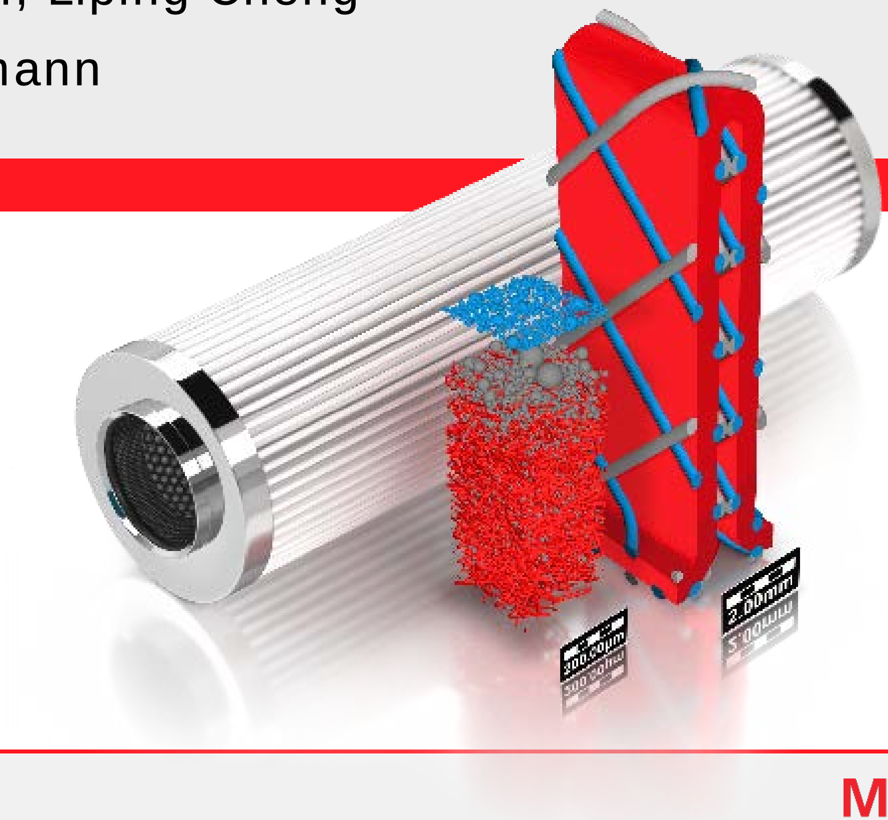
Analysis of Filter Media and Simulation of Filter Processes Based on µCT Scans

Jürgen Becker, Cornelia Kronsbein, Liping Cheng
Rolf Westerteiger, Andreas Wiegmann



Who is Math2Market ?

- Math2Market GmbH was founded 2011 in Kaiserslautern.
- Spin-off of Fraunhofer Institute for Industrial Mathematics, ITWM.
- Today: 13 full-time, 6 part-time employees, turnover >2 Mio € / year

- Our product: GeoDict software
  - Sales
  - Development and Customization
  - Consulting

What is GeoDict?

GeoDict is a digital material laboratory

- Computer Aided Material Engineering and Design by providing Geometric models and preDictions of material properties.

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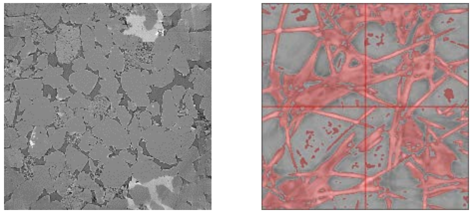

Import of CT Scans

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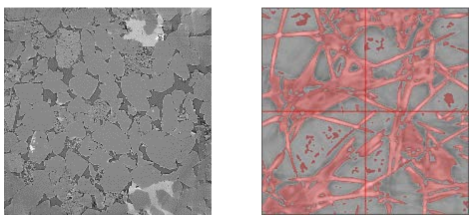

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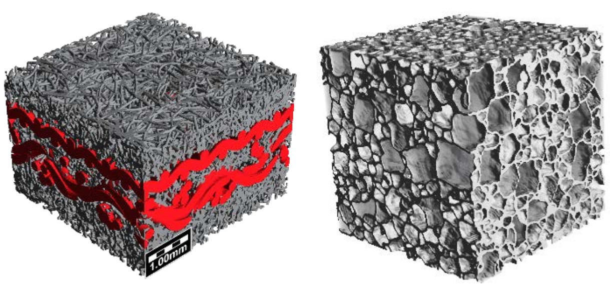

Create 3D Models of Micro-structures

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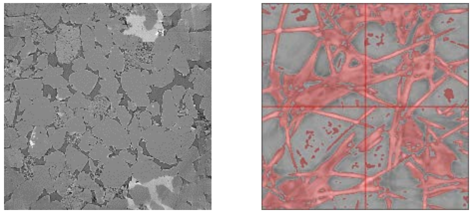

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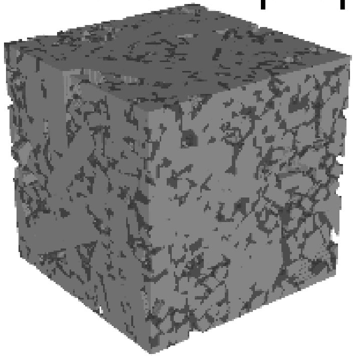
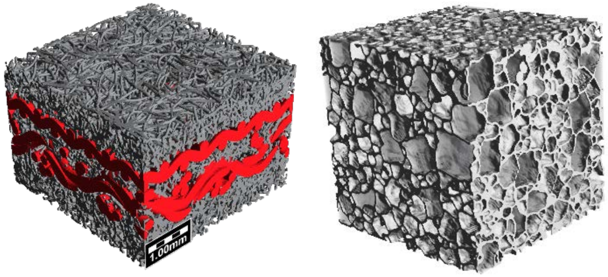


Geometric Analysis of 3D Structures



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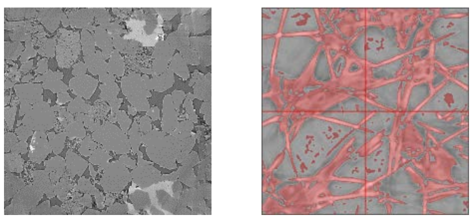

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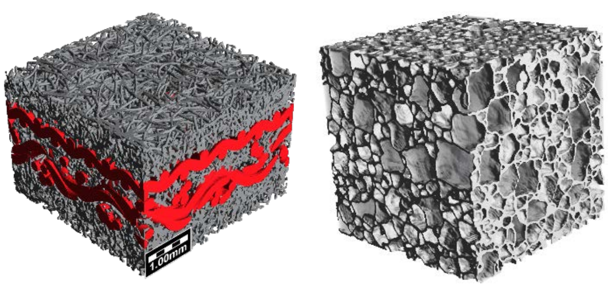
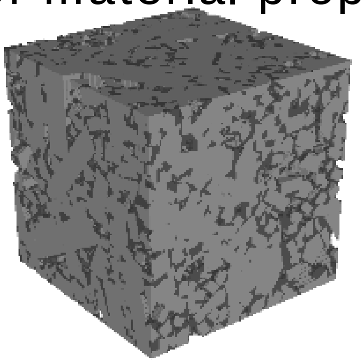
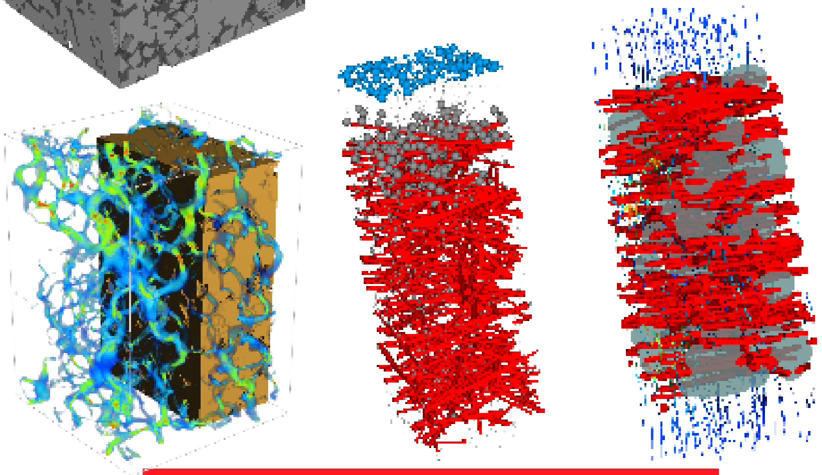


Create 3D Models of Micro-structures



Geometric Analysis of 3D Structures



Simulate advection, diffusion particle transport, stiffness

How can simulations help to improve a filter?

Step 1: Understand the existing filter material

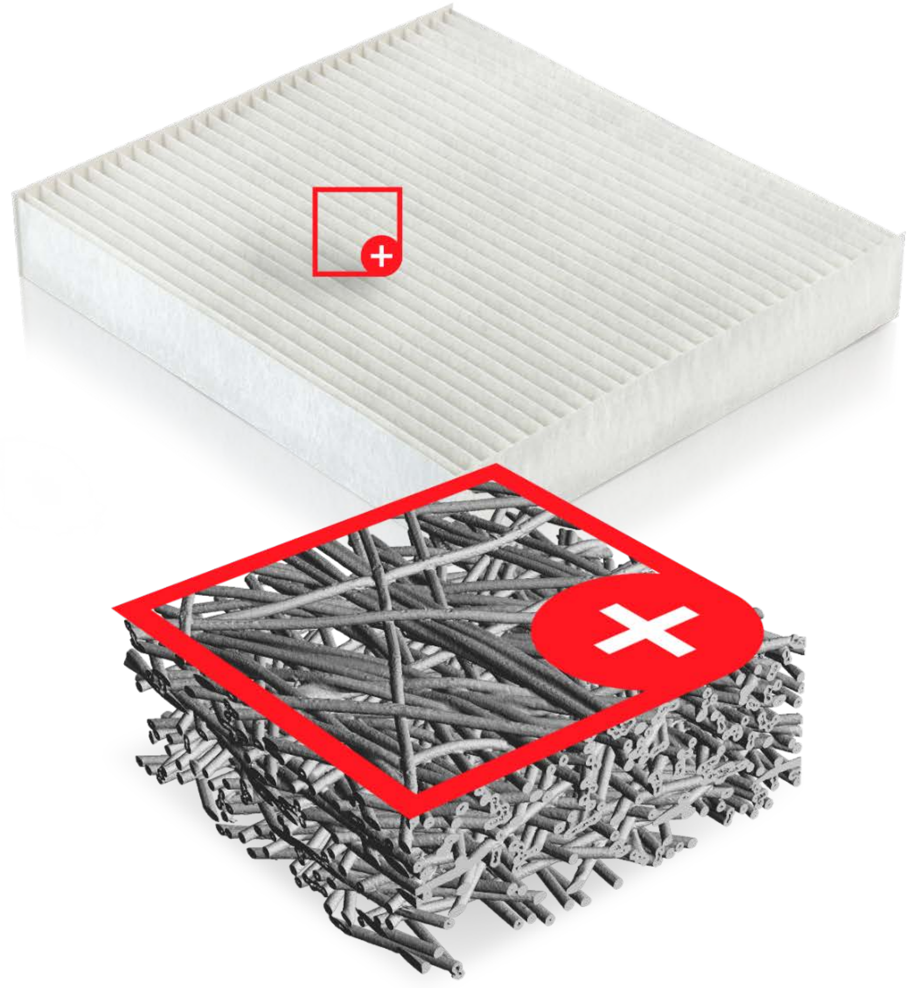
- CT Scan
- Simulations on CT Scan

Step 2: Create a model of the existing material

- Analyze CT Scan
- Create structure model
- Simulations on Structure model

Step 3: Modify the structure model

Sample Structure: Cabin Air Filter



- Commercially available filter
- CT scan by service provider RJL Micro&Analytic

Step 1:

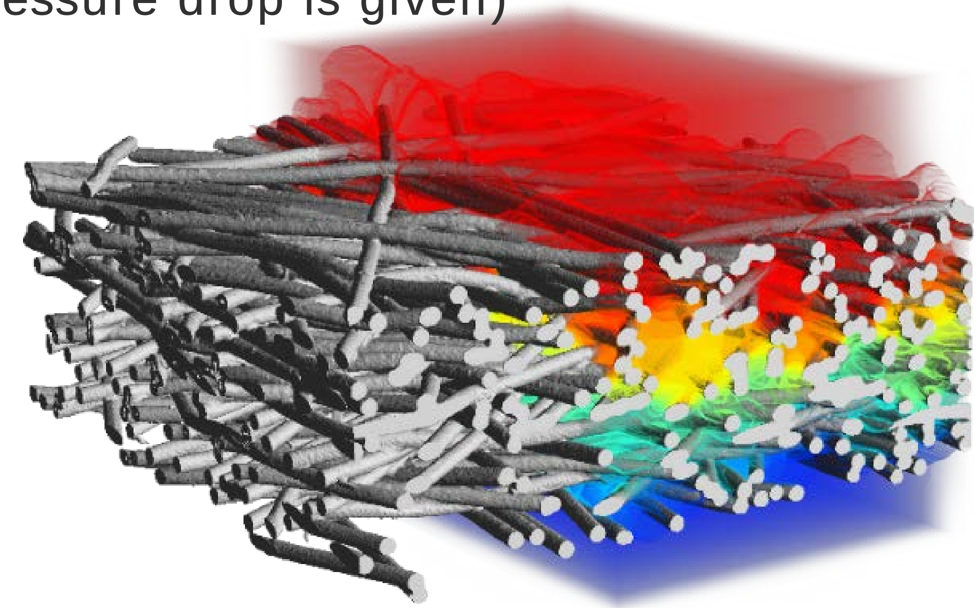
Understand the existing filter material

Determine Flow Rate or Pressure Drop

Stationary Navier-Stokes flow:

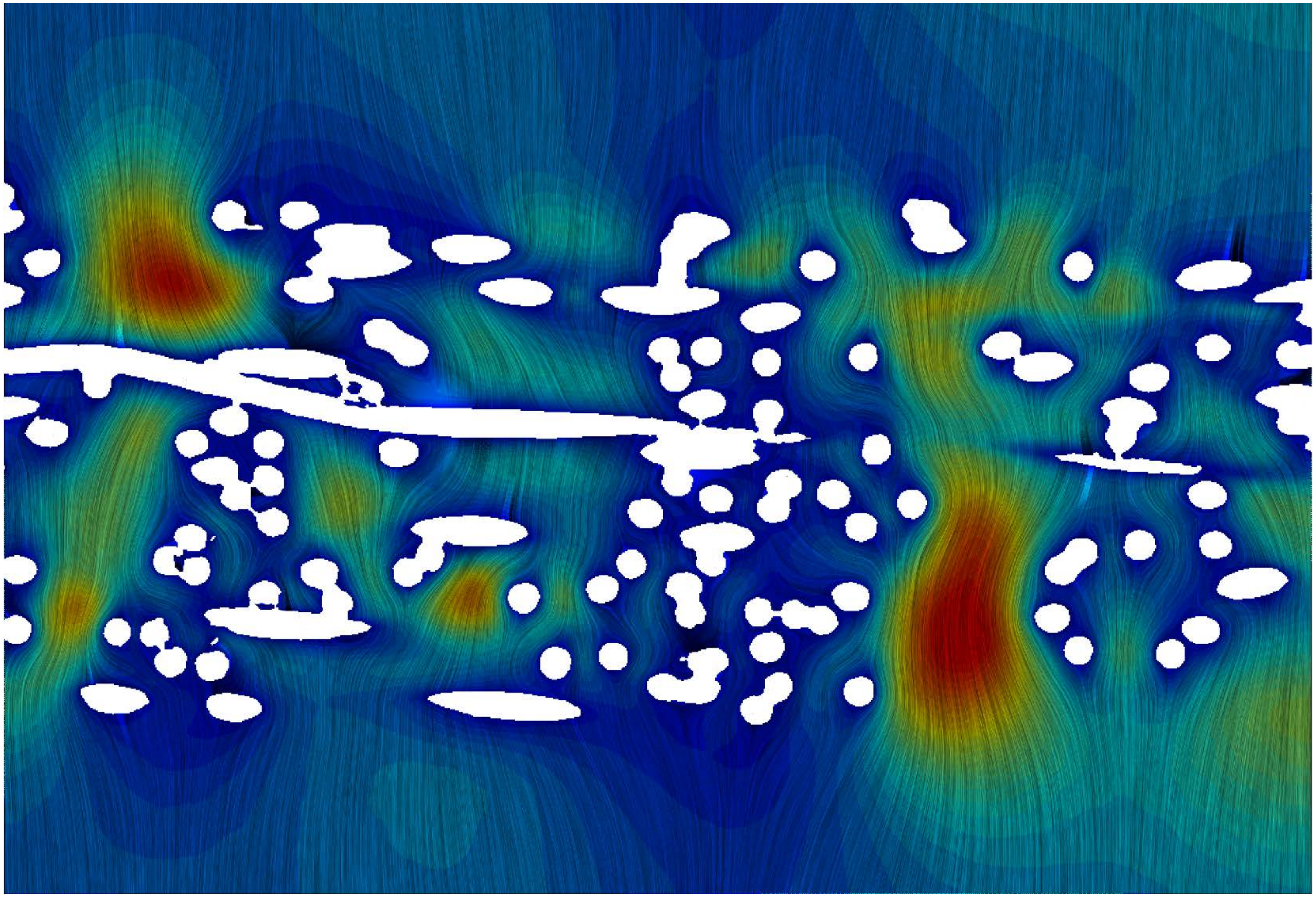
$-\mu\Delta\vec{u} + \rho(\vec{u}\cdot\nabla)\vec{u} + \nabla p = 0$ (momentum balance)
$\nabla\cdot\vec{u} = 0$ (mass conservation)

$\vec{u} = 0$ on Γ (no-slip on surface)
$P_{in} = P_{out} + const$ (pressure drop is given)



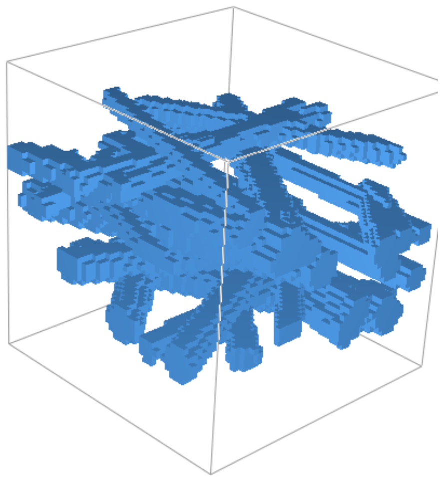
$\vec{u}$: velocity
p: pressure
μ: dynamic viscosity
ρ: fluid density

Result for Clean Cabin Air Filter Media (Flat Sheet): Pressure drop of 7.35 Pa at 0.1 m/s mean velocity



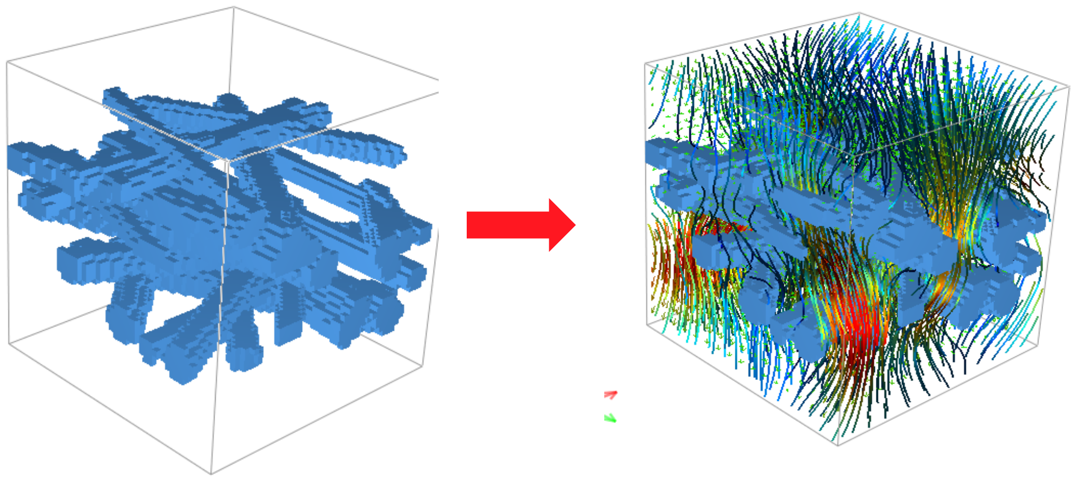
Efficiency of Clean Filter Media: Method

