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

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Math2Market GmbH
Some background information

- Math2Market creates and markets software for engineers and scientists that want to analyze and design porous and composite materials based on the material's geometric inhomogeneity.
- The materials can come from µCT, FIB-SEM or models and are represented as 3-dimensional images in the software.
- This software is called GeoDict, the Digital Material Laboratory.
- M2M is based in Kaiserslautern, Germany.
- M2M spun off from Fraunhofer Institute for Industrial Mathematics.
- Visit us at our booth

How can simulations help to improve a filter?

Step 1: Understand the existing filter material

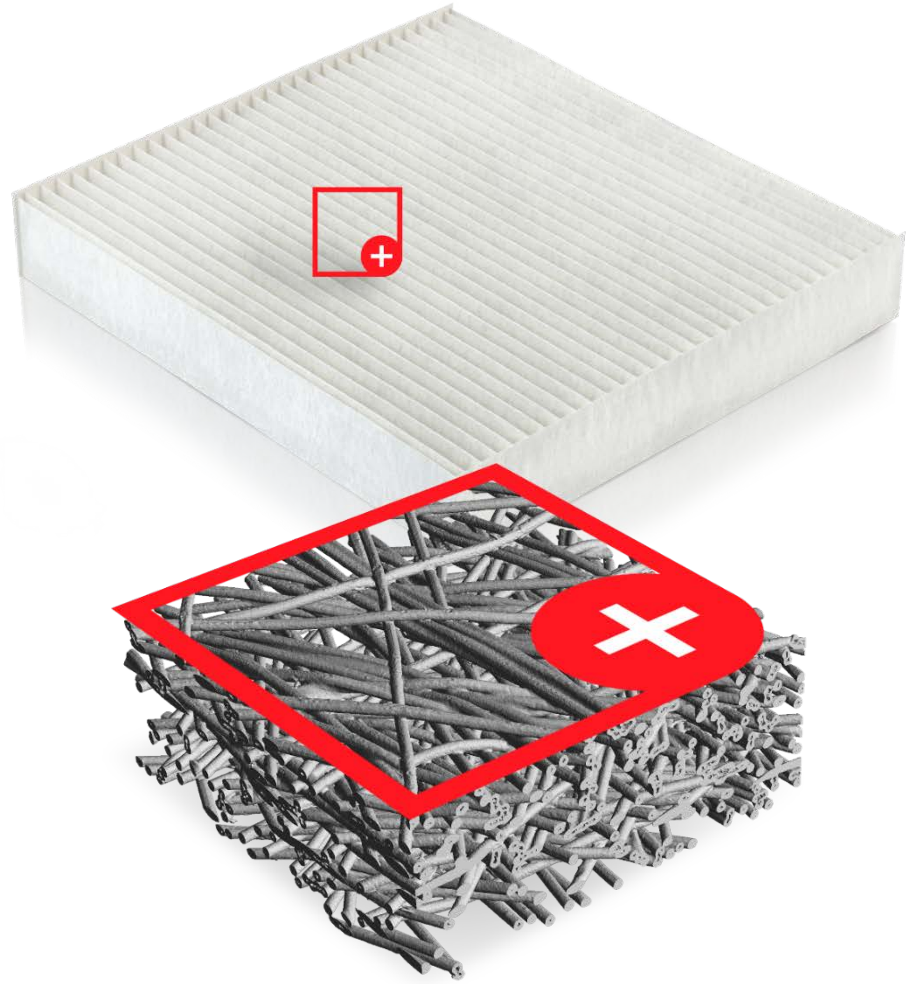
- CT Scan
- Simulations on CT Scan

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

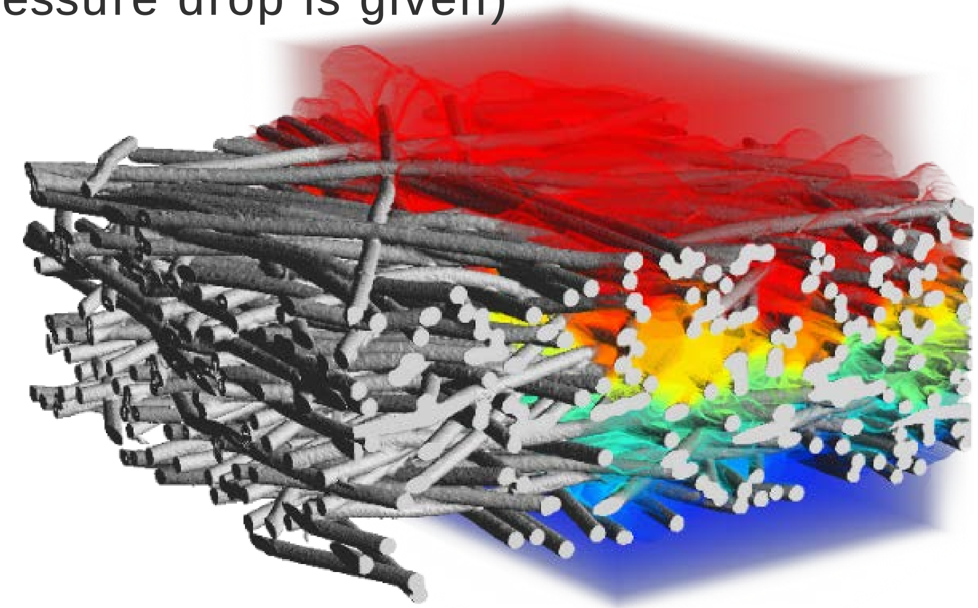
Step 1:

Understand the existing filter material

Determine Flow Rate or Pressure Drop

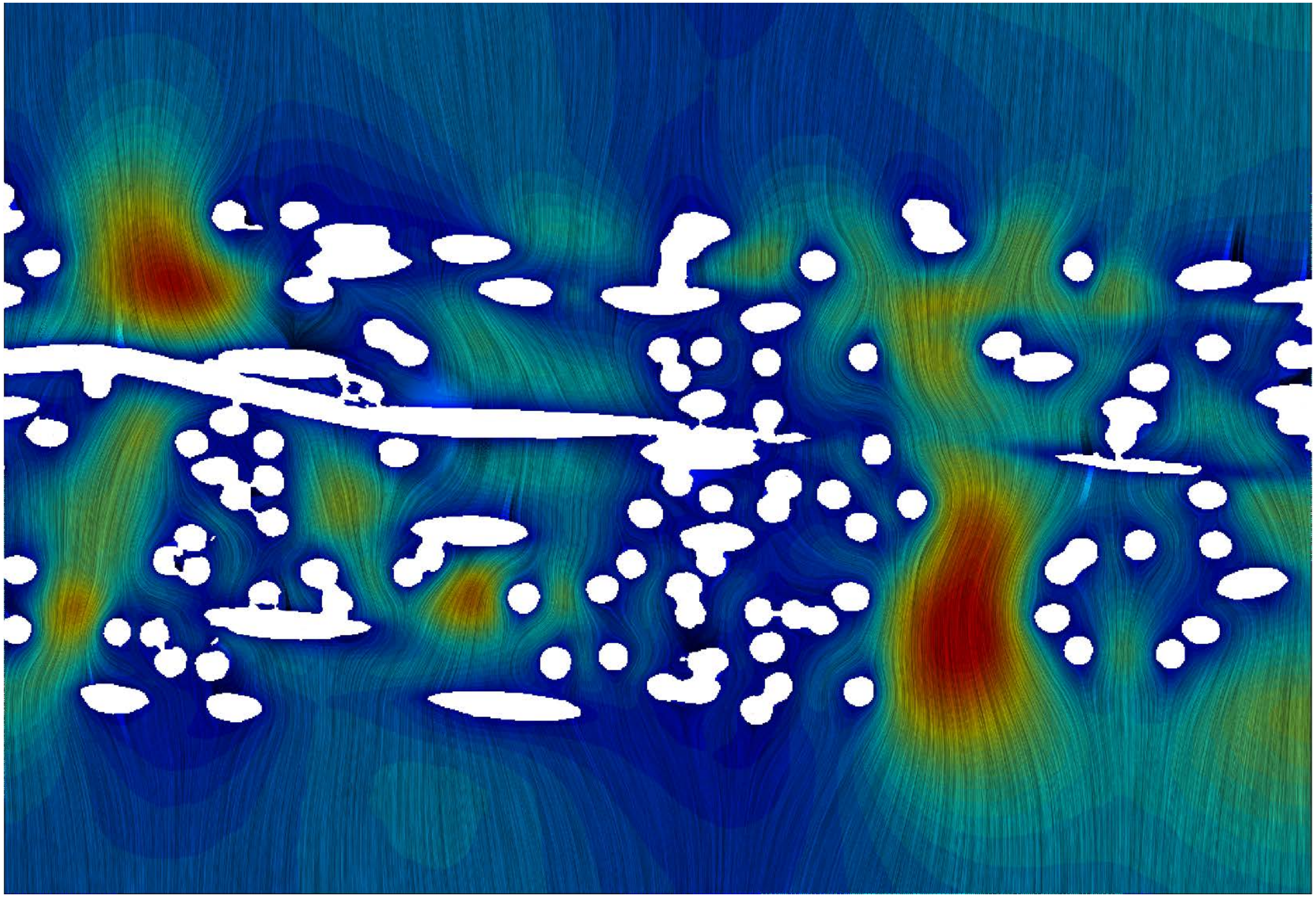
Stationary Navier-Stokes flow:

