

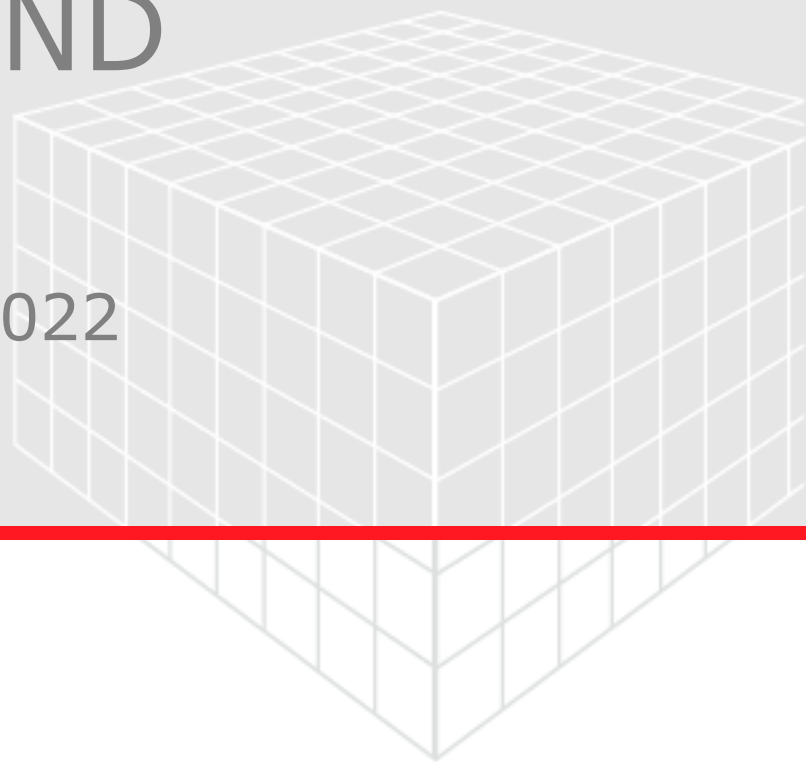
# FIBERFIND

# BINDERFIND

User Guide

GeoDict release 2022

Published: March 23, 2022



# GEO DICT

# IDENTIFICATION OF BINDER AND FIBERS AND ANALYSIS OF FIBER PROPERTIES IN FIBROUS MEDIA 1

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# IDENTIFICATION OF BINDER AND FIBERS AND ANALYSIS OF FIBER PROPERTIES IN FIBROUS MEDIA

## INTRODUCTION

The **FiberFind** module covers the functionalities in **GeoDict** that aim to understand 3D scans of fibrous materials, like nonwovens and fiber-based composites, e. g. glass fiber reinforced or carbon fiber reinforced composites. **FiberFind** requires as input 3D models that are previously obtained from segmented micro CT scans or FIB/SEM scans of the material.

Three distinct approaches are being followed in **FiberFind**:

1. Estimate statistical properties of fibers: diameter distribution, orientation distribution, curviness, and curliness
2. Identify individual fibers by classical image processing methods
3. Identify individual fibers and binder by Artificial Intelligence (AI) approaches

In **FiberFind**, we assume that pores have already been separated from solids, and that the solids consist of individual fibers and possibly some binder. Binder and fibers usually have the same gray values in the images. An automatic separation based on the gray value is therefore not possible. **FiberFind** with the submodule **FiberFind-AI** provides the possibility of separating binder from fibers automatically prior to the identification of separate fibers.

**FiberFind** analyzes the diameter, orientation, and curvature of fibers, to estimate the performance of fibrous structures.

**FiberFind** is the starting point to reproduce fibrous structures with **FiberGeo**. The user can input the statistical parameters obtained with **FiberFind** in **FiberGeo** and model isotropic and anisotropic materials. Subsequently, the statistical parameters of the modelled structure may be easily varied to investigate the effect of material structure on the performance of materials. By being used together, **FiberFind** and **FiberGeo** are intended to close the digital fibrous material design loop.

**FiberFind** is particularly well suited for the analysis in fibrous structures made of non-hollow fibers with circular cross-section.

Since the AI approach for identifying binder and fibers was only introduced in **GeoDict** 2019, currently some constraints for its application on the input data exist (see [Current constraints](#) on page 5), that will be removed in the further development of the AI capability.

The AI approach of **FiberFind** is only available in the **GeoDict** GUI if a corresponding license is available. Otherwise, only the analytic modules of **FiberFind** can be used.

Besides this handbook, several tutorials showing the possibilities of **FiberFind-AI** for different application cases are available on the [GeoDict website](#).

One tutorial is dealing with the analysis of four samples of different carbon paper gas diffusion layers used for a proton-exchange membrane in a fuel cell. Synchrotron scan data for the four samples is provided with the tutorial. The tutorial contains a

detailed description of the import and preprocessing of the data, the binder and fiber identification using the AI approach, and postprocessing options for the results.

A second tutorial deals with the **FiberFind** identification of fibers of a composite material, a glass-fiber reinforced polymer, as well as the mechanical analysis of the digital 3D model with **ElastoDict**. Input data and detailed description about preprocessing of the data is provided with the tutorial.

## SETTING UP FIBERFIND-AI AND BINDERFIND-AI FOR GPUS AND CPUS

We describe here how to install **FiberFind-AI** and **BinderFind-AI**.

In [Testing that installation of BinderFind-AI works properly](#) (below), we provide a short example (takes about 5 minutes to run) of how **BinderFind-AI** works and a short example on how the results of **BinderFind-AI** can be validated.

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*These instructions are specific for **GeoDict** 2021 and 2022 and not intended for earlier **GeoDict** releases. To install the GPU version for **GeoDict** 2020 or **GeoDict** 2019, see the [FiberFind handbook of the 2020 User Guide](#).*

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**FiberFind-AI** uses the TensorFlow Framework by Google, one of the most used and well-known machine learning libraries. Since **GeoDict** 2021, the required version of TensorFlow will be installed during **GeoDict** installation and **FiberFind-AI** and **BinderFind-AI** will work out of the box. Install **GeoDict** with Administrator rights on your machine to install TensorFlow correctly.

**FiberFind-AI** can run on the CPU (the main processor) or on the GPU (the graphics card). If a suitable GPU is detected during installation of **GeoDict**, **FiberFind-AI** and **BinderFind-AI** will run on the GPU, otherwise on the CPU.

Since **FiberFind-AI** and **BinderFind-AI** ships with a limited number of neural networks, currently some constraints on the input data exist that are listed under [Current constraints](#).

### USING THE GPU VERSION

The **GPU version** is usually **much faster** (roughly factor 10) than the CPU version but it requires:

- A good NVIDIA graphics card (GPU) installed, with compute capability of at least 3.5.

Please make sure drivers are installed and up to date. For the version of CUDA that **GeoDict** 2022 is using, you need at least version 450.80.02 of the NVidia driver for Linux or version 452.39 for Windows.

See more information on graphics cards in <https://developer.nvidia.com/cuda-gpus>. This webpage contains a helpful section with Frequently Asked Questions.

Remark: The manual installation of CUDA and TensorFlow is not necessary anymore since **GeoDict** 2021.

### THEORY – APPROACHES FOR FIBER IDENTIFICATION

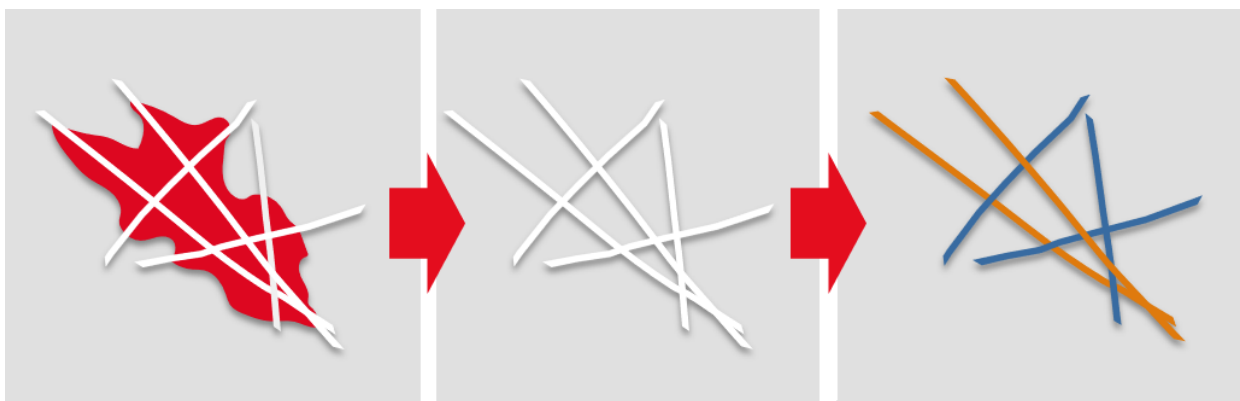
The following section explains the algorithms used by **FiberFind**. First, we explain the identification of binder and separate fibers with the AI approach, and the identification of separate fibers using the classical image processing approach.

Then follows a short explanation of the estimation of statistical fiber properties, diameter distribution, orientation distribution, curviness, and curliness.

#### AI APPROACH TO IDENTIFY BINDER AND FIBERS

The **FiberFind** module provides the possibility of using Artificial Intelligence (AI) approaches for the separation of binder and fibers as well as the identification of individual fibers in a fibrous structure.

In the image taken from a material, fibers and binder often have the same gray values, and therefore cannot be separated based on this value. The same holds true for the separation of different fibers. However, it is possible to separate binder from fibers and fibers from each other based on the shape in the image.



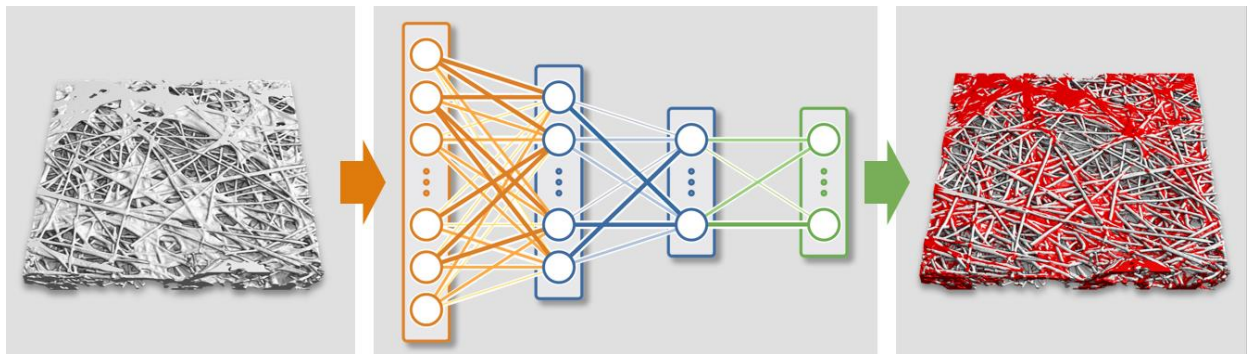
The **fundamental idea of AI** is that a neural network is trained to perform a special task, here the identification of separate fibers or the differentiation between fibers and binder. To train the neural network, enough examples need to be available to teach it. Clearly, for 3D-scans it is a very hard and time-consuming task to manually label materials or objects for the number of examples required, which are typically hundreds of millions. This is where **GeoDict's unique structure-generation capabilities** come in.

The **FiberGeo** module can create innumerable models of fibrous media and can also add binder to these models. Variations of fiber diameters, fiber shape, fiber length, fiber curvature, fiber density, etc. and also the amount and location of binder can be carried out as needed.

**As long as the models are close enough to the real 3D-scans**, **GeoDict** is capable of providing the needed ground truth data for the neural networks that embody the AI capability in **FiberFind**. Since **GeoDict 2021**, the capability to create and parameterize these neural networks is available in the module **GeoDict-AI**. For more details see the [GeoDict-AI handbook](#) of this User Guide.

Based on the trained neural network, **FiberFind** identifies for each voxel of the structure whether it is binder or fiber and sets the material ID accordingly.

In the same way, a trained neural network identifies for a fiber structure for each voxel to which fiber it belongs.



The current version of **FiberFind-AI** consists of two neural networks and **BinderFind-AI** consists of a single neural network that can be applied to segmented data sets in the **FiberFind** module. Therefore, currently some constraints on the input data exist, that may make it necessary to preprocess the input data, before applying the AI approach.

### CURRENT CONSTRAINTS OF **BINDERFIND-AI** AND **FIBERFIND-AI**

- Fiber diameters should be 4 to 10 voxels for binder identification and for fiber identification of short fibers. For the neural network for identification of long fibers, fiber diameters should be 6 to 14 voxels, ideally 8 or 9 voxels.

If fiber diameters differ from this value, **ImportGeo-Vol** can be used to resample the voxel length. During the import of an image, the 3D Image Processing functionality Image Size→Scale can be used for scaling the 3D image with a different voxel length. Details can be found in the [ImportGeo-Vol](#) handbook of this User Guide, in the section **3D Image Processing in ImportGeo-Vol → Image Processing Tools → Image Size → Scale**.

- If fiber diameters in the structure are very different, and therefore, after resampling, not all diameters lie in the range listed above, we suggest separating the fibers and applying **FiberFind-AI** for each kind of fiber.

To separate the fibers, **Estimate Fiber Diameters** in **FiberFind** can be used. Run the fiber diameter estimation and choose the number of fiber types in the Result Plots to fit to your structure. On the tab Result Visualization, you can then load a .gdt file with the fibers separated according to different fiber types. See [Estimate Fiber Diameters](#) below for detailed instructions and an example.

- Some networks require fibers to be oriented mainly in the x-y plane. Please see the individual network description in the dialog. If necessary, the structure can be rotated to fulfill this condition.

Changing the coordinate axis is done easily through **ProcessGeo → Permute** functionality. Details can be found in the [ProcessGeo](#) handbook.

Changing the coordinate axis or applying complex rotations to the structure by defining Euler angles is also possible through **ImportGeo-Vol**. Details are explained in the [ImportGeo-Vol](#) handbook in **3D Image Processing in ImportGeo-Vol → Image Processing Tools → Image Alignment → Rotation**.

- Fiber identification works for circular fibers right now, not for other cross sections such as hollow or trilobal fibers.

### IMAGE PROCESSING APPROACH TO IDENTIFY SEPARATE FIBERS

For the identification of separate fibers using the image processing approach, **FiberFind** identifies fibers using the known fiber center lines from voxel data of the structure model. A skeleton is created from the fiber center lines of the structure, that preserves the topology.

The identification of fibers with classical image processing methods is optimized for low density fibrous materials.

### ANALYSIS OF FIBER DIAMETER, ORIENTATION, CURVATURE, AND CURLINESS

The computation of the fiber diameter, fiber orientation, fiber curvature, and fiber curliness are explained directly below.

If analytic object data is already loaded in the **GeoDict** GUI, the properties are computed directly based on these objects. Otherwise, if only a voxel image is available, the fibers are identified first, using an image processing approach, before running the analysis.

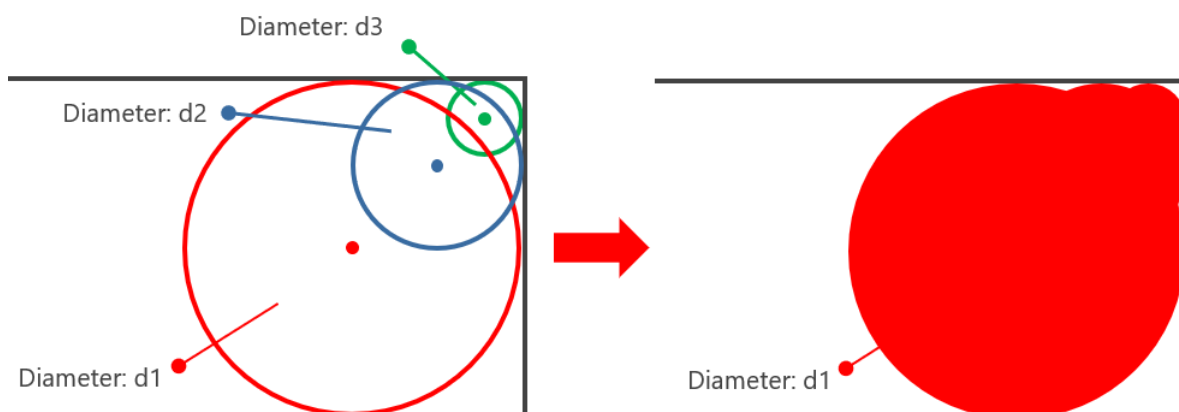
### COMPUTATION OF FIBER DIAMETERS

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The algorithm to estimate fiber diameters works as follows: At the start, each fiber voxel gets assigned the value of the largest sphere fitting into the fiber in this position. Then, it is checked for each fiber voxel if it lays inside of a larger sphere compared to the diameter of the sphere already assigned to the voxel under consideration.

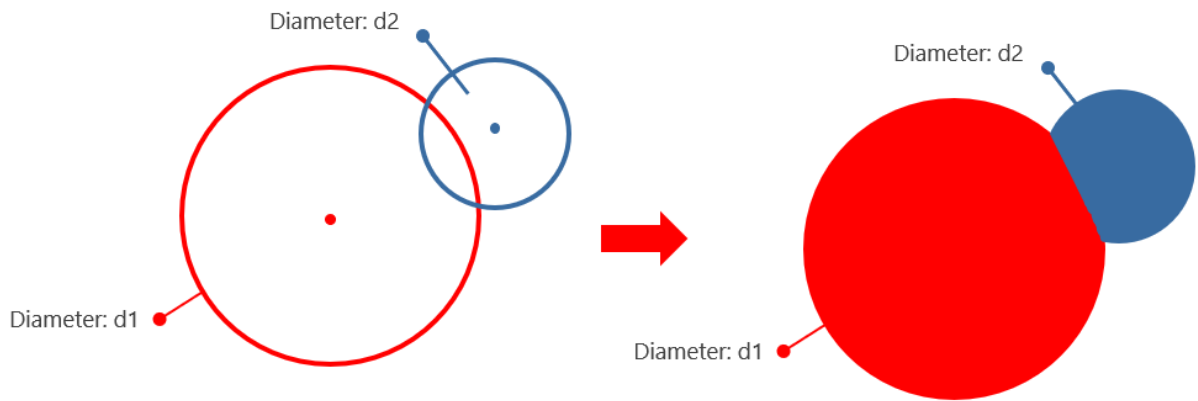
For this comparison, there are two possibilities:

- The center of the smaller sphere lays in the larger sphere. Then, the diameter value of the larger sphere is assigned to all voxels in the smaller sphere. Voxels at the end of a fiber get like this the same diameter than neighboring parts of the fibers and not a smaller one. See the following figure.



- The center of the smaller sphere does not lay in the larger sphere. Then, the overlapping area between both spheres is partitioned between both diameters. Like this, fibers overlapping each other both get the correct diameter. See the following figure.





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## COMPUTATION OF FIBER ORIENTATIONS

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To compute fiber orientations, two algorithms are used:

■ Star Length Distribution (SLD):

1. Analysis is done on a per-voxel basis.
2. For each voxel, it analyzes chord lengths through the voxel for a pre-defined set of directions.

■ Principal Component Analysis (PCA):

1. The domain is cut into blocks of a fixed size (currently 32x32x32).
2. For each block, all connected components are found. Ideally, they correspond to segments of individual fibers.
3. For each component, it is assumed that the voxels of the component form a point cloud. An ellipsoid which best approximates this point cloud is computed using the PCA method (Principal Component Analysis) and provides the principal orientation.
4. The principal orientation vectors are averaged to get a per-block orientation.
5. Per-block orientations are averaged to obtain the desired number of orientation tensors.

In summary, the PCA method cuts the fibers into segments and determines the local average of the orientation of these segments to obtain an orientation tensor.

For both algorithms, GOF files (GeoDict Orientation Files) can be saved to analyze anisotropic properties (e.g. transverse isotropic) of fibrous structures. In case of transverse isotropy, the material properties in fiber direction differ from properties in the perpendicular direction.

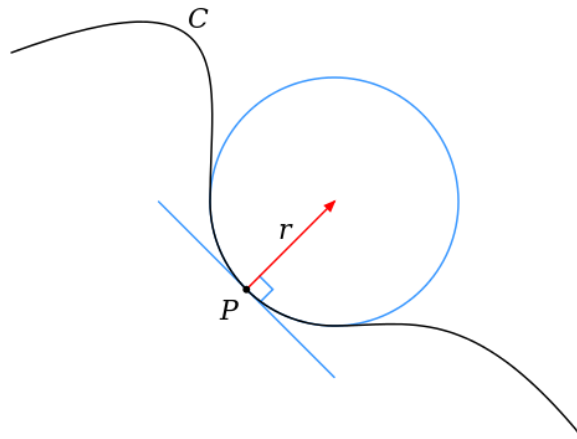
These GOF files can be used e.g. in **ElastoDict** for computations of mechanical properties in anisotropic materials.

### COMPUTATION OF CURVATURE AND CURLINESS

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**FiberFind** can calculate curliness and curvature distributions in models of fibrous structures. Curved fibers occur in materials for numerous industrial sectors: synthetic filter media, cellulose filter media, gas diffusion layers (GDL) in fuel cells, insulation materials, nonwovens for many applications, etc.

The calculated curvature is based on the definition of geometric curvature. At any point on the curve, the curvature is defined as the inverse radius of the osculating circle. The osculating circle has the same tangent vector as the curve at that point and approximates the curve locally.



The curliness factor measured by **FiberFind** is the length of the fiber divided by the distance between its start and its end. For straight fibers, this results in a curliness factor of 1.



**FiberFind** extracts the centerlines of fibers via skeletonization and calculates the curvature and curliness based on the centerline and the length of fibers. If no analytic data (.gad) is available, e.g., from a previously run fiber identification, **FiberFind** identifies the fibers with the classical image processing approach first.

The curvature estimation component is intended to be used with highly porous fibrous media (>90%). Solid volume fractions above 10% can decrease the accuracy of the result.

**MEMORY REQUIREMENTS FOR THE ALGORITHMS**

To get an estimation of the memory required by the **FiberFind** algorithms, the following table shows the memory per voxel that each of the algorithms needs for the computation. For this estimation, the number of voxels of the whole domain, not only the voxels occupied by fibers is relevant.

Algorithm	Required Memory per voxel
Estimate Fiber Diameters	5 Byte
Estimate Fiber Orientations	24 Byte
Estimate Curvature	29 Byte
Identify Fibers (AI)	5 Byte

In each case, some overhead for the structure loaded and other information for the algorithm is necessary. However, especially for large structures, where the memory requirements are crucial, the values in the table are helpful to decide whether the memory available is enough for a computation on the loaded structure or not.

### FIBERFIND SECTION

**FiberFind** starts when selecting **Analyze** → **FiberFind** in the menu bar.

Five processes are listed and can be selected from the pull-down menu in the **FiberFind** section: **Estimate Fiber Diameters**, **Estimate Fiber Orientations**, **Estimate Fiber Curvature**, **Identify Fibers (AI)** and **Identify Binder (AI)**.



The options for each process can be edited after selecting it from the pull-down menu and clicking the **Options' Edit...** button.

When the options for the selected **FiberFind** process have been entered, clicking **Run** starts the computation.

When recording a macro, e.g. to run parameter studies, the **Record** button becomes active and the **Run** button changes to **Run & Record**.

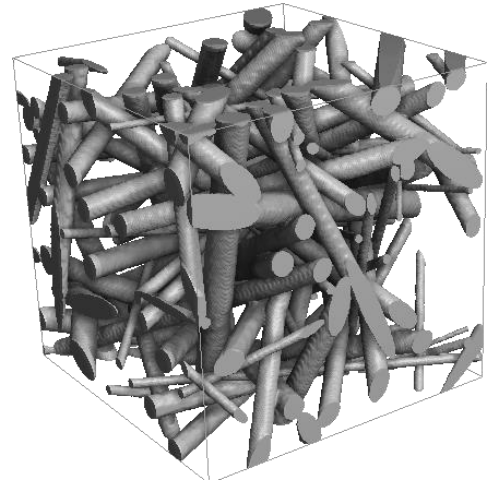
The results from all **FiberFind** computations are saved as **\*.gdr** files in the project folder.

**GeoDict** result files (.gdr files) can be opened with the **GeoDict** Result Viewer at any time by selecting **File** → **Open Results (\*.gdr)** from the Menu bar.

For the analysis with **FiberFind**, a segmented image of the material needs to be available. **ImportGeo-Vol** can be used to import data of ( $\mu$ )CT (or FIB/SEM) scans, to get a segmented three-dimensional model (see the [ImportGeo-Vol](#) handbook).

## ESTIMATE FIBER DIAMETERS

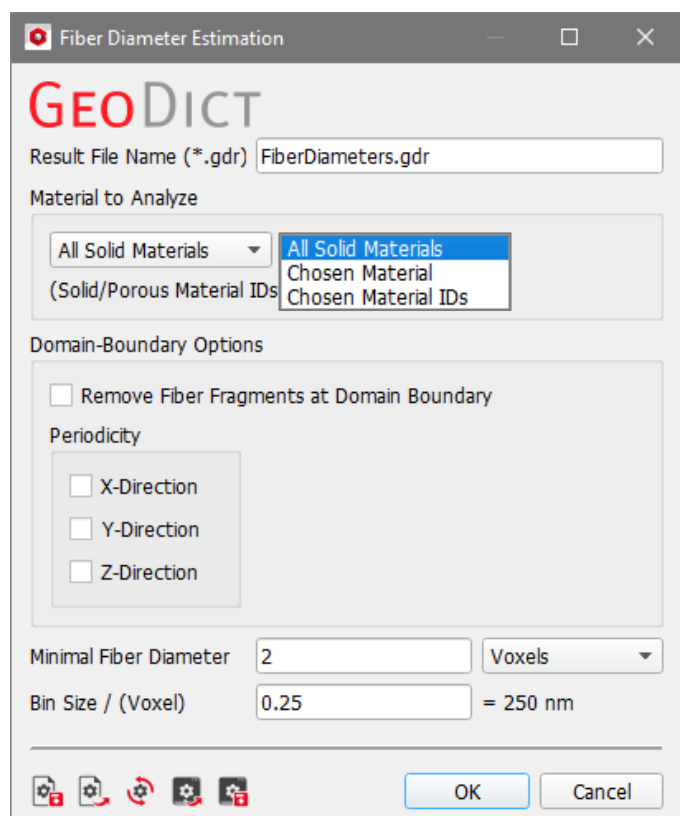
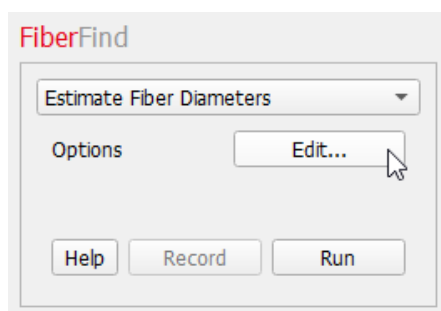
Start with a 3D-model of a fibrous material that has been loaded in memory and is displayed in the Visualization area.



In the **FiberFind** section, select **Estimate Fiber Diameters** from the pull-down menu and click the **Options' Edit...** button.

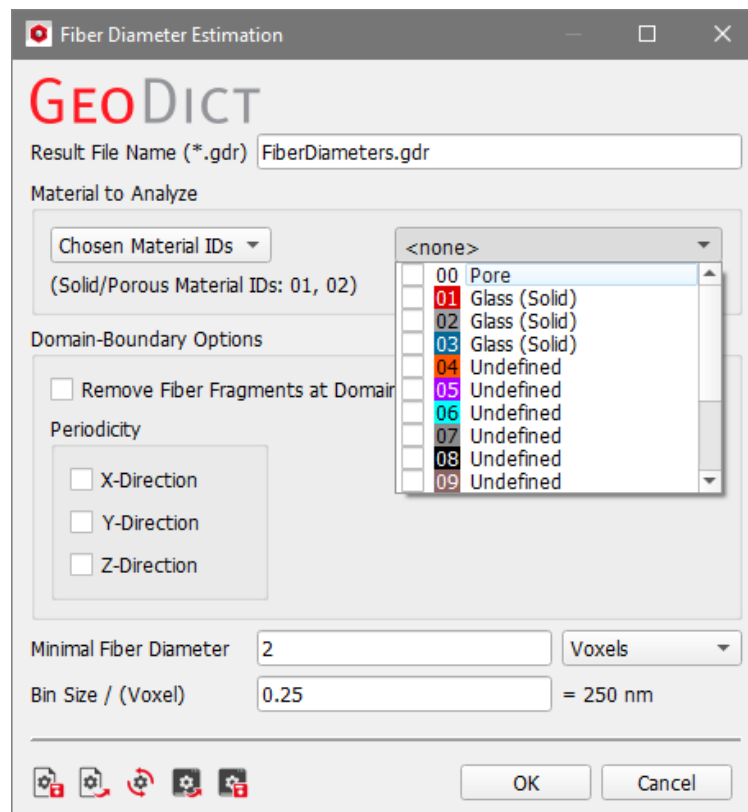
In the opening **Fiber Diameter Estimation** dialog, enter the desired **Result File Name (.gdr)** or keep the default **FiberDiameters.gdr**.

From the **Material to Analyze** pull-down menu, select to analyze **All Solid Materials** in the 3D-model (analyze all solid and porous materials), only a **Chosen Material**, or materials of the **Chosen Material IDs**.



When **Chosen Material** is selected, it is possible to analyze any material included in the model.

When **Chosen Material IDs** is selected, the user can choose to analyze any of the 16 Material IDs that could appear in a model. This can be used when a material appears through overlapping of fibers, or to exclude binder from the fiber diameter analysis.



Check **Remove Fiber Fragments at Domain Boundary** to remove fragments of fibers that touch the domain boundary after running the fiber identification algorithm. For fibers not contained in the computation domain completely, it may be not possible to estimate the correct diameter and length at the domain boundary.

If the material is periodic in one or several directions, this can be accounted for by checking the boxes for **Periodicity**. For example, for periodicity in x-direction, fibers leaving the domain on one end in x-direction will be considered to relate to a fiber starting at the other end of the domain with similar y and z values.

If any information is available about the minimal fiber diameter, this information can be entered in **Minimal Fiber Diameter**. This speeds-up the computation, as the algorithm starts with this minimal diameter and not with zero for the diameter estimation. However, since fiber segments with diameter smaller than the value given are ignored if they are not connected to a larger fiber, the recommendation is to enter a fiber diameter slightly smaller than the one known, to make sure that all fiber segments are considered. The minimal diameter can be defined in meter or as number of voxels.

The **Bin Size** (in Voxel) defines the resolution of the diameter analysis for the result visualization as histogram and for the computation of diameter distribution for one or several types of fibers. It can be changed during postprocessing in the **GeoDict Result Viewer**.

A result file with the entered Result File Name is saved in the chosen project folder (**File** → **Choose Project Folder...**) after the analysis, and a Result Viewer opens, showing the calculated values. The header section can be collapsed and expanded.

In the Result Viewer, the results are organized into **Input Map**, **Log Map**, **Post Map**, **Results**, **Data Visualization** and **Metadata**, which are accessed through the corresponding tabs.

Under the **Results - Report** subtab, the average diameter and the corresponding standard deviation for all fibers, as well as averages and standard deviations of the binned histogram values for each fiber type are displayed. An example of two different fiber types is shown here.

Below, a table lists the minimum and maximum diameter of each bin, as well as the volume fraction of fibers with this diameter.

Wed Oct 13 2021 (2022 Build 52500) .../FiberFind2022/fibrousFiberDiameters.gdr

Domain: 200 x 200 x 200 Voxel: 1  $\mu\text{m}$  Load Structure

Input Map Log Map Post Map **Results** Data Visualization Metadata

Bin Size / (Voxel) 0.25  
Thresholding Method k-Means  
Number of Fiber Types 2  
Apply ...

