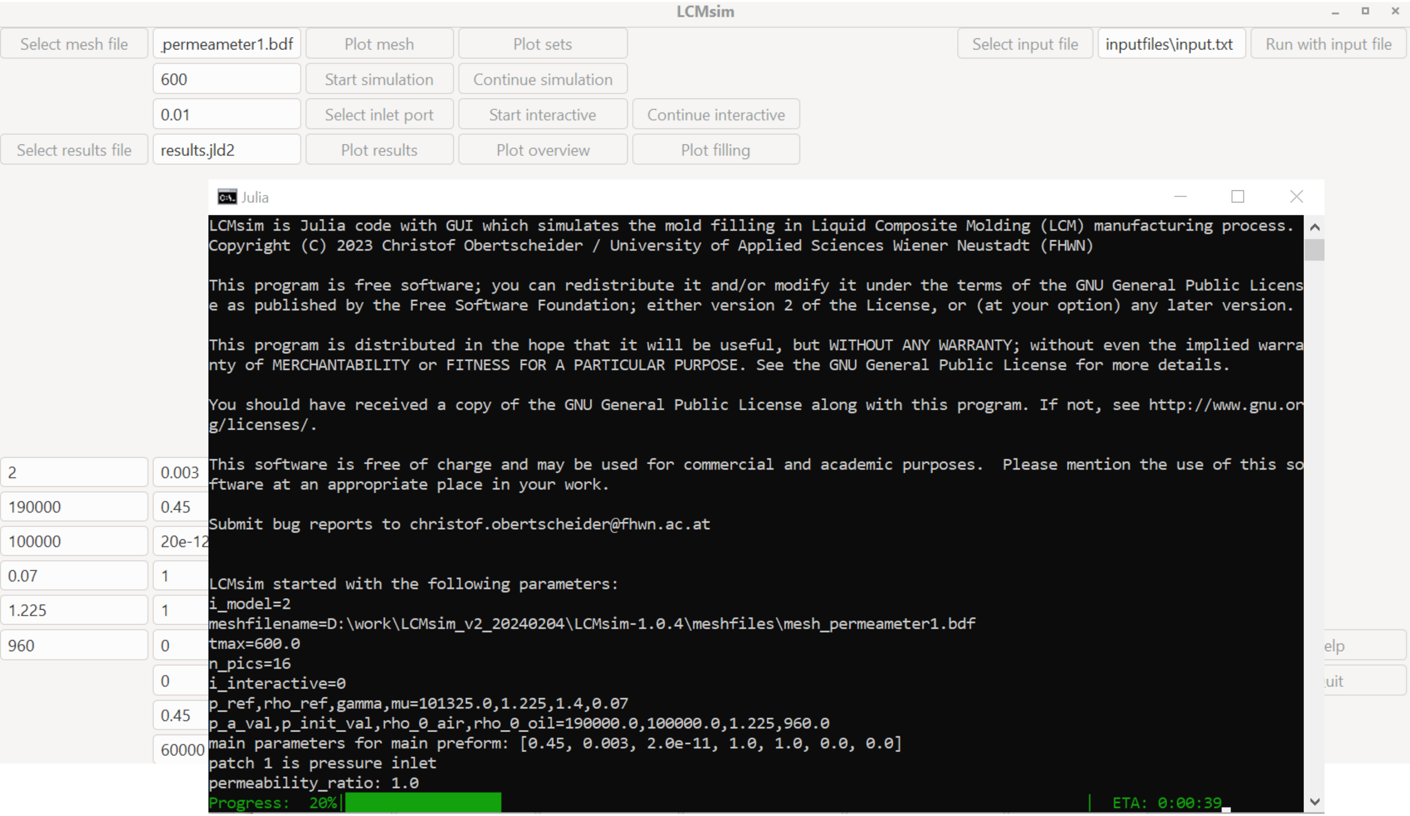
- Plot mesh
- **Plot sets**
- Start simulation
- Plot overview
- Plot results

Sets are used to define injection gates and patches with different preform properties.

No need to define vents as long as the flow front does not reach a vent before completly filled.