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



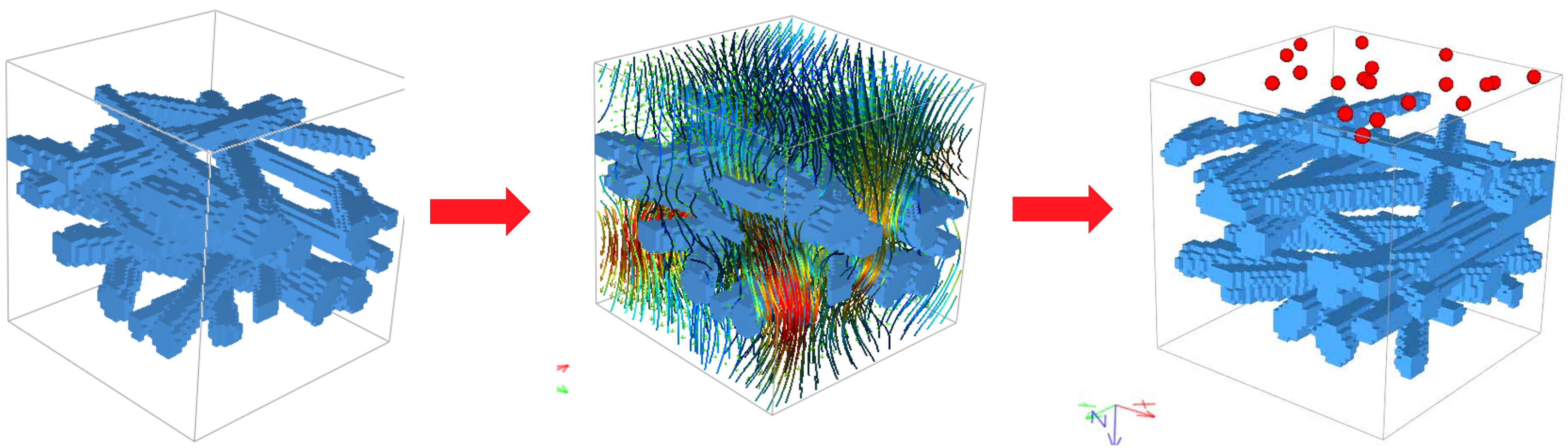
$\vec{u}$: velocity
p: pressure
μ: dynamic viscosity
ρ: fluid density

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

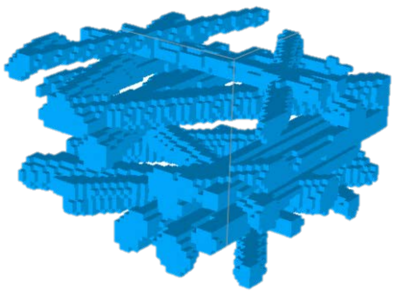


Efficiency of Clean Filter Media: Method

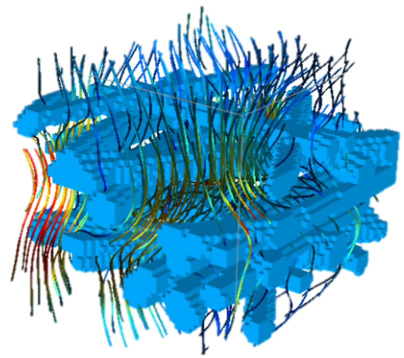
1. Filter media model
2. Determine flow field
3. Track particles (filtered or not?)
4. Result: percentage of filtered particles of each size