Report Plots Map

**FiberFind**

**General Analysis of the Size Distribution (\*.gsd):**  
Average inner diameter: 12.1954  $\mu\text{m}$   
Standard deviation: 2.77963  $\mu\text{m}$

**Fiber Type Analysis:**  
Specified Number of Types: 2

	Average Inner Diameter / ( $\mu\text{m}$ )	Standard Deviation / ( $\mu\text{m}$ )	Volume Fraction / (%)
Type 1	7.68574	2.44857	15.9505
Type 2	13.063	1.87531	84.0495

Type Threshold 1: 10.75  $\mu\text{m}$   
(result depends on the post-processing bin-size)

**Characteristic Diameters:**  
D 10: 9.80716  $\mu\text{m}$   
D 50: 12.1677  $\mu\text{m}$   
D 90: 15.5542  $\mu\text{m}$

**Histogram:**

Min. Diameter / ( $\mu\text{m}$ )	Max. Diameter / ( $\mu\text{m}$ )	Volume Fraction / (%)
0	0.25	0
0.25	0.5	0
0.5	0.75	0

Plot Options

Manage Data Load Input Map Export Close

In the post-processing section, left of the Results tab, the **Bin Size** (in Voxels), the **Thresholding Method**, and the **Number of Fiber Types** can be changed. These post-processing commands allow control on the display of the result data. The post-processing section can also be collapsed and expanded.

Changing the **Bin Size** changes the width of the histogram bin and, therefore, its resolution.

The **Thresholding Method** for the separation between fibers of different fiber types allows to choose between the **K-Means**, **Otsu's** method and a **Manual** selection of the threshold. This option is only relevant for two or more different fiber types.

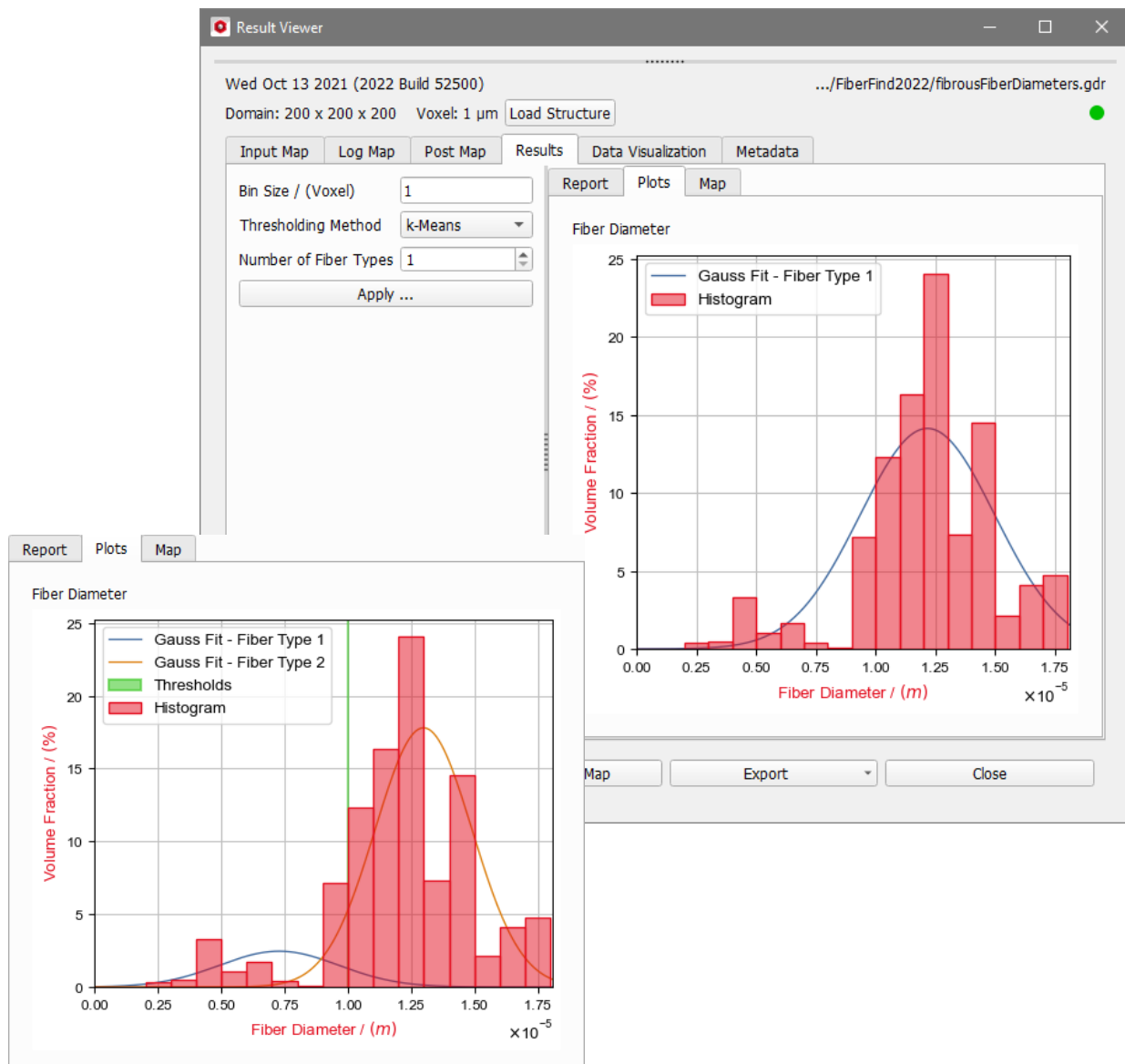
If the analyzed structure contains fibers of different types, specify the **Number of Fiber Types**, and for each type, a Gaussian is fitted to the data.

Click **Apply** to apply the changes to the histogram values shown, as well as to the plots shown on the **Plots** subtab and to the fiber type structure, that can be loaded on the tab **Data Visualization**.

Under the **Results - Plots** subtab, the histogram computed shows for each fiber diameter the volume fraction of the fibers with this diameter, together with a Gaussian fit to the histogram data. In the example shown below, for one fiber type, the highest volume fractions correspond to fibers with diameters around 12  $\mu\text{m}$ .

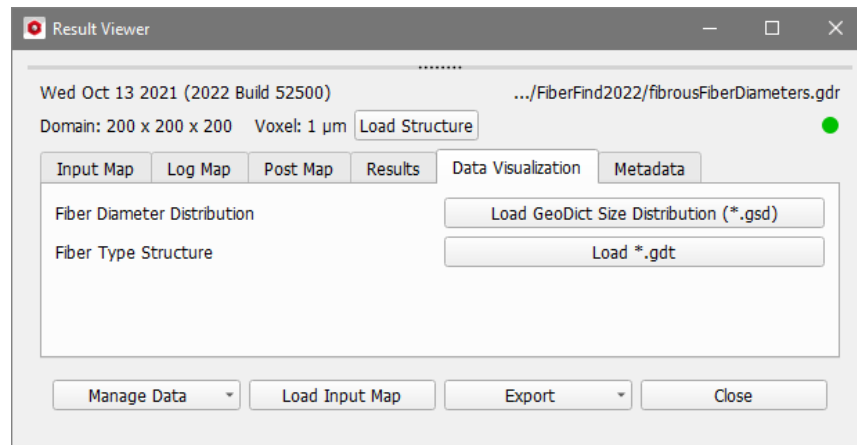
However, in the example shown here, the structure consists of two fiber types: fibers with small diameter between 2-8  $\mu\text{m}$ , and fibers with diameter between 9-18  $\mu\text{m}$ .

Choosing two different fiber types, leads to Gaussian distributions that fit much better to the fiber diameters present in the structure. The structure with a separation of the two different types of fibers is shown on page [15](#).





Under the **Data Visualization** tab, the **Fiber Type Structure** and the **Fiber Diameter Distribution** can be loaded.

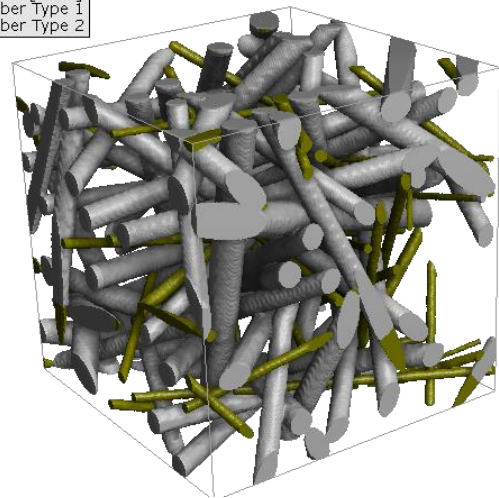


Clicking **Load \*.gdt** opens a **GeoDict** structure. All fibers assigned to one fiber type have the same Material ID in this structure. In case of two different fiber types, as shown in the example here, fibers with small diameter have the Material ID 01 (here in yellow). Fibers with large diameter have Material ID 02 (here shown in grey) and are assigned to Fiber Type 2. The corresponding histogram of fiber diameters is shown on page [14](#).

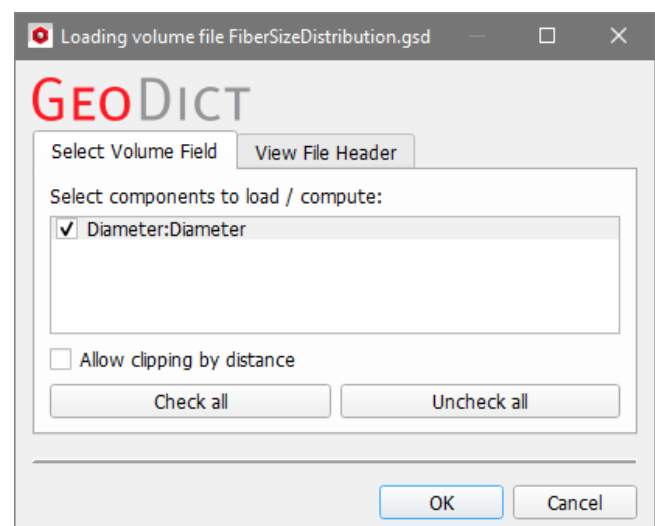
If postprocessing parameters in the **Results** tab (Bin Size, Thresholding Method, or Number of Fiber Types) are changed, the information in the .gdr file also changes.

This information can be used for the separation of fibers with different fiber diameters. Reassign e.g. all voxels with Material ID 01 to ID 00 with **ProcessGeo**. In this way, only solid voxels with Material ID 02 remain in the structure and can be analyzed separately.

Material Information:  
ID 00: Pore [Invis.]  
ID 01: Fiber Type 1  
ID 02: Fiber Type 2

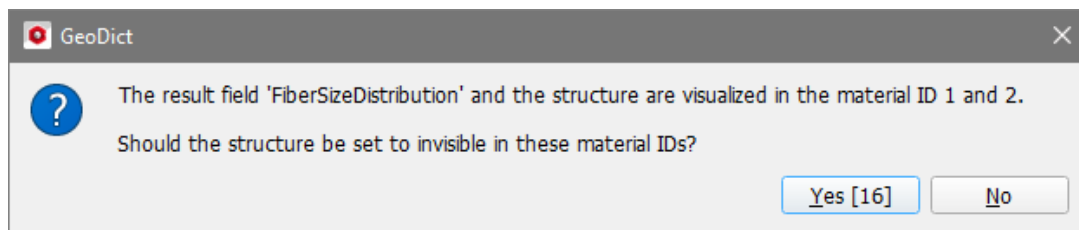


Now, click the **Load GeoDict Size Distribution (\*.gsd)** button to observe the computed fiber diameter distribution. Check **Diameter** as the volume field to be loaded and click **OK**.

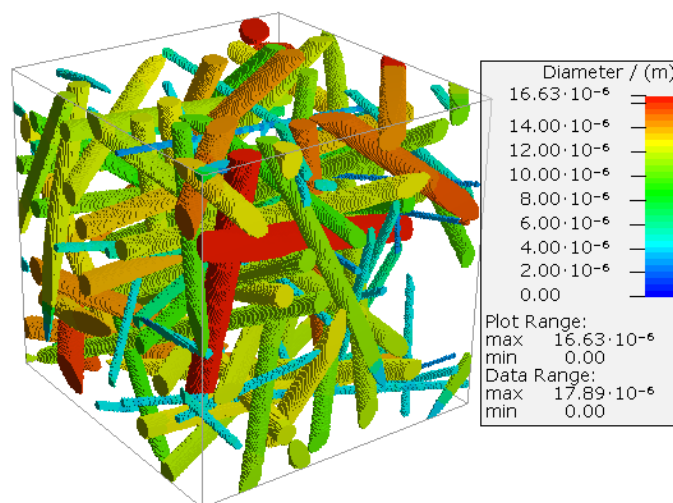


## Identification of binder and fibers, and analysis of fiber properties

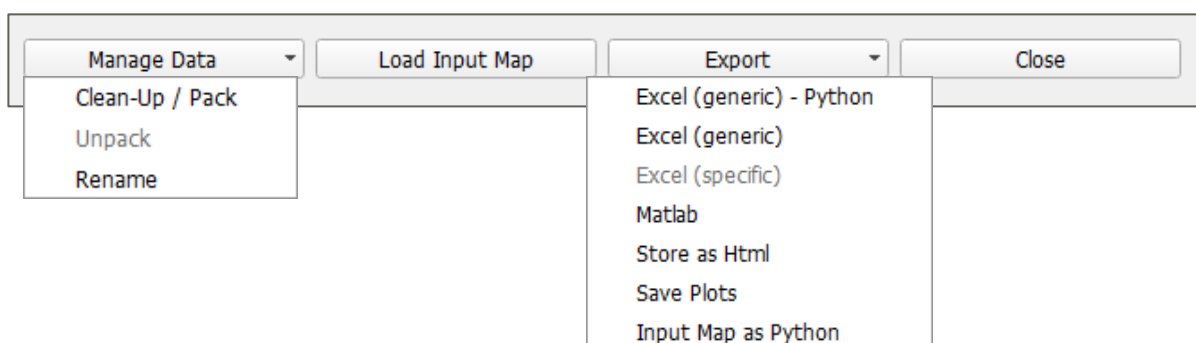
Then, deselect the visualization of the structure, by clicking **Yes** in the dialog that pops up (or by choosing **View** in the Menu bar and uncheck the **Structure** box).



In the **Volume Field** tab of the Visualization panel (above the Visualization area), with the **Visibility** set to material IDs 01 and 02, only the fibers are shown and not the pore space.



The buttons for data management available at the bottom of the Result Viewer are explained in detail in the [Result Viewer](#) handbook of this User Guide.

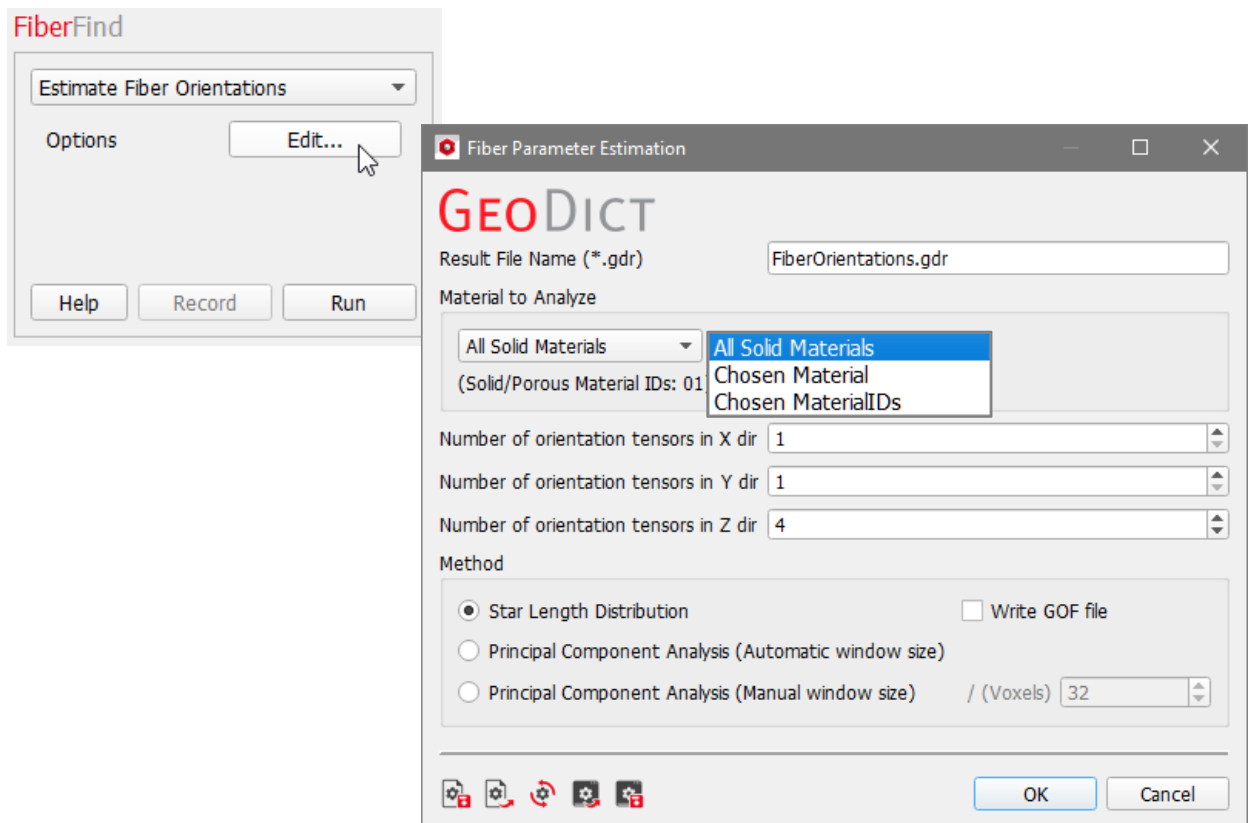


The units of length are meters (m) because, internal to GeoDict, all units are SI (Système International d'Unités) for which meter is the base unit for length.

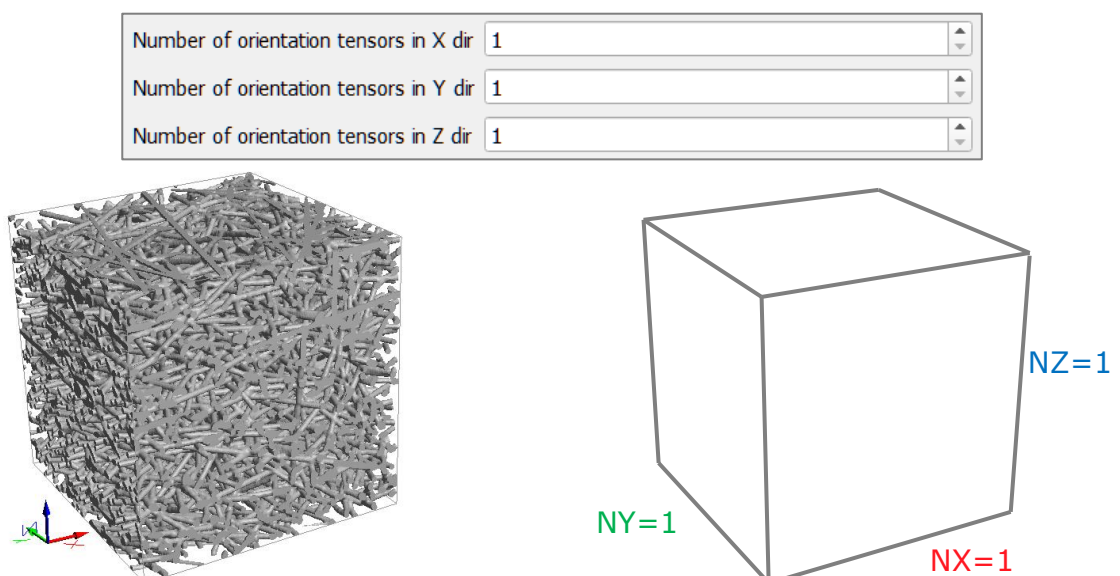
## ESTIMATE FIBER ORIENTATIONS

Start with a 3D-model of a fibrous material that has been loaded in memory and is displayed in the Visualization area. In the **FiberFind** section, select **Estimate Fiber Orientations** from the pull-down menu and click the **Options' Edit...** button.

In the opening **Fiber Diameter Estimation** dialog, enter the desired **Result File Name (.gdr)**, and select the **Material to analyze** as explained on page [11](#).



For homogeneous materials, without variations in orientation, the domain can be analyzed as a whole and, therefore, the **Number of orientation tensors in X direction, in Y direction, and in Z direction** can be set to 1, 1, and 1.

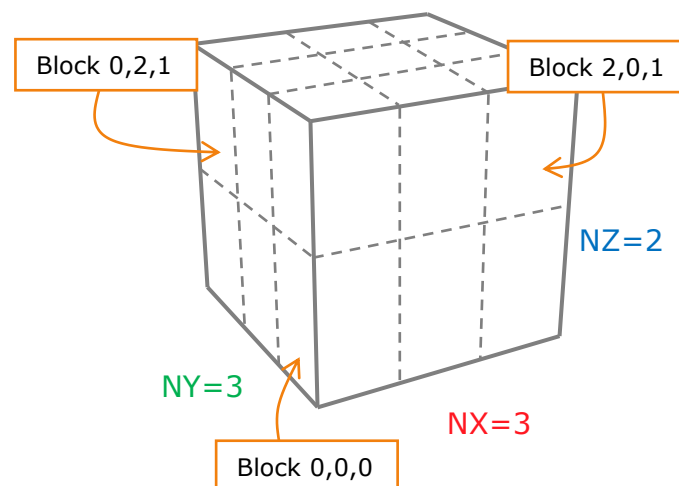
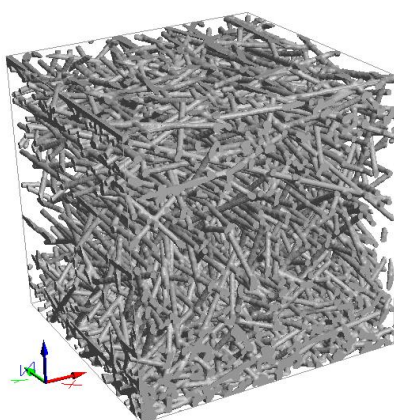


For non-homogenous fibrous materials, where fiber layers with varying orientations are present, the domain must be subdivided into blocks and an orientation tensor can be estimated for each block. The partition allows to analyze fiber orientation in these diverse areas of the domain, instead of having to cut the structure in parts and to analyze them separately.

The size of the blocks is defined by setting the **Number of orientation tensors**, for which values can be set, e.g. to 3, 3, and 2, producing 18 blocks.

Number of orientation tensors in X dir	3
Number of orientation tensors in Y dir	3
Number of orientation tensors in Z dir	2

These 18 blocks are labeled later in the result file as Block 0,0,0, Block 1,0,0, Block 2,0,0, Block 0,1,0, Block 1,1,0, etc.

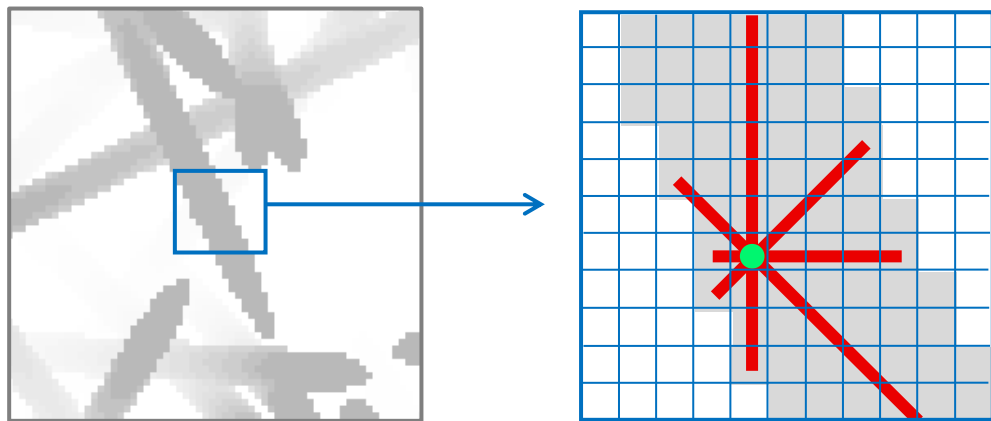


Next, choose a method for the analysis of fiber orientation: **Star Length Distribution (SLD)** or **Principal Component Analysis (PCA, Automatic or Manual window size)**.

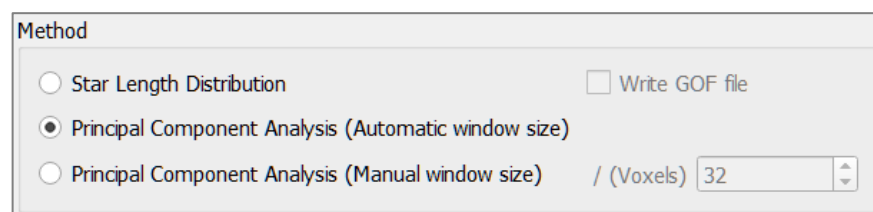
Method	
<input checked="" type="radio"/> Star Length Distribution	<input type="checkbox"/> Write GOF file
<input type="radio"/> Principal Component Analysis (Automatic window size)	
<input type="radio"/> Principal Component Analysis (Manual window size)	/ (Voxels) 32

The Star Length Distribution (SLD) method works on a per-voxel basis. For each voxel, it analyzes chord lengths through the voxel for a pre-defined set of directions.

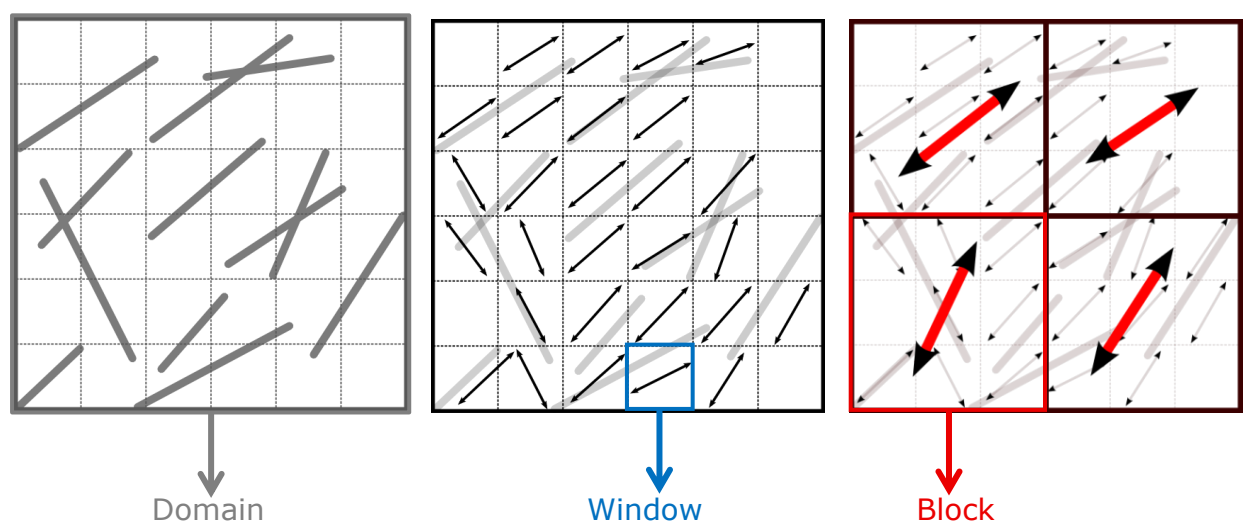
The relative length of the chords gives the per-voxel orientation tensor. Then, the tensors are averaged over all voxels included in a block.



The PCA method is an alternative approach that subdivides the domain into windows of a given size. The size of the window can be automatically determined based on maximum fiber diameter (Automatic window size) or manually entered in voxels (Manual window size).



The subdivision into windows is applied to eliminate the influence of fiber crossings. Our PCA-based algorithm identifies fiber fragments and analyzes the direction tensor within each window. Then, it averages the direction tensors over all windows within a block to obtain the orientation tensor for that block.

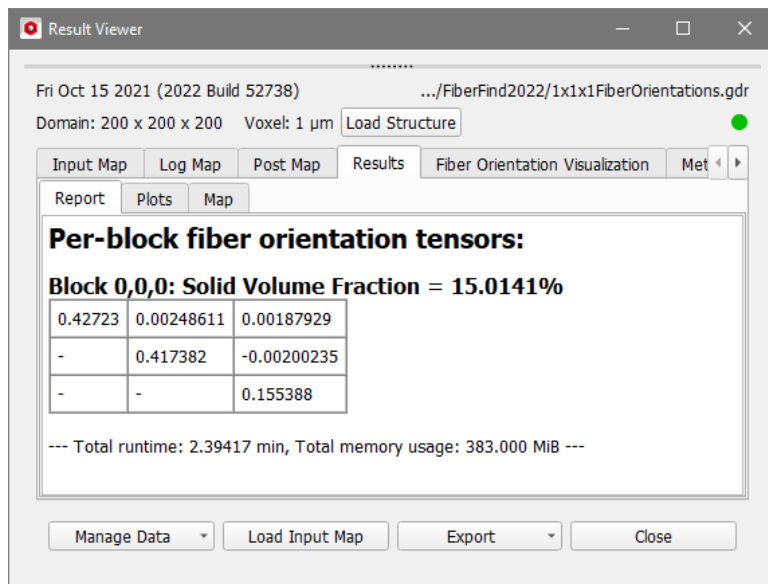


When needed, check **Write GOF file** to save a GeoDict Orientation File (GOF) with the per-voxel fiber orientation information.

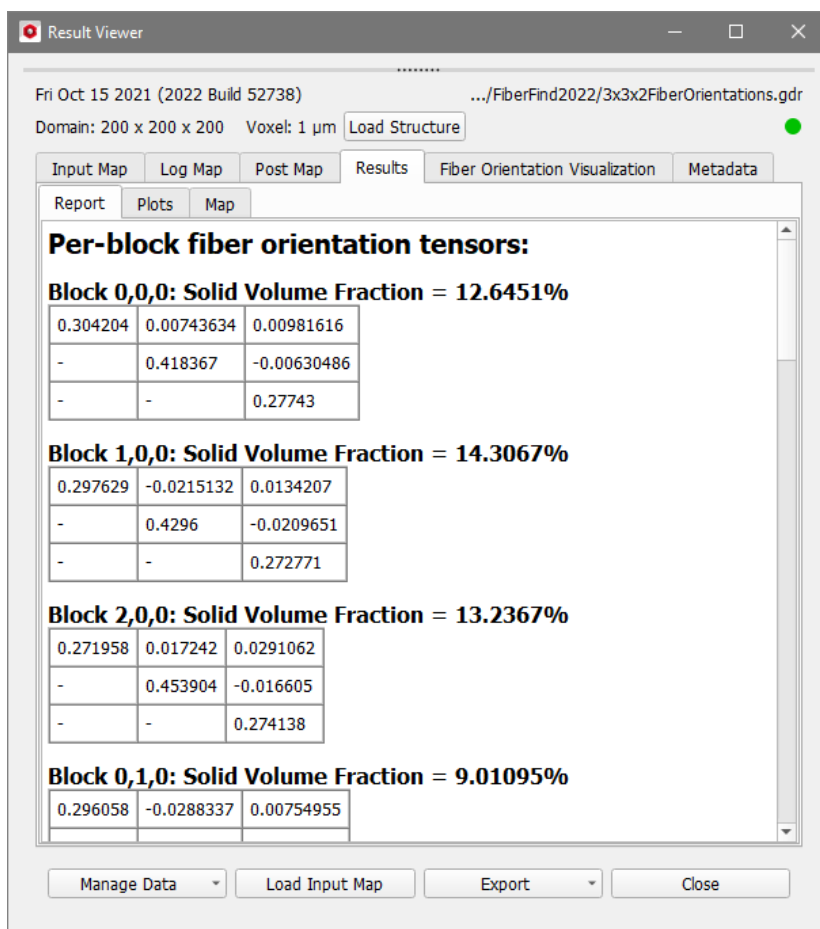
## Identification of binder and fibers, and analysis of fiber properties

After the calculations, a Result Viewer opens showing the calculated fiber orientation tensors and solid volume fraction for each block. The tensor describes the statistical distribution of orientation in that particular block.

With an undivided domain (1x1x1 blocks), only one tensor for the complete domain appears in the Result Viewer.