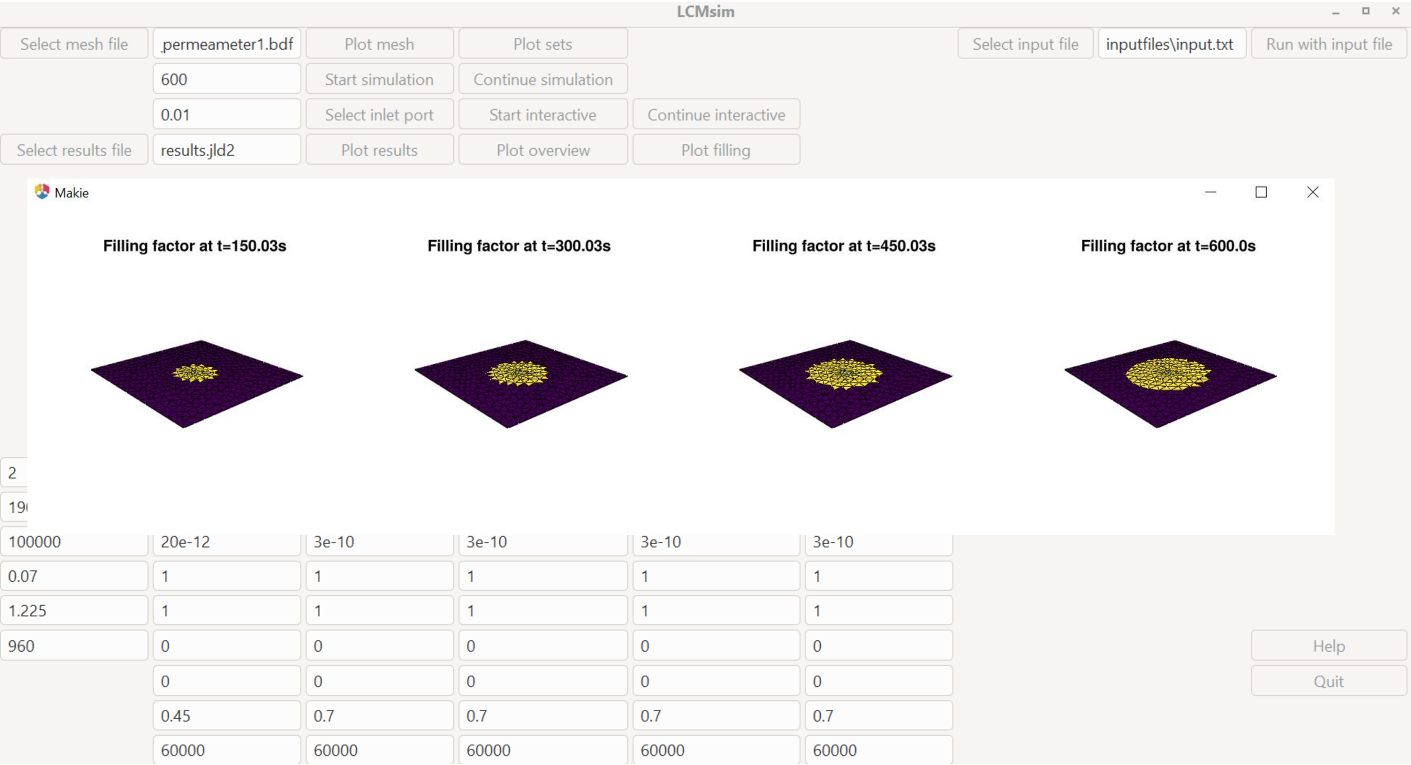
Rotate view with LMB clicked

Case 1



- Plot mesh
- Plot sets
- Start simulation
- Plot overview
- Plot results

Case 1



- Plot mesh
- Plot sets
- Start simulation
- Plot overview
- Plot results

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Case 1

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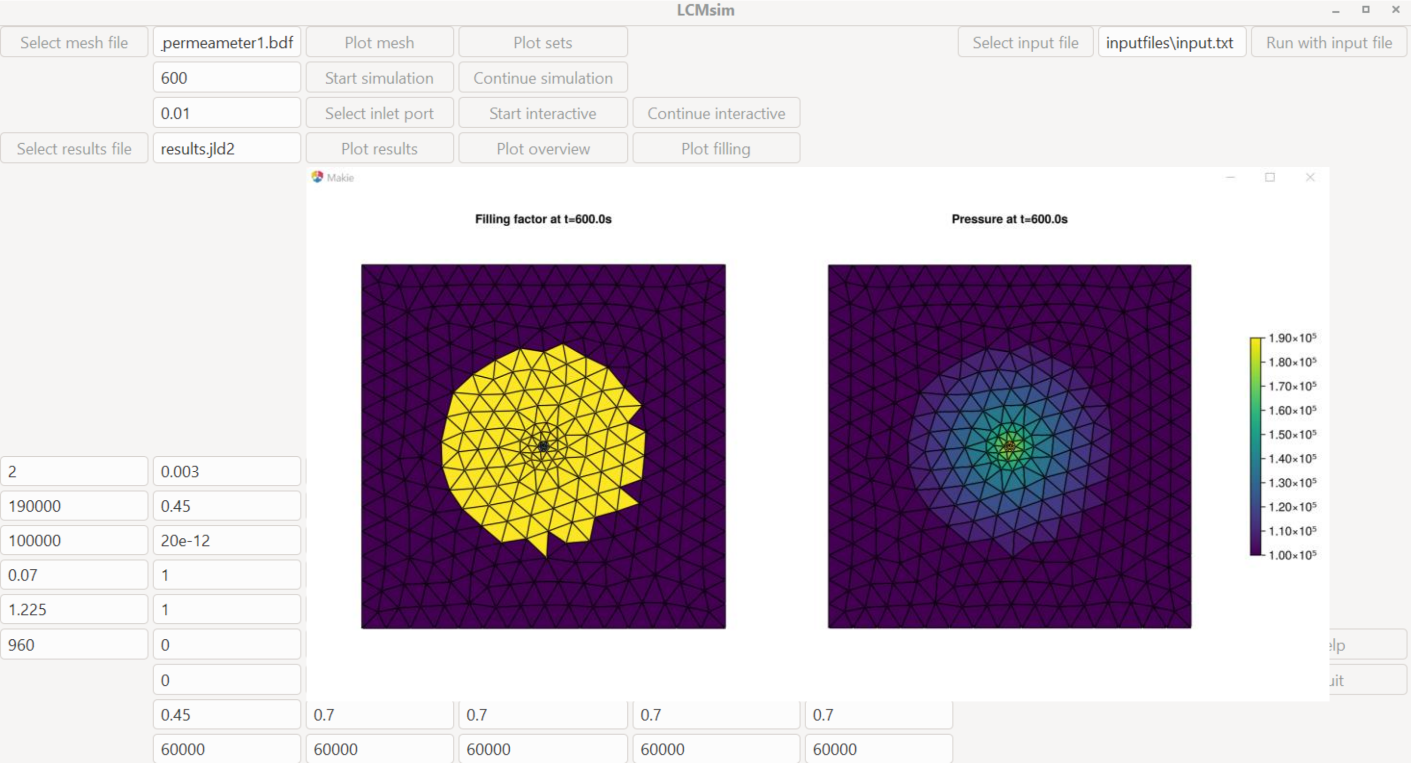