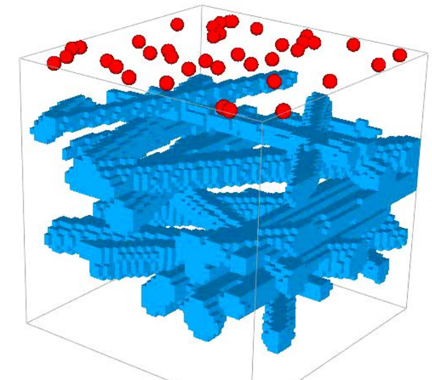
Filter Life Time Simulation - Method



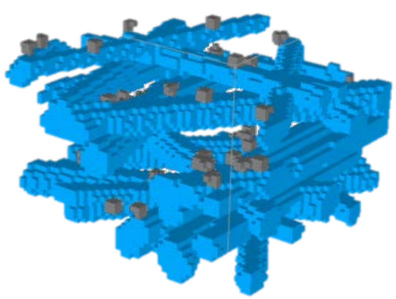
1. Filter Model



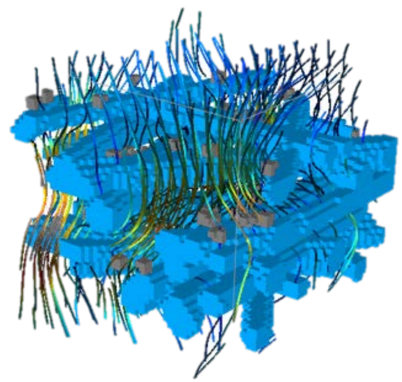
2. Flow Field



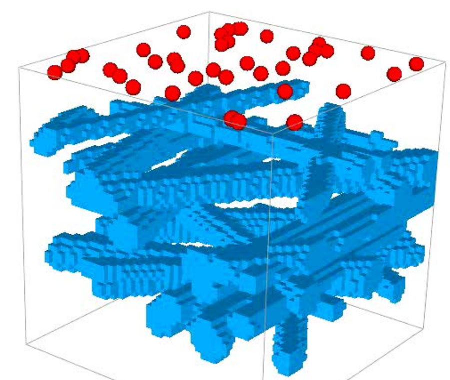
3. Track Particles



4. Deposit Particles



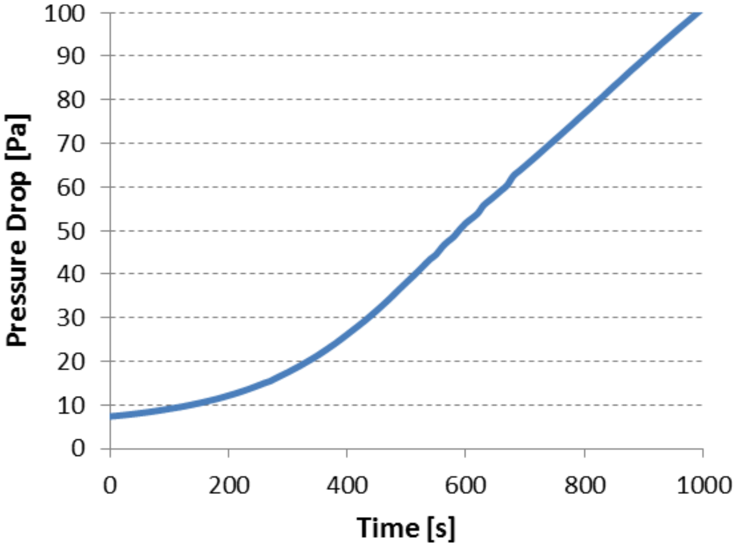
5. Recompute Flow

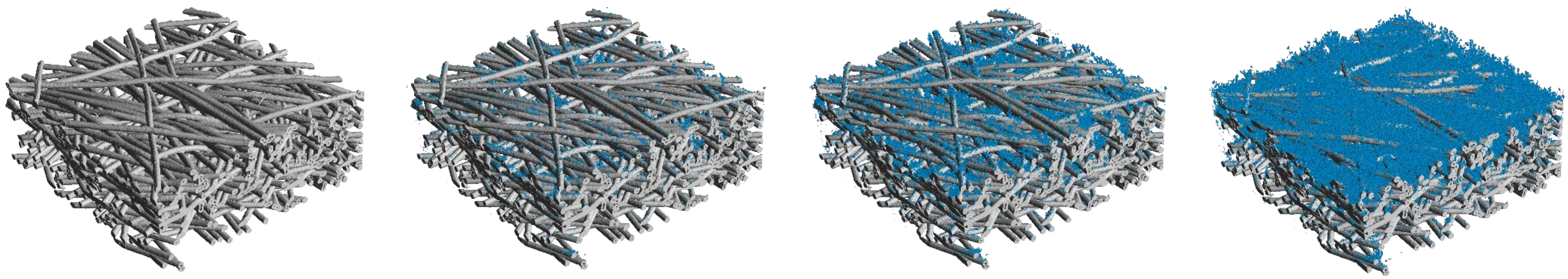


6. Repeat ...

Cabin Air Filter - Life Time Simulation

Initial pressure drop	7 Pa
Pressure drop after 1000s	101 Pa
Total deposited dust after 1000s	93 g/m^2
Total filter efficiency	93% (weight)





Step 2:

Create a model of the existing material

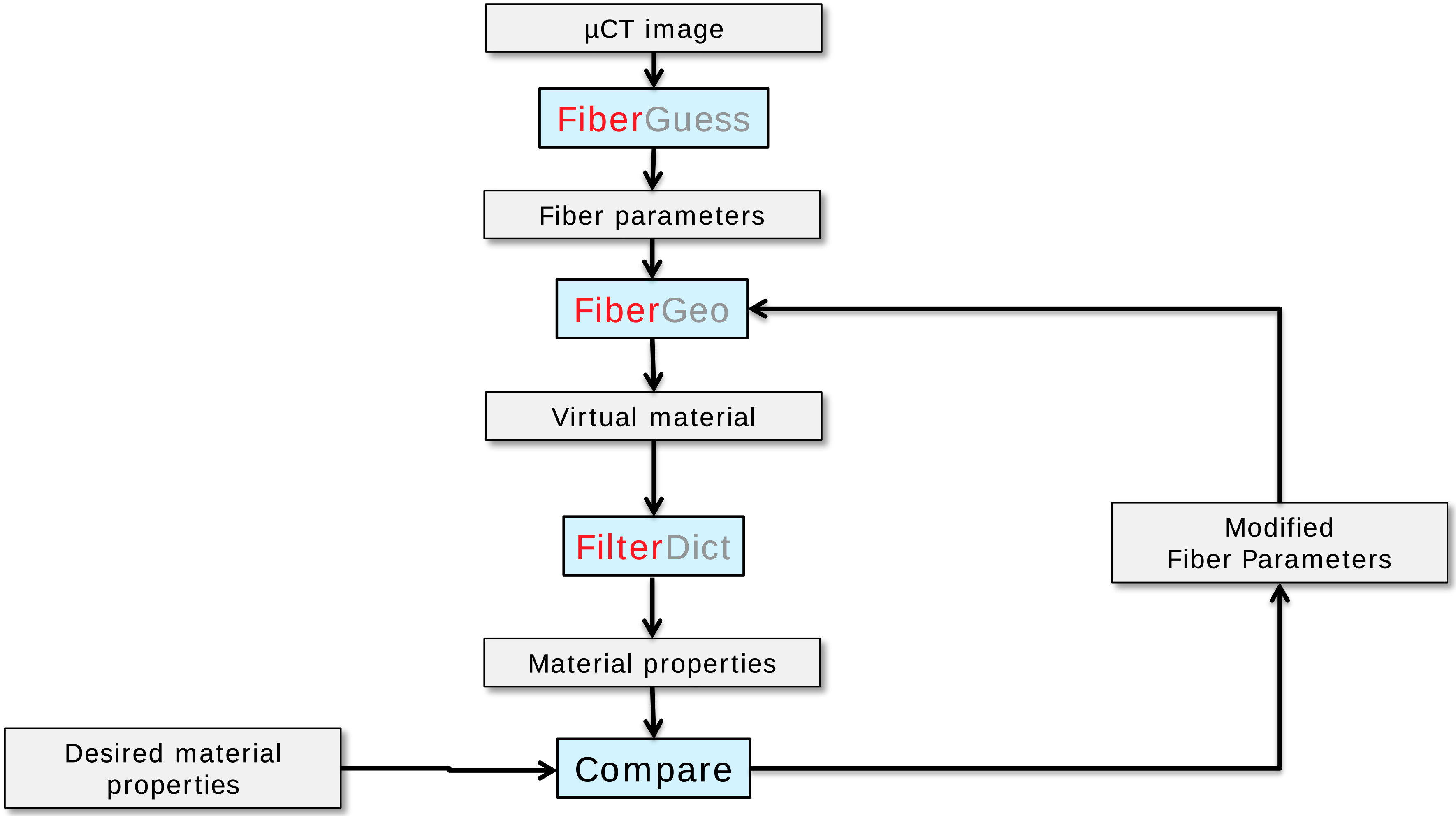
Creating a filter model

Why create a filter model?

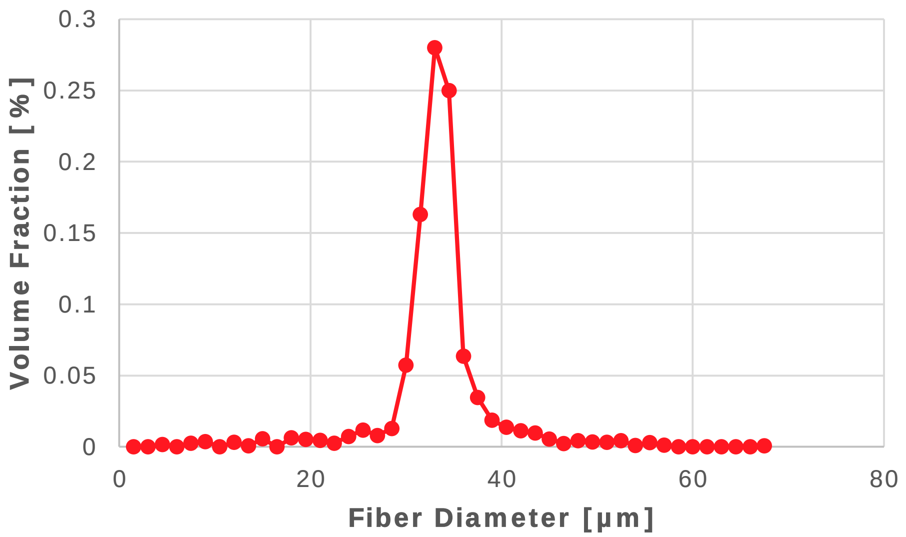
- A CT scan is an image!
  - Only changes voxel-by-voxel possible.
  - Impossible to remove a fiber
  - Impossible to change diameters or shape