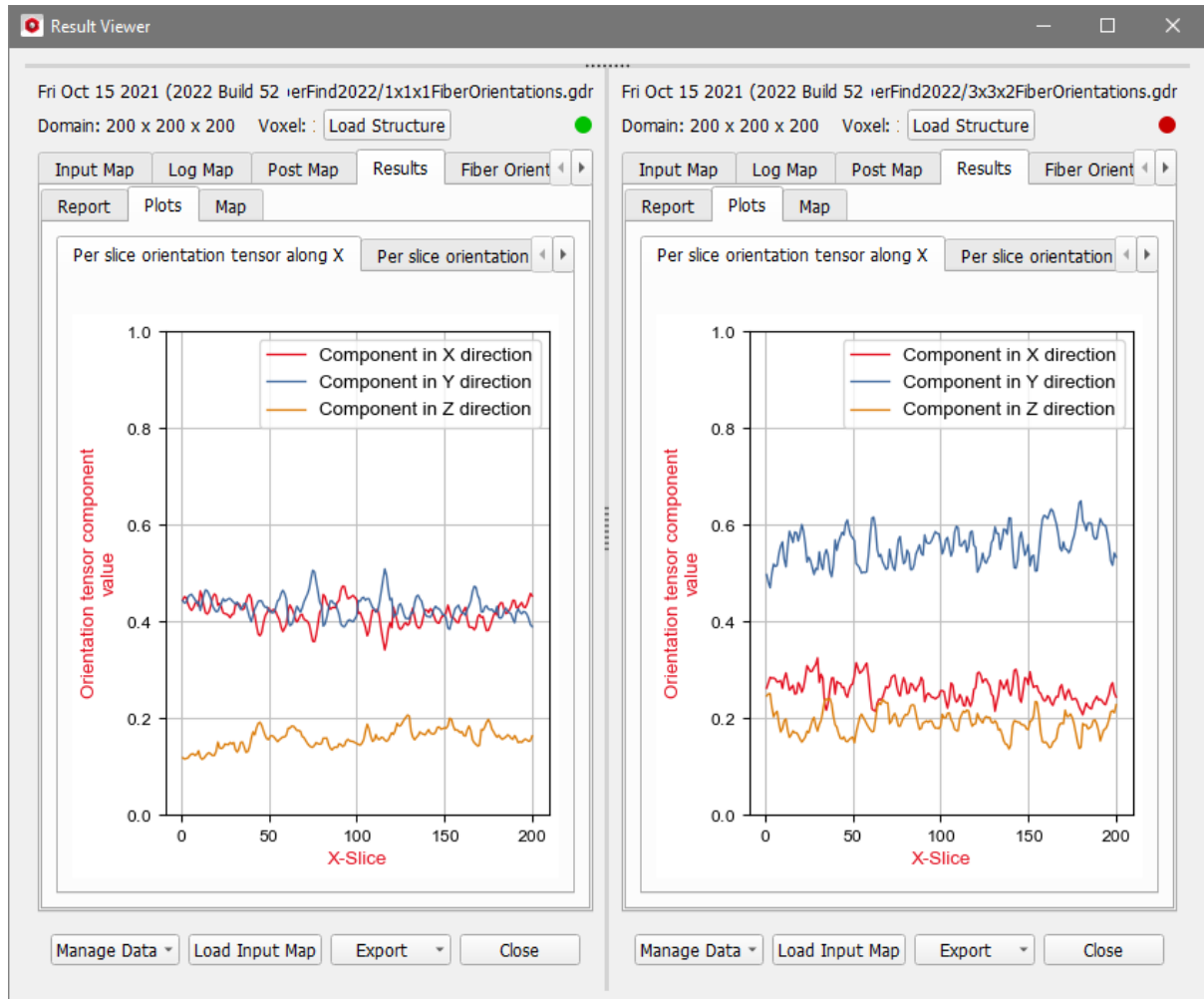


With the domain subdivided into 3x3x2 blocks, the number of tensors is 18.

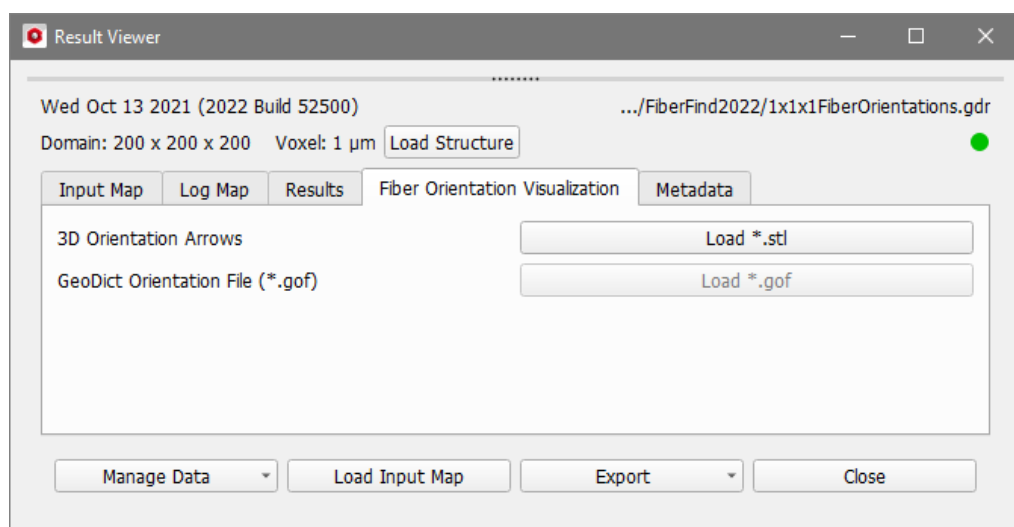


Independent on the number of blocks selected, the per slice components of the orientation tensor in X, Y and Z direction are shown for all three coordinate directions in the **Results - Plots** subtab.

These components are shown here in a single Result Viewer: on the left for the undivided domain and on the right for the second domain subdivided into 3x3x2 blocks.



The fiber orientation in the blocks can be visualized by clicking **Load .stl** to get the **3D Orientation Arrows** under the **Fiber Orientation Visualization** tab.

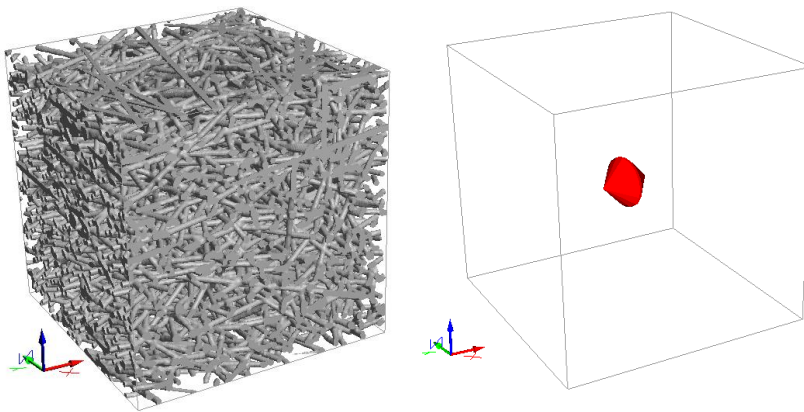




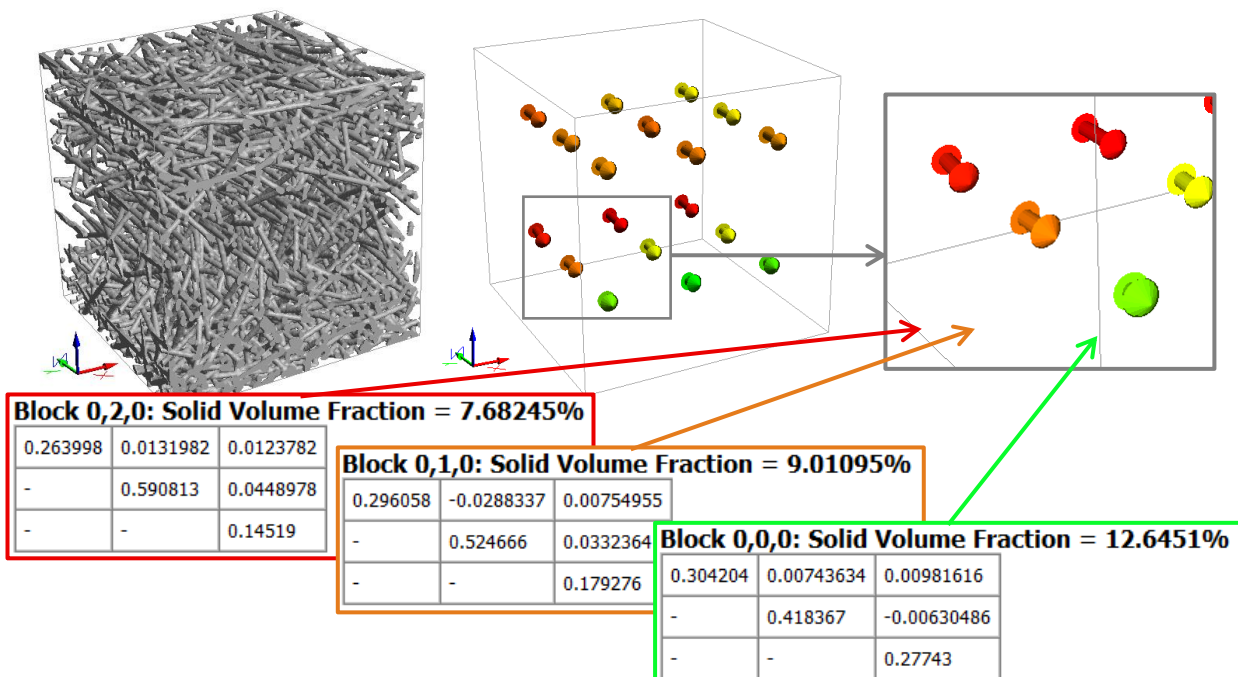
The fibers of the structure obscure the orientation arrows. Go to the menu bar and turn off the visualization of the fibers by un-checking **View** → **Structure**. Orientation arrows are visible only in 3D view. Switch to it by selecting **View** → **3D Rendering**.

The **direction** of an arrow in a particular block shows the main fiber orientation in the block, and its length shows the strength of this main fiber orientation. The **color** of the arrows indicates the fiber solid volume fraction (SVF) in a block. The color range is green-yellow-orange-red. Assignment of color in a block depends on its SVF relative to the SVF of the other blocks. The block with the highest SVF gets a green arrow. The block with the lowest SVF gets a red arrow. When there is only one block (homogeneous material), the arrow is red.

For a homogeneous material structure (no subdivision), only one arrow appears in the center of the single block. Here, the short arrow pointing in the X-direction indicates that although the fibers' main orientation is on the X-axis, there is a great deal of dispersion. Values on the main diagonal in the orientation tensor in x- and y-direction have nearly the same size (0.43 in x and 0.42 in y-direction), but the arrow shown points always in the direction of the larger one.

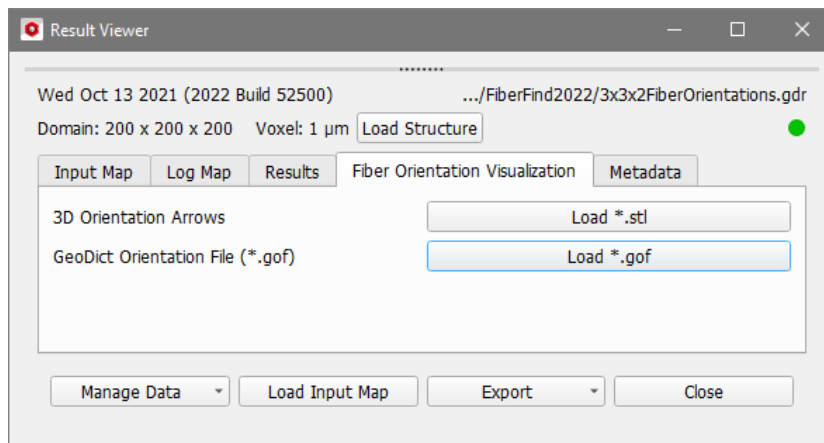


For a heterogeneous material structure, divided into 3x3x2 blocks, 18 arrows appear that occupy the centers of each of the 18 blocks. All arrows are oriented closely to the Y-axis. The range of colors indicates that the SVF of some blocks (green arrows) is higher than that of others (red arrows).

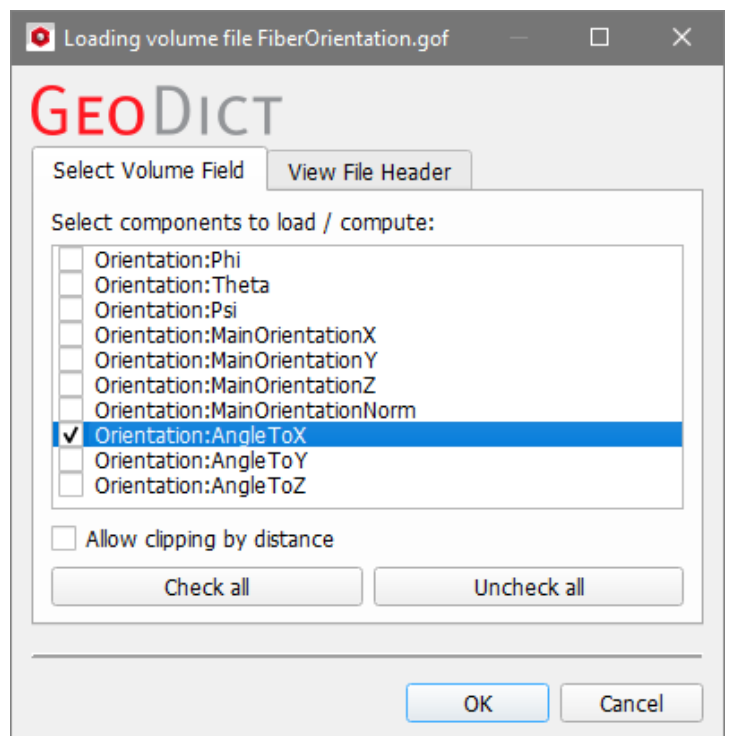




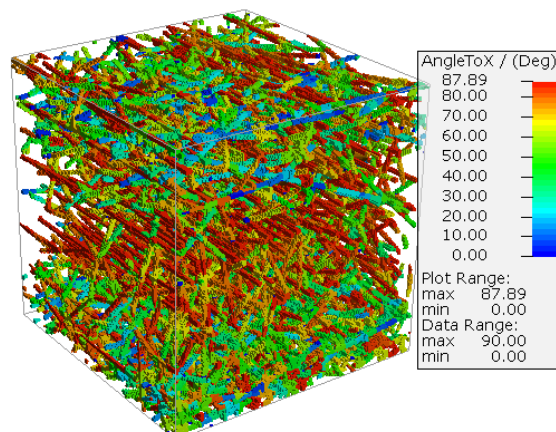
Besides the 3D Orientation Arrows it is possible to visualize the GOF file (if one was calculated). Click **Load \*.gof** under the **Fiber Orientation Visualization** tab of the Result Viewer.



Select, e.g., to load the Orientation:AngleToX to get for each fiber segment the angle to the x axis.

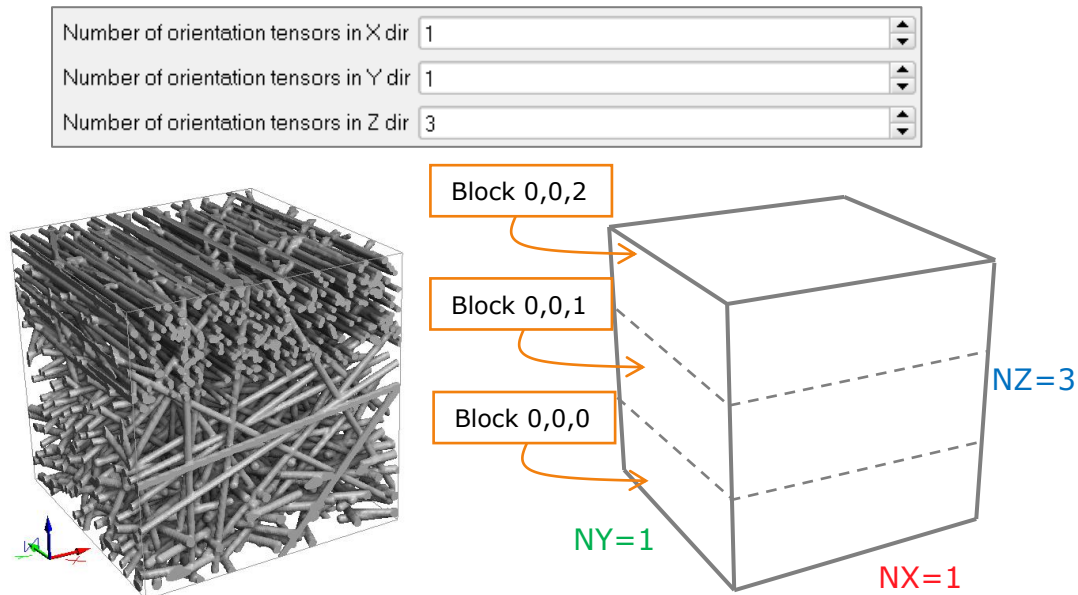


In the Visualization panel, above the Visualization area, uncheck the check box in the **Structure** tab. In the **Volume Field** tab, deselect **Visibility** for the pore space (Material 00).

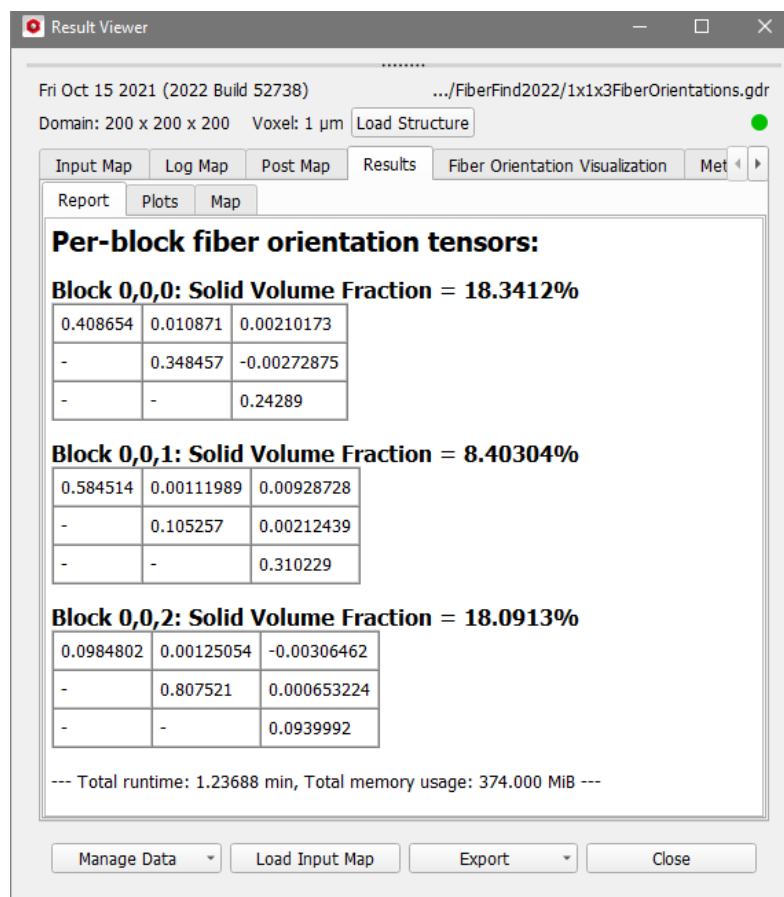


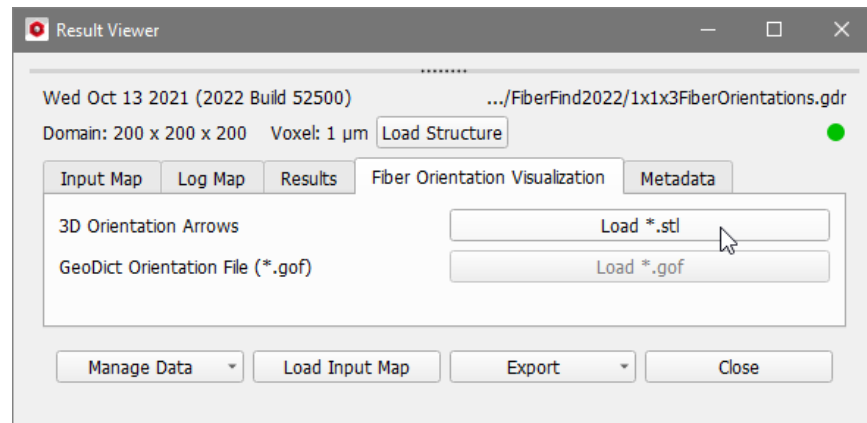
## ESTIMATING FIBER ORIENTATION IN LAYERED MATERIALS

For a layered heterogeneous material, **FiberFind** can be used to estimate the fiber orientation in the layers by subdividing the domain according to the layers. For example, the domain of a material with three layers would be subdivided as follows:

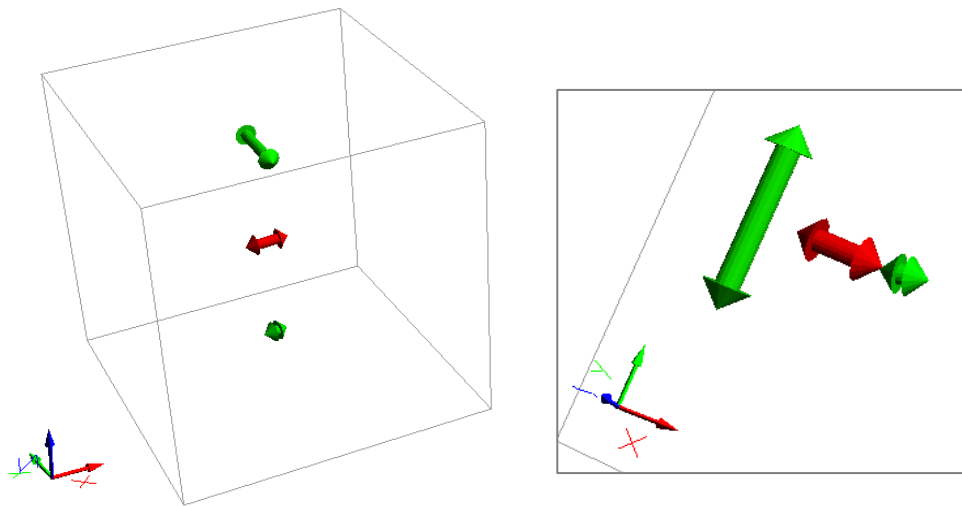


When the calculations with **FiberFind** are finished, a Result Viewer for the fiber orientation result file opens showing the calculated fiber orientation tensors and solid volume fraction for each of the three blocks. The highest fiber solid volume fractions are in the top (Block 0,0,2) and bottom (Block 0,0,0) layers as can be seen in the **Results - Report** subtab.





The main orientation of the top layer (Block 0,0,2) is in Y-direction, the main orientation of the middle layer (Block 0,0,1) is in X-direction and the main orientation of the bottom (Block 0,0,0) layer is in the X-Y-direction.



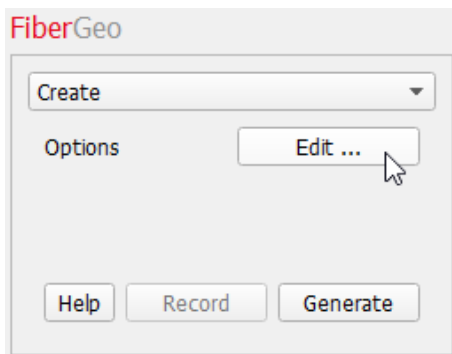
Whereas a great majority of fibers in the top layer are oriented in the Y-direction, the orientation in the middle layer and, particularly in the bottom layer, is more scattered.

### REPRODUCING FIBROUS MEDIA USING FIBERFIND AND FIBERGEO

The values of the orientation tensors and the calculated diameters can be entered in **FiberGeo** to generate a matching digital material model.

Start with the values estimated by **FiberFind** for the fibrous material: the average fiber diameter and the diameter distribution for the whole domain, as well as the fiber orientation tensors for each block. This diameter distribution and the per-block orientation tensors can now be entered in **FiberGeo** to reproduce the fibrous material.

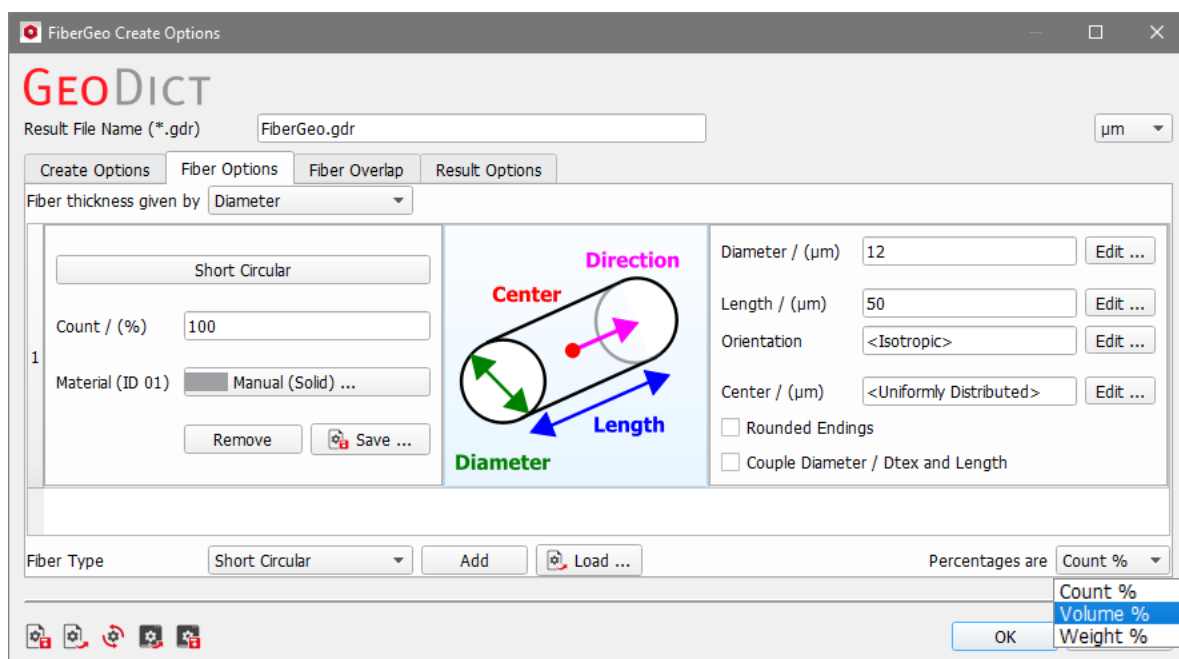
Select **Model** → **FiberGeo** in the menu bar and click the **Options' Edit...** button in the **FiberGeo** section.



In **FiberGeo**, go to the **Fiber Options** tab and begin entering as many fibers of type Short Circular or Infinite Circular as the number of blocks in which the domain has been subdivided. For a homogeneous material, this is a single fiber type. For a layered heterogeneous material, this is a fiber type per media layer. In **FiberGeo**, it is possible to use up to 4 different fiber types.

Later, all fibers can be assigned to the same Material ID.

Set the **Percentages are** as Volume % (bottom right).

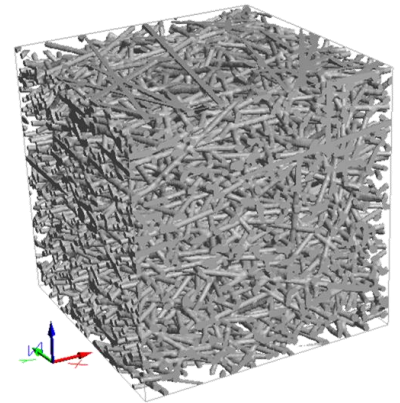


## HOMOGENEOUS FIBROUS MEDIA

For a homogeneous material (no layers), for the single fiber type, use the data from a fiber diameter result file (\*.gdr) obtained with **FiberFind** and, for **Diameter**, enter the value of the estimated **Average inner diameter**.

Alternatively, click the **Diameter's Edit...** button and choose **Gaussian** (or Log-Normal) to enter the values of the **Average inner diameter** and the **Standard deviation** from the fiber diameter result file.

It is also possible to choose **Probability Distribution** and to enter a stepwise distribution, e.g. from the histogram values of the fiber diameter estimation.



**Short Circular**

Rel. Volume / (%) 100

Abs. Volume / (%) 15.0141

Material (ID 01) Manual (Solid) ...

Remove Save ...

**Center** **Direction** **Diameter** **Length**

Diameter / ( $\mu\text{m}$ ) 3.22742 **Edit ...**

Length / ( $\mu\text{m}$ ) 250 **Edit ...**

Orientation <Isotropic> **Edit ...**

Center / ( $\mu\text{m}$ ) <Uniformly Distributed> **Edit ...**

☐ Rounded Endings

☐ Couple Diameter / Dtex and Length

**Result Viewer**

Wed Oct 13 2021 (2022 Build 52500) .../FiberFind2022/HomogeneousFiberDiameters.gdr

Domain: 200 x 200 x 200 Voxel: 1  $\mu\text{m}$  Load Structure

Input Map Log Map Post Map Results Data Visualization

Report Plots Map

**FiberFind**

**General Analysis of the Size Distribution (\*.gsd)**

Average inner diameter: 3.22742  $\mu\text{m}$

Standard deviation: 458.049 nm

**Fiber Type Analysis:**

Specified Number of Types: 1

	Average Inner Diameter / ( $\mu\text{m}$ )	Standard Deviation / ( $\mu\text{m}$ )	
Type 1	3.20318	0.394714	100

(result depends on the post-processing bin-size)

**Characteristic Diameters:**

D 10: 2.79988  $\mu\text{m}$

D 50: 2.99939  $\mu\text{m}$

D 90: 4.05779  $\mu\text{m}$

Manage Data Load Input Map Export Close

**GEO DICT**

☐ Constant

☐ Uniformly in interval

☒ Gaussian

Mean Value / ( $\mu\text{m}$ ) 3.22742

Standard Deviation / ( $\mu\text{m}$ ) 0.458049

Distribution Width / ( $\mu\text{m}$ ) 1.5

☐ Cut-Off Distribution

☐ Probability Distribution

☐ Log-Normal

Relative count / (1)

density function

distribution function

10% percentile

50% percentile

90% percentile

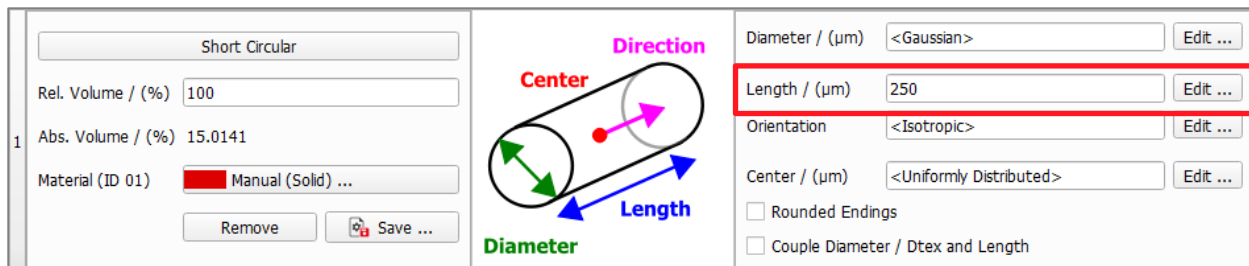
Diameter / ( $\mu\text{m}$ )

OK Cancel

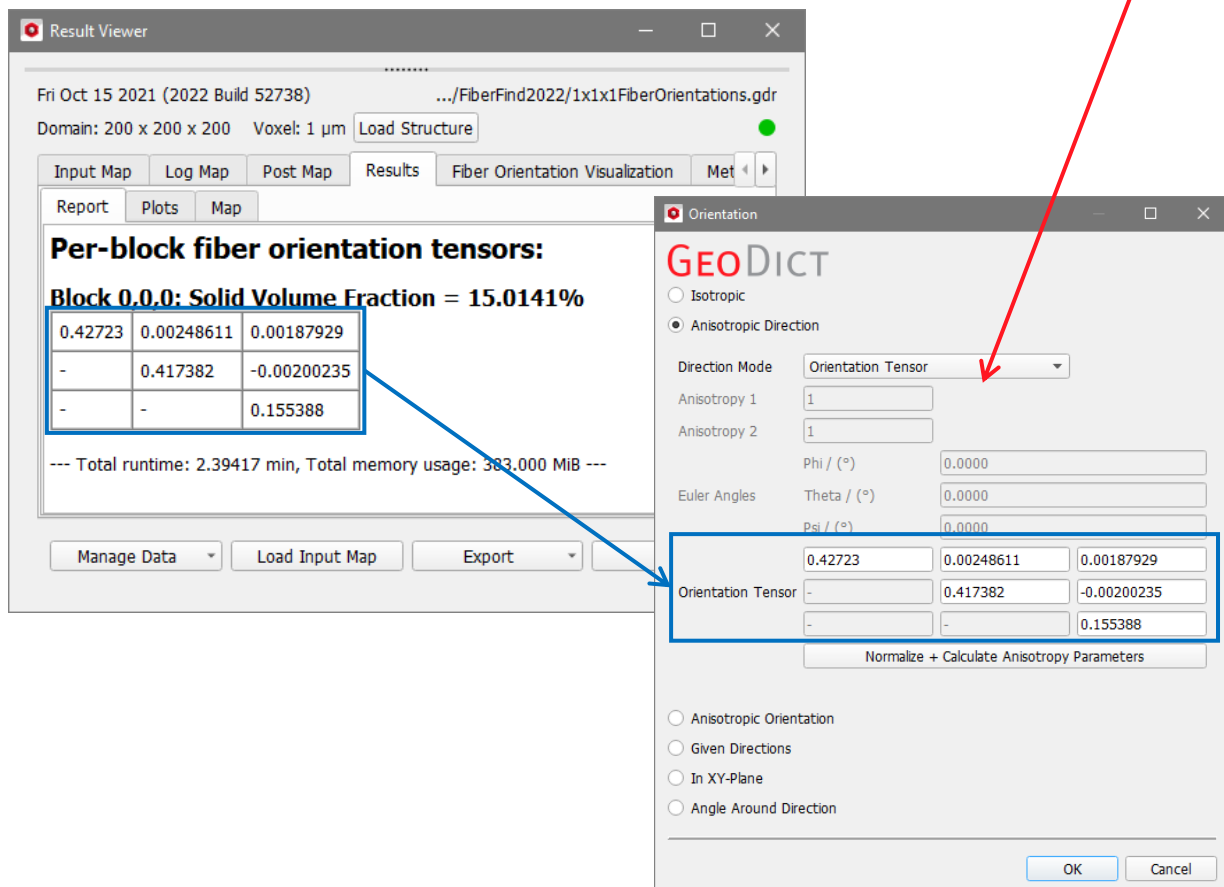
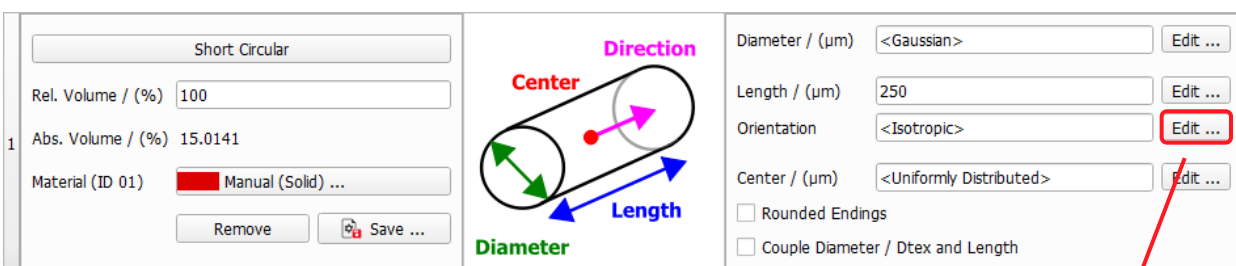
Enter a **Length** that fits to the length of fibers in the structure (e.g. the length estimated during fiber identification (see [Identify Fibers](#))).