- Plot mesh
- Plot sets
- Start simulation
- Plot overview
- Plot results

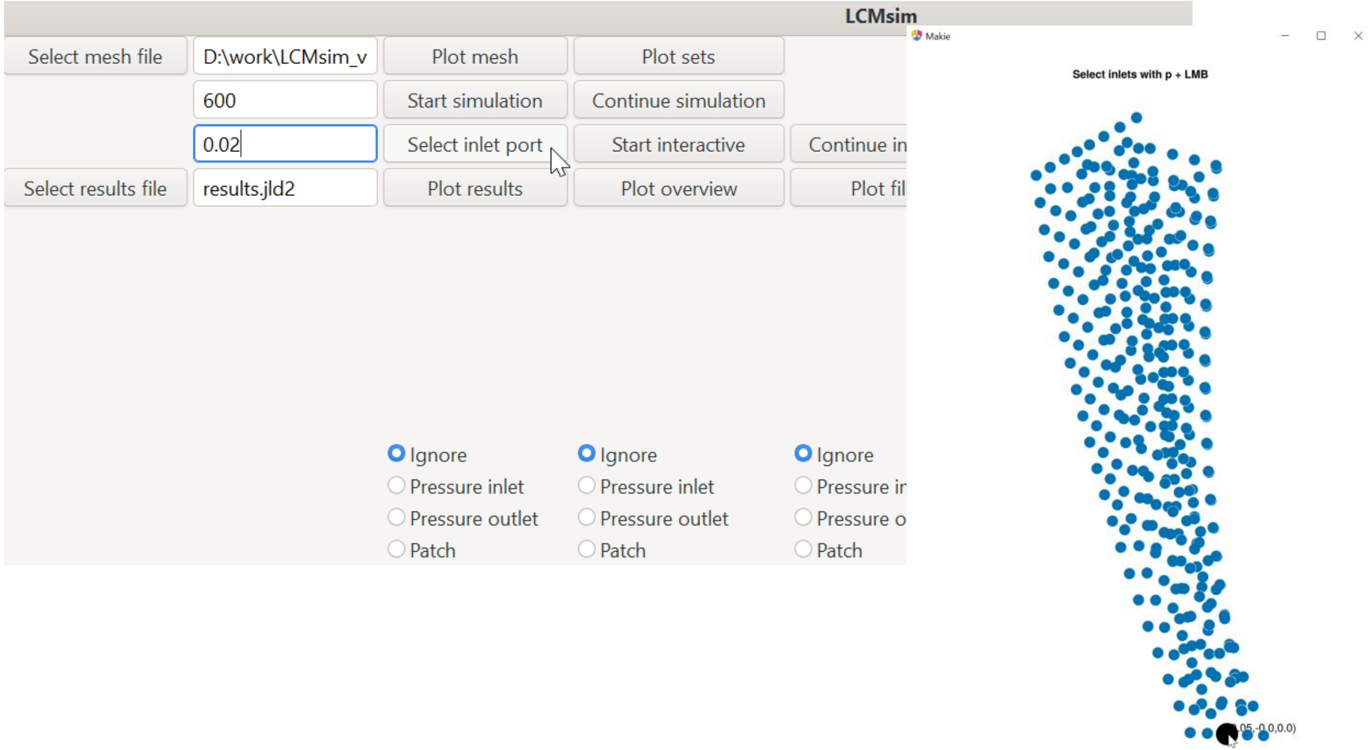
Case 1

Sim 1.2: Use software LCMsim to simulate the flow front propagation for the annulus filler. Should the injection gate be placed at the front, the top rear or the bottom rear? And where should the vents be placed?

Simulation input:

- Same parameters, except different mesh file mesh_annulusfiller1.bdf
- Disable pressure inlet, select injection gate radius 0.02 m and select injection gates interactively instead.

Case 1



Selection of multiple points possible

Case 1

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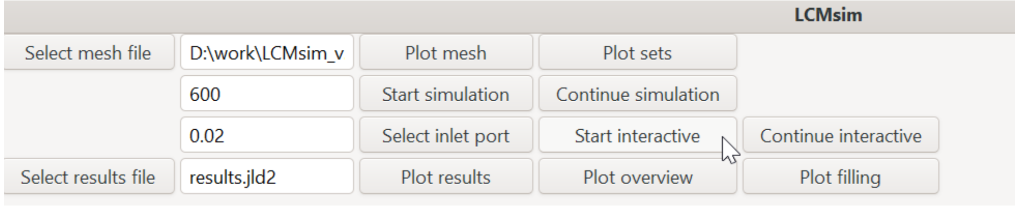
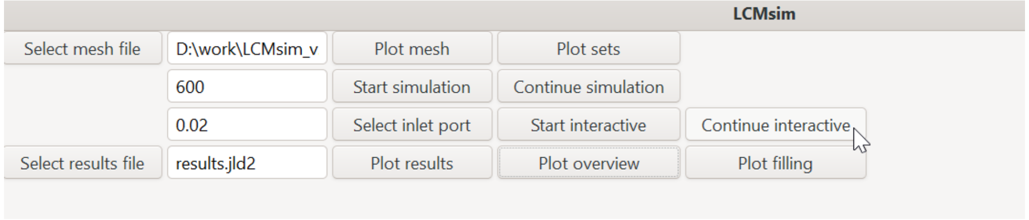
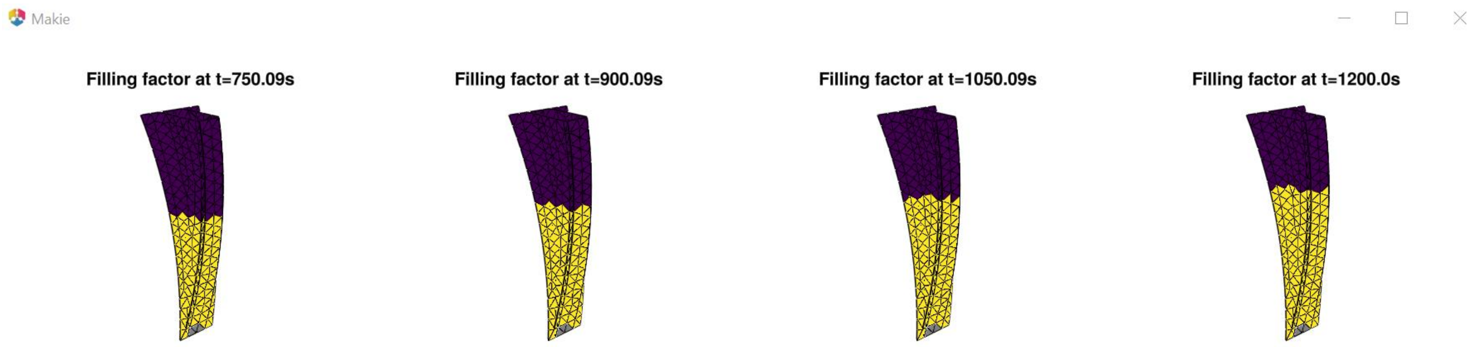


Case 1



Continue for another 600 s.
Position of injection gates can be changed before (e.g. cascade injection)



Case 1

Sim 1.3: Study the influence of the mesh size, specially around injection gates.