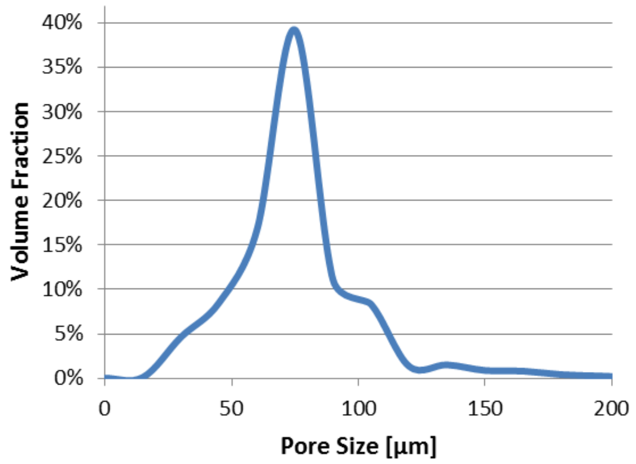
=> We need to "understand" the image!

GeoDict Workflow

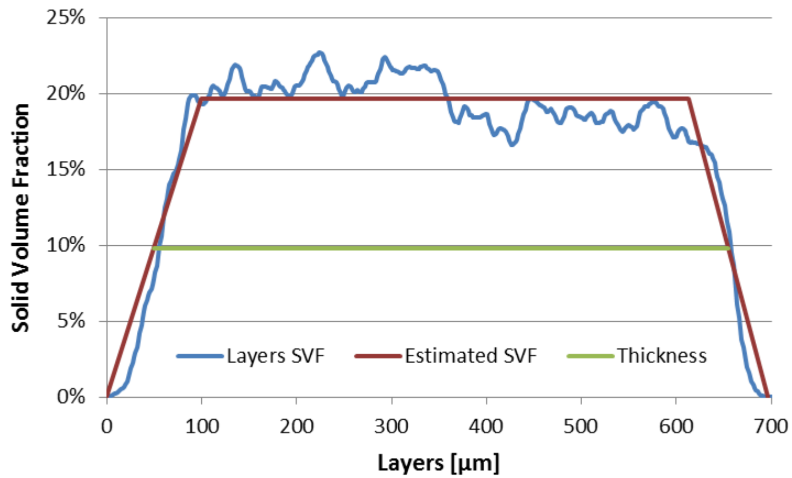


Geometric Analysis I:
Media Thickness, Porosity, Pore Sizes, Fiber Diameter





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



Geometric Analysis II: Fiber Orientation

How is fiber orientation measured?

0.33	0	0
0	0.33	0
0	0	0.33

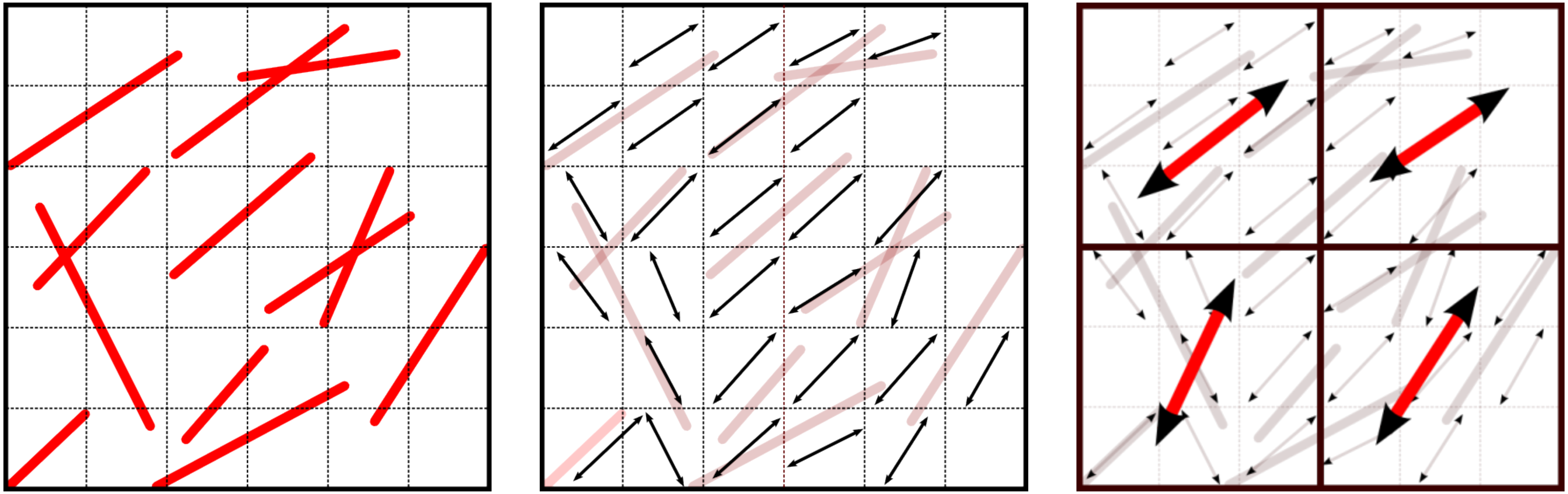
0.5	0	0
0	0.5	0
0	0	0

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)

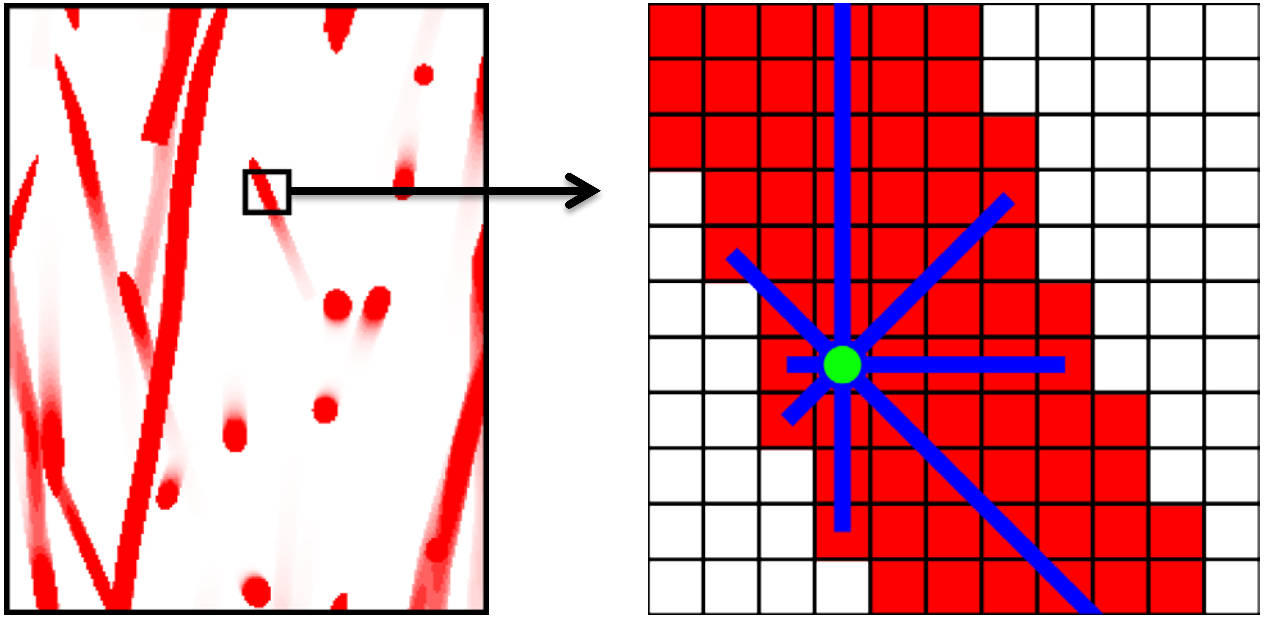
1. PCA subdivides domain into windows of given size
   - Automatic window size estimates about 2x fiber diameter
2. For each window, finds fiber fragments and analyzes direction tensor
3. For each block, averages direction tensors over windows in that block