1. Filter media model



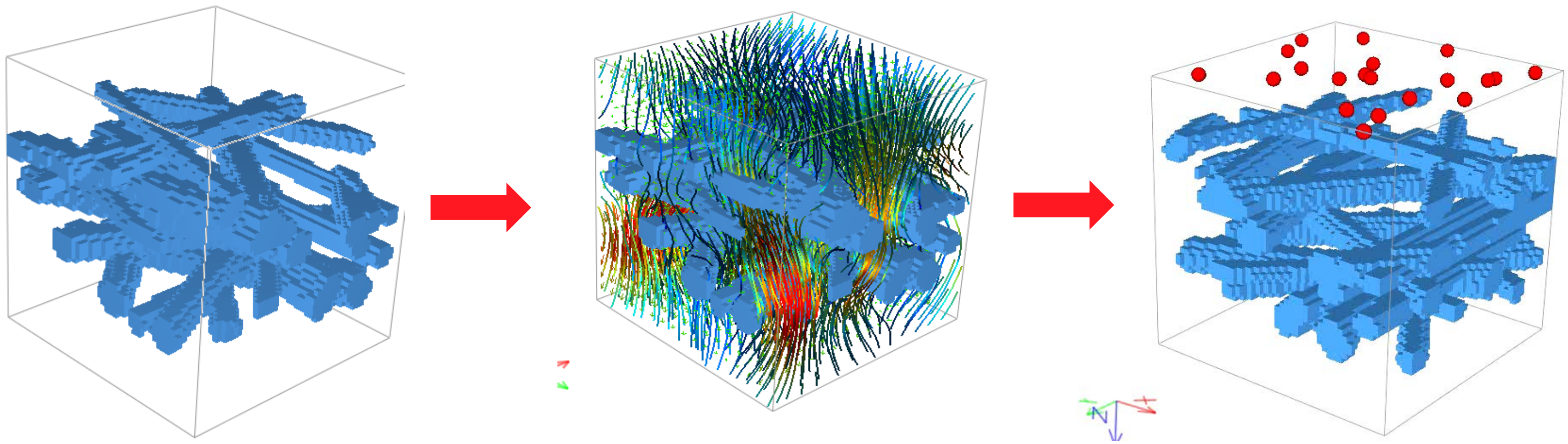
Efficiency of Clean Filter Media: Method

1. Filter media model
2. Determine flow field



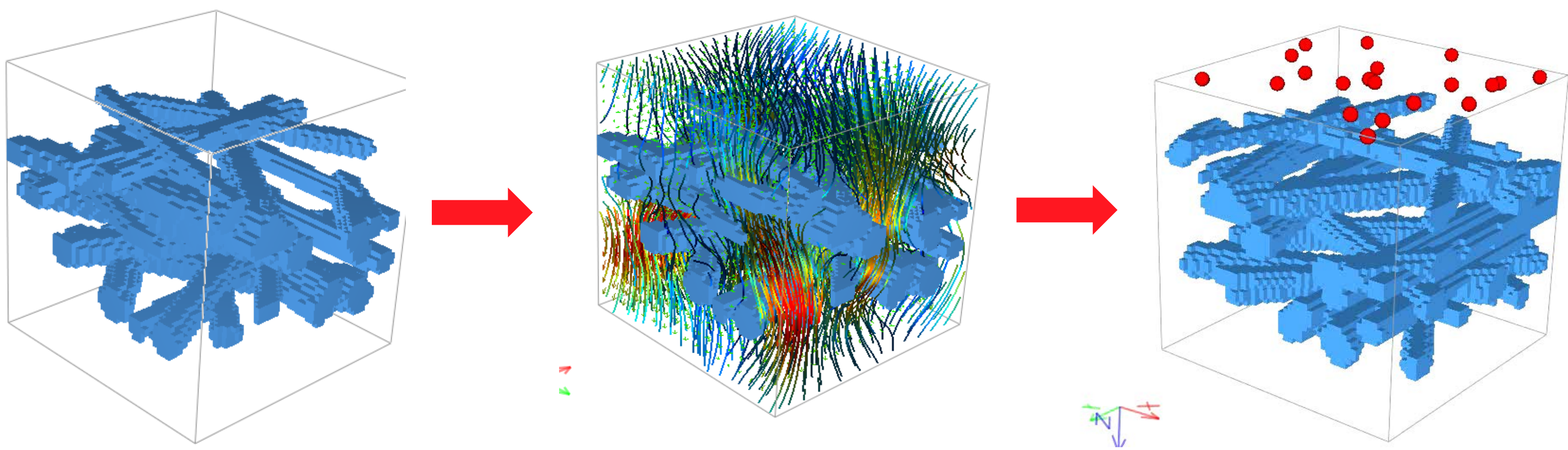
Efficiency of Clean Filter Media: Method

1. Filter media model
2. Determine flow field
3. Track particles (filtered or not?)



Efficiency of Clean Filter Media: Method

1. Filter media model
2. Determine flow field
3. Track particles (filtered or not?)
4. Result: percentage of filtered particles of each size



Movement of Particles in a Flow Field: Balance of Forces Equation

Impulse | Stokes Drag | Electrostatic Force

$$m\frac{d\vec{v}}{dt} = 6\pi\mu\frac{R}{C_c}\left(\vec{u} - \vec{v} + \sqrt{2D}\frac{d\vec{W}(t)}{dt}\right) + Q\vec{E}$$

$\vec{v}$: particle velocity [m/s]
$\vec{u}$: fluid velocity [m/s]
R : particle radius [m]
C_c : Cunningham correction
m : particle mass [kg]
μ : dynamic viscosity [kg/m·s]
Q : particle charge [C]
E : electric field [V/m]
D : Diffusivity [m²/s]
$d\vec{W}$: 3D Wiener process

Movement of Particles in a Flow Field: Balance of Forces Equation

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Cunningham Corrected Particle Radius

$\vec{v}$	: particle velocity [m/s]	μ	: dynamic viscosity [kg/m·s]
$\vec{u}$	: fluid velocity [m/s]	Q	: particle charge [C]
R	: particle radius [m]	E	: electric field [V/m]
C_c	: Cunningham correction	D	: Diffusivity [m²/s]
m	: particle mass [kg]	$d\vec{W}$	: 3D Wiener process

Movement of Particles in a Flow Field: Balance of Forces Equation

Impulse | Stokes Drag | Electrostatic Force

$$m\frac{d\vec{v}}{dt} = 6\pi\mu\frac{R}{C_c}\left(\vec{u} - \vec{v} + \sqrt{2D}\frac{d\overrightarrow{W}(t)}{dt}\right) + Q\vec{E}$$

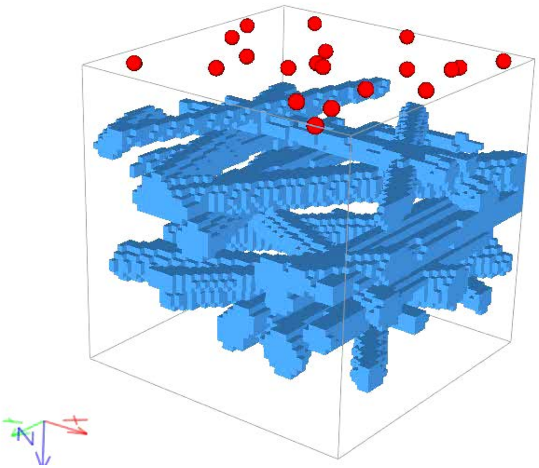
Brownian Motion

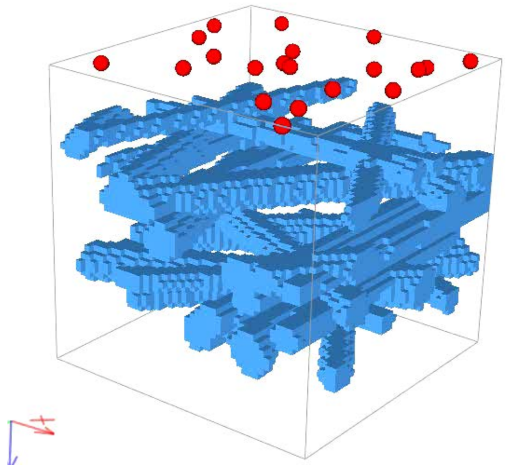
Cunningham Corrected Particle Radius

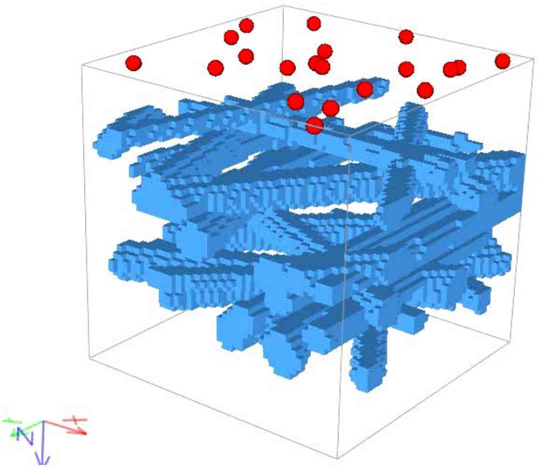
$\vec{v}$	: particle velocity [m/s]	μ	: dynamic viscosity [kg/m·s]
$\vec{u}$	: fluid velocity [m/s]	Q	: particle charge [C]
R	: particle radius [m]	E	: electric field [V/m]
C_c	: Cunningham correction	D	: Diffusivity [m²/s]
m	: particle mass [kg]	$d\overrightarrow{W}$	: 3D Wiener process

Particle Adhesion Models

What happens when a particle touches a fiber?







Caught on first touch

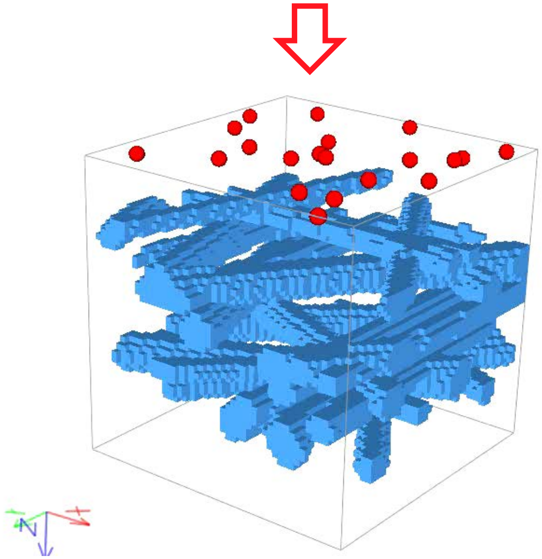
Compare Kinetic and Adhesive Forces

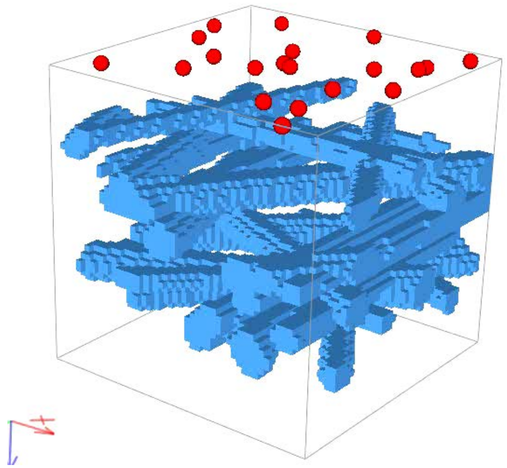
Sieving

Particle Adhesion Models

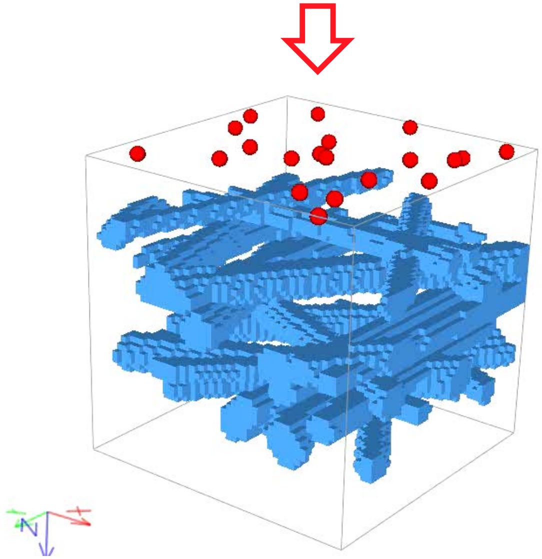
What happens when a particle touches a fiber?