Simulation input:

- Same parameters, except different mesh file mesh_permeameter1_meshrefinement.bdf

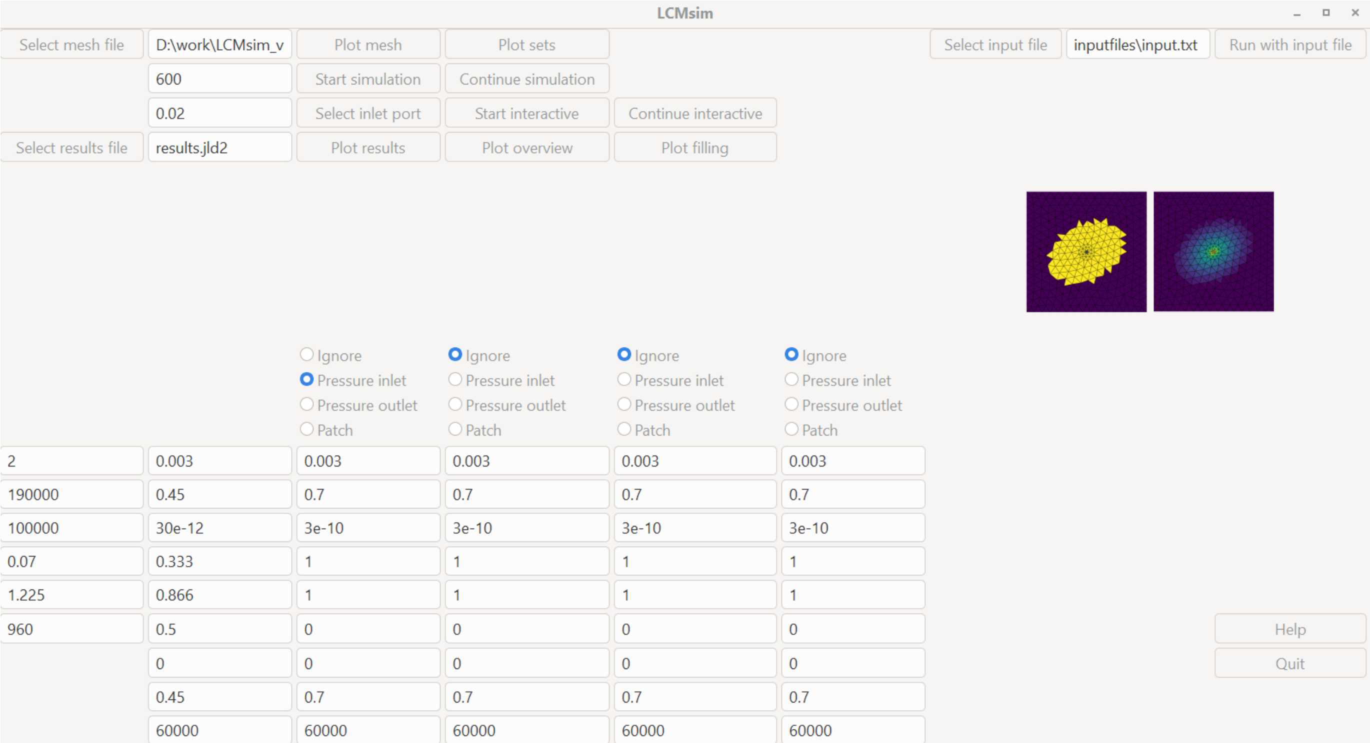
Case 1

Sim 1.4: If the layup is not quasi-isotropic, the flow front in the permeameter is a tilted ellipse instead of a circle.

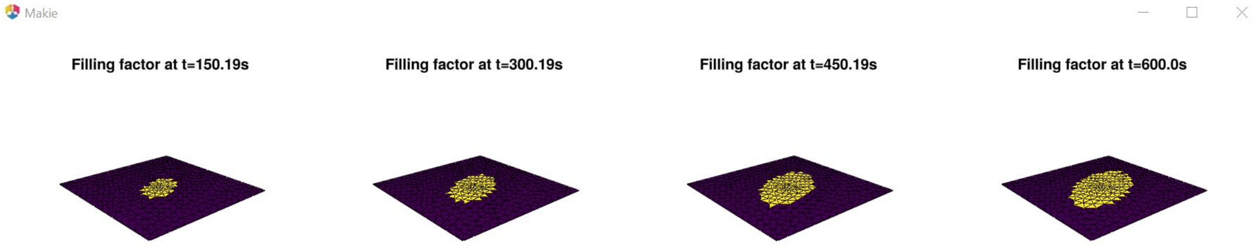
Simulation input:

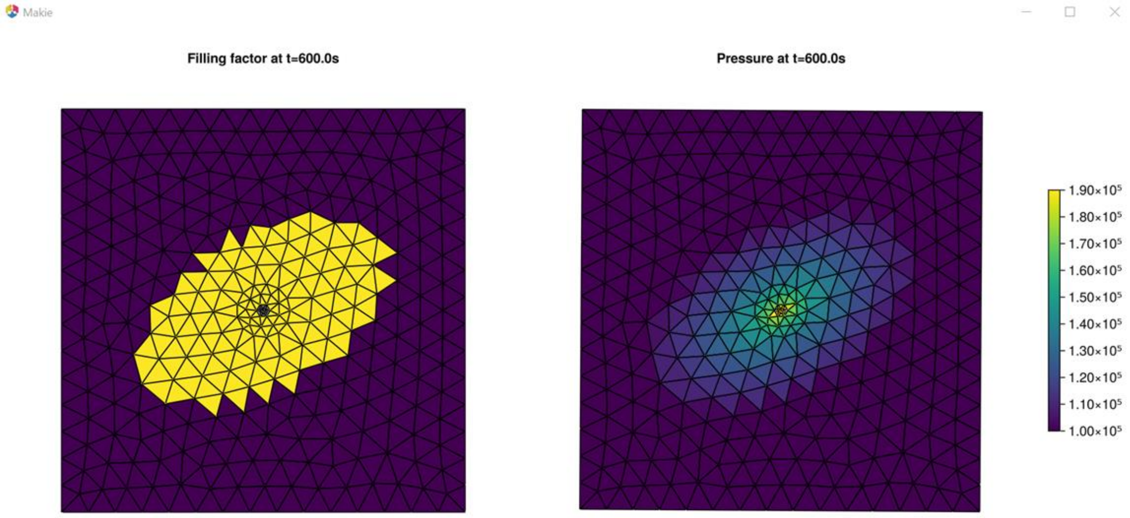
- Same as for Sim 1.1, except permeability 30e-12 m^2 in first principal direction 30° to the horizontal and permeability 10e-12 m^2 in second principal direction

Case 1

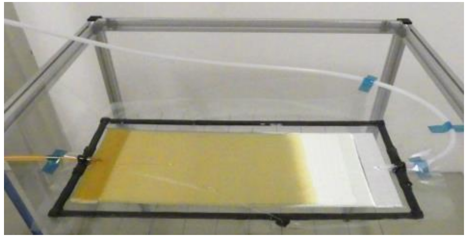

LCMsim
Select mesh file
D:\work\LCMsim_v
Plot mesh
Plot sets
Select input file
inputfiles\input.txt
Run with input file
600
Start simulation
Continue simulation
0.02
Select inlet port
Start interactive
Continue interactive
Select results file
results.jld2
Plot results
Plot overview
Plot filling
Ignore
Pressure inlet
Pressure outlet
Patch
Ignore
Pressure inlet
Pressure outlet
Patch
Ignore
Pressure inlet
Pressure outlet
Patch
Ignore
Pressure inlet
Pressure outlet
Patch
2 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003
190000 | 0.45 | 0.7 | 0.7 | 0.7 | 0.7
100000 | 30e-12 | 3e-10 | 3e-10 | 3e-10 | 3e-10
0.07 | 0.333 | 1 | 1 | 1 | 1
1.225 | 0.866 | 1 | 1 | 1 | 1
960 | 0.5 | 0 | 0 | 0 | 0
0 | 0 | 0 | 0 | 0
0.45 | 0.7 | 0.7 | 0.7 | 0.7
60000 | 60000 | 60000 | 60000 | 60000
Help
Quit