## Identification of binder and fibers, and analysis of fiber properties

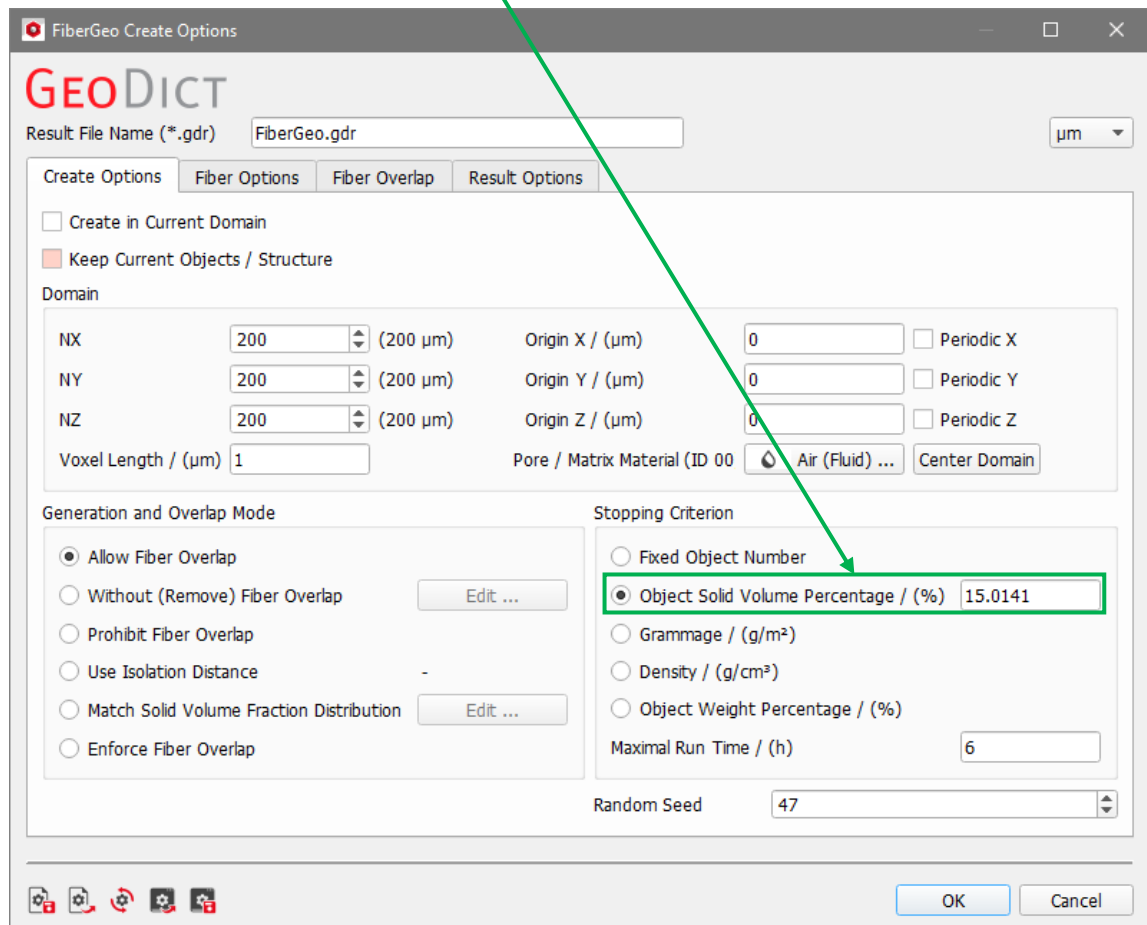
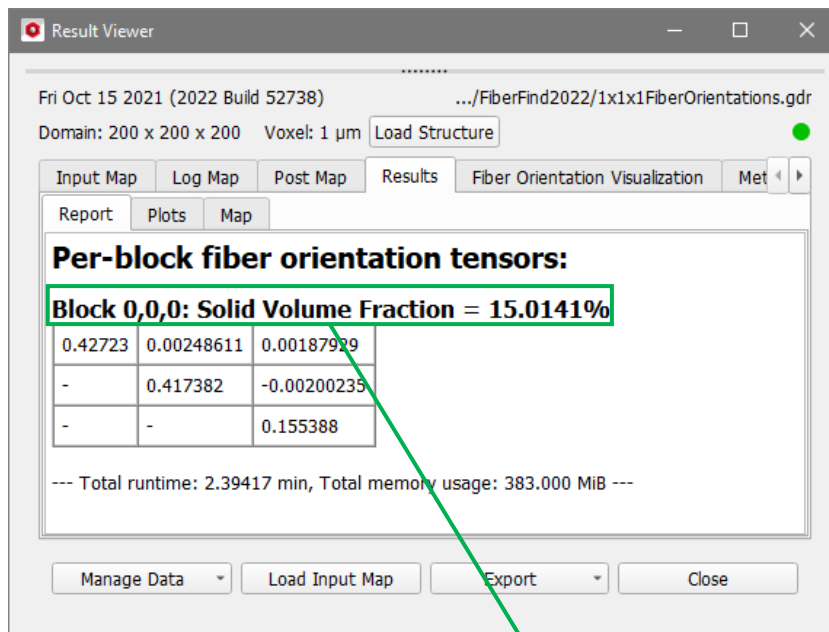
For the example shown above, with fibers going through the domain, enter a **Length** that is larger than the largest side of the domain. For a domain of 200 x 200 x 200 used here, enter e.g. a length of 250  $\mu\text{m}$ . Infinite circular fibers could be chosen as fiber type as well here. They already extend beyond the domain.



Using a fiber orientation file (\*.gdr) obtained with **FiberFind**, click now the **Orientation Edit...** button to enter these computed values.



Now, under the **Create Options** tab of **FiberGeo**, enter the estimated **Solid Volume Fraction** as **Object Solid Volume Percentage** in the Stopping Criterion panel. There are no layers and, thus, the calculated SVF corresponds to the **Object Solid Volume Percentage** of the complete media.

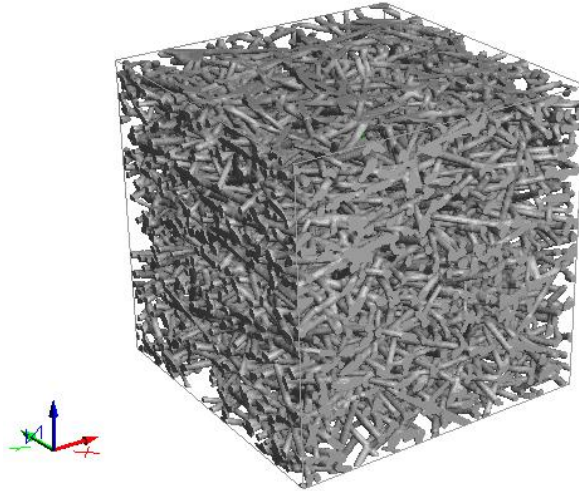




Remember to set the correct domain size (**NX, NY, NZ**) and **Voxel Length** in the Domain panel (**Create Options** tab).

Click **OK** to close the **FiberGeo Create Options** dialog and click **Generate** in the **FiberGeo** section.

The reproduced fibrous material model appears in the Visualization area, matching the values estimated by **FiberFind** for the 3D material model obtained from importing ( $\mu$ )CT images.

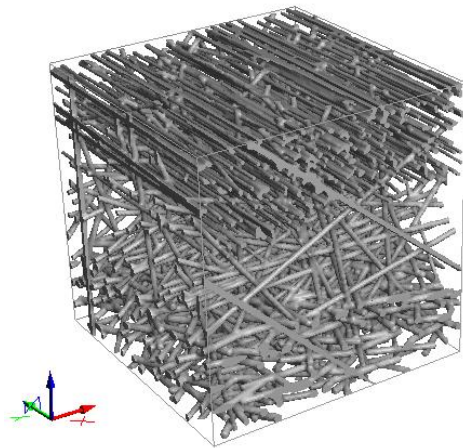


### HETEROGENEOUS (LAYERED) FIBROUS MEDIA

---

For a heterogeneous material (layered), add as many fiber types as layers are in the media, corresponding to the blocks estimated by computations with **FiberFind** (for example, on a 3D material structure model obtained from importing a ( $\mu$ )CT image).

To enter the fiber type and the fiber diameter for each of them, use the data from the fiber diameter estimation result file (\*.gdr) obtained with **FiberFind** and enter the estimated **Average inner diameter** directly.



Alternatively, click the **Diameter Edit...** button for each fiber type, choose **Gaussian** (or Log-Normal), and enter the value of the estimated **Average inner diameter** and the value of **Standard deviation** for all fiber types (as shown above on page [27](#)).

Notice that the fiber diameters of the different layers look fairly similar in the example shown. Because of this, only one fiber type (short circular) and the same values for the Gaussian distribution are selected. If the diameters should be different



in each layer, it is possible to choose three different fiber types and a different diameter distribution for each layer under the **Fiber Options** tab in **FiberGeo**.

**FiberFind**

Wed Oct 13 2021 (2022 Build 52500) .../FiberFind2022/HeterogeneousFiberDiameters.gdr

Domain: 200 x 200 x 200 Voxel: 1  $\mu\text{m}$  Load Structure

Input Map Log Map Post Map Results Data Visualization Metadata

Report Plots Map

**General Analysis of the Size Distribution (\*.gsd):**

Average inner diameter: 4.29423  $\mu\text{m}$   
Standard deviation: 918.335 nm

**Fiber Type Analysis:**

Specified Number of Types: 1

	Average Inner Diameter / ( $\mu\text{m}$ )	Standard Deviation / ( $\mu\text{m}$ )	Volume Fraction / (%)
Type 1	4.04612	1.0474	100

**FiberGeo Create Options**

Result File Name (\*.gdr) FiberGeo.gdr  $\mu\text{m}$

Create Options Fiber Options Fiber Overlap Result Options

Fiber thickness given by Diameter

1 Short Circular

Rel. Volume / (%) 100

Material (ID 01) Manual (Solid) ... Remove Save ...

2 Short Circular

Rel. Volume / (%) 100

Material (ID 02) Manual (Solid) ... Remove Save ...

3 Short Circular

Rel. Volume / (%) 100

Material (ID 03) Manual (Solid) ... Remove Save ...

Fiber Type Short Circular Add Load ... Percentages are Volume %

OK Cancel

## Identification of binder and fibers, and analysis of fiber properties

In the example shown, most fibers do not end inside the domain. For short circular fibers, enter therefore a **Length** that is larger than the largest side of the domain. For example, being the domain 200x200x200, enter a length of 250  $\mu\text{m}$ .

The fiber type Infinite Circular cannot be used here, since we want to model a structure with three different layers and therefore also need to define the center of the fibers for each layer, see below.

From the fiber orientations file (\*.gdr), enter the values from the orientation tensors calculated for each block (layer) by clicking the **Orientation's Edit...** buttons in the right panels.

The image displays the 'Result Viewer' window and three 'GEODict Orientation' dialog boxes. The 'Result Viewer' window shows the 'Per-block fiber orientation tensors' for three blocks. The 'GEODict Orientation' dialog boxes show the 'Orientation Tensor' values for each block, which are being edited.

**Block 0,0,0: Solid Volume Fraction = 18.747%**

0.413599	0.0101655	-0.00474351
-	0.343741	0.00361791
-	-	0.24266

**Block 0,0,1: Solid Volume Fraction = 8.294%**

0.581382	-0.00328144	0.000782094
-	0.118961	0.00136107
-	-	0.299657

**Block 0,0,2: Solid Volume Fraction = 17.7374%**

0.081956	0.00125727	0.00188731
-	0.836593	0.000894001
-	-	0.0814513

--- Total runtime: 1.12285 min, Total memory usage: 362.000 MiB ---

**Block 0,0,0 GEODict Orientation**

Direction Mode: Orientation Tensor

Anisotropy 1: 1.584

Anisotropy 2: 0.8463

Phi / (°): 37.7832

Euler Angles: Theta / (°): 2.8034, Psi / (°): -29.7807

Orientation Tensor: 0.413599, 0.0101655, -0.00474351, -0.343741, 0.00361791, 0.24266

**Block 0,0,1 GEODict Orientation**

Direction Mode: Orientation Tensor

Anisotropy 1: 1.037

Anisotropy 2: 8.178

Phi / (°): -90.0179

Euler Angles: Theta / (°): 41.1969, Psi / (°): 85.1967

Orientation Tensor: 0.081956, 0.00125727, 0.00188731, -0.836593, 0.000894001, 0.0814513

**Block 0,0,2 GEODict Orientation**

Direction Mode: Orientation Tensor

Anisotropy 1: 1.85

Anisotropy 2: 0.2695

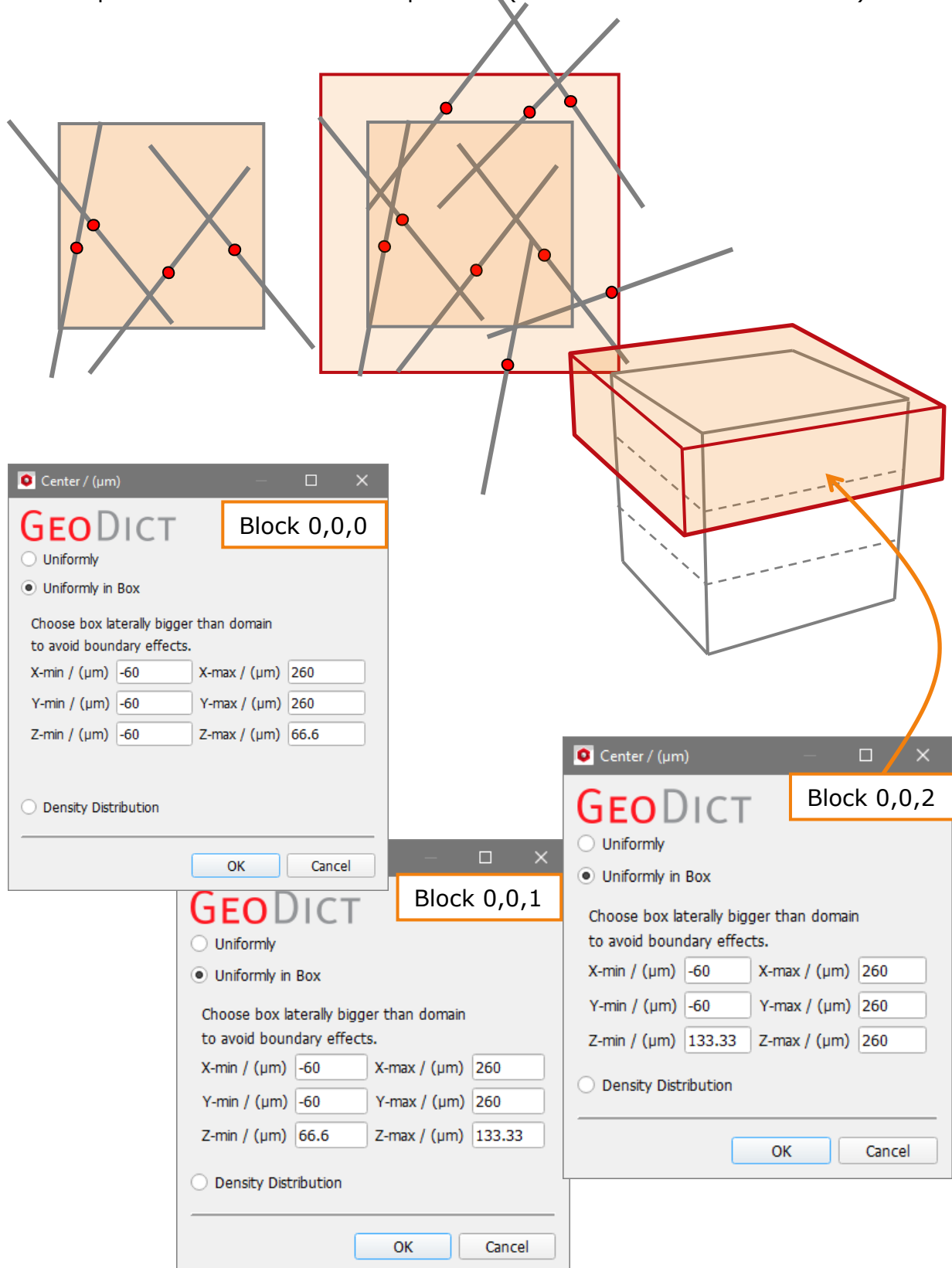
Phi / (°): -160.4775

Euler Angles: Theta / (°): 4.4608, Psi / (°): 100.0708

Orientation Tensor: 0.581382, -0.00328144, 0.000782094, -0.118961, 0.00136107, 0.299657

Next, for each layer, click the **Center' Edit...** button and place the three types of fibers in layers by setting their centers uniformly in a box.

The box for each layer should be constructed laterally bigger than the domain (200x200x200  $\mu\text{m}$ ). When the box is constrained to the domain, only fibers whose centers are inside of the domain are created. For a larger box, also fibers with a smaller part inside the domain are possible (see also the illustration below).



Finally, it is necessary to consider the contribution of every layer (fiber type) to the domain's solid volume fraction (object solid volume percentage).

Under the **Fiber Options** tab, the percentages had been selected to be viewed as **Volume%** (bottom right, see page 26). Enter the estimated solid volume fractions of the three blocks (18.747%, 8.294%, 17.7374%).

After clicking **OK** in the dialog, **FiberGeo** adjusts the percentages automatically to sum up to 100%. For example, for Block 0,0,0 with SVP of 18.747%, the contribution is 41.8662% after percentages are automatically updated.

**Result Viewer**

Fri Oct 15 2021 (2022 Build 52738) .../FiberFind2022/HeterogeneousFiberOrientation.gdr  
Domain: 200 x 200 x 200 Voxel: 1  $\mu$ m Load Structure

Input Map Log Map Post Map Results Fiber Orientation Visualization Metadata

Report Plots Map

**Per-block fiber orientation tensors:**

**Block 0,0,0: Solid Volume Fraction = 18.747%**

0.413599	0.0101655	-0.00474351
-	0.343741	0.00361791
-	-	0.24266

**Block 0,0,1: Solid Volume Fraction = 8.294%**

0.581382	-0.00328144	0.000782094
-	0.118961	0.00136107
-	-	0.299657

**Block 0,0,2: Solid Volume Fraction = 17.7374%**

0.081956	0.00125727	0.00188731
-	0.836593	0.000894001
-	-	0.0814513

--- Total runtime: 1.12285 min, Total memory usage: 362.000 MiB ---

Manage Data Load Input Map Export Close

**Stopping Criterion**

☐ Fixed Object Number

☒ Object Solid Volume Percentage / (%) 15

☐ Grammage / (g/m<sup>2</sup>)

☐ Density / (g/cm<sup>3</sup>)

☐ Object Weight Percentage / (%)

Maximal Run Time / (h) 6

**Statistics** Camera ☒ Structure

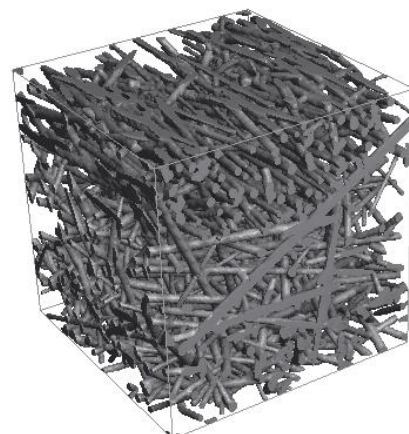
Volume % 3D: ID 01 : 15.00

Enter the Solid Volume Percentage of fibers in the structure as the Object Solid Volume Fraction in the Stopping Criterion panel, under the **Create Options** tab. The value is available under the Statistics tab in the Visualization Area.

Remember to set the correct domain size (**NX**, **NY**, **NZ**) and **Voxel Length** in the Domain panel.

Click **OK** to close the **FiberGeo Create Options** dialog and click **Generate** in the **FiberGeo** section.

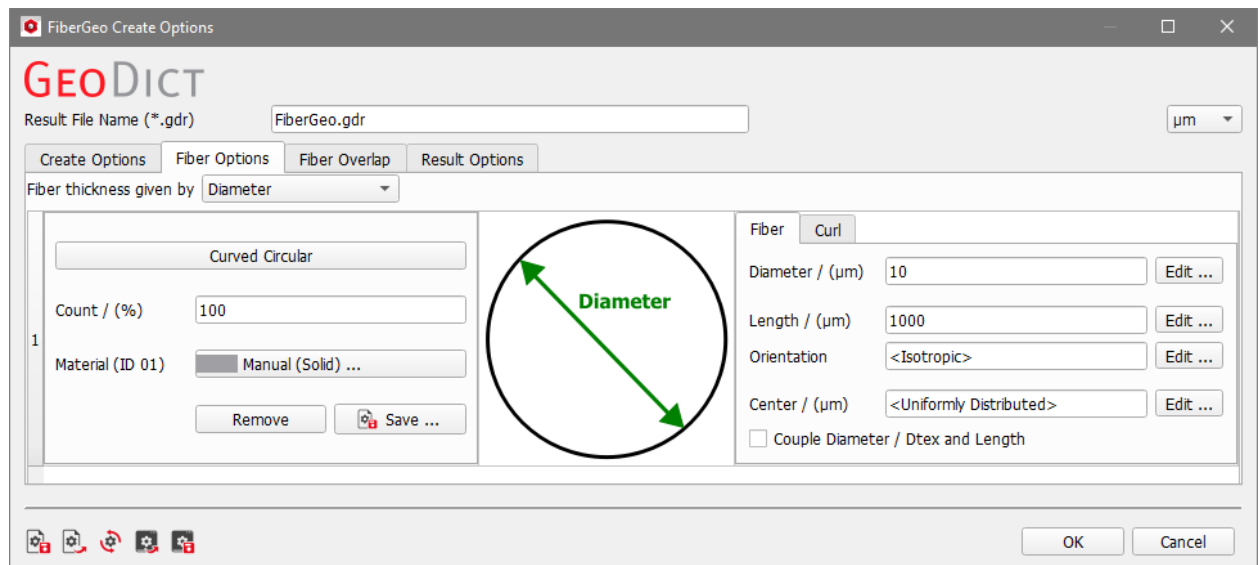
The reproduced fibrous material model is shown in the Visualization area, matching the values estimated by **FiberFind** for the 3D material model obtained from importing ( $\mu$ )CT images.



## REPRODUCING CURVATURE OF FIBROUS MEDIA

Like the fiber diameter and fiber orientation, it is also possible to create a model of a fiber structure with **FiberGeo**, using the curvature computed in **FiberFind** (see page [36](#)).

For a curved fiber type, like Curved Circular, the Curl Mode **Curvature** can be chosen, and the **Curvature Radius** as well as other parameters can be defined. The Curvature Radius is the inverse of the curvature computed in **FiberFind**. For more details on using this feature, see the [FiberGeo handbook](#) of this User Guide in the section **Curl Parameters**.

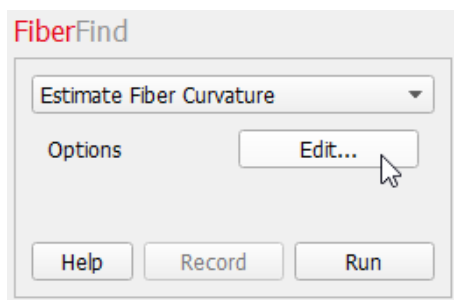


## ESTIMATE FIBER CURVATURE

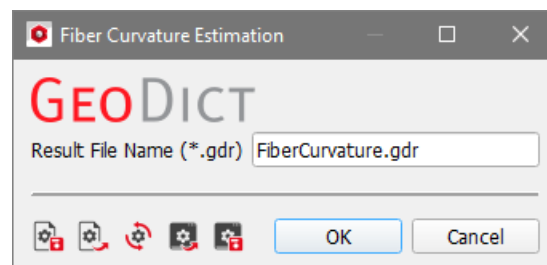
An analytic representation of the fibers (.gad file in **GeoDict** or .gdt file containing analytic data) is used for the estimation of curvature and curliness in **FiberFind**.

If such analytic data is available and loaded into the **GeoDict** GUI, the algorithm works directly on this representation, which can be created e.g. by running a fiber identification with **FiberFind** (see [Identify Fibers](#)).

If the computation is started on a voxel image, the analytic fiber identification algorithm (i.e., the one available for the Identification Method **Analytic**, see page [40](#)) is applied to the structure before the curvature estimation.



For the estimation of curvature and curliness in **FiberFind**, in the **FiberFind** section, select **Estimate Fiber Curvature** from the pull-down menu and click the **Options' Edit...** button.

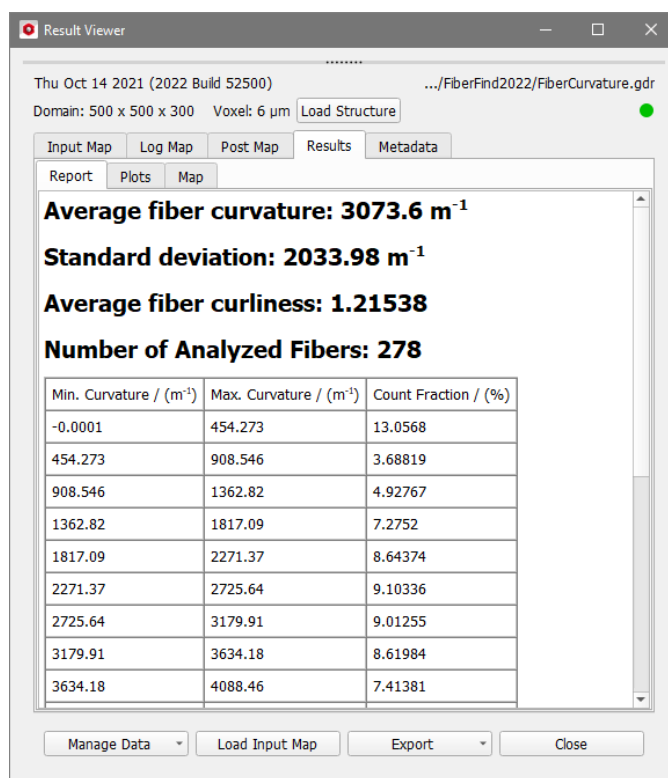


In the **Fiber Curvature Estimation** dialog, enter the desired **Result File Name (.gdr)**.

After the fiber curvature calculations are finished, a Result Viewer for the FiberCurvature.gdr file opens.

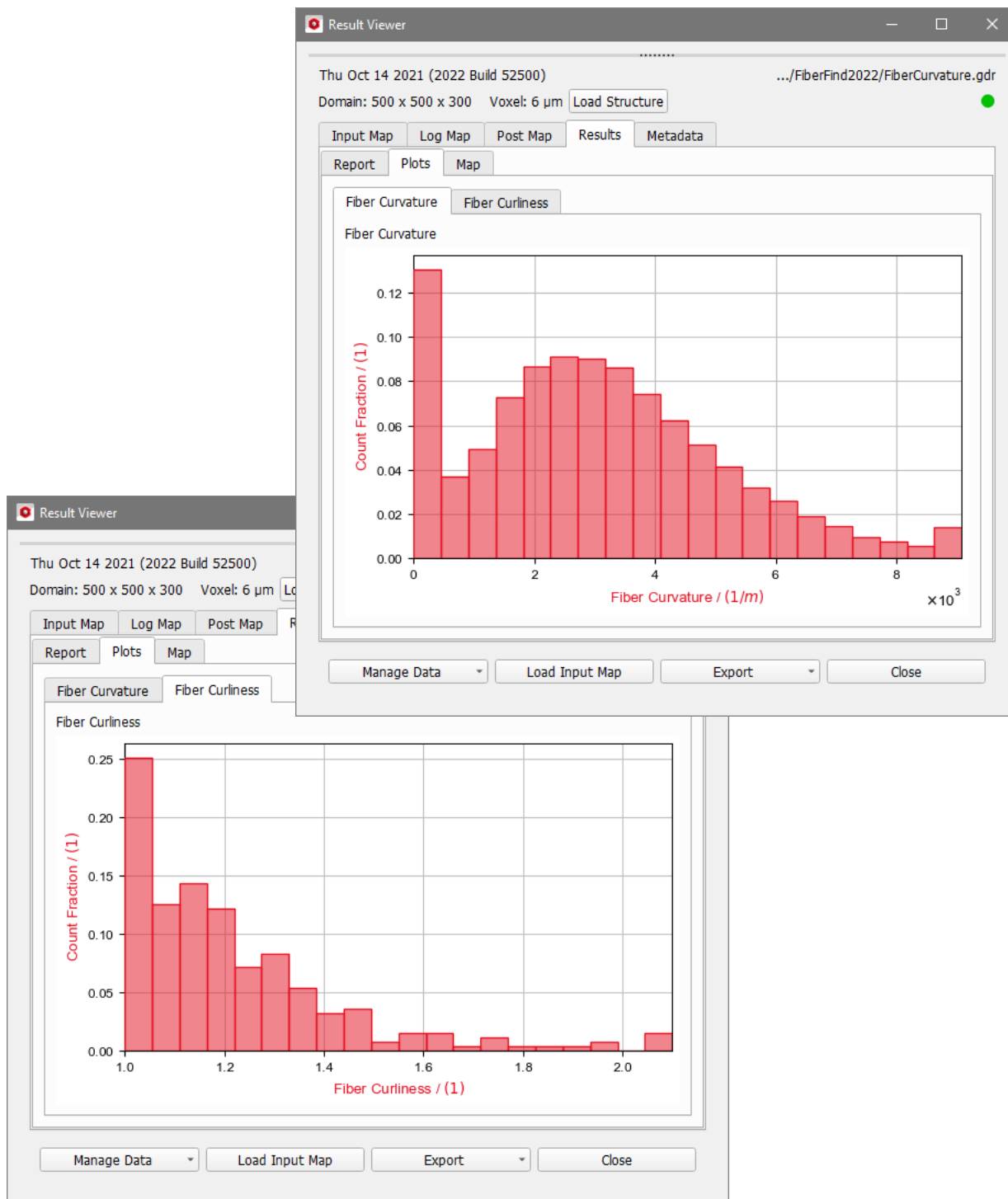
Under the **Results - Report** tab, it displays the measured **Average fiber curvature** (and its **Standard deviation**) and the **Average fiber curliness** for the given **Number of Analyzed Fibers**.