Air Filtration



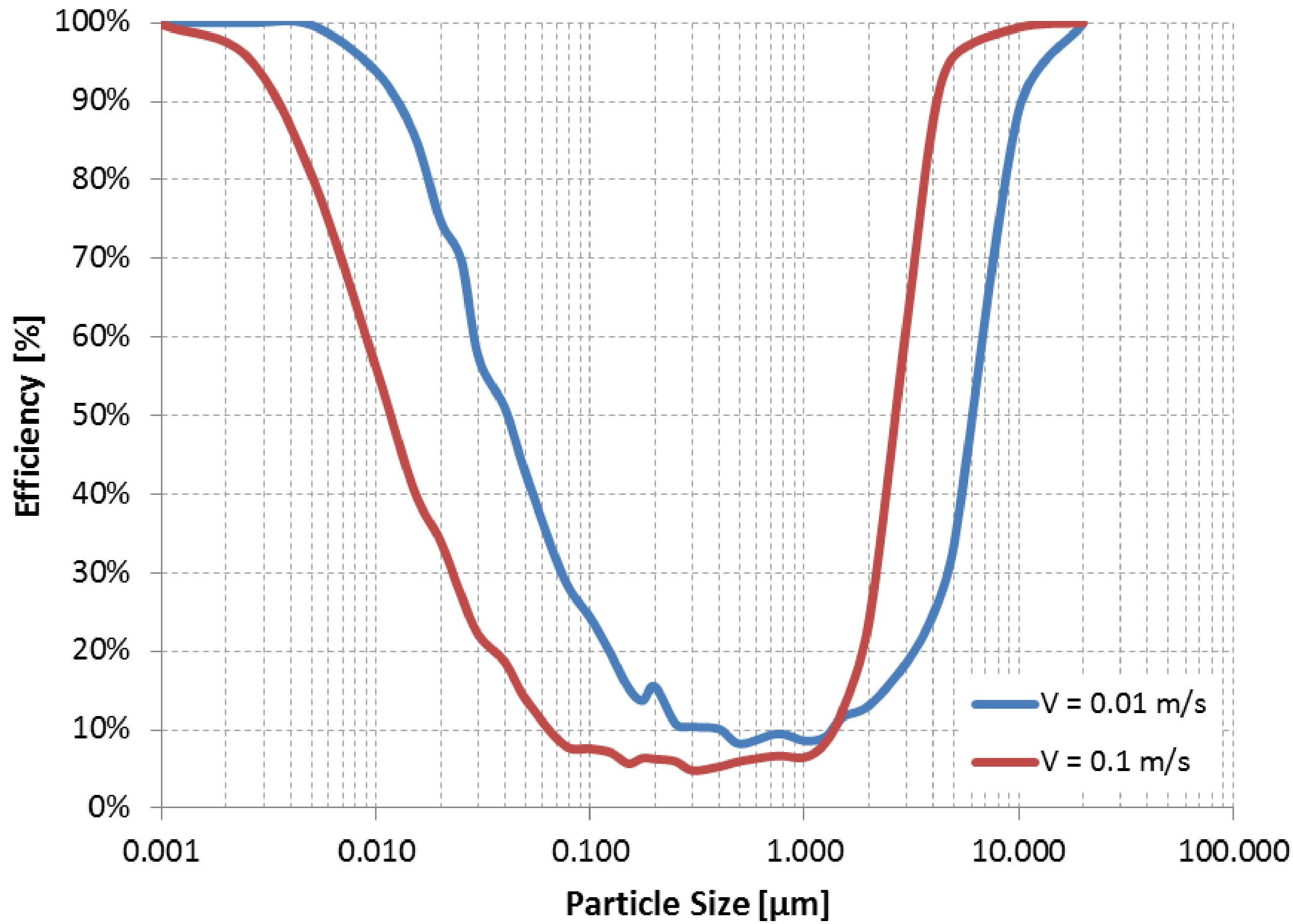


Oil Filtration

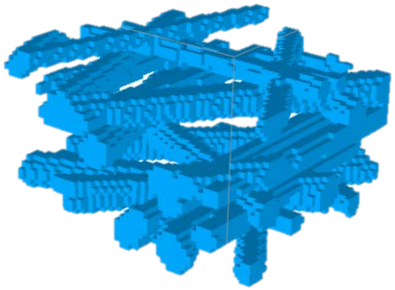


Caught on first touch	Compare Kinetic and Adhesive Forces	Sieving

Cabin Air Filter
Fractional Efficiency (w / o Electrostatic Attraction)

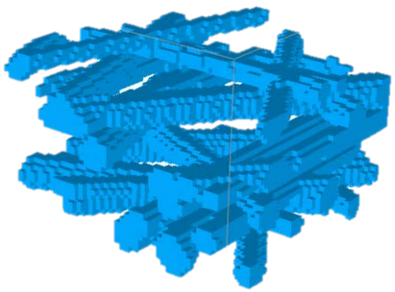


Filter Life Time Simulation - Method



1. Filter Model

Filter Life Time Simulation - Method



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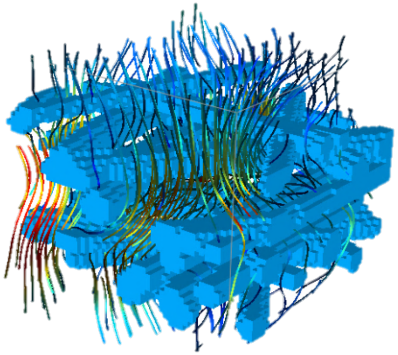
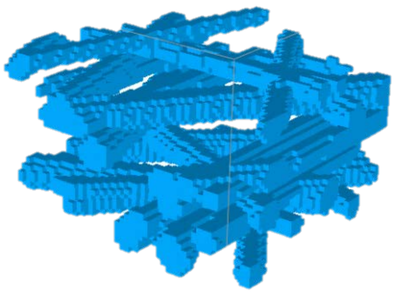


2. Flow Field

Filter Life Time Simulation - Method



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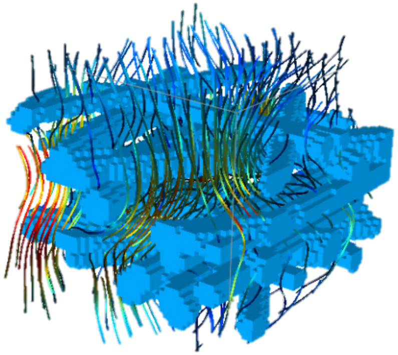

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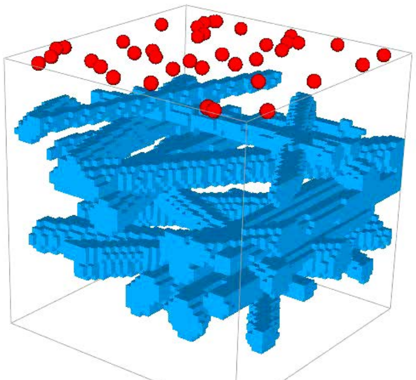
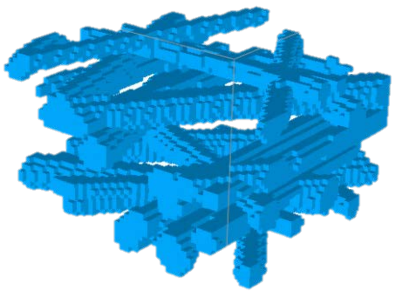


3. Track Particles

Filter Life Time Simulation - Method



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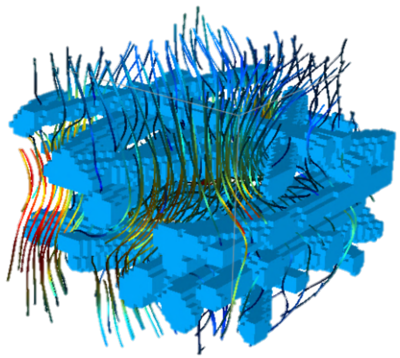

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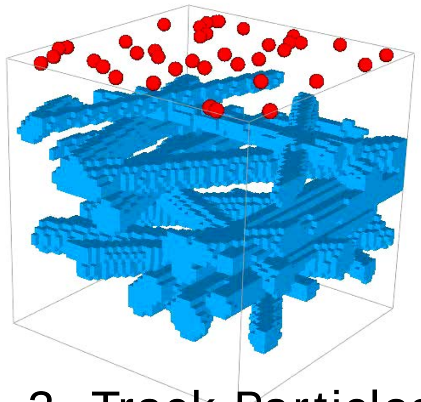

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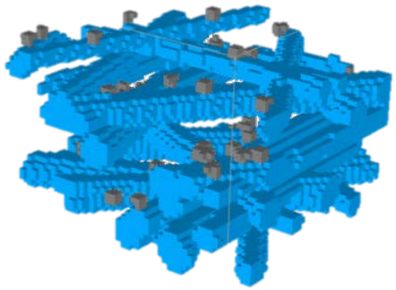
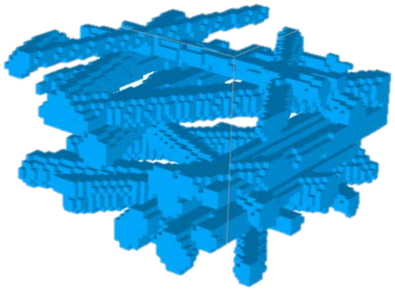


4. Deposit Particles

Filter Life Time Simulation - Method



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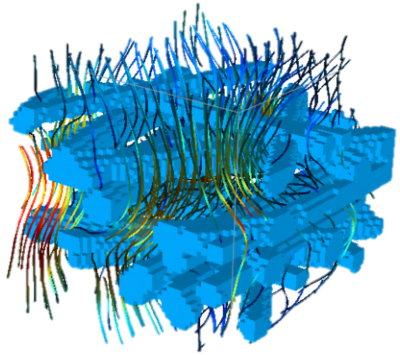