Case 1


Makie
Filling factor at t=150.19s
Filling factor at t=300.19s
Filling factor at t=450.19s
Filling factor at t=600.0s


Makie
Filling factor at t=600.0s
Pressure at t=600.0s
1.90×10⁵
1.80×10⁵
1.70×10⁵
1.60×10⁵
1.50×10⁵
1.40×10⁵
1.30×10⁵
1.20×10⁵
1.10×10⁵
1.00×10⁵

Case 2



VARI flow without flow distribution medium

VARI requires more input than RTM. Aslo a validation experiment must be performed, e.g. rectilinear flow experiment. One needs t, ε, k_1, k_2 if vacuum is drawn and at least t, ε at one other condition (easiest to estimate at ambinent pressure where the cured thickness and porosity serve as approximation; otherwise more sensors for t and p are required during the characterization experiment).

If t, areal weight Af and fiber density ρf are known, the porosity is $\varepsilon = t/(Af/\rho f)$.

The permeability constants c_1 and c_2 in the Kozeny-Carman relations for the porosity-dependent peremability can be determined from the above ε, k_1, k_2 at full vacuum:

$$k_1 = c_1 \cdot (\varepsilon)^3/(1-\varepsilon)^2$$

$$k_2 = c_2 \cdot (\varepsilon)^3/(1-\varepsilon)^2$$

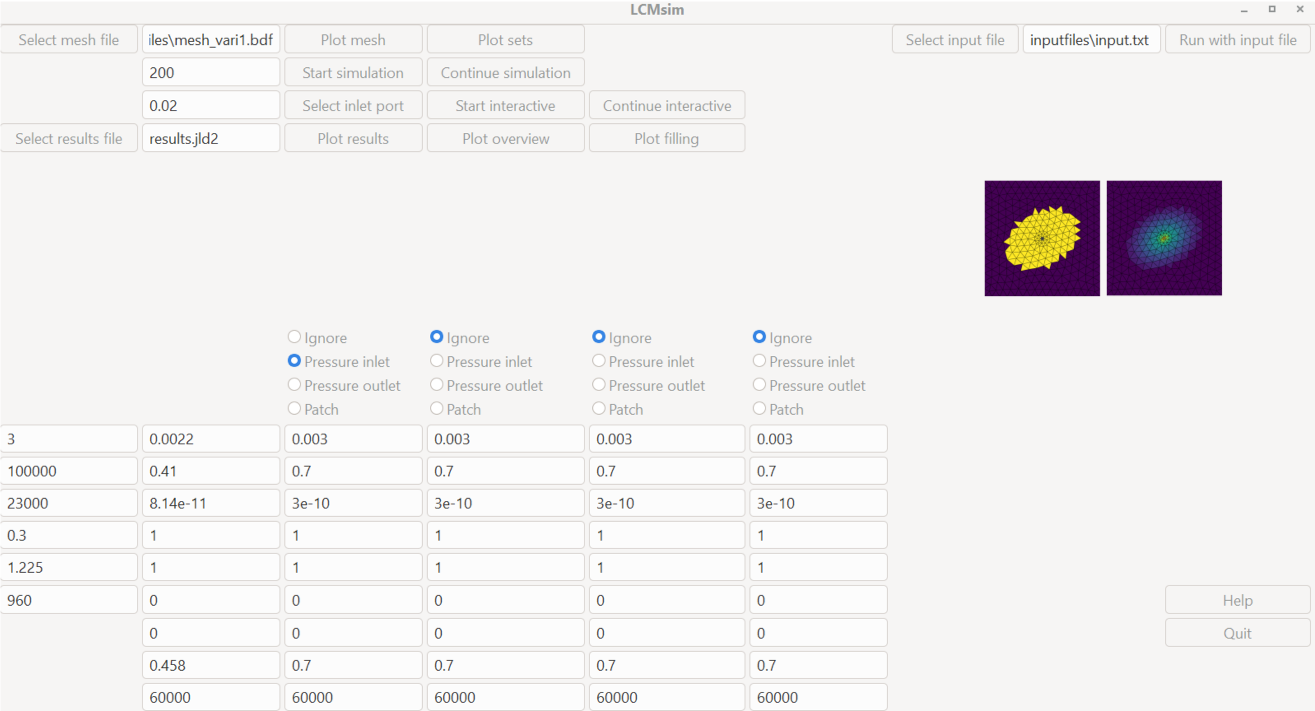
Case 2

VARI flow without flow distribution medium

Preform size 0.2 x 0.05 x 0.0022 m^3, Line injection gate at left boundary, 77000 Pa injection pressure, dynamic viscosity 0.3 Pas, porosity 0.41 at vacuum and 0.458 at 60000 Pa, isotropic permeability according to Kozney-Carman relationship with factor 8.14e-11 m^2

Sim 2.1: Use software LCMsim to simulate the rectilinear vari flow.