Below, a table gives the distribution of fiber curvature, listing the **Count Fraction (%)** for the ranges of calculated fiber curvatures.



Under the **Results - Plots** subtab, diagrams show the distribution of fiber curvature and fiber curliness, corresponding to the count fractions for curvatures and curliness of fibers present in the domain.

In our example, the highest count fractions correspond to fibers with low curvature and low curliness.



Besides analyzing the fiber curvature in the structure, **FiberFind** creates a model of the structure by extracting all fibers of the structure and creating fitting analytic fiber models if no analytic data was available for the structure before.



### IDENTIFY FIBERS (AI)

The final goal of all **FiberFind** tools is to obtain accurate statistical parameters for advanced material design, that can be used e.g., as input data for **FiberGeo**.

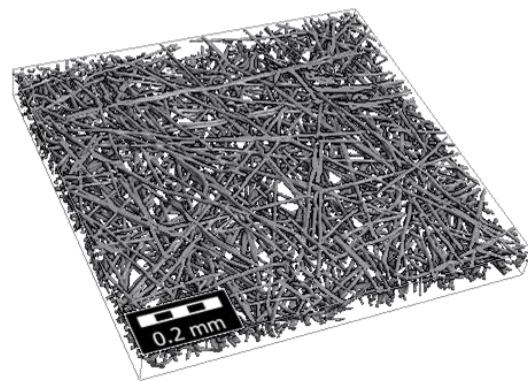
Since **GeoDict** 2019, two distinct approaches are followed in **FiberFind**'s **Identify Fibers** for the identification of individual fibers. The first approach uses classical image processing methods, the second one is an Artificial Intelligence (AI) approach. See [Theory – Approaches for fiber identification](#) for more details.

1. The identification of fibers with classical image processing methods is optimized for low density fibrous materials. **FiberFind** identifies fibers by creating a skeleton, that preserves the topology of the fibers. This skeleton is used to determine the center lines of the fibers.
2. The AI approach uses a neural network that has been trained with great amounts of input data. The training data for ground truth is created with **FiberGeo**. Therefore, this approach is capable of identifying individual fibers in a structure, as long as the input data for the training was close enough to the fiber properties in the real 3D-scan.

The start of the computation is again a three-dimensional model that has been obtained from segmented computer tomography (or FIB/SEM) images of the material. Fiber identification provides advanced structure statistics, such as fiber length, number of fibers and better local fiber orientation, as well as object-based image manipulation (for example, changing the diameter of fibers directly from the imported CT-scan images).

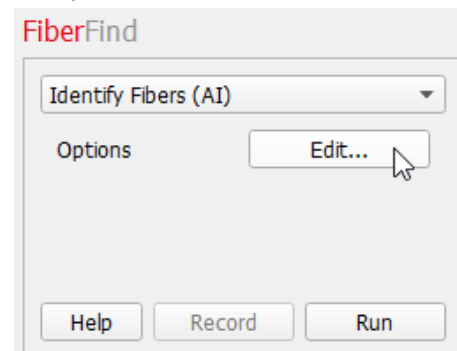
The example shown here, is a part of the imported FIB/SEM image of a carbon paper gas diffusion layer (GDL) used for a proton-exchange membrane (PEM) fuel cell. The binder has already been removed with **BinderFind**-AI (see [Identify Binder \(AI\)](#)).

The input data used, as well as a detailed description of the necessary processing steps, can be found in the tutorial *Digital analysis of fibers and binder content of four carbon paper GDLs*, on the [GeoDict website](#).



To start, select **Analyze → FiberFind** from the menu bar and, in the **FiberFind** section, select **Identify Fibers (AI)** from the pull-down menu. Click the **Options' Edit...** button.

The **Fiber Identification** dialog that opens contains three tabs: **Solver Options**, **Fiber Identification** and **Output Options**.

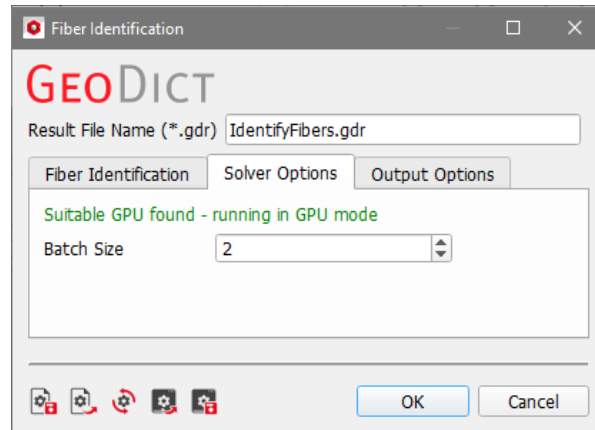




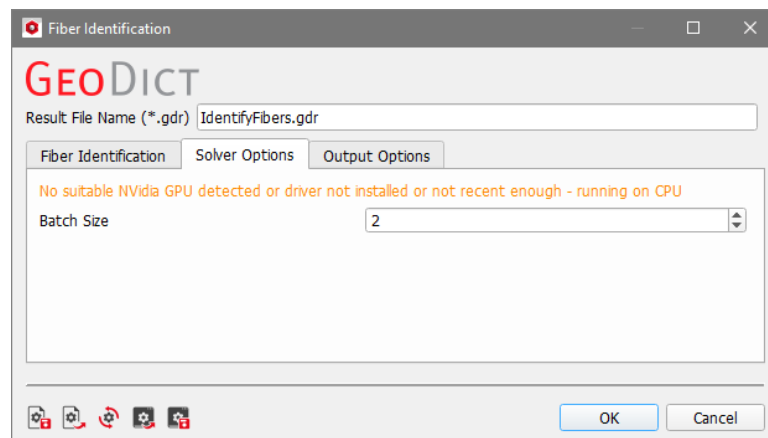
## SOLVER OPTIONS

Note that this tab is only used, as long as **Machine Learning** is selected from the **Identification Method** pull-down menu under the **Fiber Identification** tab.

If a suitable graphics card is detected during installation of **GeoDict**, the GPU mode is used for running **FiberFind-AI**, otherwise it is running in CPU mode.

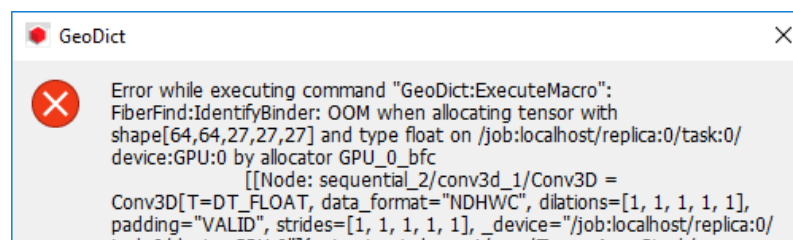


The version used is displayed on the **Solver Options** tab.



Second, the choice for **Batch Size** is related to the memory available on the graphics card (GPU). Conceptually, **FiberFind** loads the graphics card with portions of work called **batches**. Currently, the selection must be made manually, and the parameter is set following the value entered in **Batch Size**.

The batch size might be chosen too large for what is available on the graphics card. In this case, an error message appears.

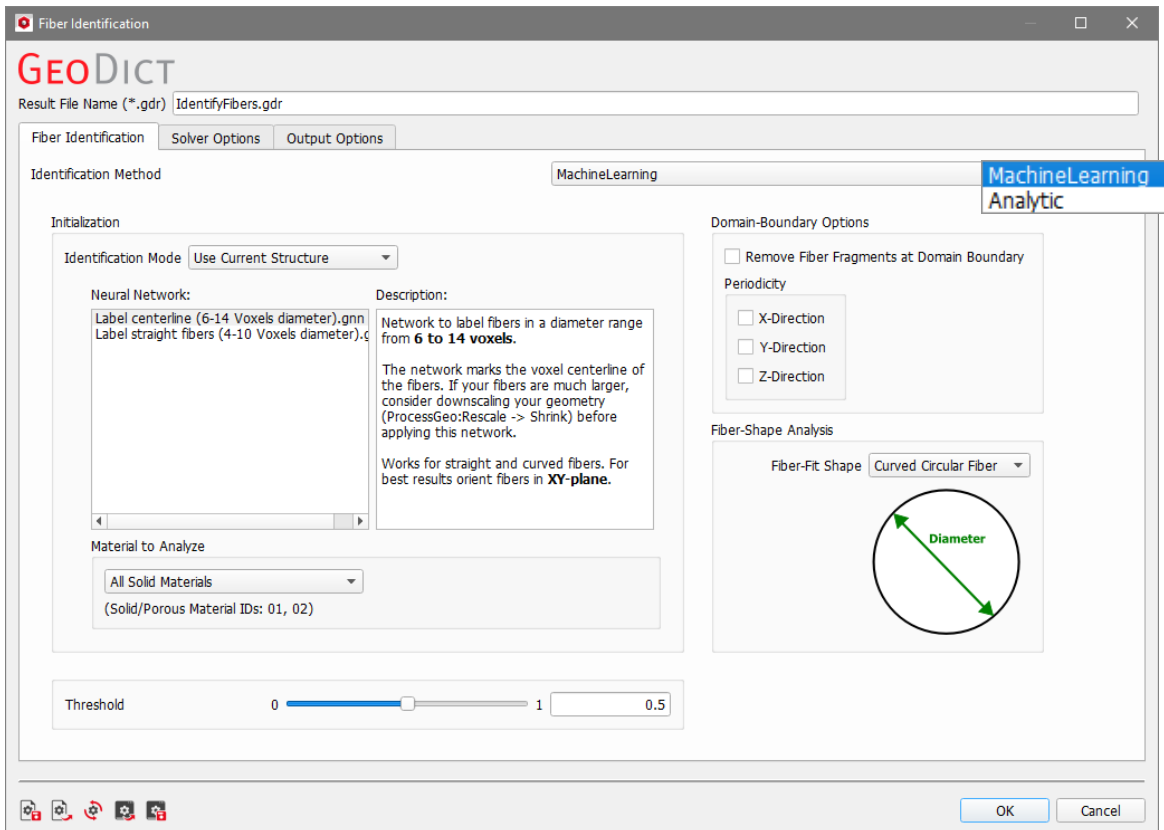


In this case, the number of batches needs to be reduced. Note that for CPU-based computation, the choice of batch size is not critical and can be left at the default.

For the neural networks, available since **GeoDict** 2020 SP3 it is recommended to reduce the batch size to 1 or 2 (for Fiber Identification: *Label straight fibers (4-10 Voxels diameter).gnn* and for Binder Identification: *Label binder in round fiber structures.gnn*).

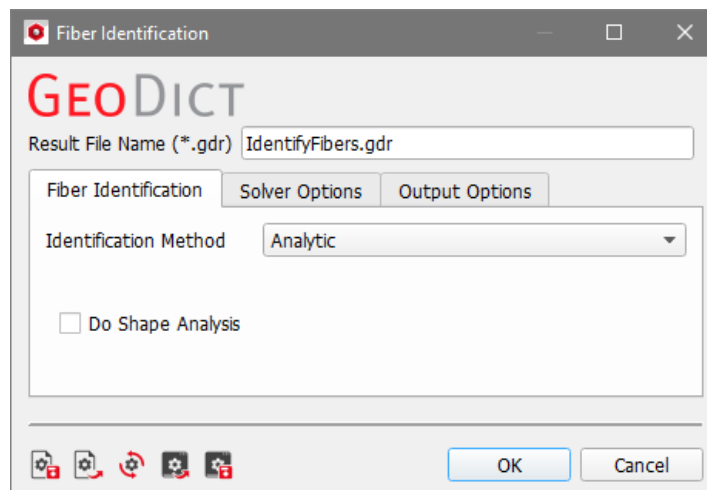
### FIBER IDENTIFICATION

First, choose between two **Identification Methods**: **Machine Learning** for the AI approach, or **Analytic** to use the classical image processing approach.



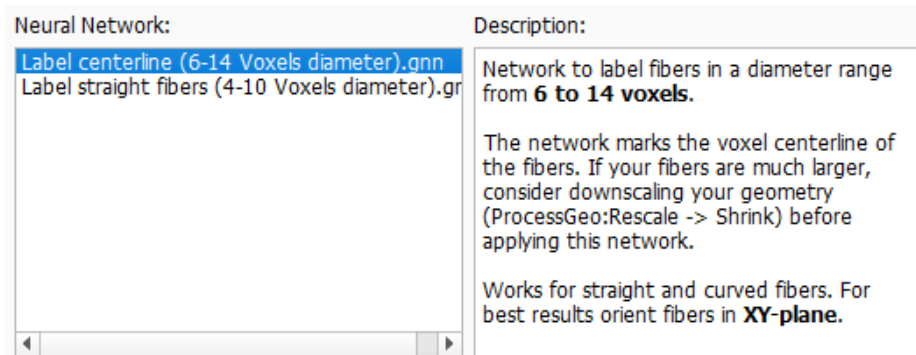
If **Analytic** is selected as **Identification Method**, the **Fiber Identification** dialog changes and then contains the single option to **Do Shape Analysis**.

Checking **Do Shape Analysis** allows a more detailed analysis of the fiber shape to detect parallel fibers but increases the runtime significantly. If the user does not check **Do Shape Analysis**, the regular analytic fiber identification method is carried out.



After choosing **Machine Learning** as the **Identification Method**, several other options are available in the **Fiber Identification** dialog. However, for most of the application cases, the default values can be kept for most of the options.

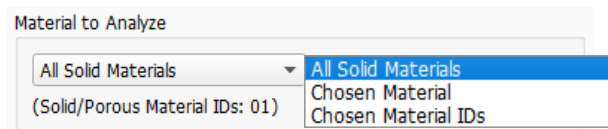
Select the neural network best suitable for the structure under consideration under **Neural Network** (.gnn stands for **GeoDict neural network**).



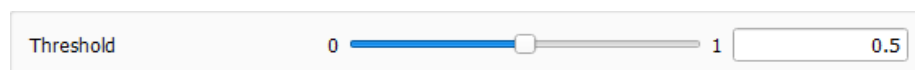
For the second neural network available, *Label straight fibers (4-10 Voxels diameter).gnn*, it is recommended to set the batch size for the computation on the tab **Solver Options** (see page 39) to a small value (1 or 2).

In the **Description**, the current constraints for the application of the neural network are listed, like the diameter range of the fibers for that the neural network was trained.

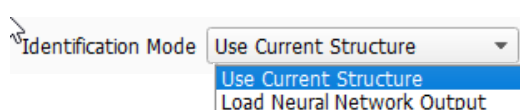
The **Material to Analyze** panel offers the choice of whether **FiberFind-AI** should be applied to all solid and porous materials in the structure or only on a subset, defined either by choosing material IDs or materials.



The **Threshold** is an internal (or expert) parameter that is mostly applied by proficient users at **Math2Market**. It is used for the decision whether a voxel is a centerline voxel or not. If the identified fibers are over-segmented, choosing a smaller threshold can lead to better results.

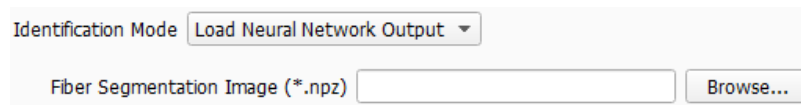


Two choices are available as **Identification Mode: Use Current Structure** and **Load Neural Network Output**.

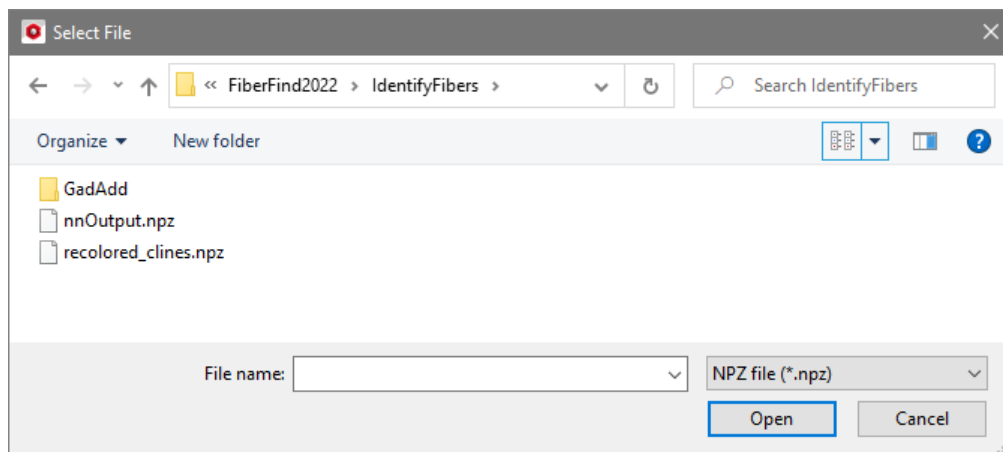


The default **Use Current Structure** should usually not be changed, meaning that **FiberFind-AI** will be applied to the structure that **GeoDict** currently has in memory.

On occasion, the user may want to change the threshold, without having to run the identification for each voxel with the neural network again and in that case, the option **Load Neural Network Output** may be very useful.

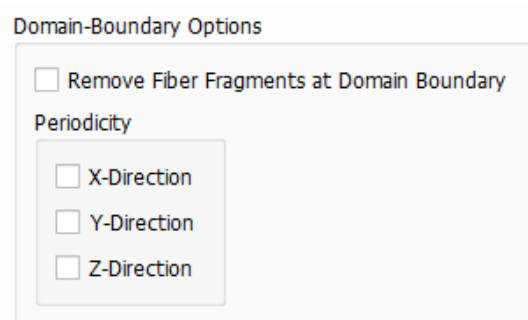


Browse to a **GeoDict** result folder of a previous run of **FiberFind-AI** and select a **nnOutput.npz** file from that folder. Accordingly, the **Material to Analyze** and the **Neural Network** to be used cannot be changed, and the loaded structure needs to be the same.



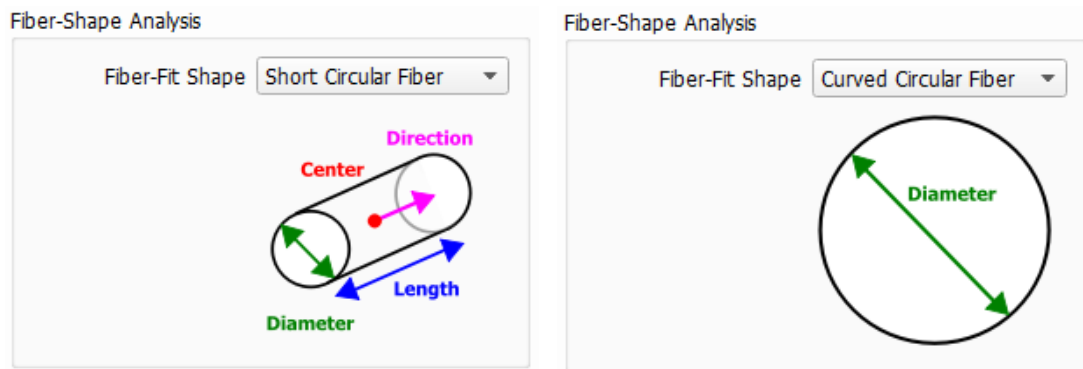
The underlying domain can be set as periodic for the fiber identification by checking one or several of the boxes in the **Domain-Boundary Options** panel.

However, periodicity is unusual for most 3D scans and this setting is rarely changed.



Check the **Remove Fiber Fragments at Domain Boundary** in this panel, to remove all fibers that touch the boundary of the domain after the fiber identification algorithm.

Finally, in the lower right of the **Fiber Identification** dialog, in the **Fiber-Shape Analysis** panel, select the type of fibers in the structure. **Curved Circular Fiber** or **Short Circular Fiber** are available.



Selecting **Curved Circular Fiber**, **FiberFind** performs the identification under the assumption that the structure might contain curved fibers.

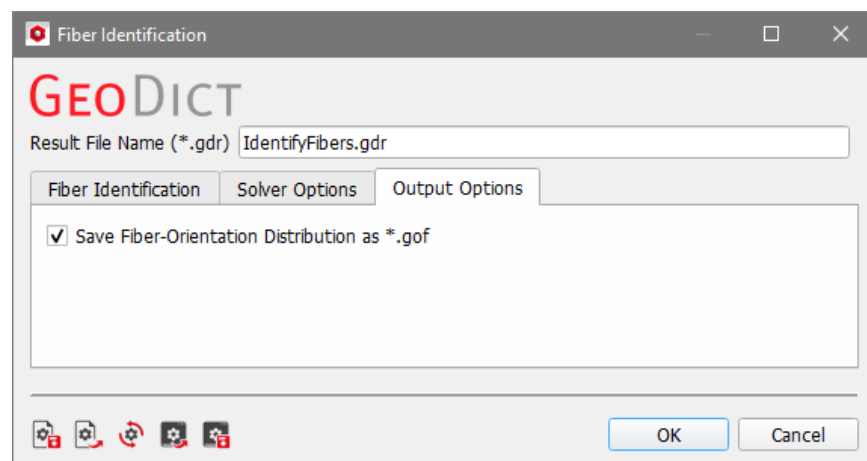
If **Short Circular Fiber** is chosen, fibers are identified twice: once with the default option of curved fibers and once under the assumption of straight fibers only. For the computation of fiber length distribution and fiber orientation, the result of the curved fiber identification is always used.

## OUTPUT OPTIONS

On the output options tab, check **Save Fiber-Orientation Distribution as \*.gof**, if the information about fiber orientation should be saved for later visualization, see page 57.

The .gof file contains a volume field with an orientation tensor for each voxel. This option is available only, for the Fiber Identification Mode **MachineLearning**, see page 40.

For the Fiber Identification Mode **Analytic**, a .gof file is always saved in the result folder.

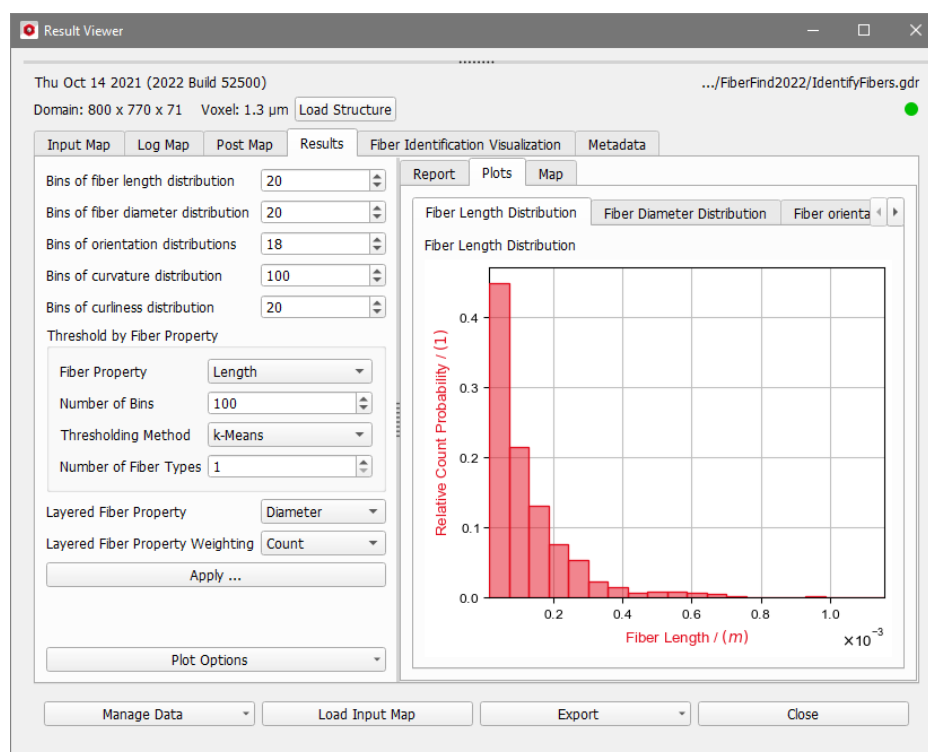


## FIBER IDENTIFICATION RESULTS

After running the fiber identification, a folder with the same name as the **GeoDict** result file is saved in the chosen project folder (**File → Choose Project Folder...** in the menu bar). This folder contains folders and files needed internally for the calculations. The content of the folder depends on the selected **Identification Method** and parameters. The original structure model on which the identification was done is also saved in the folder.

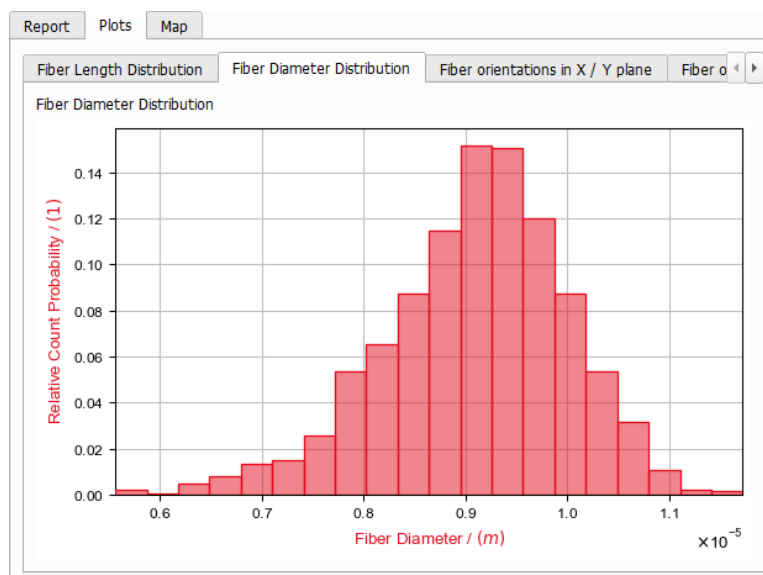
The **GeoDict** Result Viewer opens for the result file and statistical properties of the identified fibers are shown.

In the Result Viewer, under the **Results - Plots** subtab, the user finds histogram plots of the fiber length distribution and, for **Identification Method Machine Learning**, the fiber diameter distribution.

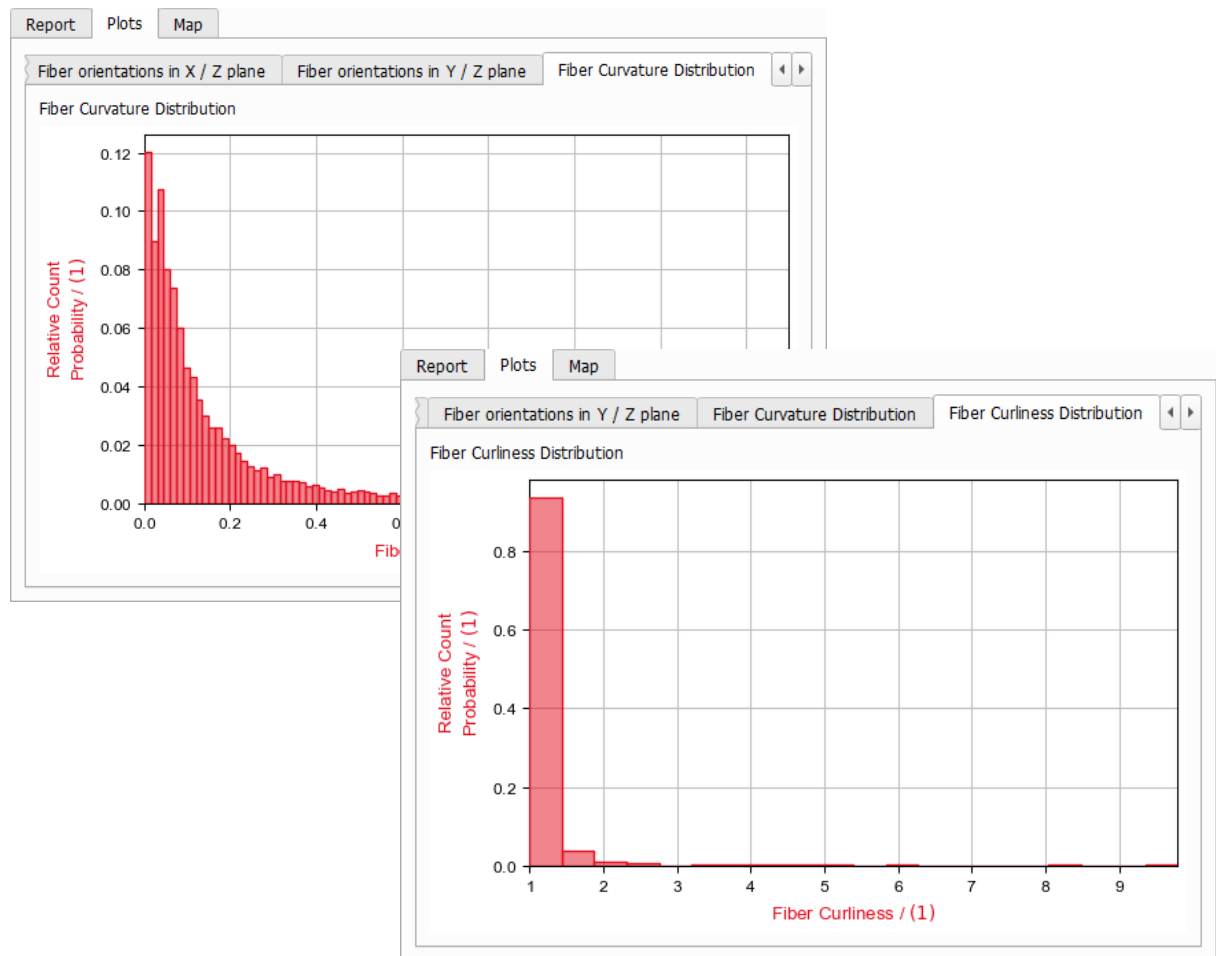


On the left panel of the **Plots** subtab, the number of bins for all distributions shown in the plots can be selected. Click **Apply** to generate the plots for a different number of bins.

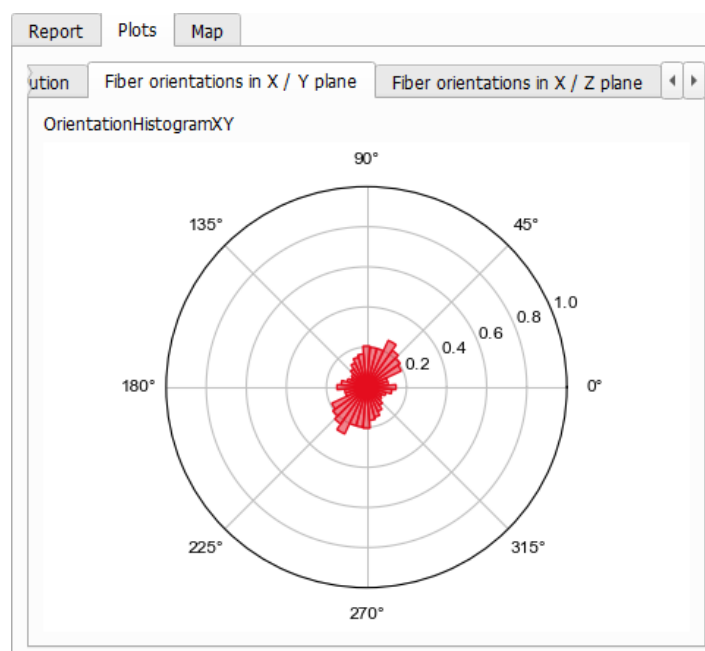
Other options that can be selected in the post-processing panel on the left, are explained below, see page [47](#).



Also present are plots of the **Fiber Curvature Distribution** and the **Fiber Curliness Distribution**, as well as three plots showing the fiber orientation as histograms of projections of the fibers to two-dimensional planes.