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

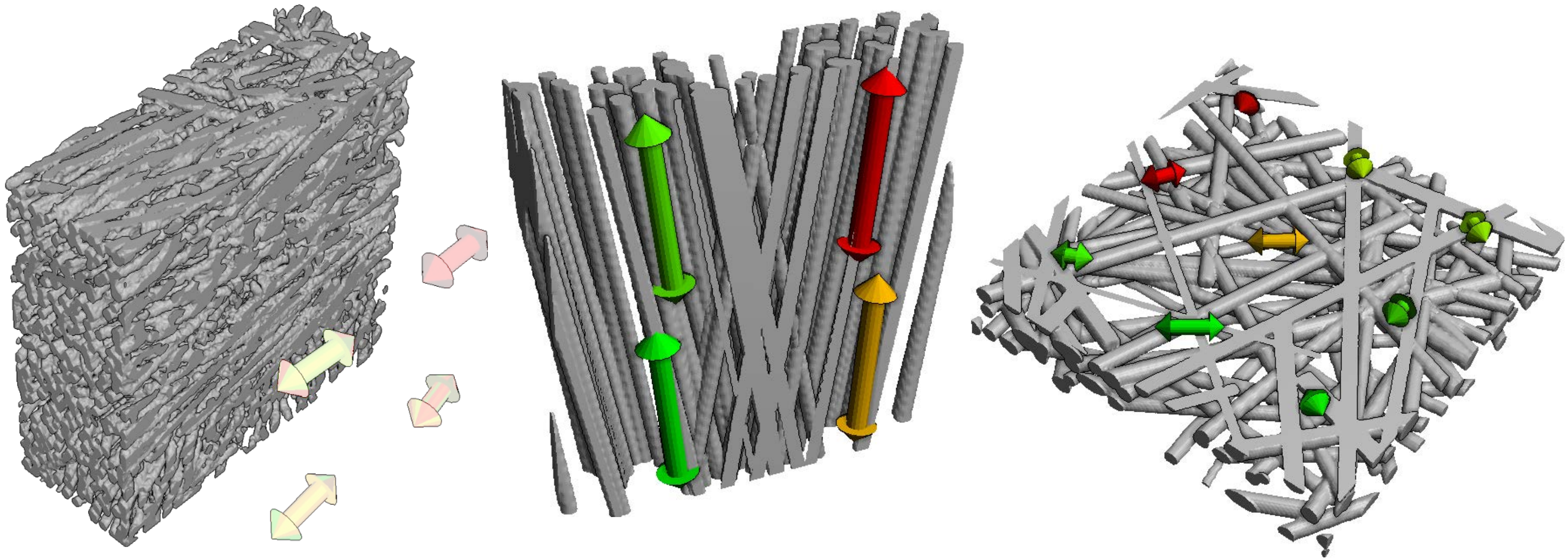
- For each voxel, SLD analyzes chord lengths through it for fixed set of directions
- The relative length of the chords gives per-voxel orientation tensor
- The tensors are averaged over all voxels in the block (similar to PCA)

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.



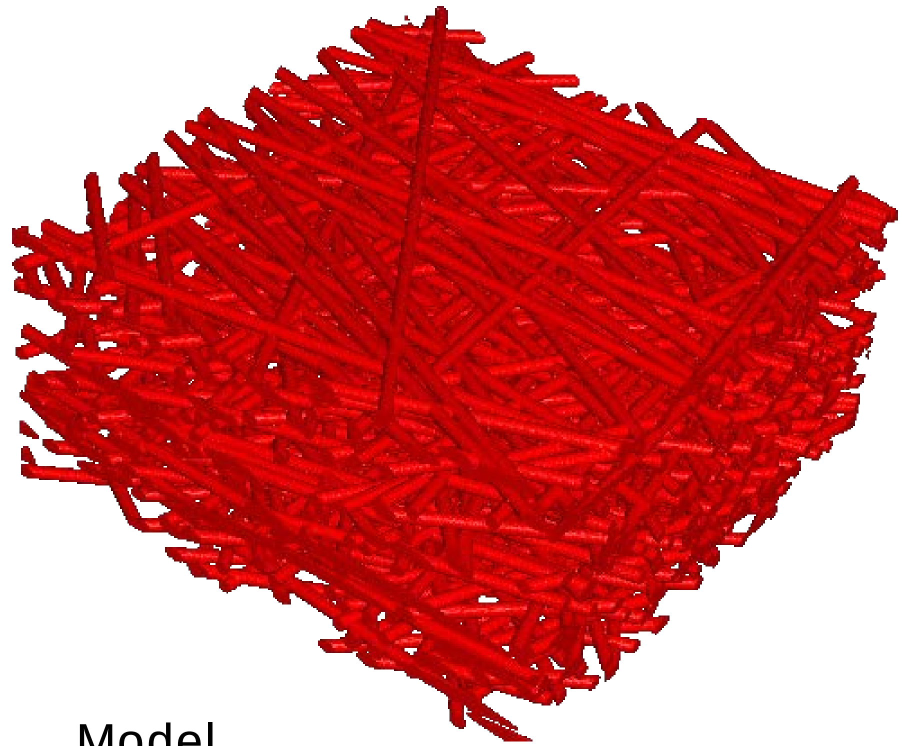
Orientation analysis - Visualization

- Arrows indicate the main fiber orientation for each block
  - Long arrows correspond to strong preference in orientation
  - Compare homogeneous material (left) with material with two main fiber directions (middle) and with isotropic in plane (right)