Case 2



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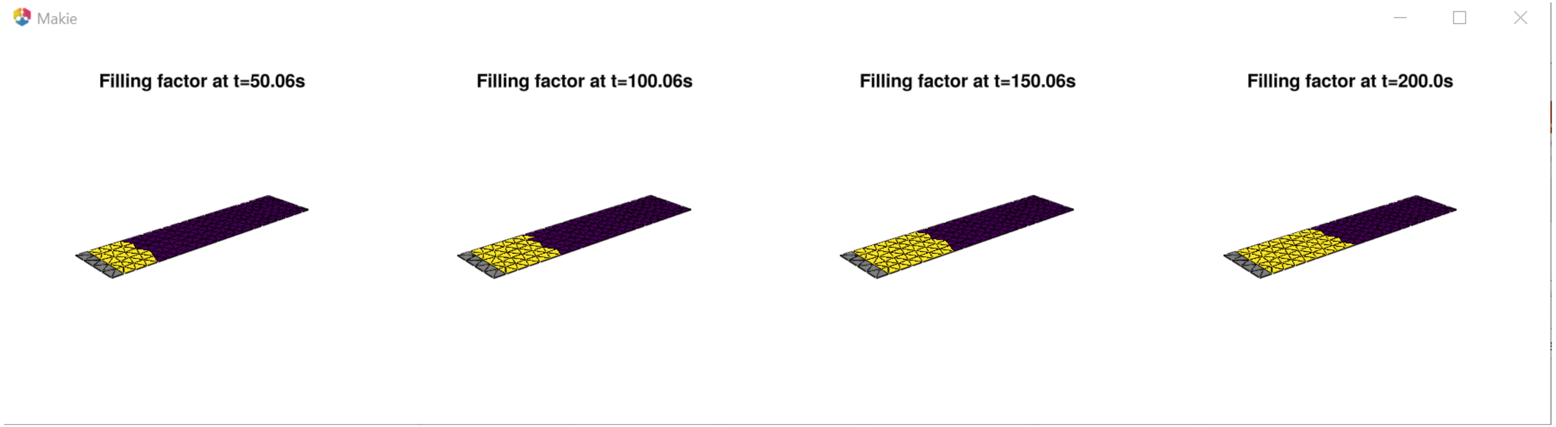
Case 2



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Case 2

- The contour plot with the preform thickness is not available via the GUI.
- In the LCMsim folder are the output files (index 0:16 for initial and 16 equidistant output time instances; output_ for general output, output3_ for dedicated VARI output) and the Julia code (lcmsim.jl with the core functions and lcmsim_GUI.jl with the GUI functions)
- The comments at the top of lcmsim.jl list the call of popular functions:

```
# LCMsim - A Julia module for filling simulations in Liquid Composite Molding (LCM) with the Finite Area Method
#
#   Popular functions are:
#       VARI:
#       lcmsim.lcmsim_solver(2,"meshfiles\\mesh_vari1.bdf",200, 101325,1.225,1.4,0.3, 1.00e5,0.23e5, 1.2,960, 2.2e-3,
#       lcmsim.lcmsim_solver(3,"meshfiles\\mesh_vari1.bdf",200, 101325,1.225,1.4,0.3, 1.00e5,0.23e5, 1.2,960, 2.2e-3,
#           >> tf=200,K=8.14e-11;deltap=77000;mu=0.3;porosity=0.410;xf=sqrt((2*K*(deltap)*tf)/(mu*porosity))
#           tf =
#           200
#           xf =
#           0.1428
#           >> tf=200,porosity=0.410;K=8.14e-11*(1-(1-porosity))^3/(1-porosity)^2,deltap=77000;mu=0.3;xf=sqrt((2*K*(
#           tf =
#           200
#           K =
#           1.6117e-11
#           xf =
#               0.0635
#           If porosity<0.58 permeability factor is <1, otherwise>1
#       lcmsim.lcmsim_solver(3,"meshfiles\\mesh_vari1.bdf",200, 101325,1.225,1.4,0.3, 1.00e5,0.23e5, 1.2,960, 2.2e-3,
#       lcmsim.plot_mesh("meshfiles\\mesh_vari2.bdf",1)
#       lcmsim.plot_sets("meshfiles\\mesh_vari2.bdf")
#       lcmsim.lcmsim_solver(3,"meshfiles\\mesh_vari2.bdf",200, 101325,1.225,1.4,0.3, 1.00e5,0.23e5, 1.2,960, 2.2e-3,
#       lcmsim.plot_overview(-1,-1)
#       lcmsim.plot_filling(-1,-1)
#       lcmsim.plot_thickness("output3_16.jld2")
#       lcmsim.lcmsim_solver(2,"meshfiles\\mesh_permeameter1_foursets.bdf",200, 101325,1.225,1.4,0.06, 1.35e5,1.00e5,
#       lcmsim.start_lcmsim("inputfiles\\input_case1_coarsemesh.txt")
#
```

› Dieser PC › Data (D:) › work › LCMsim_v2_20240204 › LCMsim-1.0.4

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meshfiles	03.04.2024 13:04	Dateiordner	
inletpostions.jld2	03.04.2024 13:37	JLD2-Datei	1 KB
lcmsim.jl	09.01.2024 15:22	JL-Datei	148 KB
lcmsim_GUI.jl	09.01.2024 15:22	JL-Datei	32 KB
LICENSE	09.01.2024 15:22	Datei	18 KB
output_0.jld2	04.04.2024 13:32	JLD2-Datei	50 KB
output_1.jld2	04.04.2024 13:32	JLD2-Datei	50 KB
output_2.jld2	04.04.2024 13:32	JLD2-Datei	50 KB
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output3_1.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
output3_2.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
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output3_6.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
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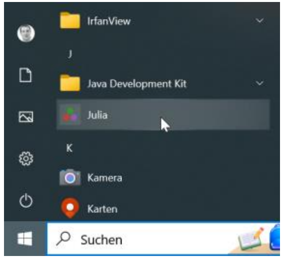
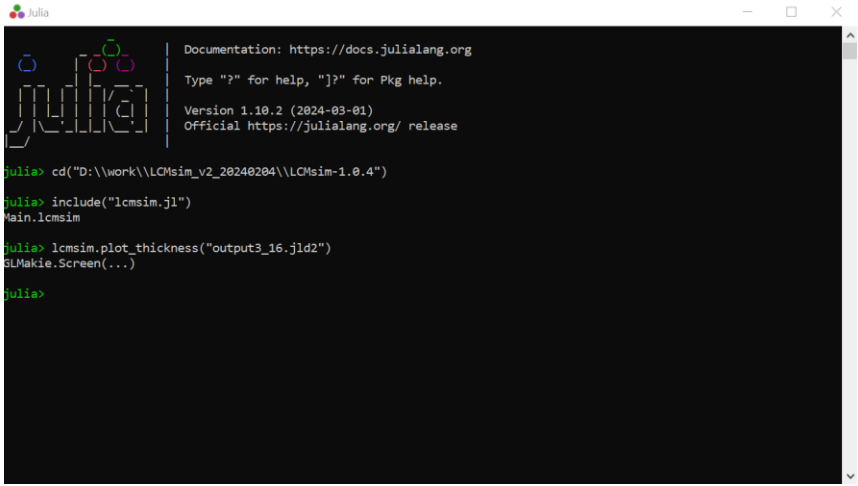
output3_11.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
output3_12.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
output3_13.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
output3_14.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
output3_15.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
output3_16.jld2	04.04.2024 13:32	JLD2-Datei	43 KB
pset.jld2	03.04.2024 13:38	JLD2-Datei	6 KB