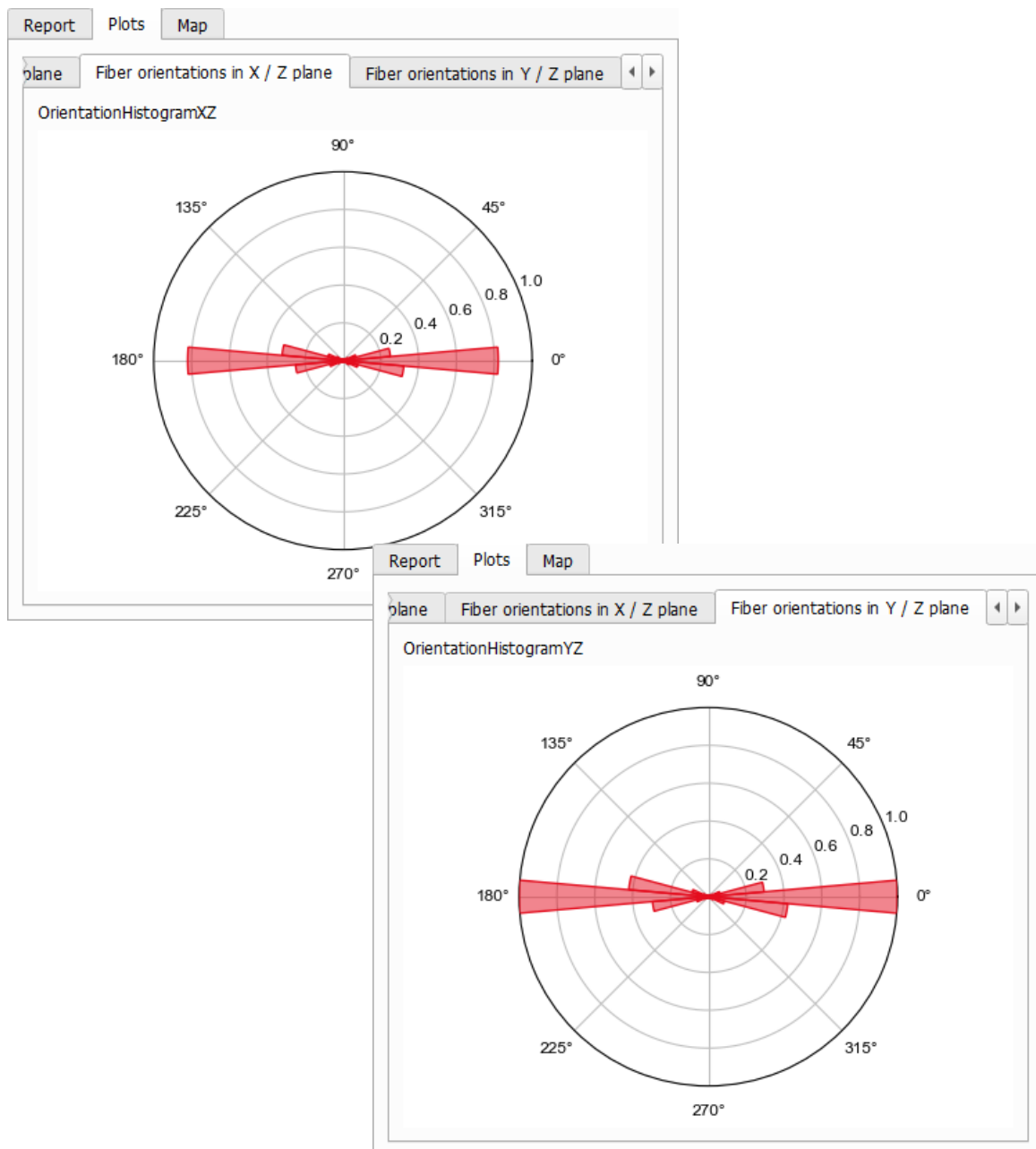
To compute the three orientation histograms, each fiber is projected to the two-dimensional plane. The angle of each fiber segment, weighted with the length of the segment, gives an entry in one bin of the histogram, i.e., in one segment of the circle.





The number of fiber segments for an orientation in the plane is given by the size of a segment of the circle. Since the histograms are normalized, this number is always a value between 0 and 1. The histogram is symmetric since fiber orientations of  $0^\circ$  and  $180^\circ$  are undistinguishable.

Fibers in this example are oriented mainly in the X/Y plane, a bit more in Y-direction than in X-direction. Histograms of X/Z plane and Y/Z plane show large segments for  $0^\circ$  and  $180^\circ$ , and segments in Y-direction are even a bit larger. In contrast, the plot of X/Y plane shows a more homogeneous distribution of fibers in this plane, but the preference for Y-direction is also visible there.



Besides the bin length for each of the histograms shown, that can be selected by the user, additional post-processing options are now available in GeoDict 2022.

In the histograms of fiber length and diameter, the fibers can be classified with respect to a lot of fiber properties.

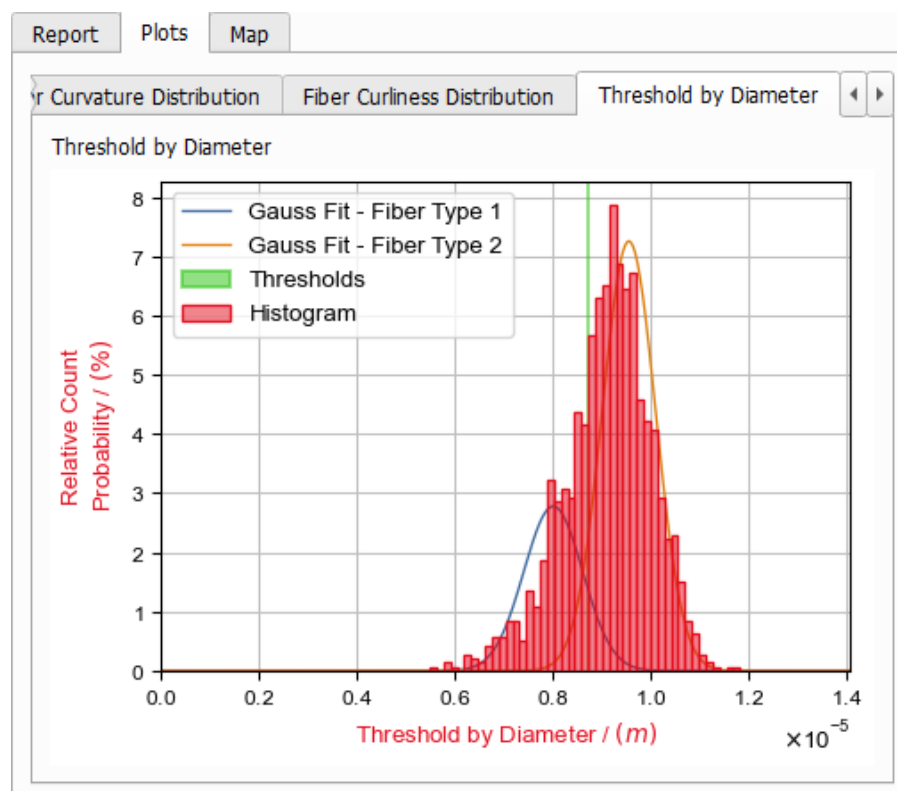
Threshold by Fiber Property

Fiber Property	Diameter	Length Diameter Curliness Curvature CenterOfMassZ AngleToX AngleToY AngleToZ
Number of Bins	100	
Thresholding Method	k-Means	k-Means Otsu Manual
Number of Fiber Types	2	

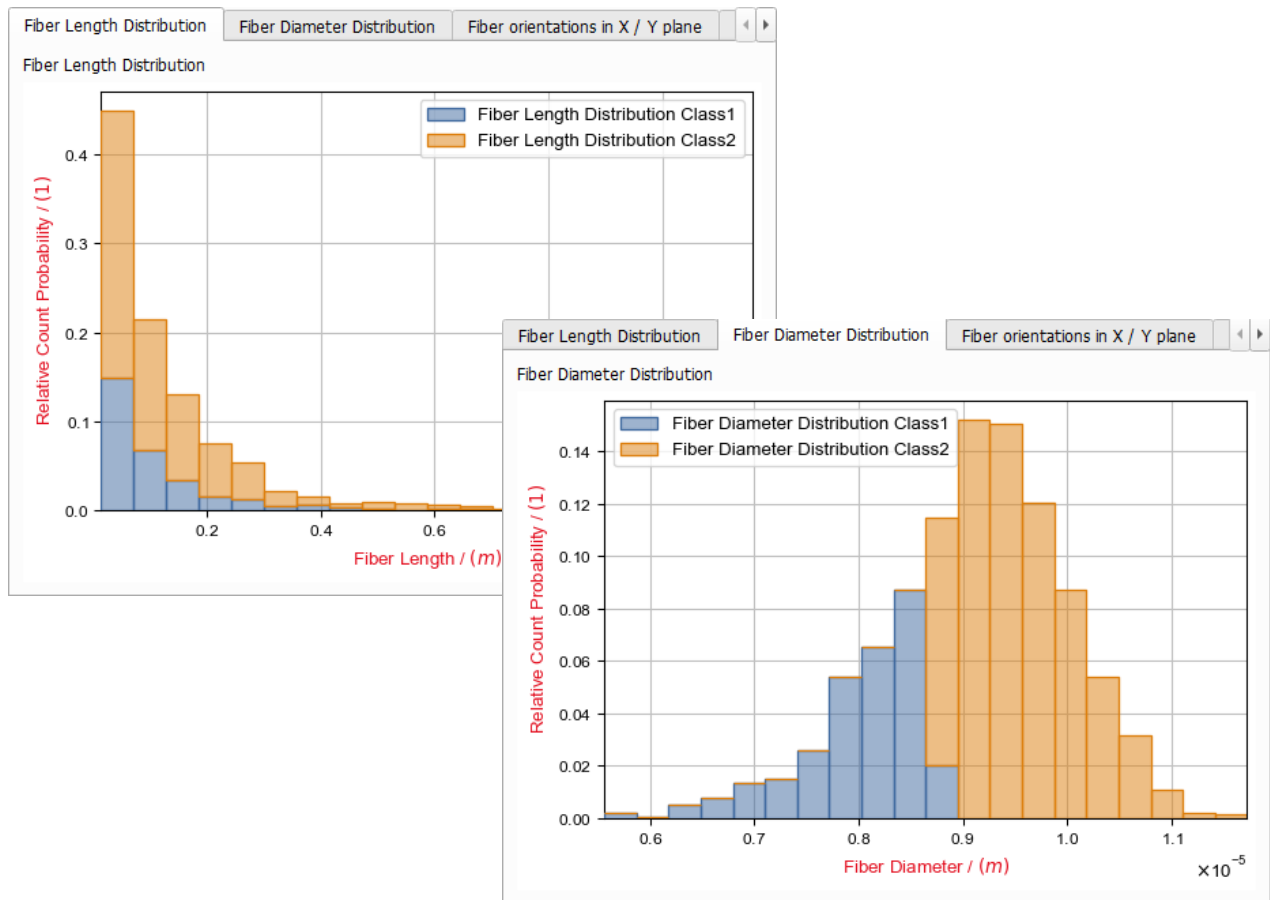
Select a **Fiber Property** for the classification and define the number of different classes by choosing the **Number of Fiber Types**. In the example shown, fibers are separated into two classes according to their diameter.

Select a **Thresholding Method** for the differentiation of fibers of different type (**k-Means**, **Otsu's method** or define a **Manual** threshold) and the **Number of Bins** used for the separation of fibers.

Here, 100 bins are used to separate the fibers according to the k-Means method. Click **Apply** to change the **Fiber Length Distribution** histogram and, if available, the **Fiber Diameter Distribution** histogram. An additional tab (here **Threshold by Diameter**), containing the fiber diameter distribution with the number of bins defined for the thresholding, the resulting threshold for the method selected, and a Gaussian fit for both fiber types, is created.



On the **Fiber Length Distribution** histogram and the **Fiber Diameter Distribution** histogram tabs, the histograms are shown now as stacked values for both fiber types.



The classification of fibers is also included in the Results Report, see page [50](#).

The structure with the separated fiber types, can be loaded to the Visualization Area under the **Fiber Identification Visualization** tab, see page [52](#).

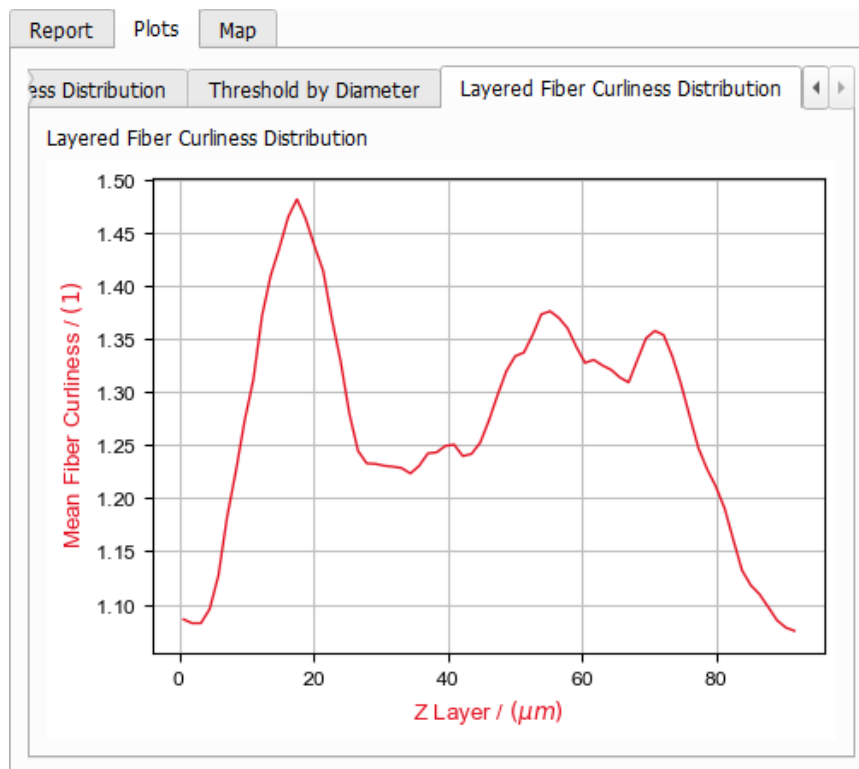
To create an additional tab, showing the layered values in z-direction for a fiber property, select a **Layered Fiber Property** from the pull-down menu. With **Layered Fiber Property Weighting** define if the mean in each layer is computed with respect to the number, the volume or the length of the fibers.

Click **Apply**.

Layered Fiber Property	Curliness	Length Diameter Curliness Curvature CenterOfMassZ AngleToX AngleToY AngleToZ
Layered Fiber Property Weighting	Volume	
<input type="button" value="Apply ..."/>		
		Count Volume Length

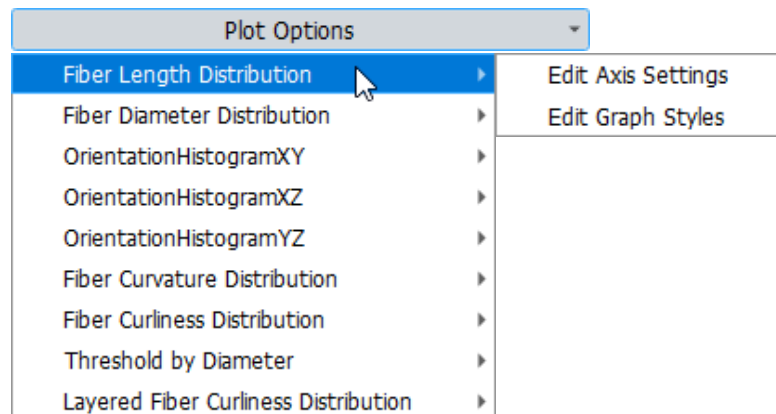
A new tab for the layered distribution is added to the **Plots** subtab, according to the values selected.

For the example shown here, the tab **Layered Fiber Curliness Distribution** is created, showing the mean fiber curliness (weighted with respect to the fiber volume) for each layer in z-direction of the structure.



Note that the visualization of layered fiber properties in z-direction is only possible for **Identification Method Machine Learning**.

Click on **Plot Options** and select one of the histograms available, to access directly the dialog boxes for changing the Axis Settings or Graph Styles. These dialogs can be accessed as well by a right mouse-click in the histogram.



For more details on modifying plot settings, see the [Result Viewer handbook](#) of this User Guide.

The information about fiber orientation, fiber length distribution, fiber diameter distribution, fiber curvature distribution and fiber curliness distribution is also available in tables under the **Results - Report** subtab.

In this report, first the total number of identified fibers is shown, here 1397.

Next, a table shows the number of fibers, the mean diameter, mean length, mean curvature, and mean curliness and the orientation for each fiber type, defined via the Threshold by Fiber Property, see page [47](#).

Thu Oct 14 2021 (2022 Build 52500) .../FiberFind2022/IdentifyFibers.gdr

Domain: 800 x 770 x 71 Voxel: 1.3 µm Load Structure

Input Map Log Map Post Map Results Fiber Identification Visualization Metadata

Bins of fiber length distribution 20

Bins of fiber diameter distribution 20

Bins of orientation distributions 18

Bins of curvature distribution 100

Bins of curliness distribution 20

Threshold by Fiber Property

Fiber Property Diameter

Number of Bins 100

Thresholding Method k-Means

Number of Fiber Types 2

Layered Fiber Property Curliness

Layered Fiber Property Weighting Volume

Apply ...

Plot Options

Manage Data Load Input Map Export Close

**FiberFind**

Found 1397 individual Fibers in the structure

Fiber properties segmented by Diameter:

Property	Class1	Class2																		
Number of Fibers	414	983																		
Diameter	8.01051 µm	9.5502 µm																		
Length	107.364 µm	132.341 µm																		
Curvature	13156.8 1/m	inf 1/m																		
Curliness	1.14131	1.12611																		
Orientation	<p>Orientation Tensor:</p> <table border="1"> <tr> <td>0.4247</td> <td>0.0605</td> <td>-0.0047</td> </tr> <tr> <td>-</td> <td>0.5308</td> <td>-0.0103</td> </tr> <tr> <td>-</td> <td>-</td> <td>0.0445</td> </tr> </table> <p>Anisotropy 1: 4.989 Anisotropy 2: 1.401 Euler Angles (Phi, Theta, Psi): 155.003, 1.261, -179.375</p>	0.4247	0.0605	-0.0047	-	0.5308	-0.0103	-	-	0.0445	<p>Orientation Tensor:</p> <table border="1"> <tr> <td>0.4094</td> <td>0.0762</td> <td>-0.0049</td> </tr> <tr> <td>-</td> <td>0.5436</td> <td>-0.0071</td> </tr> <tr> <td>-</td> <td>-</td> <td>0.0470</td> </tr> </table> <p>Anisotropy 1: 4.572 Anisotropy 2: 1.531 Euler Angles (Phi, Theta, Psi): 139.451, 0.947, -163.781</p>	0.4094	0.0762	-0.0049	-	0.5436	-0.0071	-	-	0.0470
0.4247	0.0605	-0.0047																		
-	0.5308	-0.0103																		
-	-	0.0445																		
0.4094	0.0762	-0.0049																		
-	0.5436	-0.0071																		
-	-	0.0470																		

The fiber type specific information is followed by the values for all fibers. First, the orientation of all fibers is reported.

Report Plots Map

Fiber properties for all fibers:

Orientation Tensor:

0.4132	0.0723	-0.0048
-	0.5404	-0.0079
-	-	0.0464

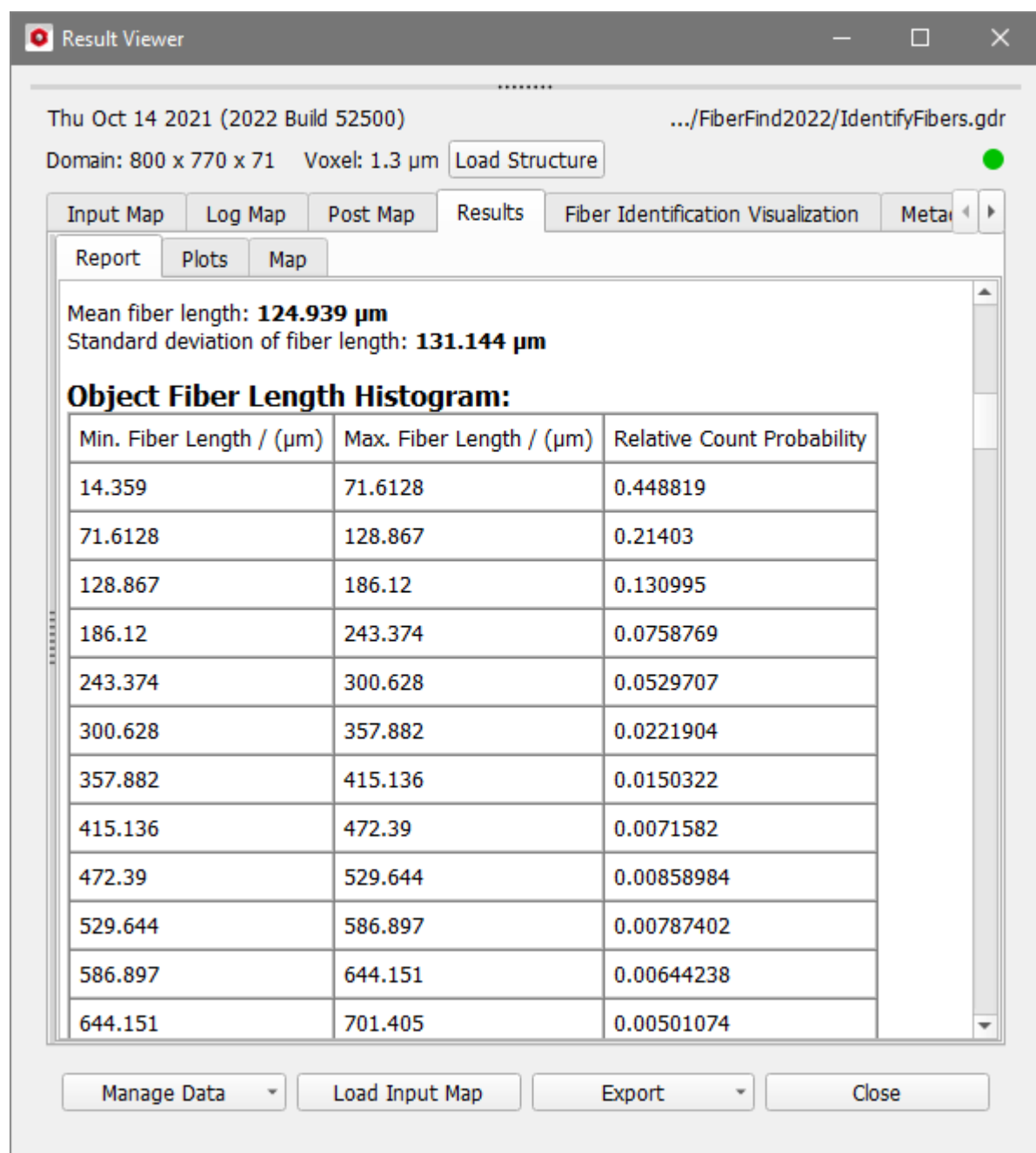
Anisotropy 1: 4.674  
Anisotropy 2: 1.498  
Euler Angles (Phi, Theta, Psi): 144.338, 1.014, -168.678

Since most of the fibers in the example are oriented in X/Y plane, the diagonal entries of the orientation tensor for X-direction (0.4132) and Y-direction (0.5404) are larger than for Z-direction (0.0464). The value for Y is higher than the one for X, showing again the dominance of Y- over X-direction.

The anisotropy values, together with the Euler angles, are another representation of the orientation tensor.

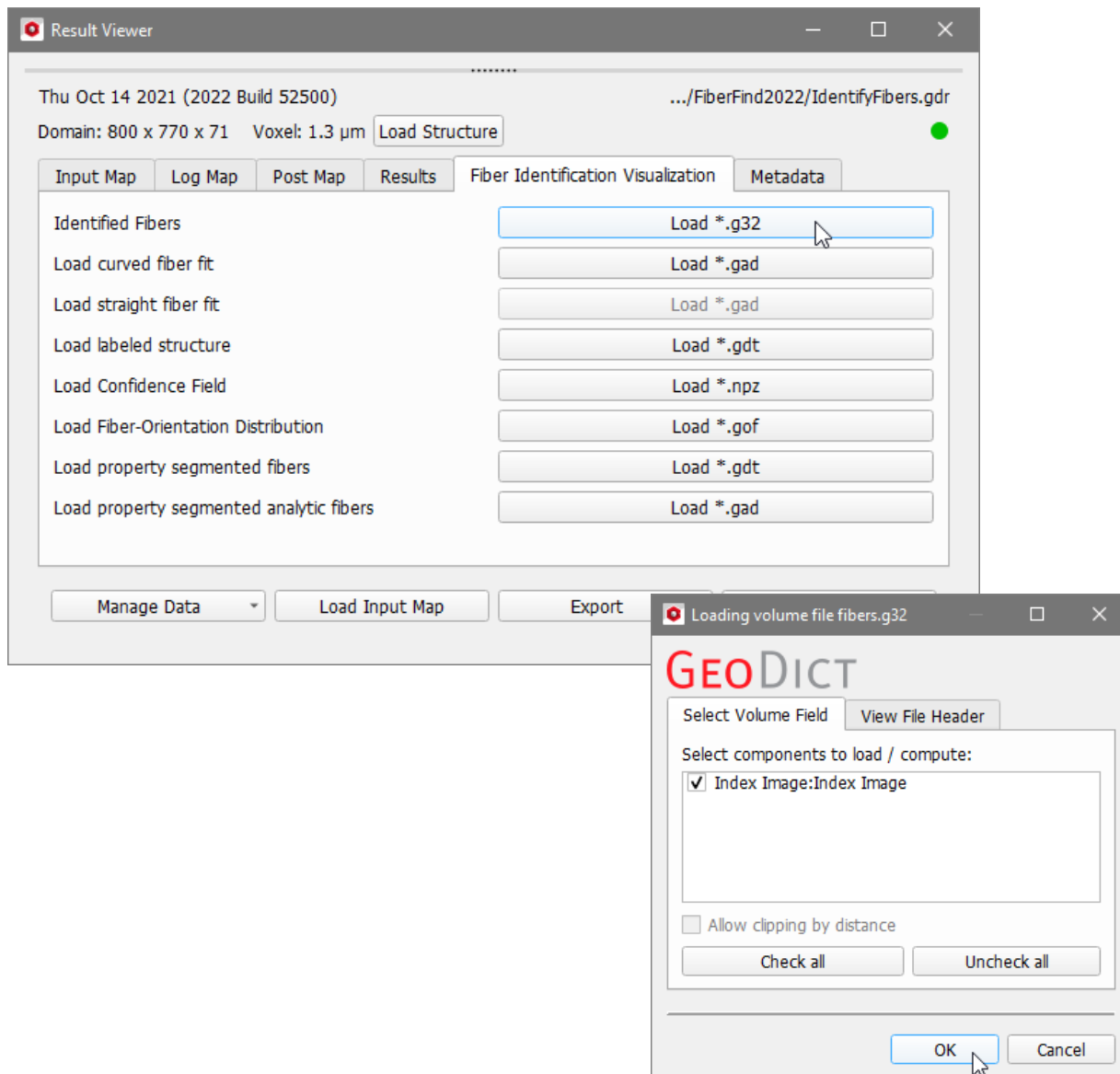
Both representations of the orientation tensor can be used directly in **FiberGeo** to create a structure with the same properties than the structure analyzed (see [Reproducing fibrous media using FiberFind and FiberGeo](#)).

Next, in the **Report**, for fiber length and fiber diameter, the mean value and the standard deviation and for fiber curvature and fiber curliness, the mean value are shown, followed by tables with the histogram values of the **Plots** subtabs.

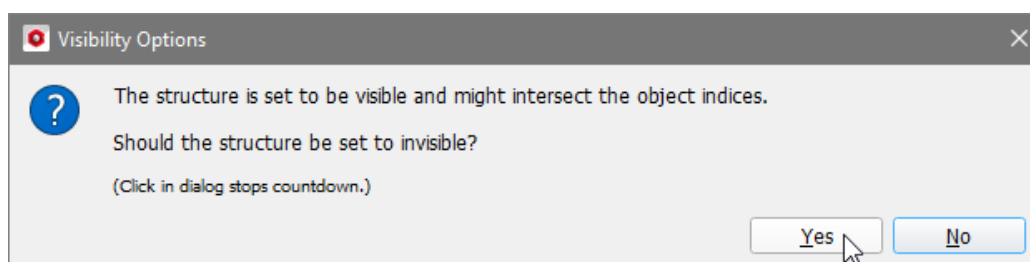


On the **Fiber Identification Visualization** tab, several possibilities of visualizing the results are listed. If **Identification Method** was set to **Analytic** (see page 40) only the .gad file with the curved fiber fit and the segmented analytic fibers is available for visualization.

To visualize the fibers identified by the algorithm, click **Load \*.g32** in the **GeoDict** Result Viewer under the **Fiber Identification Visualization** tab.

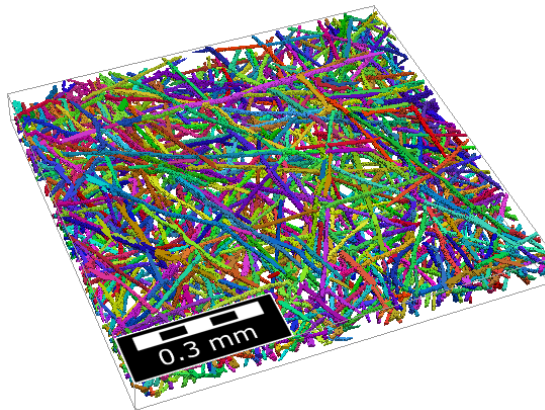


Set the structure to invisible, to see only the identified fibers, by clicking **Yes** in the opening dialog.

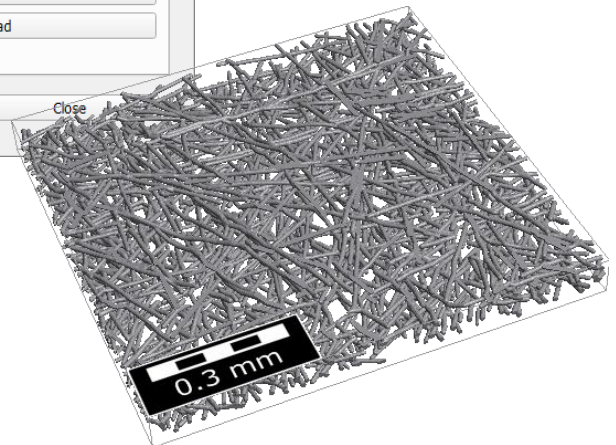
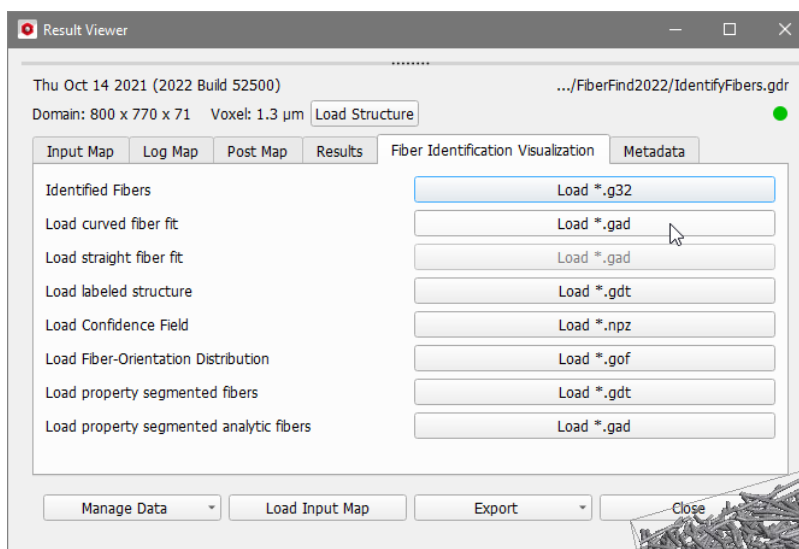




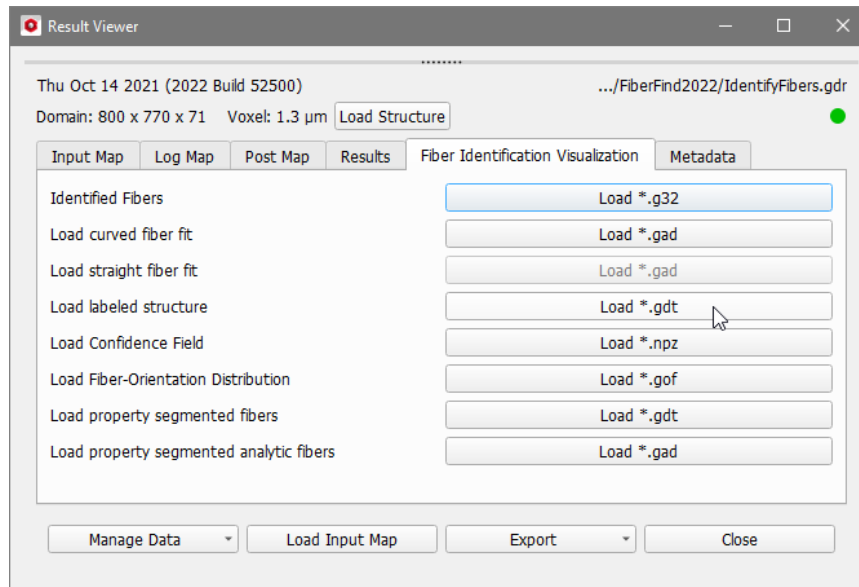
The identified fibers are shown in a variety of colors.