Comparison of CT Scan and Model

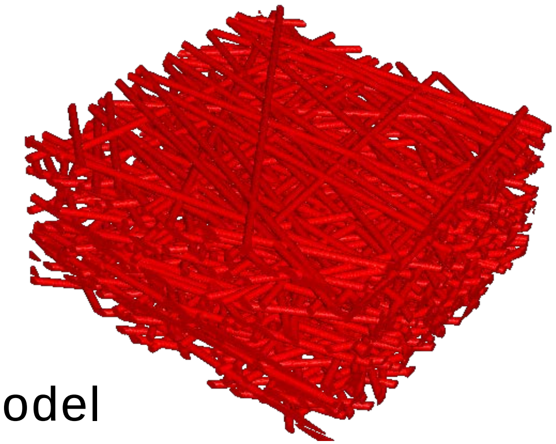
CT Scan



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

GeoDict

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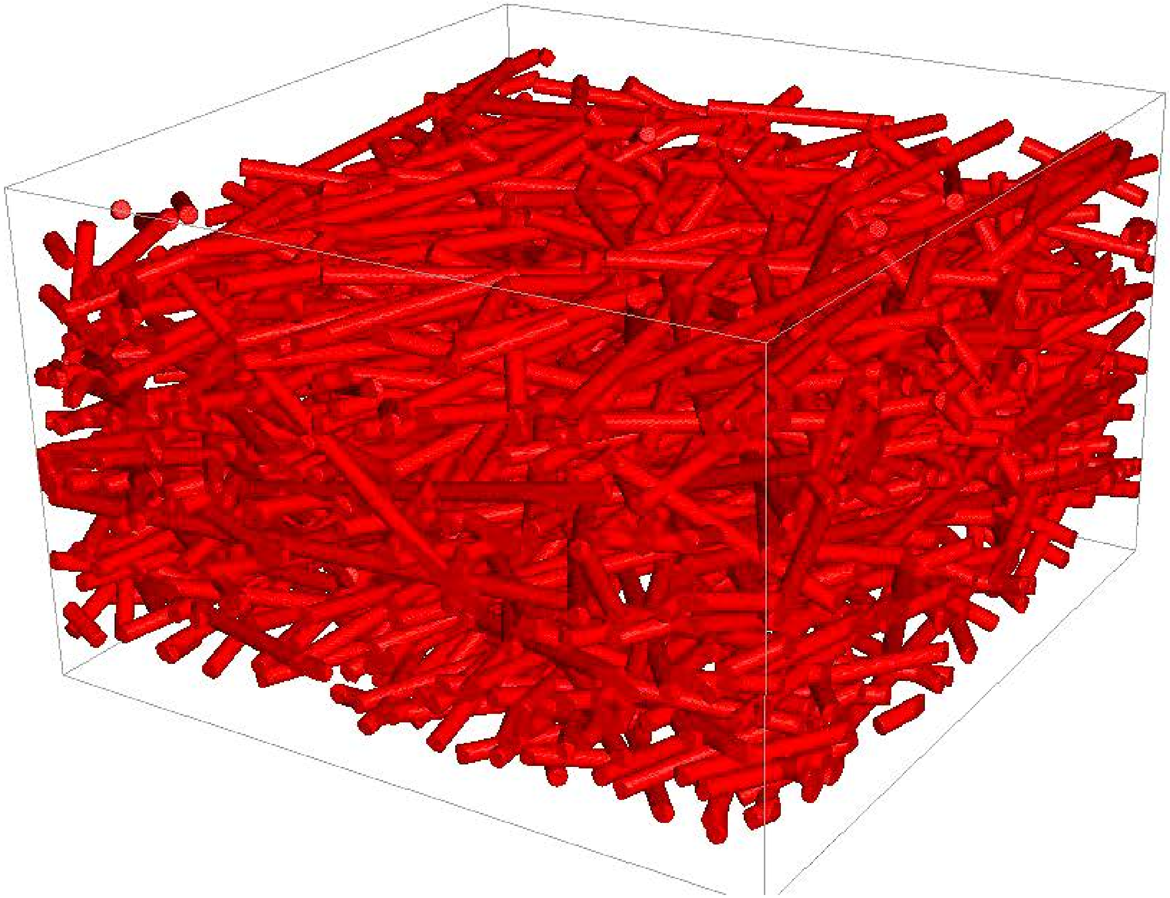
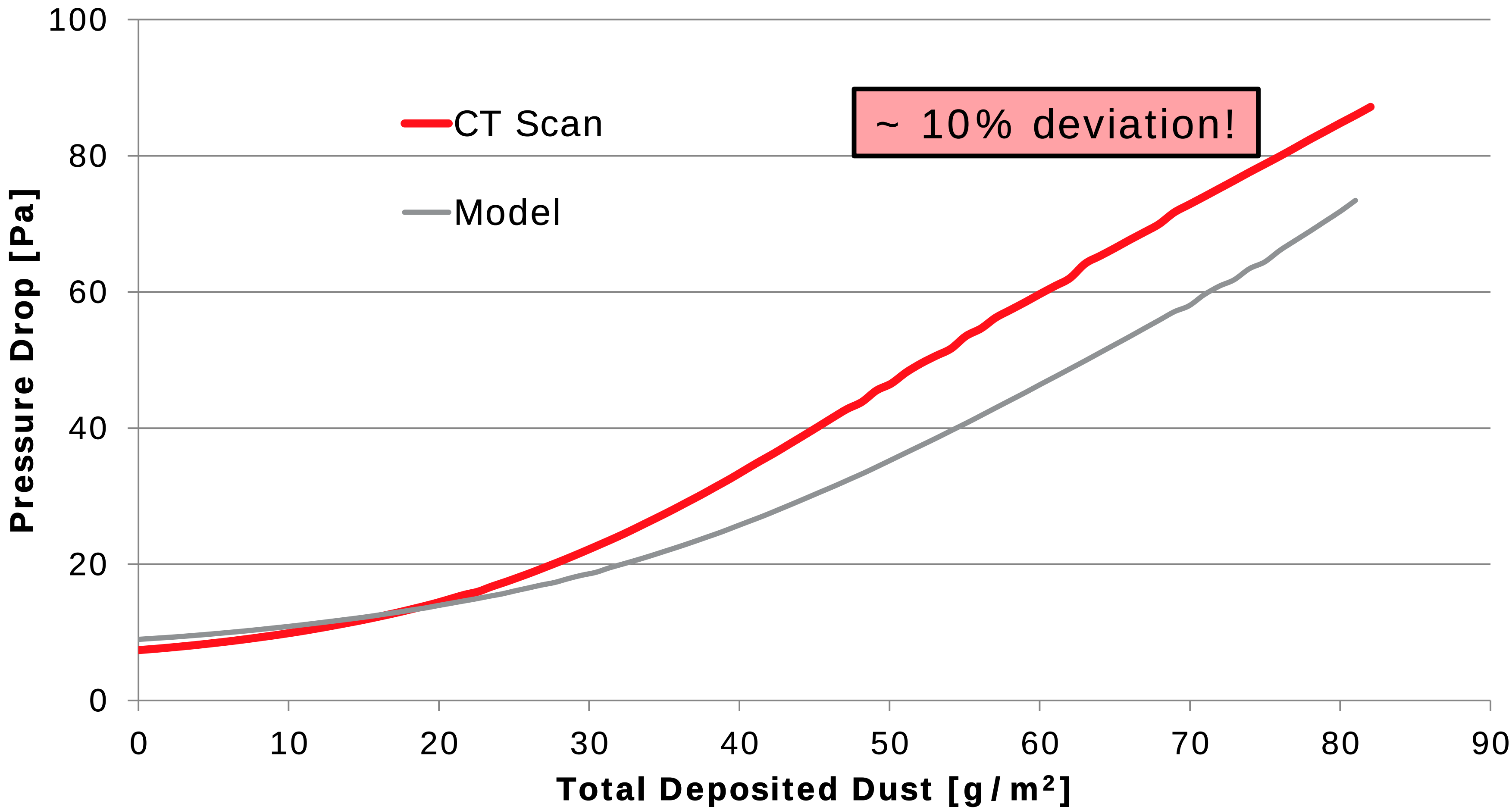
Filter Life Time

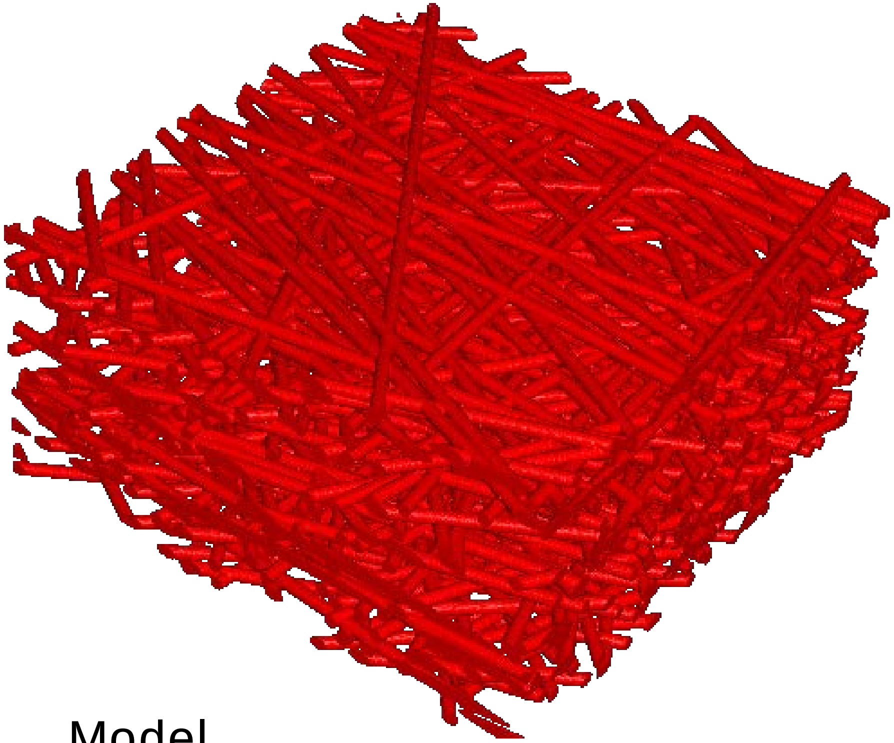


Filter Life Time Simulation
Comparison CT Scan vs Model



Comparison of CT Scan and Model

CT Scan



Model

Fiber Curvature and Curliness

In many applications, materials consist of curved fibers

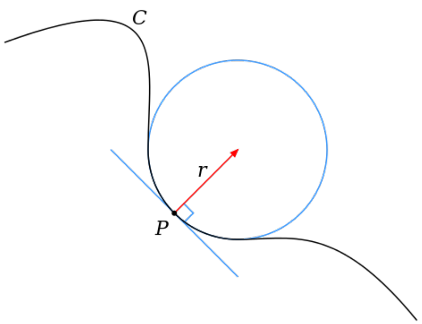
- Nonwoven
- GDL (fuel cells)
- Insulation