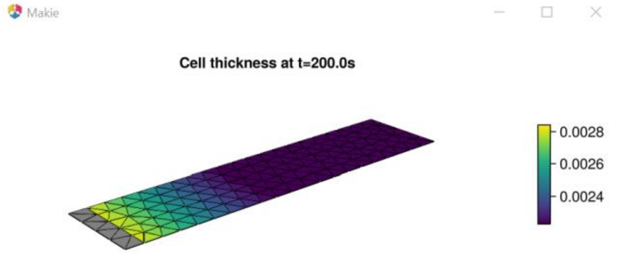
Case 2

Access to all functions:

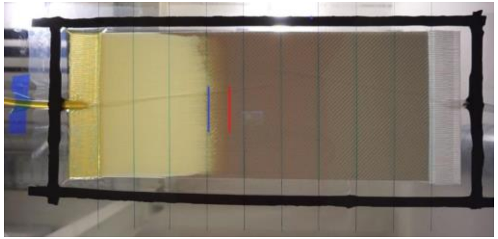
- Open a Julia terminal
- Change to the working directory: `cd(“path\\to\\workingdirectory“)` with `\\` as separator
- Load the Julia module: `include(“lcmsim.jl“)`
- Create the thickness plot: `lcmsim.plot_thickness(“output3_16.jld2“)`







Case 3



VARI flow with flow distribution medium

Preform size 0.2 x 0.05 x (0.0022+0.0005) m^3, Line injection gate at left boundary, 77000 Pa injection pressure, dynamic viscosity 0.3 Pas.

An effective in-plane permeability must be calculated as an average permeability of the two layers (flow distribution medium and preform) such that the simulated flow front corresponds with the flow front in the flow distribution medium for flow through a preform of combined thickness. Also an averaged porosity must be calculated.

The simplest of such averages is a simple rule of mixture:

$$k_1 = 1/(t_1+t_2) \cdot (t_1 \cdot (k_1)_1 + t_2 \cdot (k_1)_2)$$

$$k_2 = 1/(t_1+t_2) \cdot (t_1 \cdot (k_2)_1 + t_2 \cdot (k_2)_2)$$

$$\varepsilon = (t_1 \varepsilon_1 + t_2 \varepsilon_2)/(t_1+t_2)$$

Case 4

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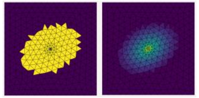
Complete workflow:

PrePoMax



CAD model of part mid-surface (e.g. STEP file) → Create mesh and sets → Develop injection strategy

https://obertscheiderfhwn.github.io/LCMsim/build/assets/geom/mesh_spar3.stp

Determine simulation time for central injection gate and for injection gate at front end.

VARI (initial cavity pressure 20000 Pa) with flow distribution medium (t_1=0.5 mm, eps_1=0.85, k_1=k_2=1e-8 m²) on top of preform (t_2=3 mm in the inner section and 2 mm in the outer section, eps_2=0.6, k_1=160e-12 m², k_2=60e-12 m²). Primary direction is [0.3030 0.3326 0.8931] in the inner section [0.4316 0.5892 0.6831] in the outer section.

Calculate equivalent orthotropic permeability:

```
t1=0.0005;
eps1=0.85;
k1_1=1e-8;
k2_1=1e-8;

t2=0.003;
eps2=0.6;
k1_2=160e-12;
k2_2=60e-12;

k1=1/(t1+t2) * (t1*k1_1+t2*k1_2)
k2=1/(t1+t2) * (t1*k2_1+t2*k2_2)
eps=(t1*eps1+t2*eps2)/(t1+t2)
k1 = 1.5657e-09
k2 = 1.4800e-09
eps = 0.6357
```

```
t1=0.0005;
eps1=0.85;
k1_1=1e-8;
k2_1=1e-8;

t2=0.002;
eps2=0.6;
k1_2=160e-12;
k2_2=60e-12;

k1=1/(t1+t2) * (t1*k1_1+t2*k1_2)
k2=1/(t1+t2) * (t1*k2_1+t2*k2_2)
eps=(t1*eps1+t2*eps2)/(t1+t2)
k1 = 2.1280e-09
k2 = 2.0480e-09
eps = 0.6500
```

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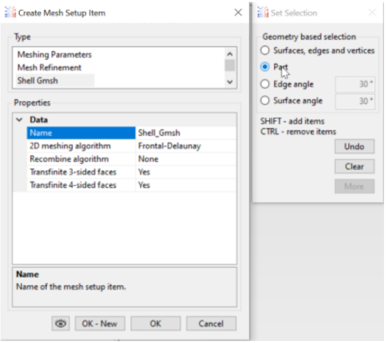
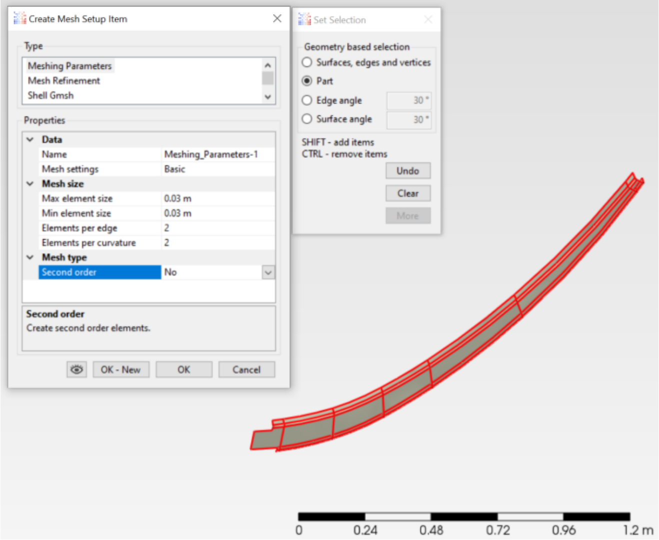
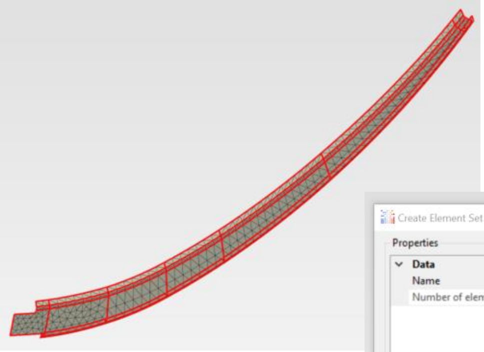
- Create new PrePoMax file with length unit m: File / New
- Import (defeaured) step file and if required scale part: File / Import and Geometry / Part / Transform / Scale
- Create mesh setup items (Shell Gmsh for the whole part, Meshing parameters for the whole part): Mesh / Mesh Setup Item / Create