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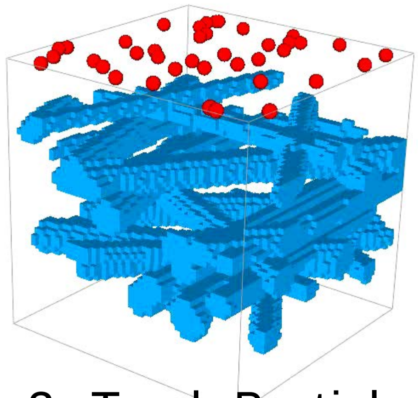

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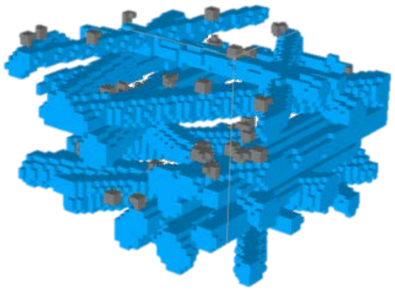

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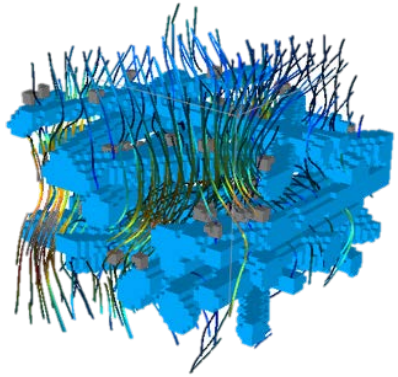
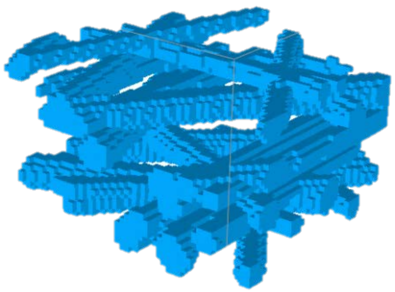


5. Recompute Flow

Filter Life Time Simulation - Method



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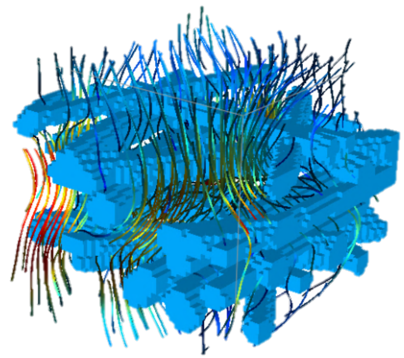

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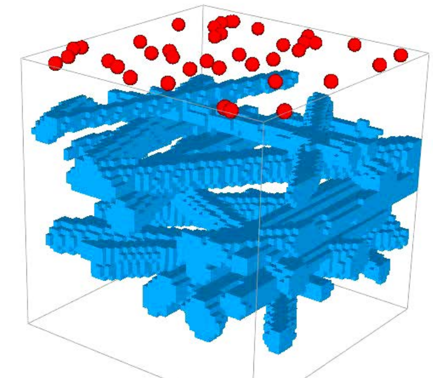

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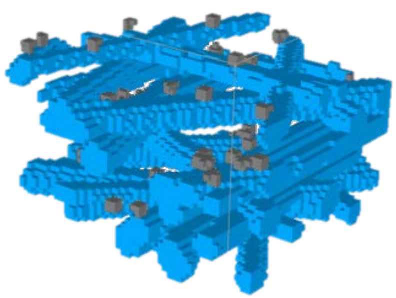

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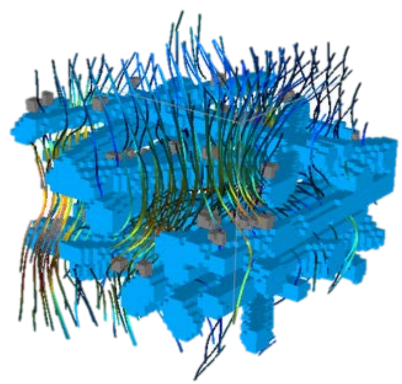

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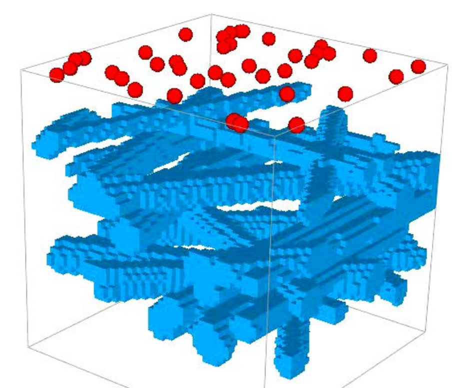
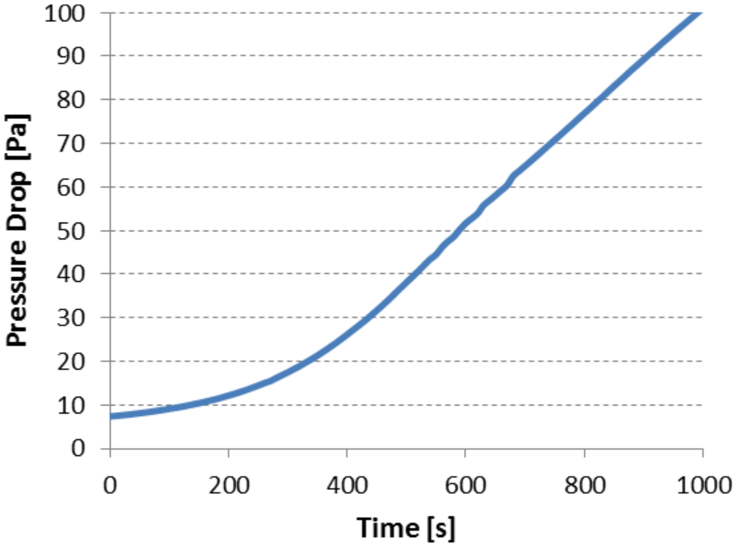
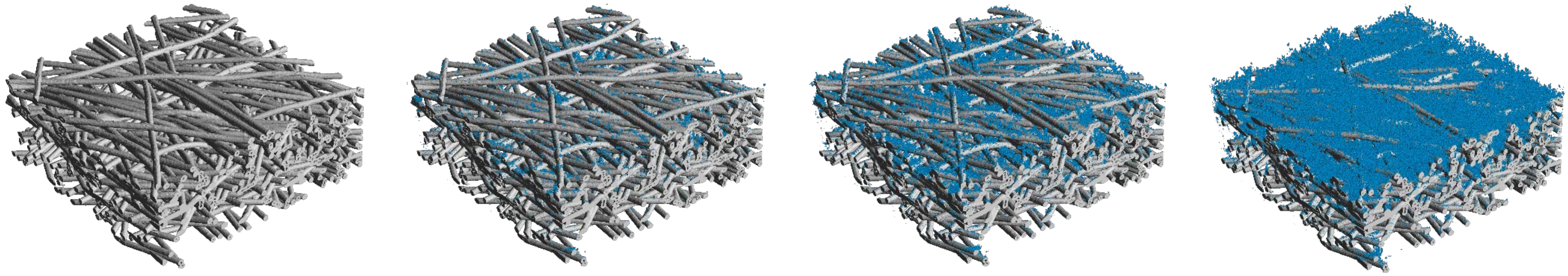


6. Repeat ...

Cabin Air Filter - Life Time Simulation

Initial pressure drop	7 Pa
Pressure drop after 1000s	101 Pa
Total deposited dust after 1000s	93 g/m²
Total filter efficiency	93% (weigth)





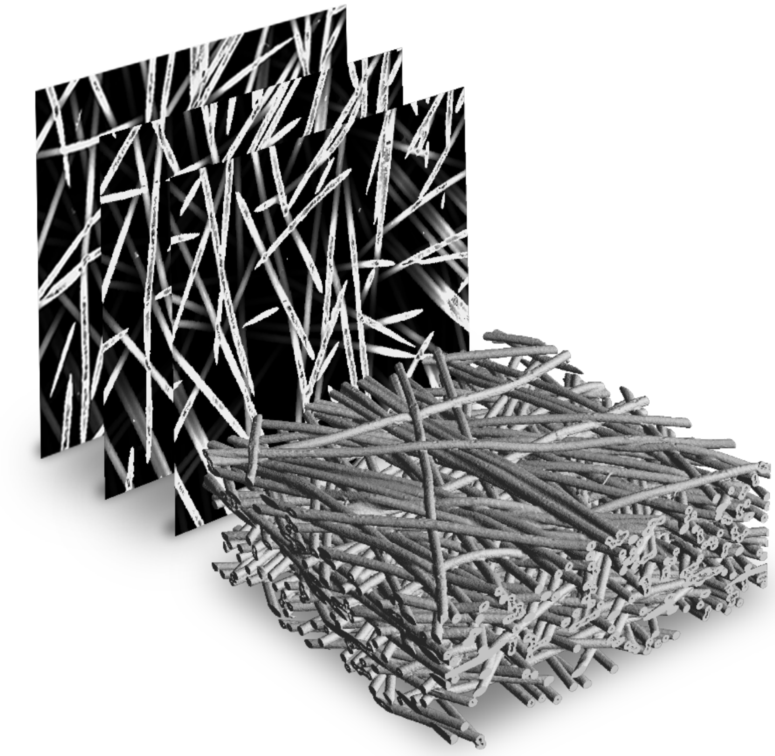
Step 2:

Create a model of the existing material

Creating a filter model

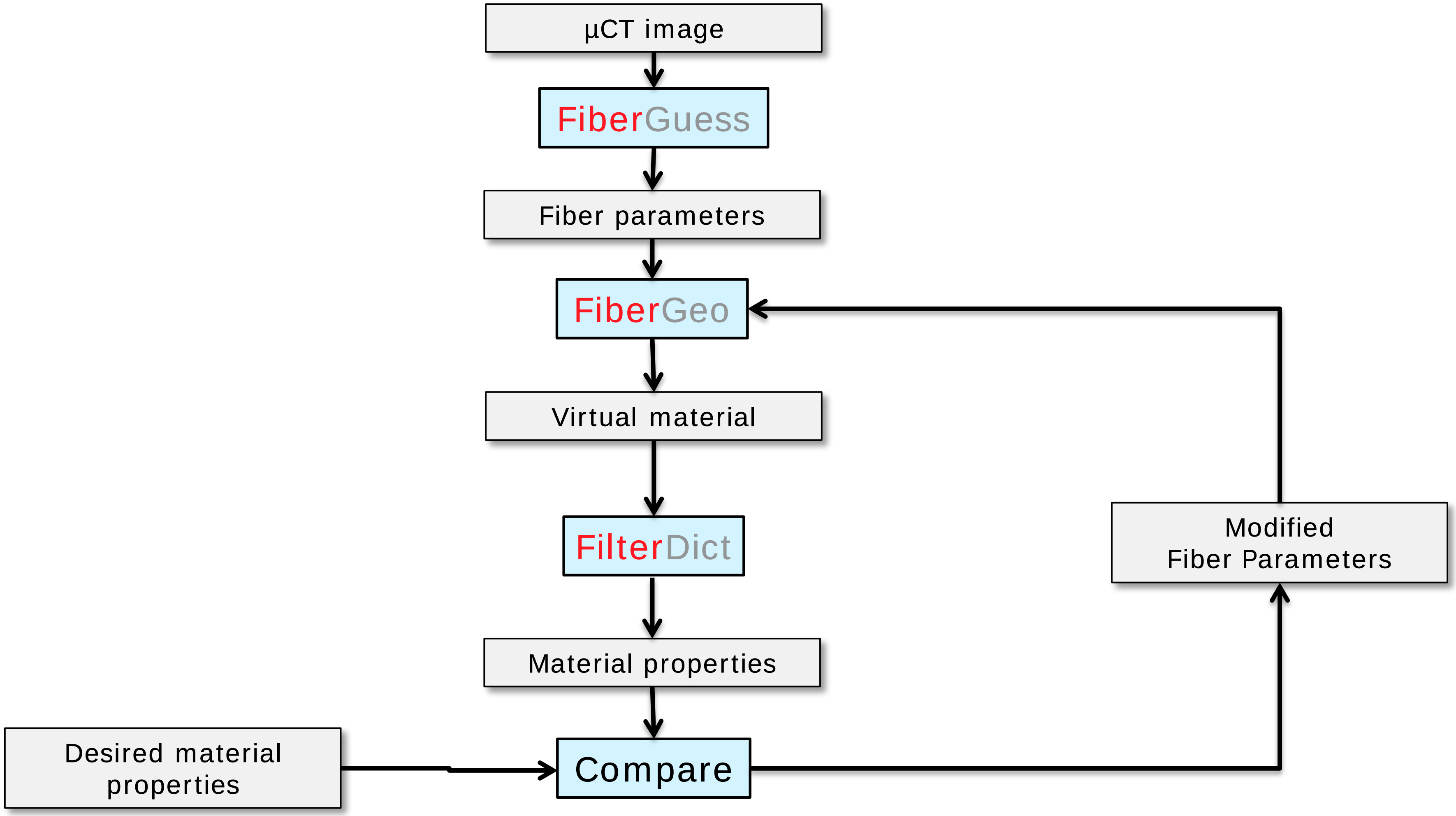
Why create a filter model?

- A CT scan is an image!
  - It can only be changed voxel-by-voxel.
  - It is not possible to remove a fiber
  - It is not possible to change diameters or shape

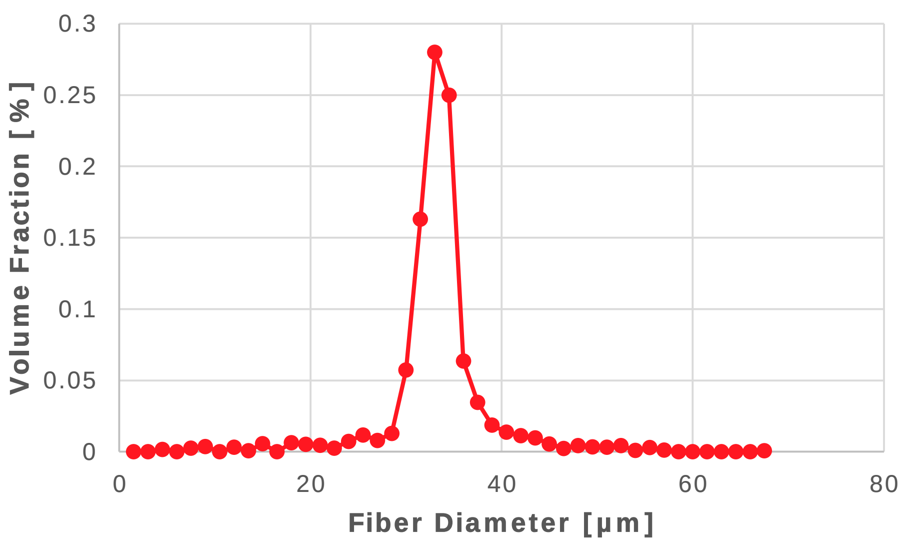


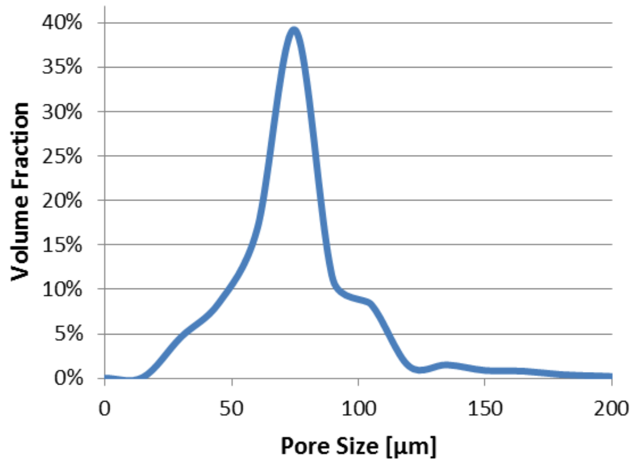
=> We need to "understand" the image!

GeoDict Workflow

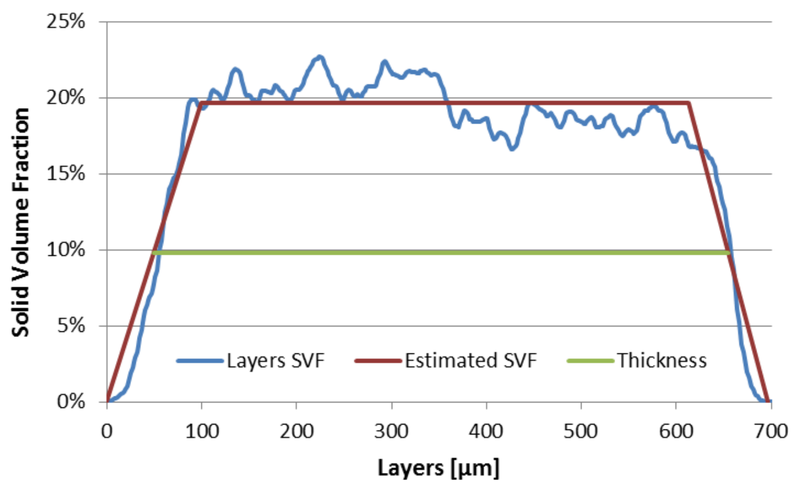


Geometric Analysis I:
Media Thickness, Porosity, Pore Sizes, Fiber Diameter





Average fiber diameter: 33.6 µm
Porosity: 80.4 %
Thickness: 605 µm



How is fiber orientation measured?

0.33	0	0
0	0.33	0
0	0	0.33

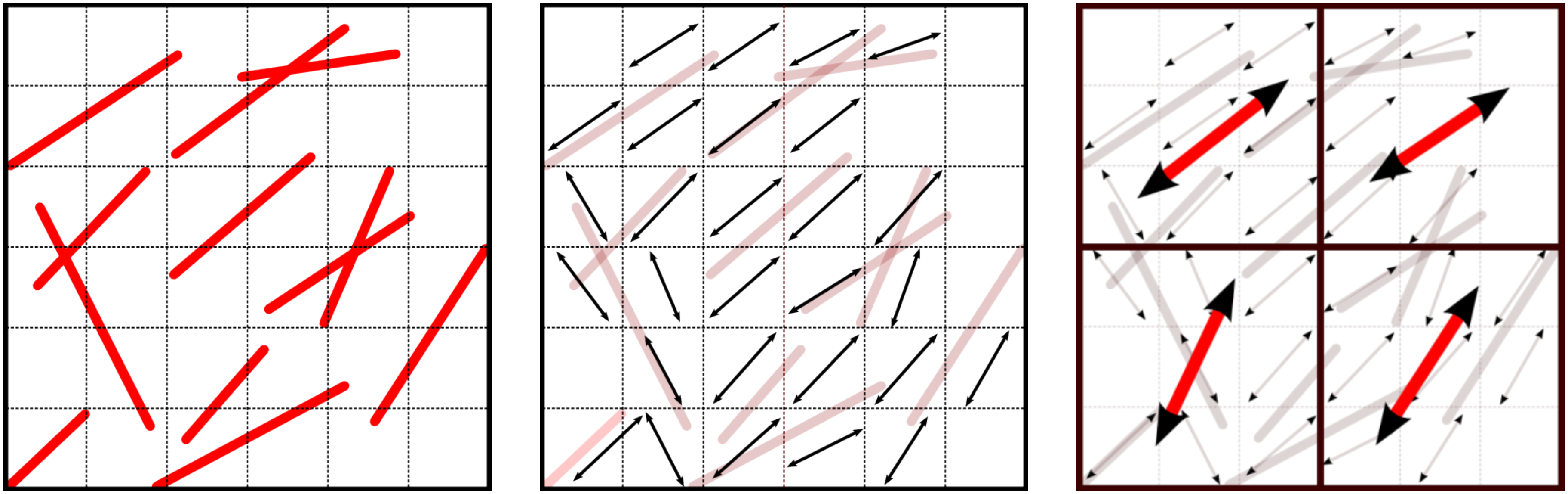
0.5	0	0
0	0.5	0
0	0	0

0.9	0	0
0	0.05	0
0	0	0.05

Orientation tensor describes probability of direction component.