Curvature and curliness parameters are needed to create an accurate model from a C-scan

Curvature and Curliness - Definition

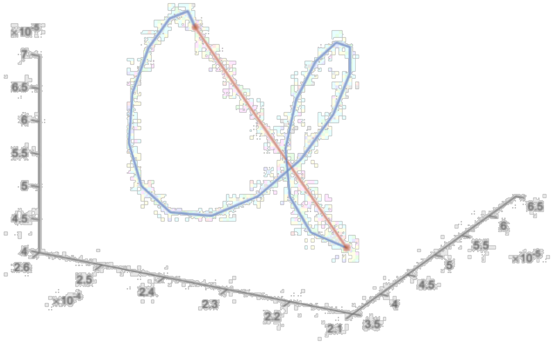
Curvature:

- local measurement for every centerline point of a fiber
- describes the inverse of the radius of the circle that is tangent to the centerline in this point



Curliness:

- measurement for every fiber
- Describes ratio between distance of straight line between fiber start and fiber end and the actual fiber length

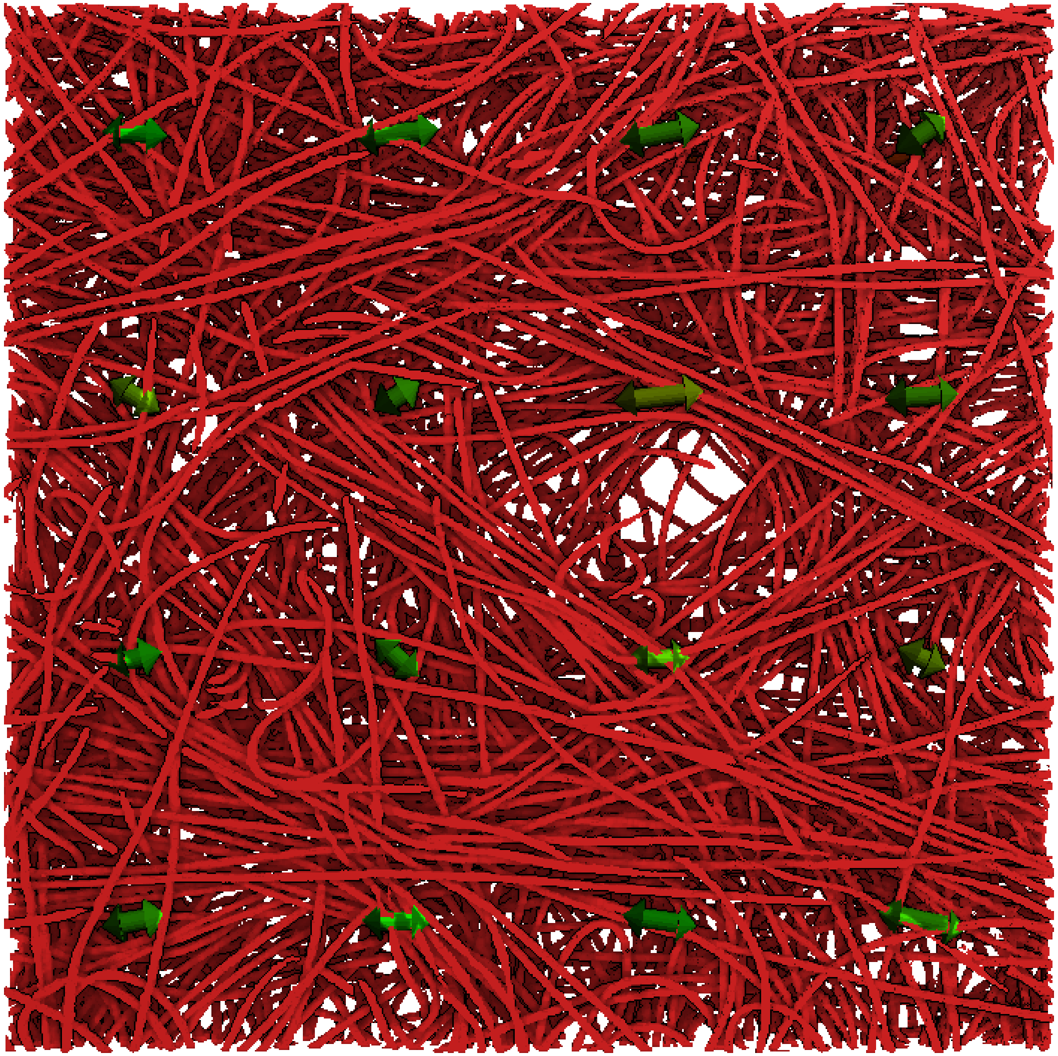


Curvature and Curliness - Solution

How to estimate the curliness and curvature distribution of the fibers in a carded nonwoven?

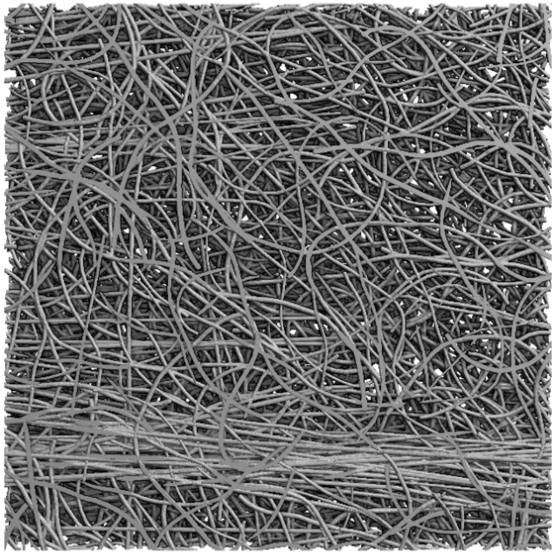
1. Extract fiber centerlines via skeletonization
2. Identify single fibers and de-noise them
   - for fiber-fiber intersections
   - for roughness of individual consecutive voxels
3. Compute length along the centerline and distance between endpoints for curliness / tortuosity
4. Calculate curvature based on centerline
   - per centerline
   - for all the fibers in a 3d scan