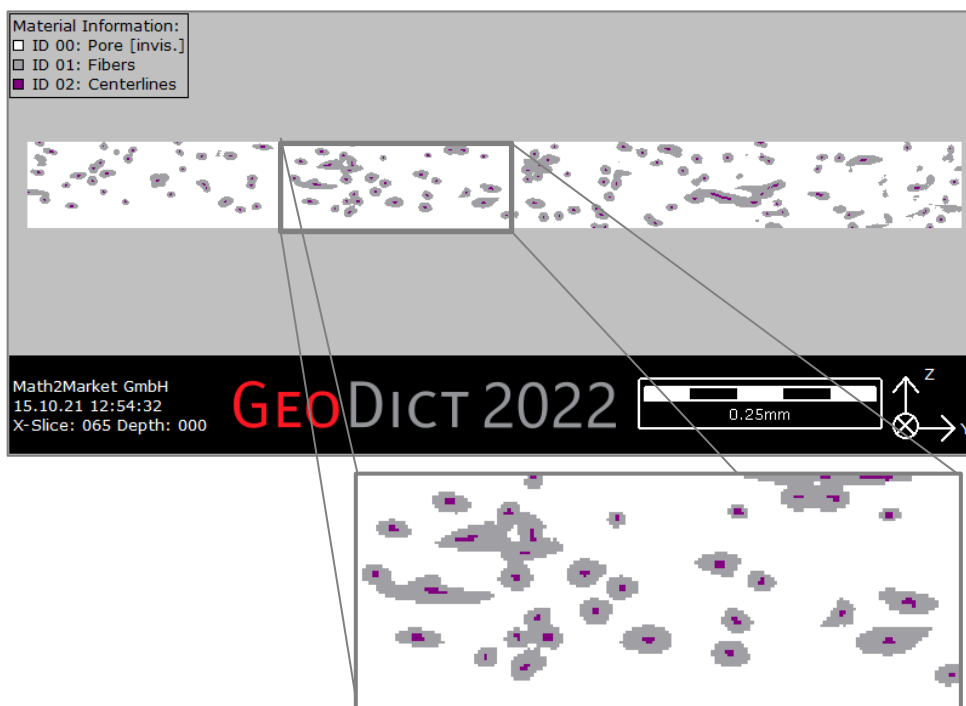
In the same way, the curved fiber fit (and the straight fiber fit if **Short Circular Fiber** was selected in the **Fiber-Shape Analysis** panel of the **FiberFind** options) can be loaded by clicking on their **Load \*.gad** buttons under the **Fiber Identification Visualization** tab. In the loaded .gad files, fibers are contained as analytical objects, with information about fiber diameter, etc. After the identification of fibers, the analytic information contained in the .gad files can be used for modifications of the structure model or further calculations that require fiber analytic data.



Clicking the (Load labeled structure) **Load \*.gdt** button under the **Fiber Identification Visualization** tab, loads the fibers together with the identified centerlines.

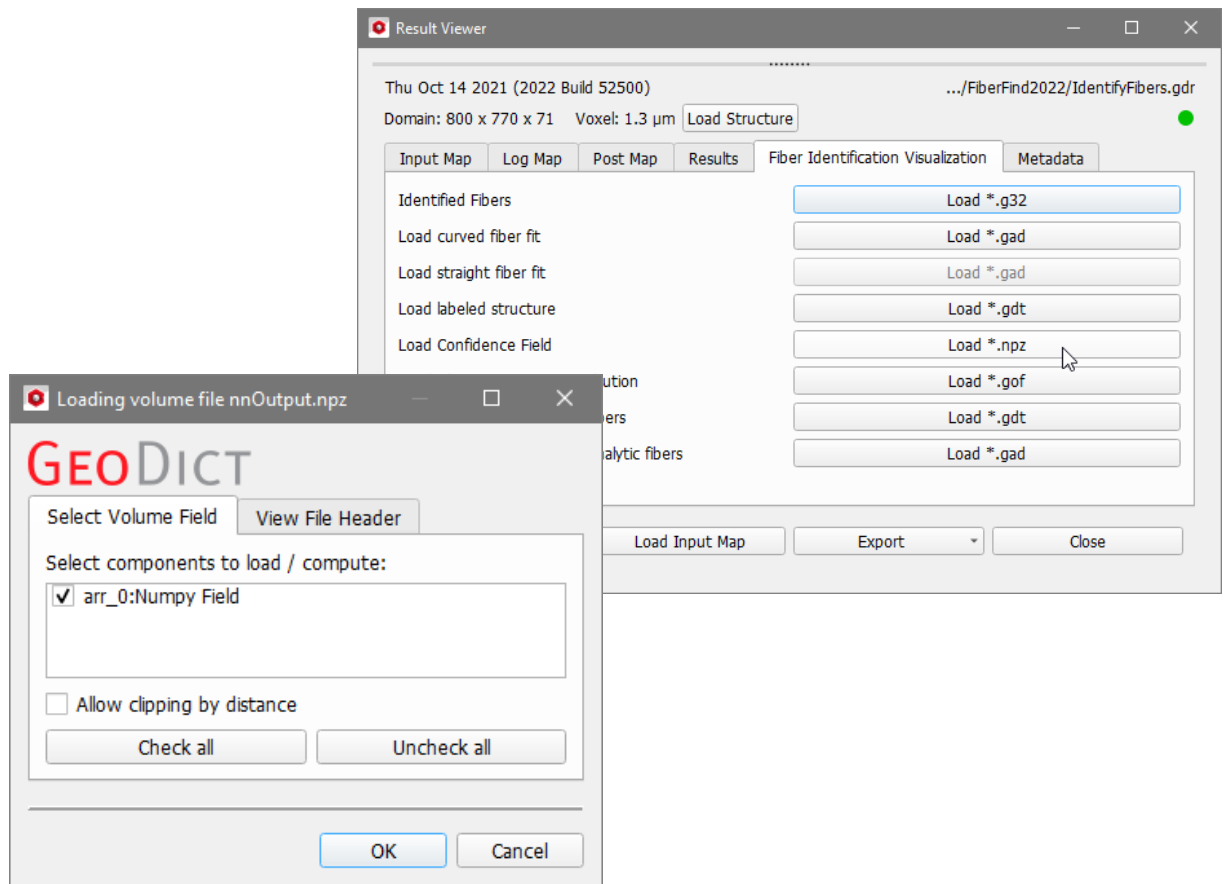


Visualize the loaded labeled structure with the centerlines in 2D (**View → 2D Cross section** in the menu bar).

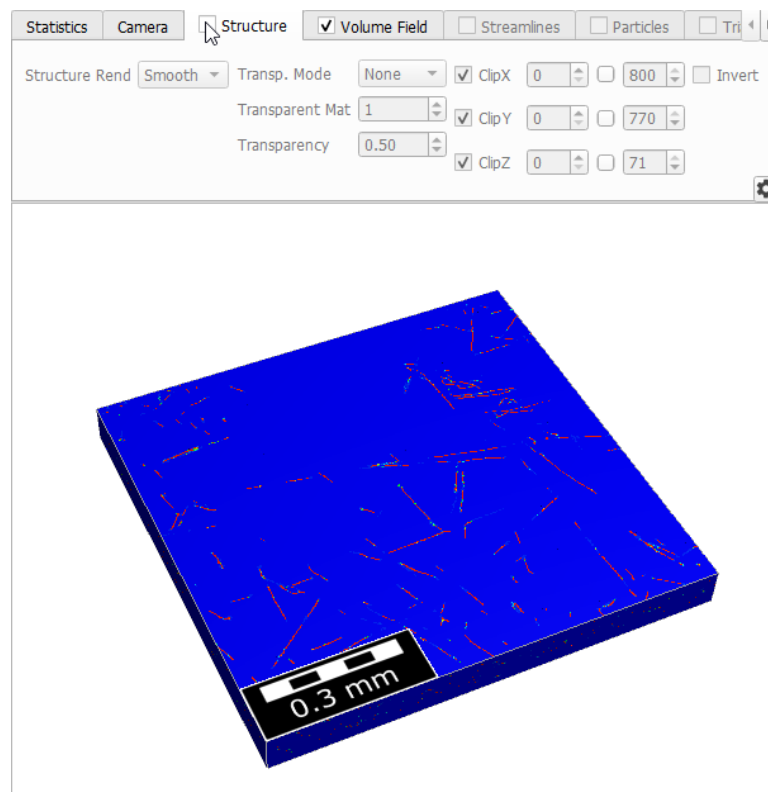


If the centerlines are fragmented, the user might want to re-run **FiberFind** with a lower threshold. If the centerlines appear too thick, a higher threshold value might be beneficial. In order to visualize how the threshold affects the result interactively, perform the following steps.

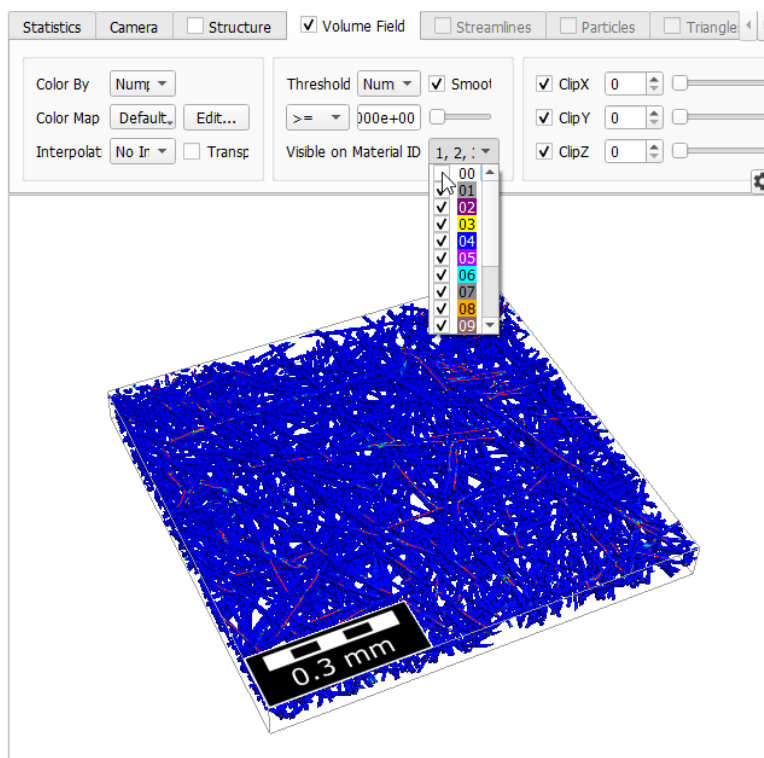
Click the (Load Confidence Field) **Load \*.npz** button to load the unsegmented data of the fiber identification.



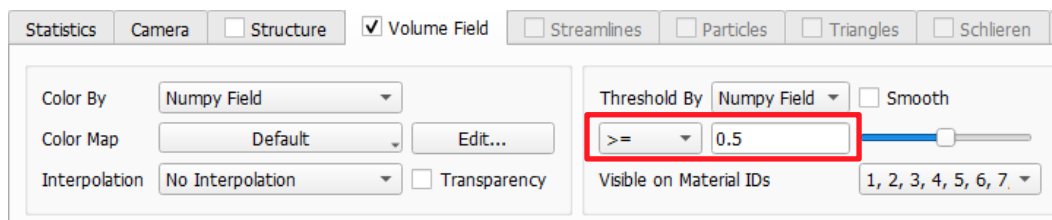
Set the structure to invisible, by unchecking the **Structure** tab in the Visualization panel, above the Visualization area of the GUI.



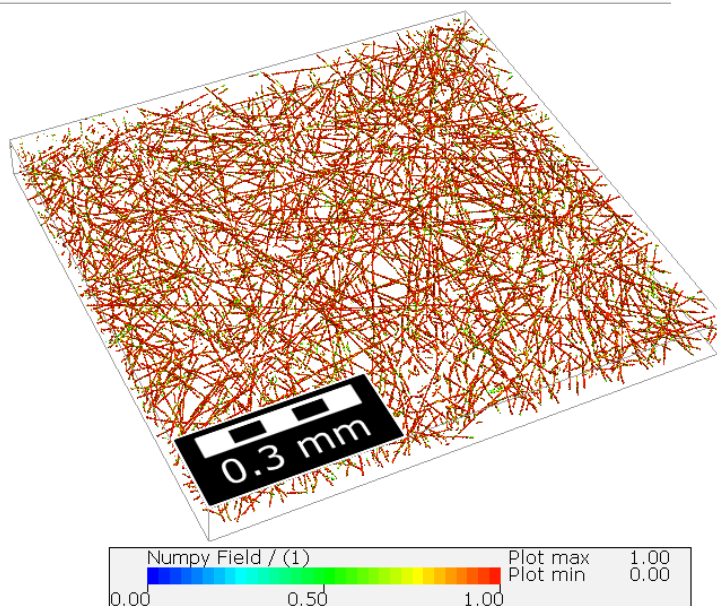
Show the result only for the fibers, by deselecting the material with ID 0 in the **Visibility** pull-down menu of the **Volume Field** tab.



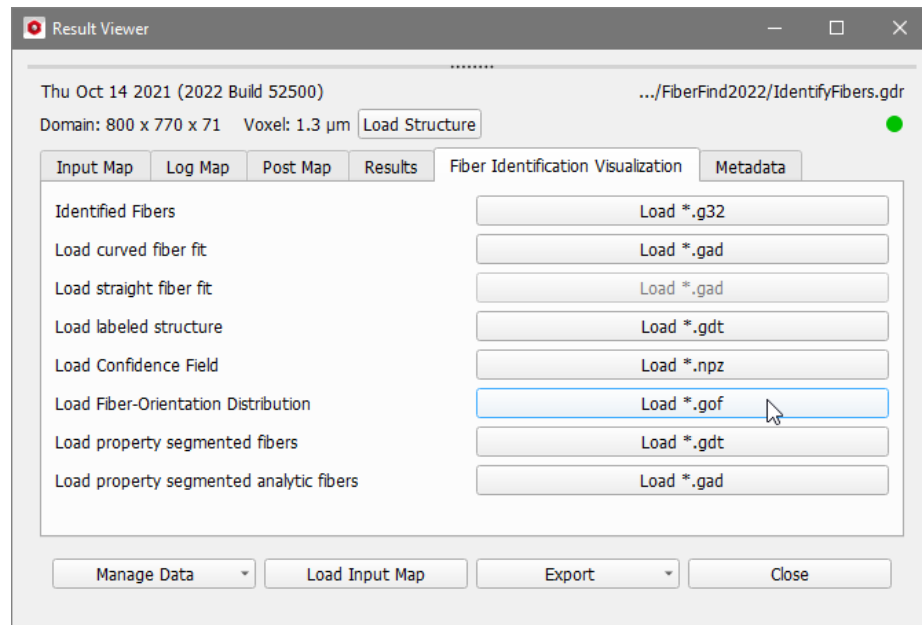
Select a threshold value between 0 and 1 (here 0.5). Then, select **>=** as **Clip Mode** to see the voxels that are identified for separate fibers if this value were to be set as Threshold for the fiber identification (see page [41](#)).



The goal is to find a threshold which does not result in fragmented centerlines but also does not fuse the centerlines of neighboring fibers.

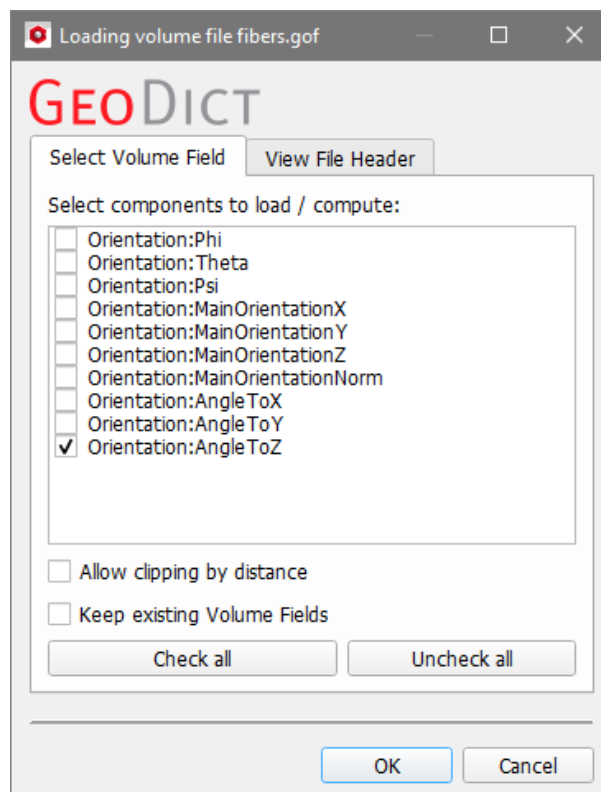


Select the (Load Fiber-Orientation Distribution) **Load \*.gof** button to load information about the fiber orientation.



Select e.g. Orientation:AngleToZ to get a visualization of the angle with respect to the z-axis for each identified fiber segment.

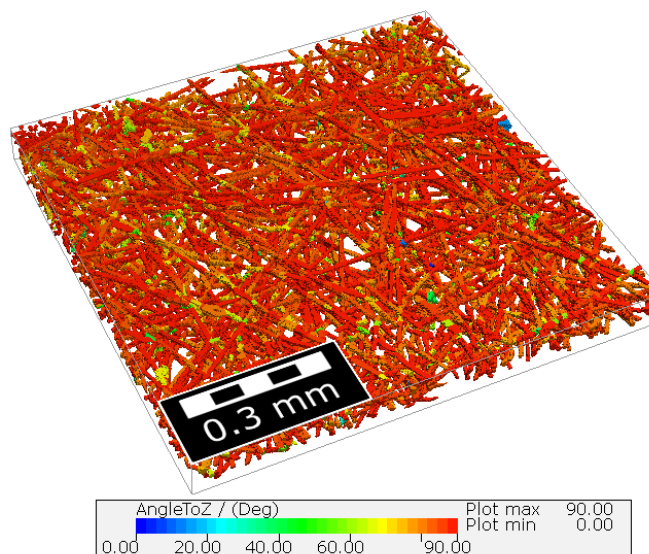
This option is available only, if **Save Fiber-Orientation Distribution as .gof** was selected on the Output Options tab, see page [43](#).



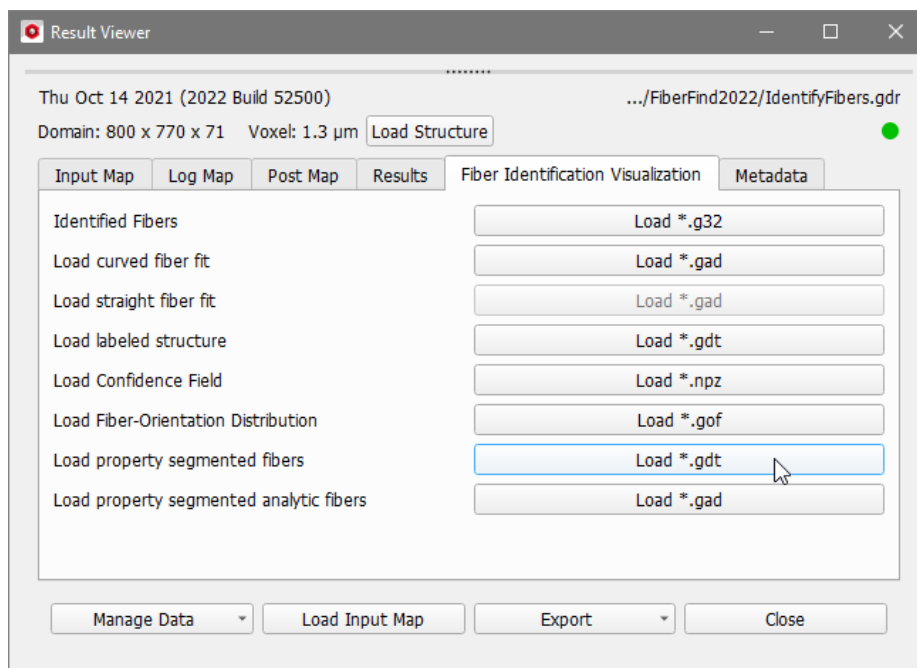
Again, set the structure to invisible, by unchecking the **Structure** tab in the Visualization panel, above the Visualization area of the GUI. Show the result only for

the fibers, by deselecting the material with ID 0 in the **Visibility** pull-down menu of the **Volume Field** tab.

Since in the example shown here, fibers are oriented mainly in x- and y-direction, the angle to the z-axis is high for most of the segments.

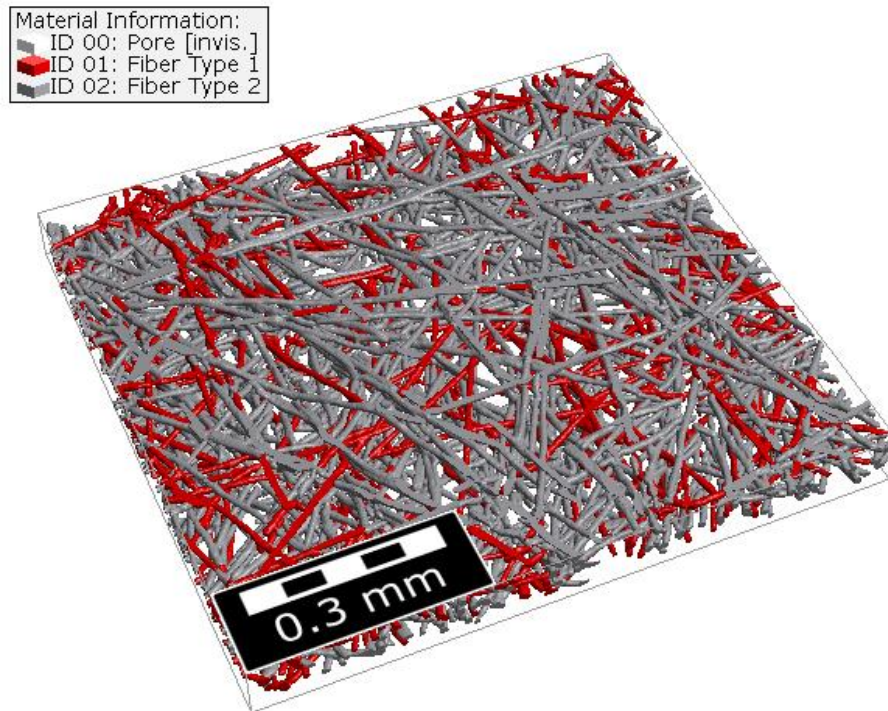


Load the structure with fibers of different type assigned to different material IDs in .gdt format or with analytic data in .gad format, by clicking **Load \*.gdt** for Load property segmented fibers and **Load \*.gad** for Load property segmented analytic fibers respectively.

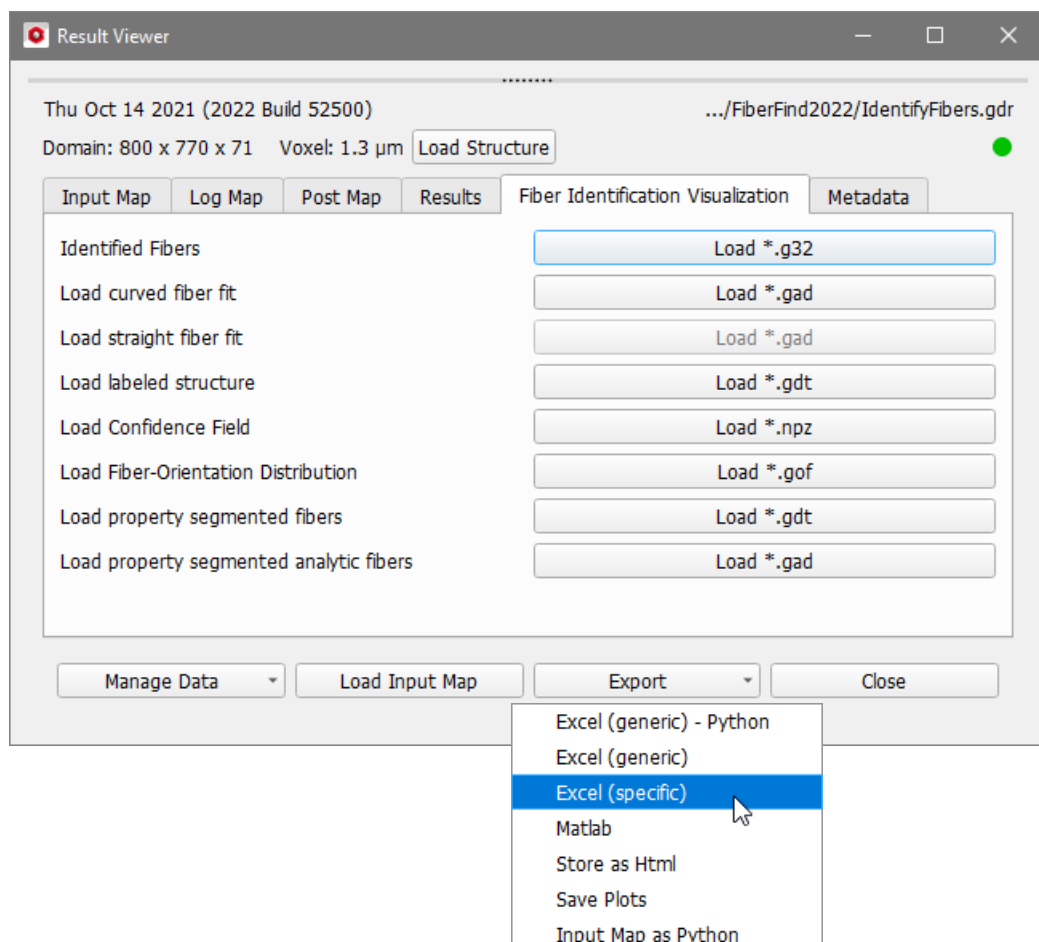


Fibers with different material IDs, according to the number of different fiber types selected under the Results tab (see page [47](#)), are shown in the Visualization Area.





Select **Export** → **Excel (specific)** at the bottom of the Result Viewer, to export the identified fiber properties to a Microsoft Excel file. A python script is executed that creates the file **FiberInformation.xlsx** and opens this file if Microsoft Excel is installed on the computer.





## Identification of binder and fibers, and analysis of fiber properties

The file created contains for each fiber, the identified diameter, length, direction vector and the fiber center of gravity.

For the file created for the example above, the information for the first 8 fibers is shown in the following figure.

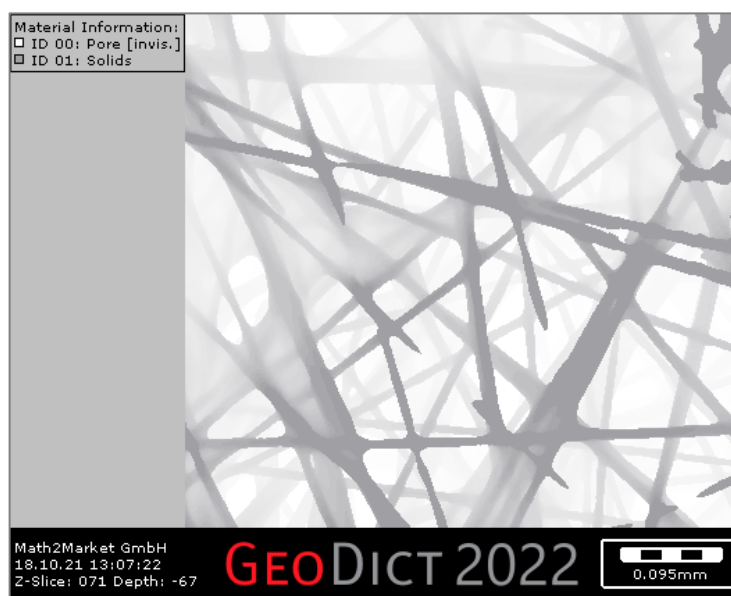
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Fiber ID		Fiber Diameter /(m)		Fiber Length /(m)		Fiber Vector of Direction				Fiber Center of Gravity		
2							X Direction	Y Direction	Z Direction		X Direction	Y Direction	Z Direction
3	1		8.61039E-06		0.000366483		-0.08899841	0.99322224	-0.074759		0.00078353	0.00018096	1.989E-05
4	2		8.6158E-06		0.000490292		-0.03206494	0.99935719	-0.016032		0.00021692	0.0002442	1.686E-05
5	3		8.89752E-06		0.000202178		0.62023321	0.78175228	-0.064608		0.00097599	7.9852E-05	1.59E-05
6	4		1.08827E-05		7.51959E-05		-0.58963478	-0.780399	-0.208106		0.00037513	0.00096633	1.693E-05
7	5		1.07822E-05		6.58483E-05		0.18054244	0.96289303	0.2006027		0.000407	0.00096741	1.981E-05
8	6		8.66796E-06		6.80061E-05		-0.30757858	-0.9419594	-0.134566		0.00094273	0.0009662	2.066E-05
9	7		1.0482E-05		9.2825E-05		0.08518569	0.99383303	-0.070988		0.00089344	4.545E-05	2.514E-05
10	8		8.56726E-06		0.000163193		0.8876592	0.43183421	0.1599386		0.00096605	0.00072551	3.704E-05

## IDENTIFY BINDER (AI)

The separation between solid and pores of a structure, can usually be done using image processing methods during the import of the scanned data sets (see the [ImportGeo-Vol](#) handbook of this User Guide for more details). However, the separation of binder from fibers is often not possible, since they have the same gray values in the scan.

The structure shown here is a segment of a sample of a carbon paper gas diffusion layer (GDL) used for a proton-exchange membrane (PEM) in a fuel cell. The fibers and binder contained in it are undistinguishable by their gray value in the FIB/SEM image.

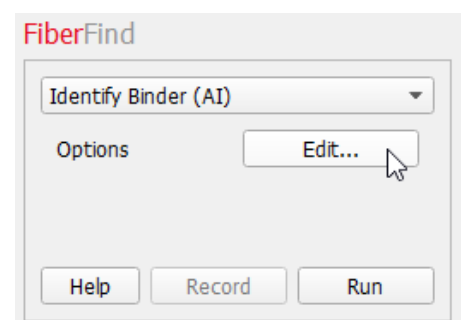
Slices of the structure in X and Z-direction, imported into **GeoDict**, are shown here.