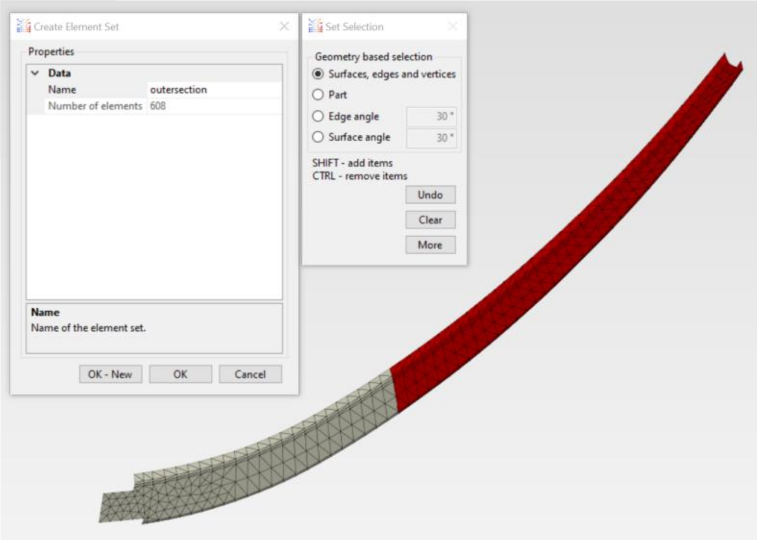




Case 4

- Create mesh: Mesh / Create Mesh



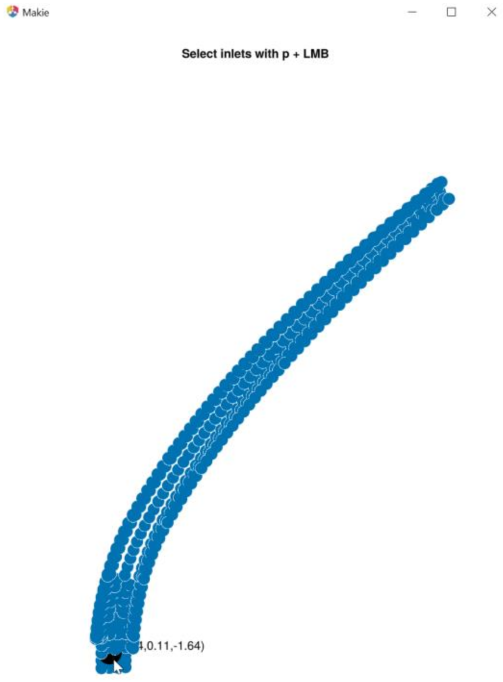


- Create element sets: RMB on Element Sets / Create, Multiple selection with LMB and box selection or with or Shift+LMB

- File/Export/Calculix *inp

Case 4

- Launch LCMsim GUI and Plot sets:



- Select inlet port with 0.0065 m radius:

Case 4

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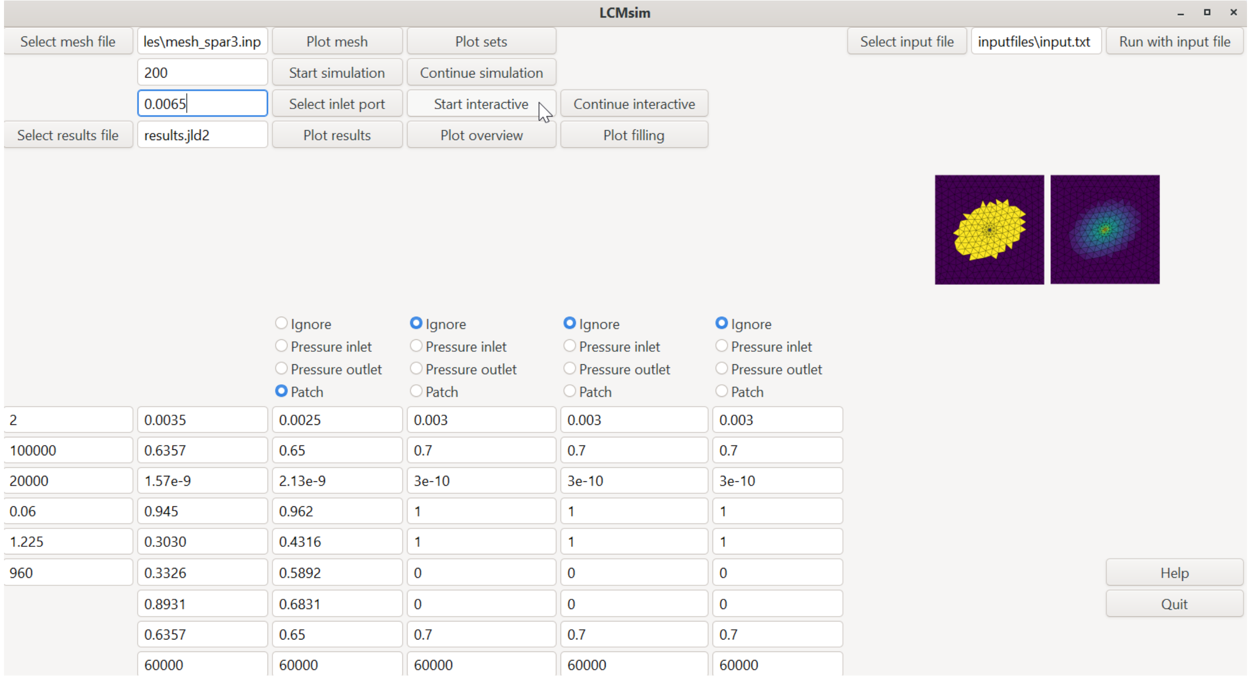
- Start interactive:



Case 4

- Plot overview:

Case 5

Redo complete workflow for your own part and choose appropriate RTM or VARI parameters

Case 6

Reproduce cases 1 and 2 of the filling simulation of MUL permeameter experiment with different permeability patches. Use mesh files mesh_permeameter5.bdf for case 1 and mesh_permeameter5isse_meshrefinement2.bdf for case 2. Look up the preform, process and fluid parameters in https://www.tandfonline.com/doi/full/10.1080/20550340.2023.2282310