Curvature and Curliness - example

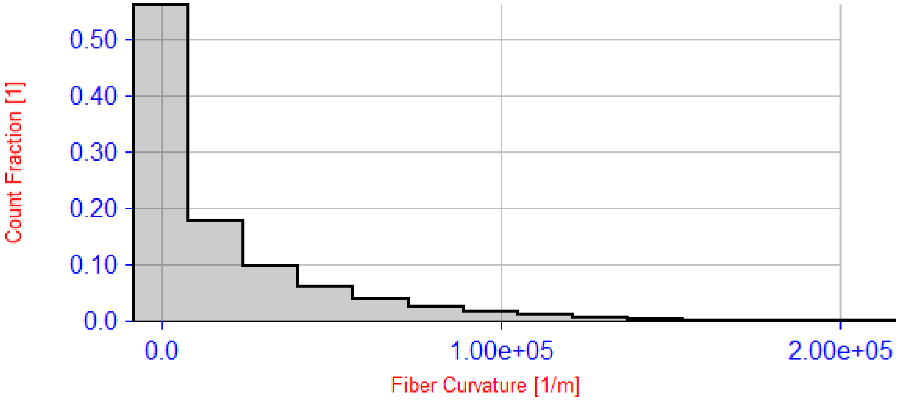


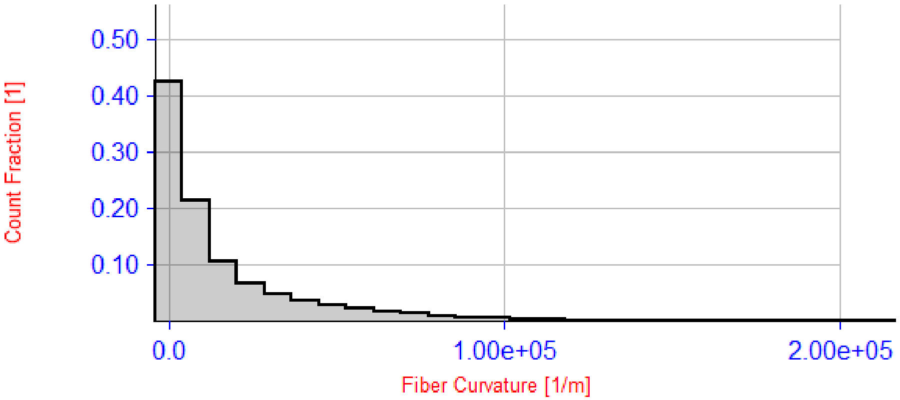
Using estimated parameters to generate a Structure

Original structure



Generated structure



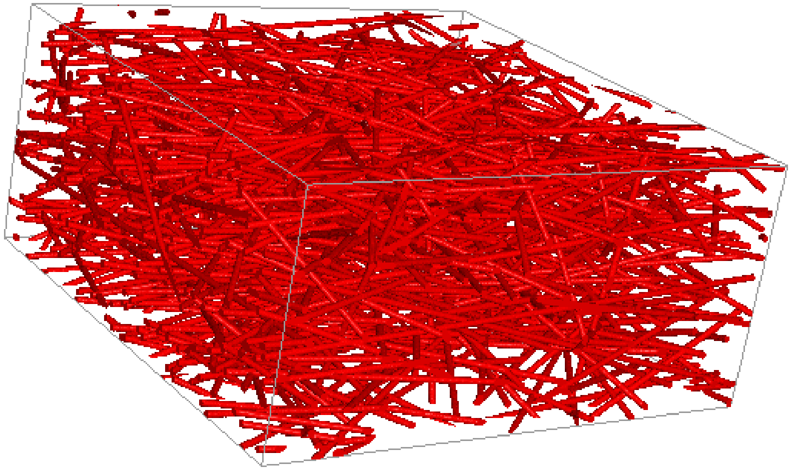


Step 3:

Modify the structure model

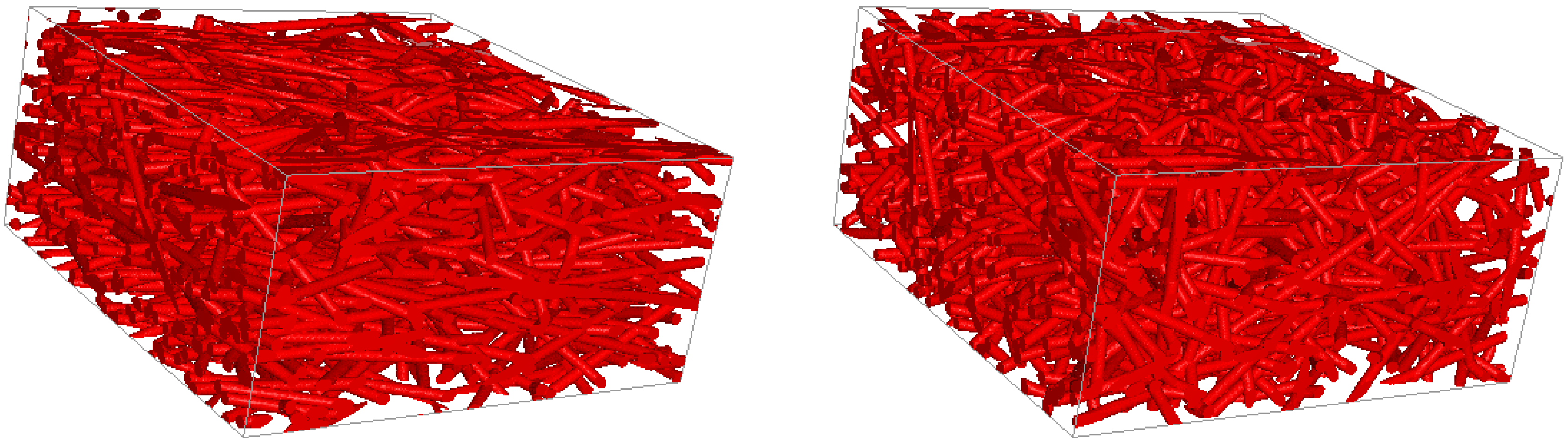
Possibilities in GeoDict to vary the structure model

1. Fiber diameter



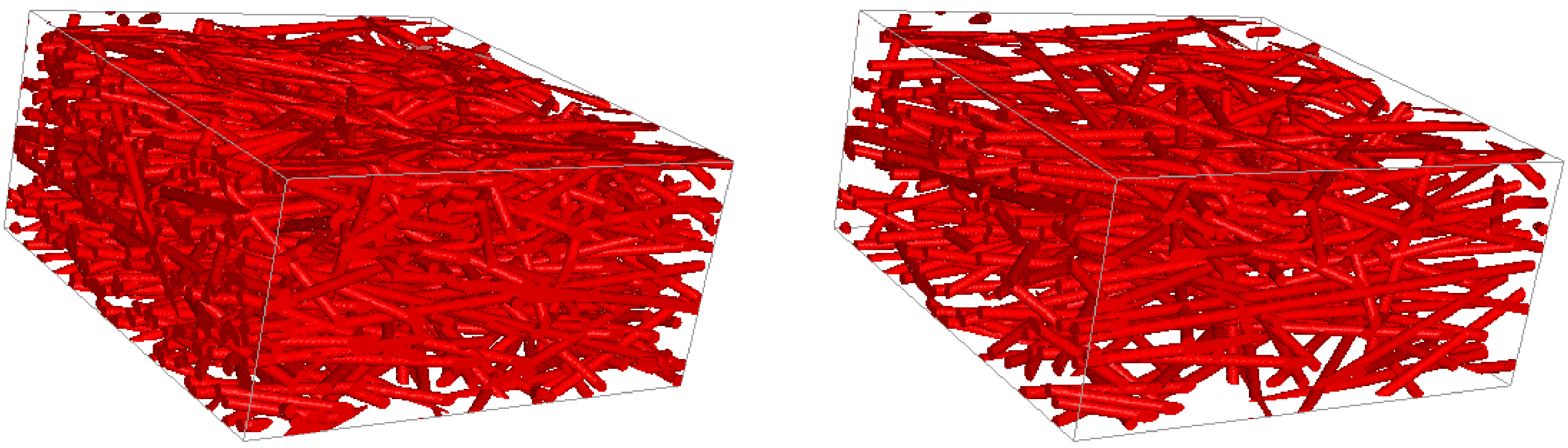
Possibilities in GeoDict to vary the structure model

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 is:

- get automatically from CT-scan to structure model

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!

GeoDict

The Digital Material Laboratory

Standard Edition

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and Andreas Wiegmann, PhD

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