Orientation analysis – Method 1: Principal Component Analysis (PCA)

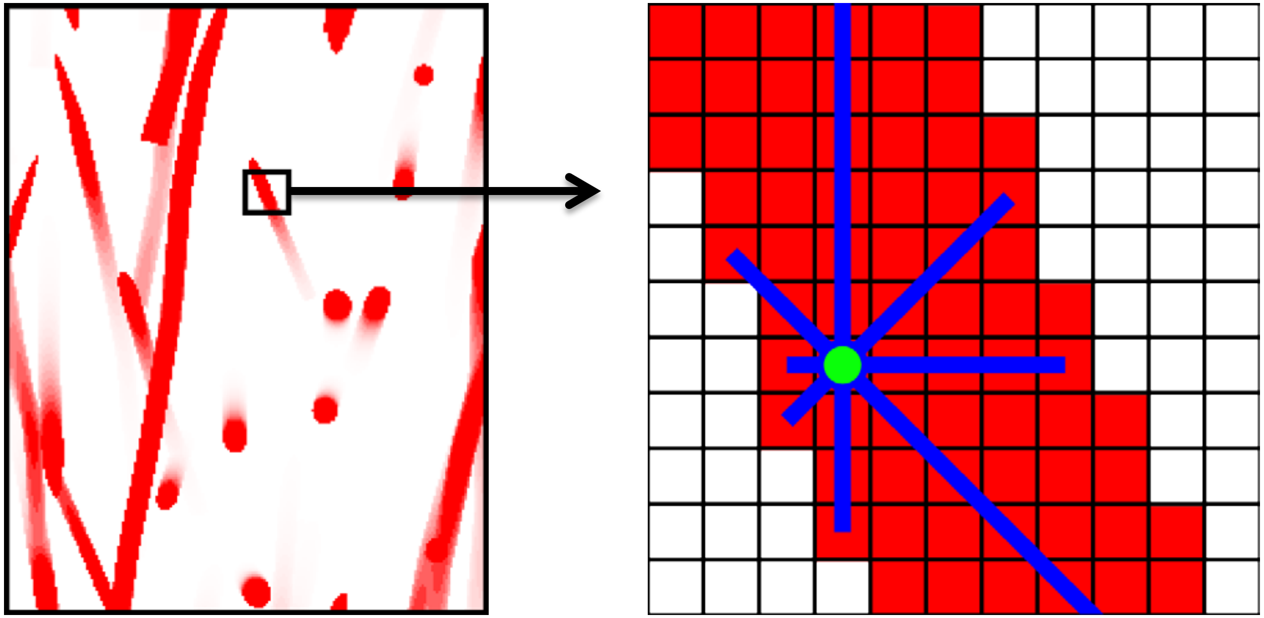
1. PCA subdivides domain into windows of given size
   - Automatic window size estimates about 2x fiber diameter
2. For each window, finds fiber fragments and analyzes direction tensor
3. For each block, averages direction tensors over windows in that block



Orientation analysis – Method 2: Star Length Distribution (SLD)

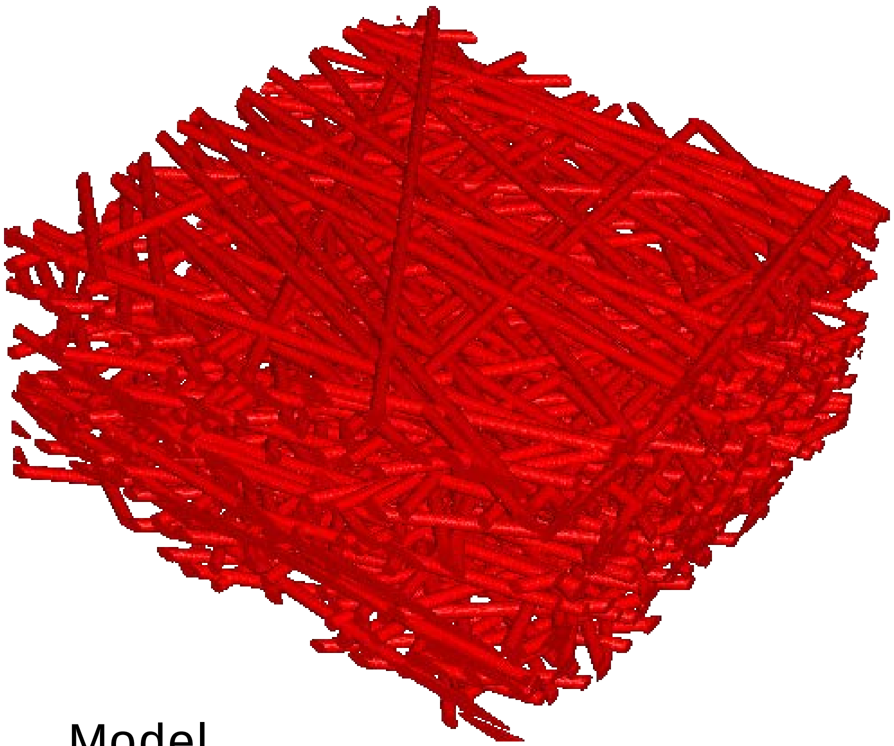
- For each voxel, SLD analyzes chord lengths through it for fixed set of directions
- The relative length of the chords gives per-voxel orientation tensor
- The tensors are averaged over all voxels in the block (similar to PCA)

Smit, Th H., E. Schneider, and A. Odgaard. "Star length distribution: a volume-based concept for the characterization of structural anisotropy." *Journal of microscopy* 191 (1998): 249-257.



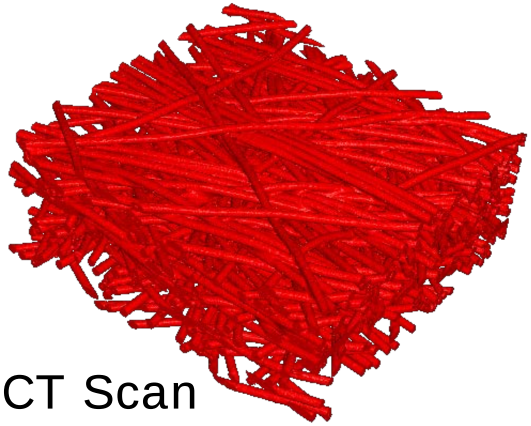
Comparison of CT Scan and Model

CT Scan

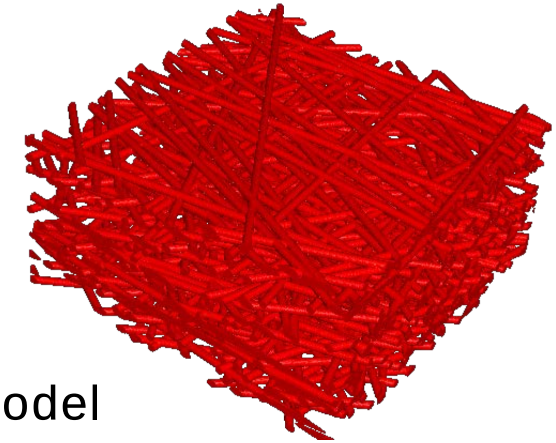


Model

Comparison of CT Scan and Model



CT Scan



Model

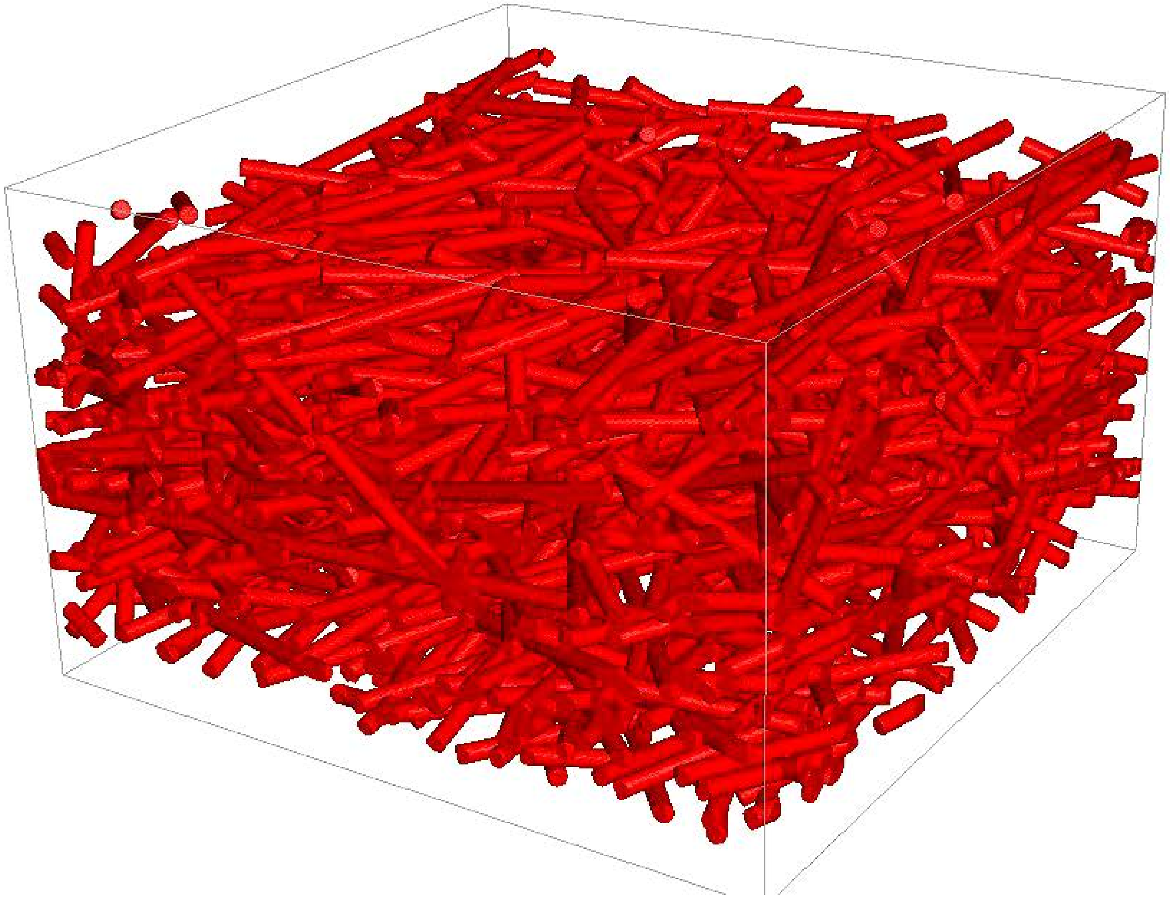
Input parameters found by CT-Scan analysis:

- media thickness
- porosity
- fiber diameter
- in-plane anisotropy

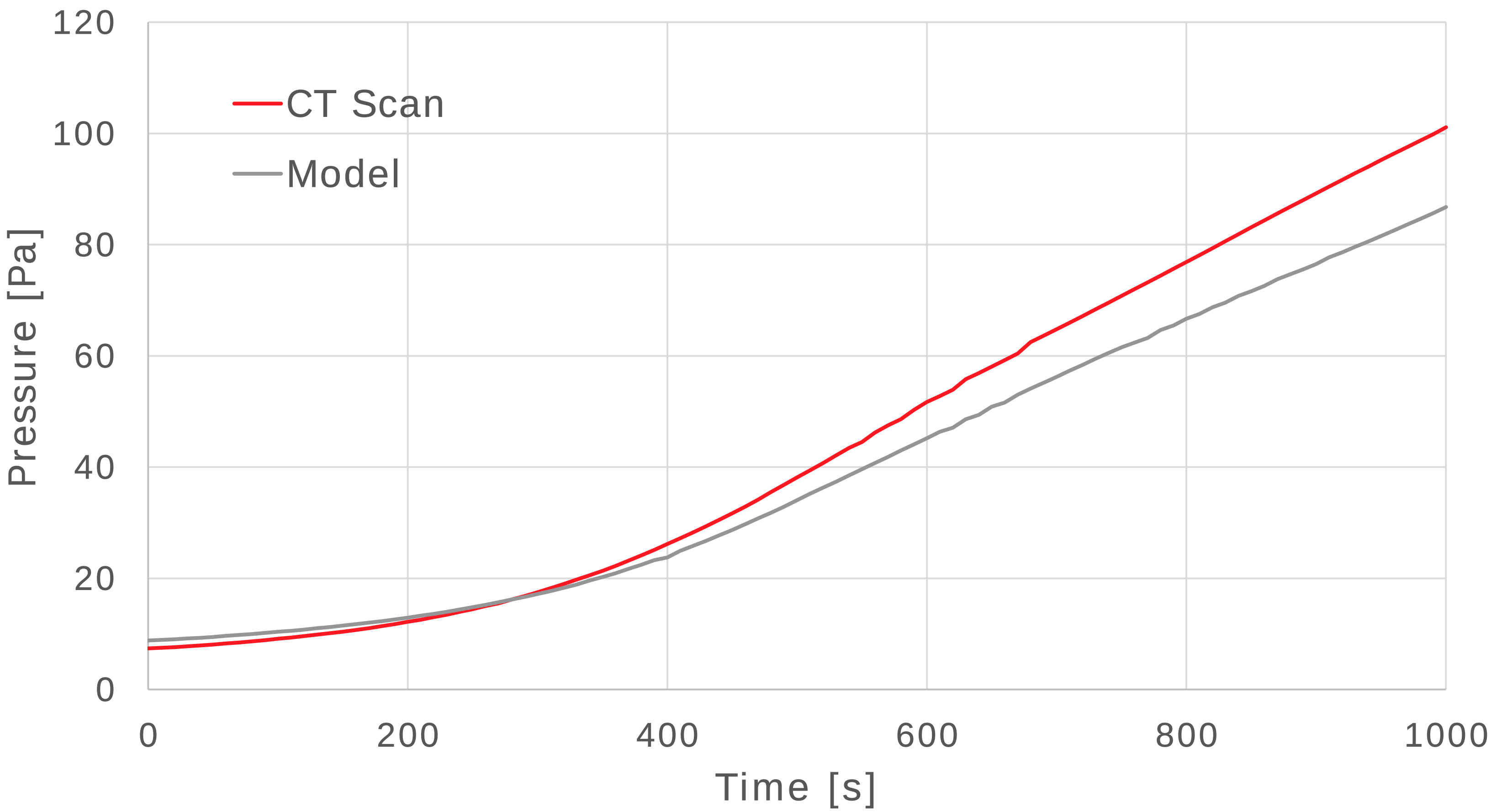
Input parameters taken from assumptions:

- straight fibers
- fibers oriented in-plane
- homogeneous distribution
- circular cross section

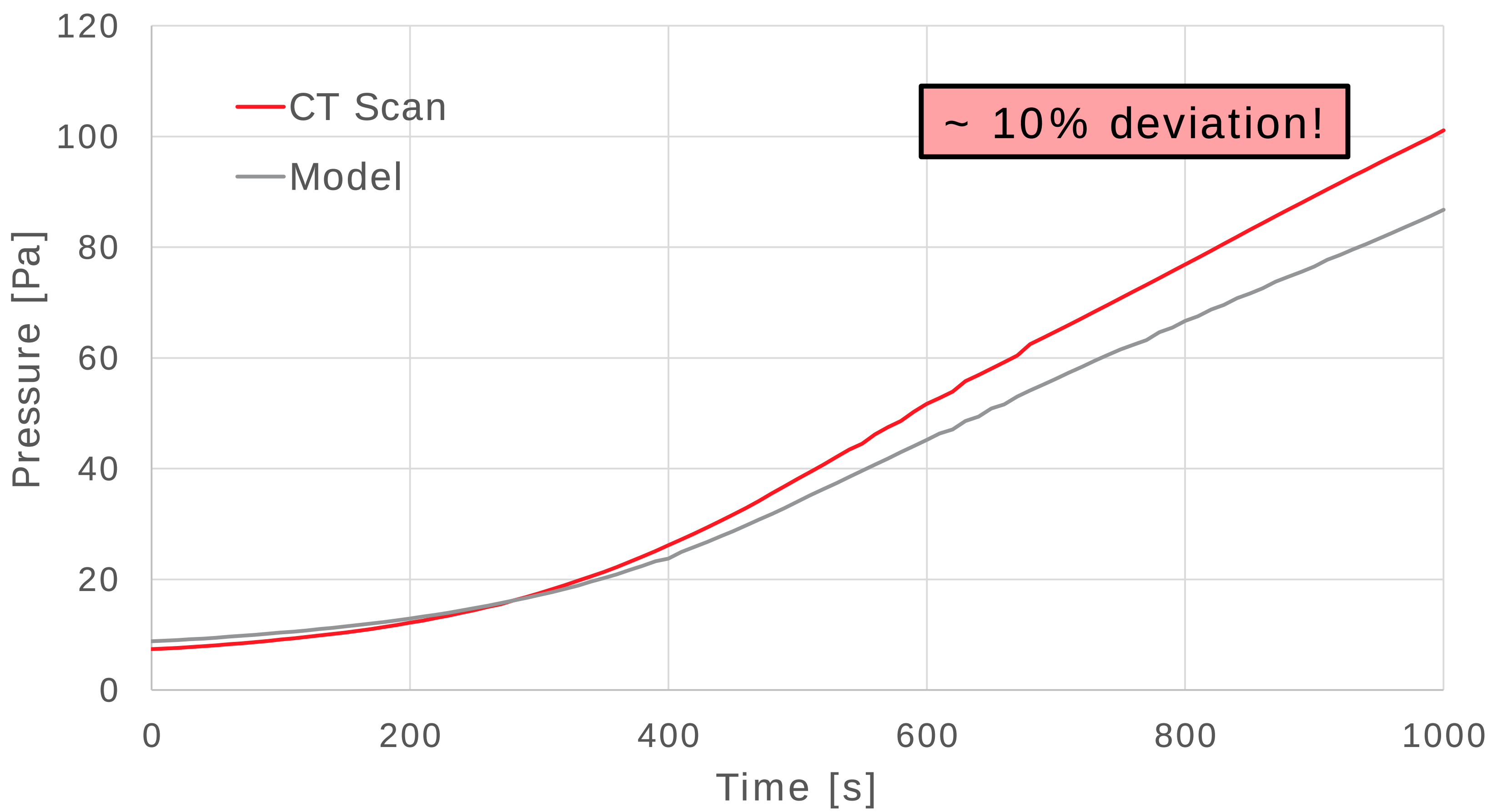
Filter Life Time



Filter Life Time Simulation
Comparison CT Scan vs Model



Filter Life Time Simulation
Comparison CT Scan vs Model

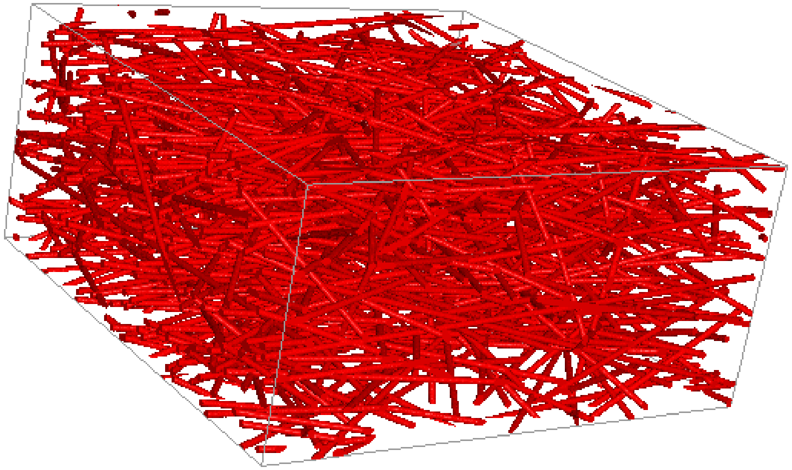


Step 3:

Modify the structure model

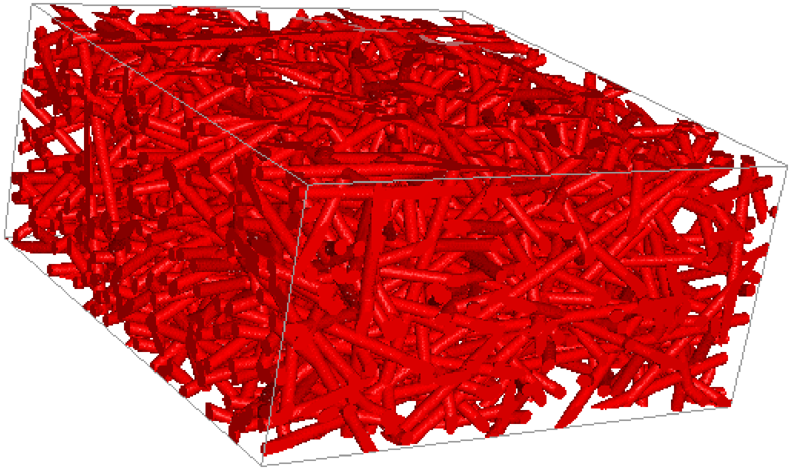
Possibilities in GeoDict to Vary the Structure Model

1. Fiber diameter



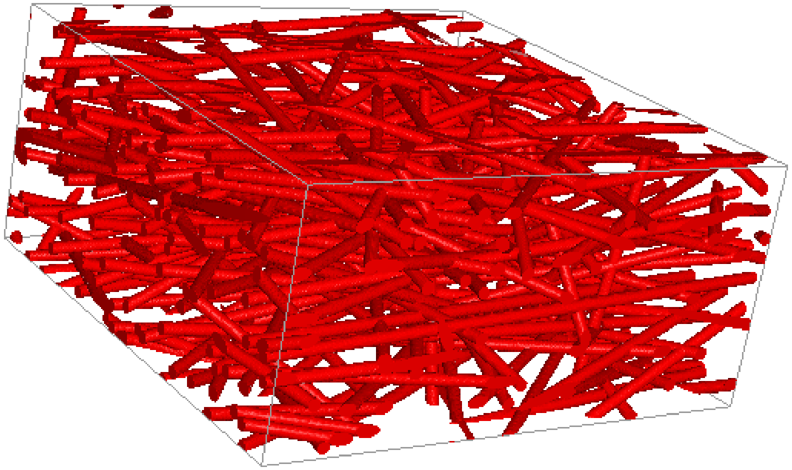
Possibilities in GeoDict to Vary the Structure Model

2. Fiber orientation



Possibilities in GeoDict to Vary the Structure Model

3. Porosity



Possibilities in GeoDict to Vary the Structure Model

4. Fiber cross sectional shape
5. Curved fibers instead of straight fibers
6. Density gradient in through-plane direction
7. Media thickness
8. ......

Summary and Outlook

Overall goal of this work:

- get from CT-Scan to Model structure automatically

Current state:

- works for straight fibers with circular cross section

Work in progress: curved fibers with circular cross section

- Determine curvature distribution from CT
- Realize given curvature distribution in a model

Thank You!

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