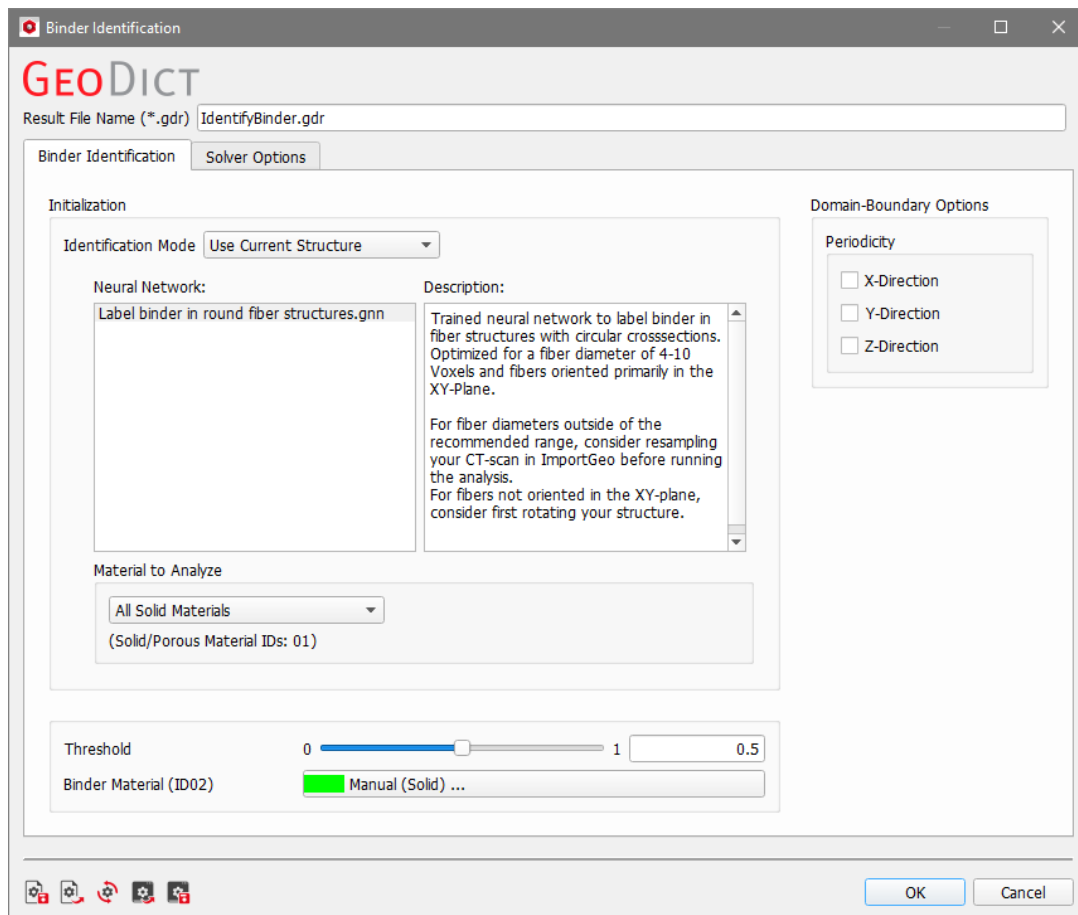
Details on how to import the image and to separate between pores and solid material, can be found in the tutorial *Digital analysis of fibers and binder content of four carbon paper GDLs*, on the [GeoDict website](#).

To start, select **Analyze** → **FiberFind** from the menu bar and, in the **FiberFind** section, select **Identify Binder (AI)** from the pull-down menu. Click the **Options' Edit...** button.

The **Binder Identification** dialog that opens includes the **Solver Options** and the **Binder Identification** tabs. The **Solver Options** tab is similar to the **Solver Options** tab for **FiberFind-AI**, explained in pages [39ff](#).

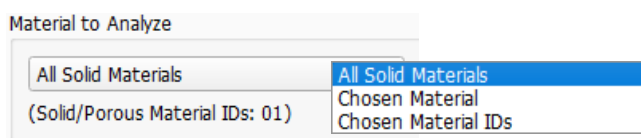


On the **Binder Identification** tab, select the neural network available under **Neural Network**. In future versions of **GeoDict**, more than one neural network (.gmn stands for **GeoDict** neural network parameter file) will be provided, making it possible to select the best suitable one for the structure under consideration.

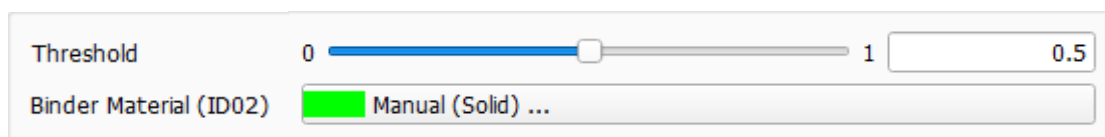


In the **Description**, the current constraints for the application of the neural network are listed, like the fiber cross-section or diameter for that the neural network was trained.

The **Material to Analyze** panel offers the choice of whether **BinderFind-AI** should be applied to all solid and porous materials in the structure or only on a subset, defined either by choosing material IDs or materials.

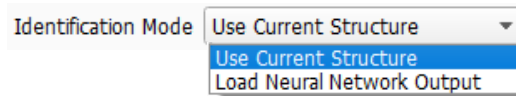


The **Threshold** is an internal (or expert) parameter that is mostly applied by proficient users at **Math2Market**. The neural network provides probabilities that a solid voxel is binder or not. The **Threshold** defines the limit for labelling a voxel as binder.

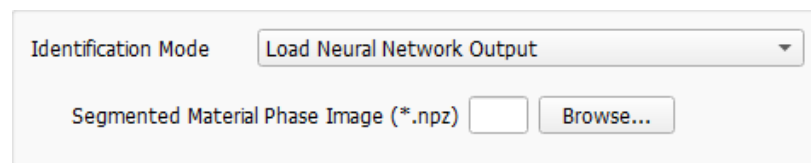


In the lower left of the **Fiber Identification** dialog, the **Binder Material** specifies the material to label the binder. The material chosen should be different from the material of any solid or pore material present in the original structure. The ID for the binder material is the first ID that is not present in the structure loaded.

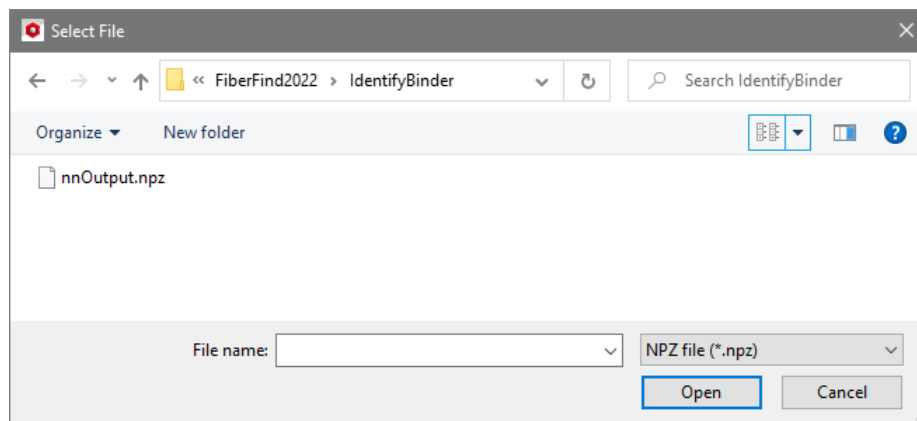
Two choices are available as **Identification Mode: Use Current Structure** and **Load Neural Network Output**.



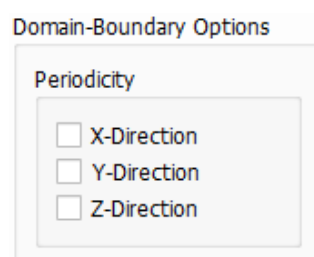
The default **Use Current Structure** applies the binder identification to the structure currently available in **GeoDict** memory and is used for most of the cases. If the evaluation of the output of the neural network should be run again, with a different threshold and without having to re-run the neural network inference step, **Load Neural Network Output** may be chosen.



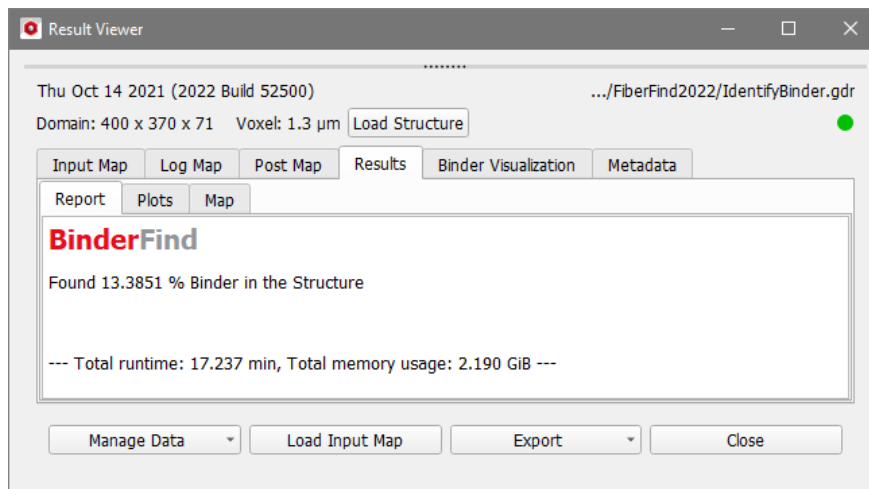
Browse to a .npz file from the result folder of a previous run of **BinderFind-AI**. Since already the output of the neural network is used in that case, no selection of **Neural Network** or **Material to Analyze** is possible and the loaded structure needs to be the same.



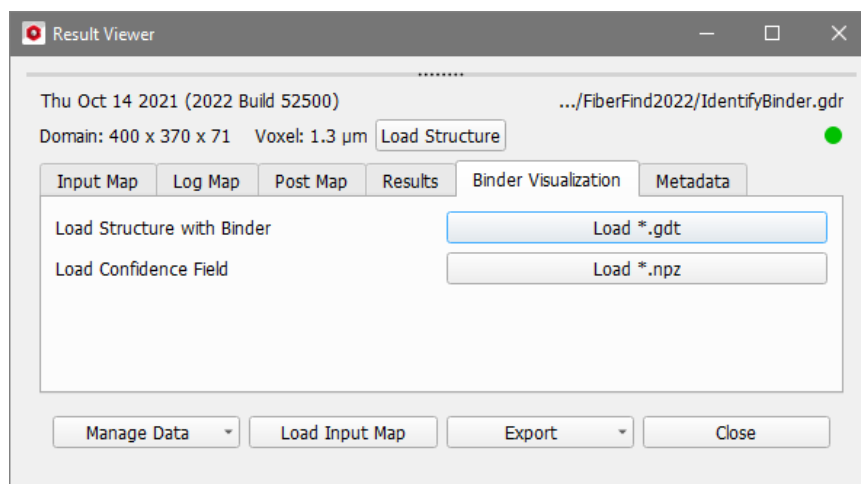
Select one or several boxes on the **Domain-Boundary Options** panel if the underlying structure for the binder identification is periodic in one or several directions. However, periodicity is unusual for most 3-D scans and this setting is rarely changed.



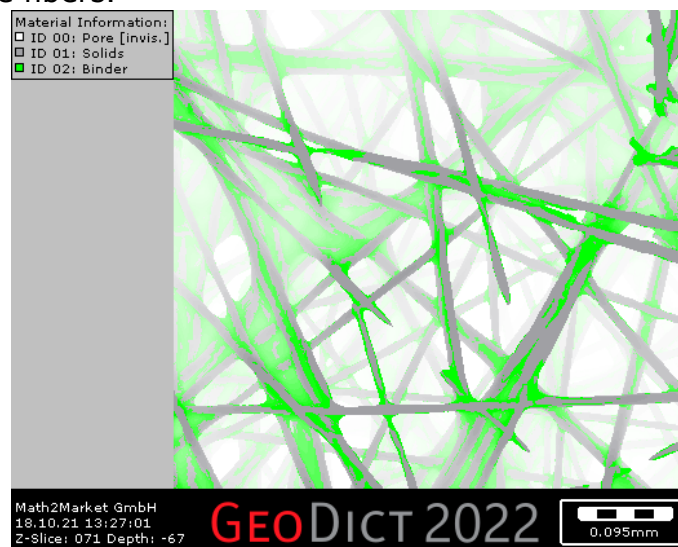
After the successful binder identification, the **GeoDict** Result Viewer opens for the result file (.gdr). Under the **Results - Report** tab, the percentage of solid voxels identified as binder is shown.



Load the structure with identified binder, by clicking **Load \*.gdt** under the **Binder Visualization** tab.

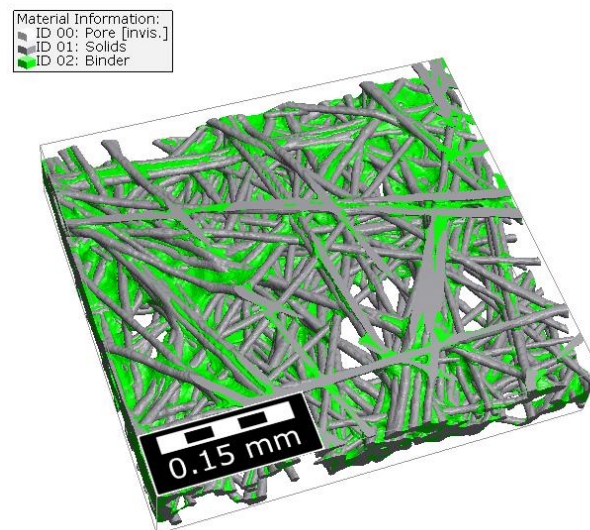


The same slice of the structure as shown above in 2D (page [61](#)), can be seen here, now with binder separated from the fibers.



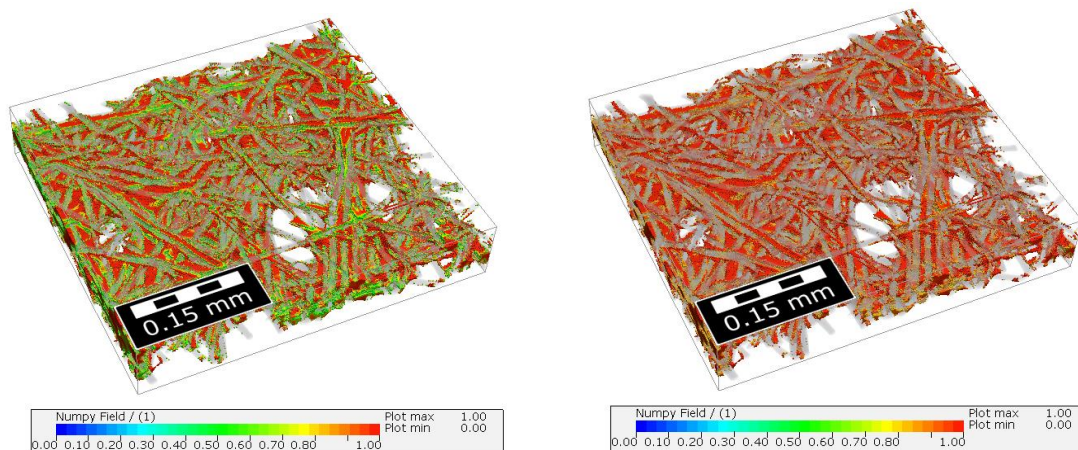


In the 3D visualization, the distribution of binder between the fibers is visible for the whole domain.



Load the confidence field, by selecting **Load \*.npz** under the **Binder Visualization** tab, i.e., the unsegmented data of the binder identification.

Keep only the values larger than the threshold 0.5 (selected for the identification) by choosing a threshold value of **0.5** and the Clip Mode **>=**, to see the binder (in green to red) identified from the solid voxels (shown in transparent gray) in the left figure. This can be compared e.g., with the result for a threshold of 0.8, where less voxels are identified as binder (in orange and red), see figure on the right.



### TESTING THAT INSTALLATION OF BINDERFIND-AI WORKS PROPERLY

With the subfolder **FiberFindSetupUserGuide**, that is available in the folder **FiberFind** of the **GeoDict** installation folder, we provide a short example to test that the installation of **BinderFind** works properly, how the results of **BinderFind** can be validated, and to illustrate the essence of the method by testing the algorithm. It only takes around 5 minutes to run.

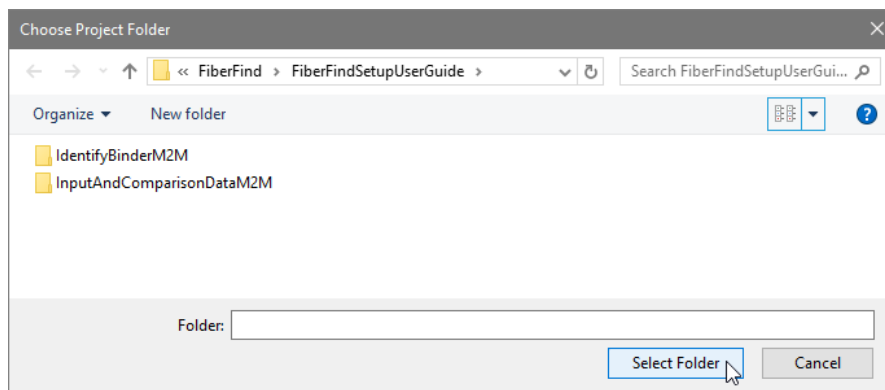
The example can be run directly from this folder if you have writing access there. However, we recommend creating a copy of the folder first, and use this copy to run the example.

#### TEST THE INSTALLATION

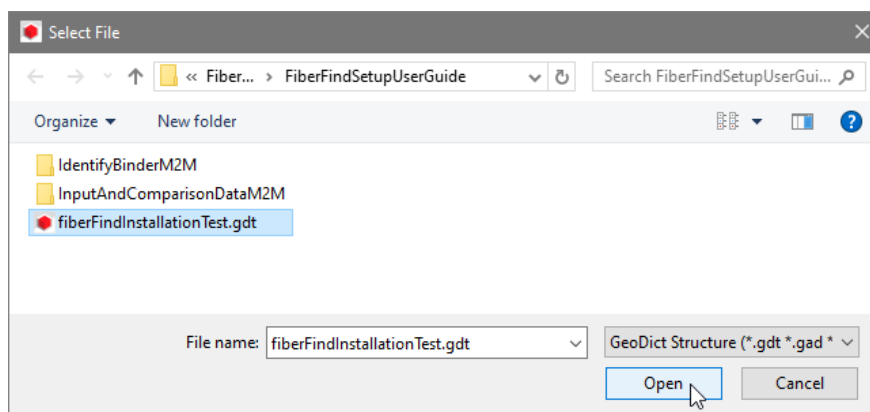
The procedure to test the installation is as follows:

1. Start **GeoDict** 2022
2. Change the project folder to the folder **FiberFindSetupUserGuide**:

Select **File** → **Choose Project Folder** → **Select Project Folder** in the menu bar and navigate to the folder **FiberFindSetupUserGuide**.

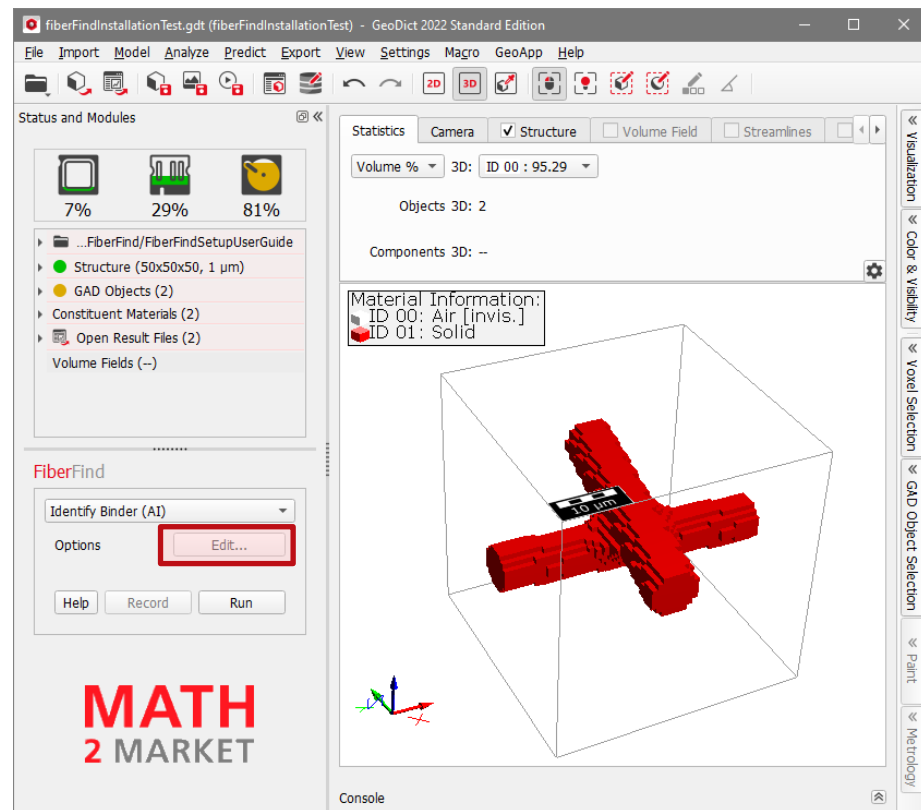


3. Select **File** → **Open structure (\*.gdt, \*.gad)...** in the menu bar
4. Select **fiberFindInstallationTest.gdt** in the folder **FiberFindSetupUserGuide**

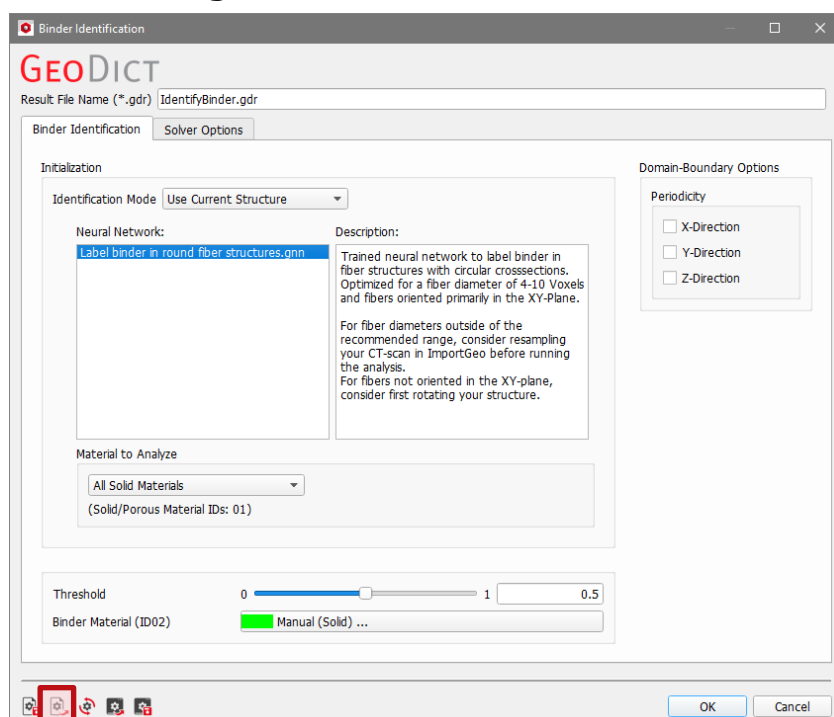




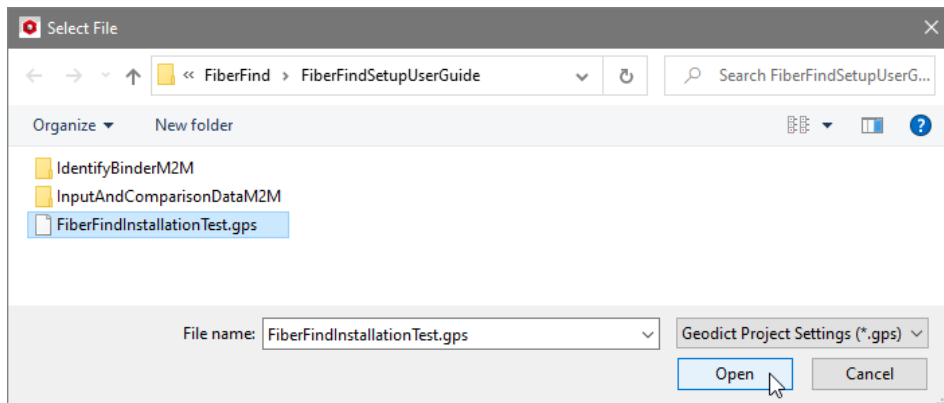
If the structure appears in 2D, press Ctrl-3 on the keyboard or select **View** → **3D Rendering** in the menu bar. The structure displayed in the Visualization area shows binder at the point where two fibers join, but fibers and binder are undistinguishable by their material ID. It should look like this:



5. Select **Analyze** → **FiberFind**
6. Select **Identify Binder (AI)** from the pull-down menu in the **FiberFind** section on the left side of the **GeoDict** GUI
7. Click the **Options' Edit ...** button, to open the **Binder Identification** dialog.
8. Click on the **Load Settings from File** icon at the bottom left.



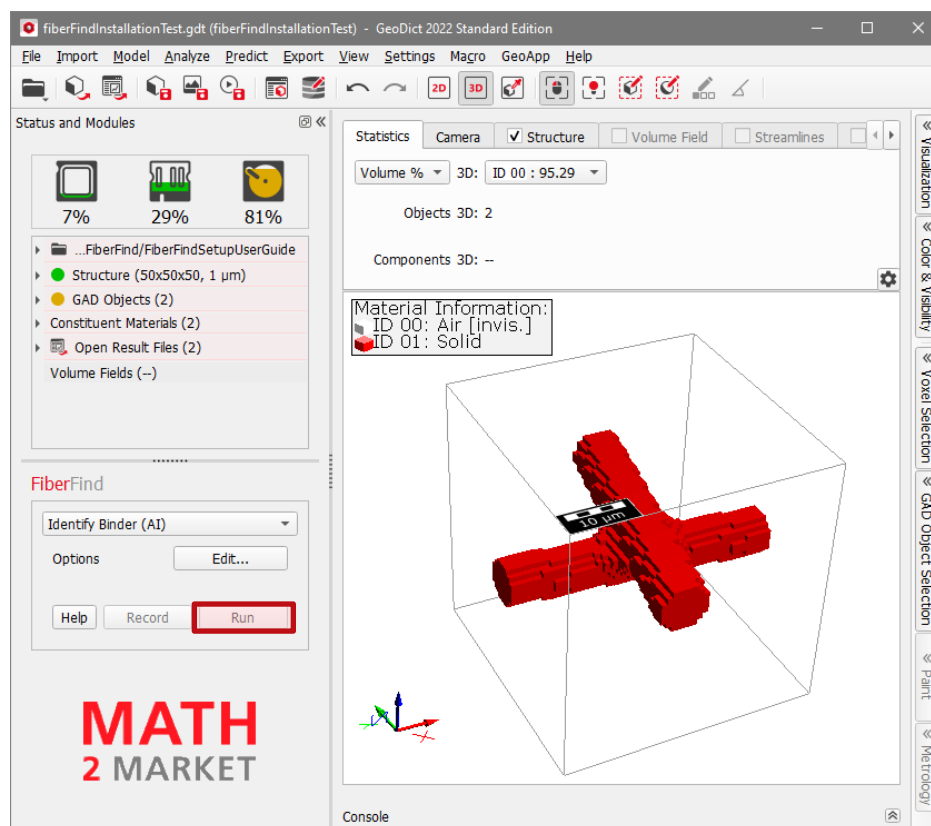
9. Select the file **FiberFindInstallationTest.gps** and click **Open**



Since in this case, the .gps file contains the default options, you can also load the build-in default settings.



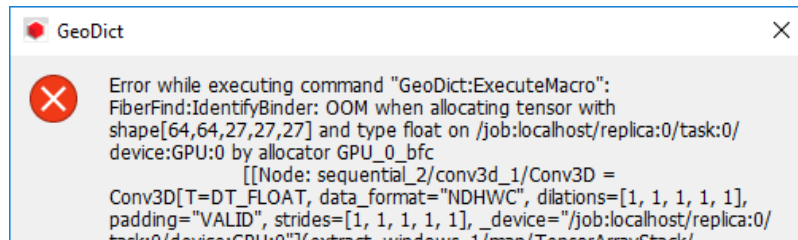
10. Click **OK** to close the **Binder Identification** dialog and then, click **Run** on the left side of the **GeoDict** GUI.



If an error message appears, the default settings to use the graphics card need to be changed, to make the example run on your machine. Follow [Step 11](#) to [Step 16](#) below.

Otherwise, continue with the results shown from [Step 17](#) on.

11. In case an error message similar to the following appears, your graphics card might not have enough memory to run the binder identification with the default settings:

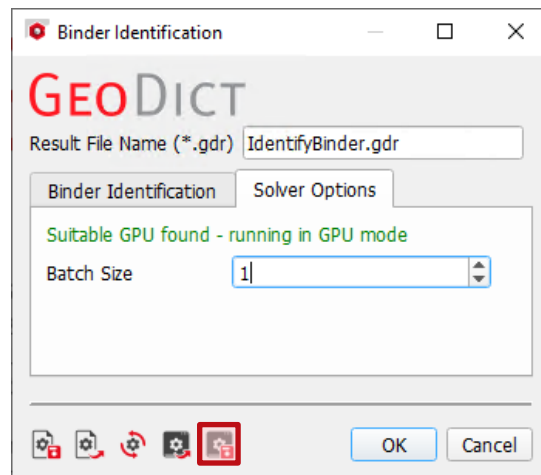


Look for the OOM in the second line. It indicates that the graphics card is *Out Of Memory* (OOM) and the settings need to be changed.

Conceptually, **FiberFind** loads the graphics card with chunks of work called batches.

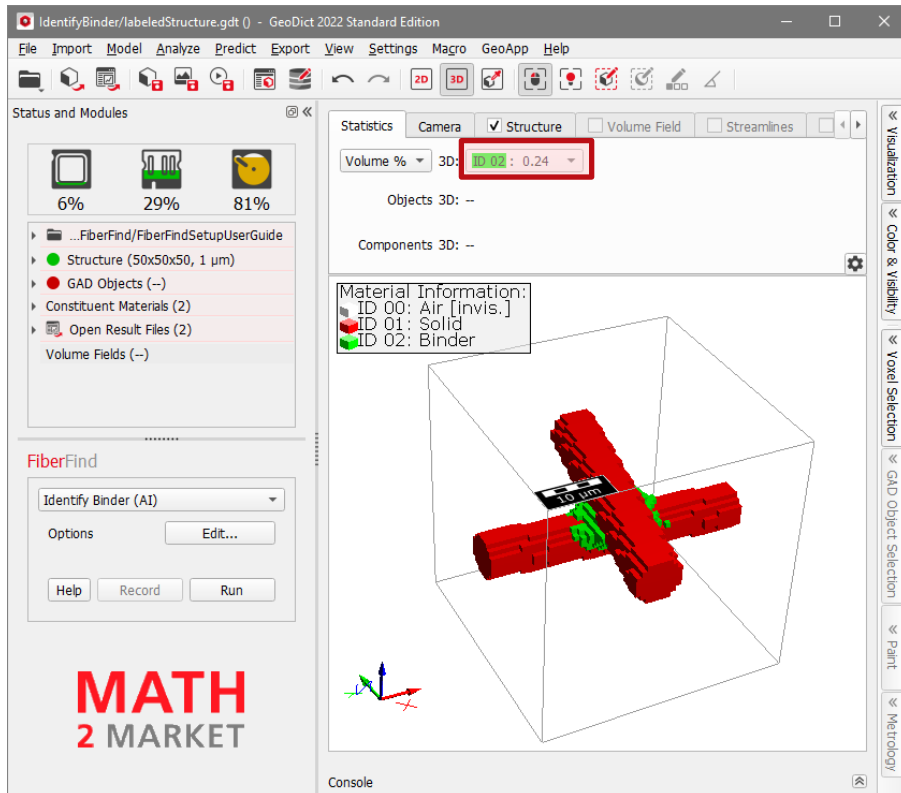
Currently, the user has to make the selection of batch size manually, and the parameter is set when calling **FiberFind**.

12. Click again the Options' **Edit ...** button (as in [Step 5](#) above)
13. Switch to the **Solver Options** tab of the **Binder Identification** dialog.
14. Enter 1 as the **Batch Size** instead of the default value of 2.



15. **Set current settings as start-up settings** using the icon on the bottom left. It is very probable that you need smaller batch sizes also for your other **FiberFind** and **BinderFind** uses. **GeoDict** will then use this value by default. Close the dialog by clicking **OK**.
16. Click the **Run** button on the left side of the **GeoDict** GUI (same as in [Step 10](#)).

17. After the computation, the GeoDict Result Viewer opens and shows the results of the computation.
  - a. GeoDict reports that 0.24 % of the volume is occupied by binder
  - b. GeoDict displays the labeled binder as follows, after clicking **Load \*.gdt** on the tab **Binder Visualization**:



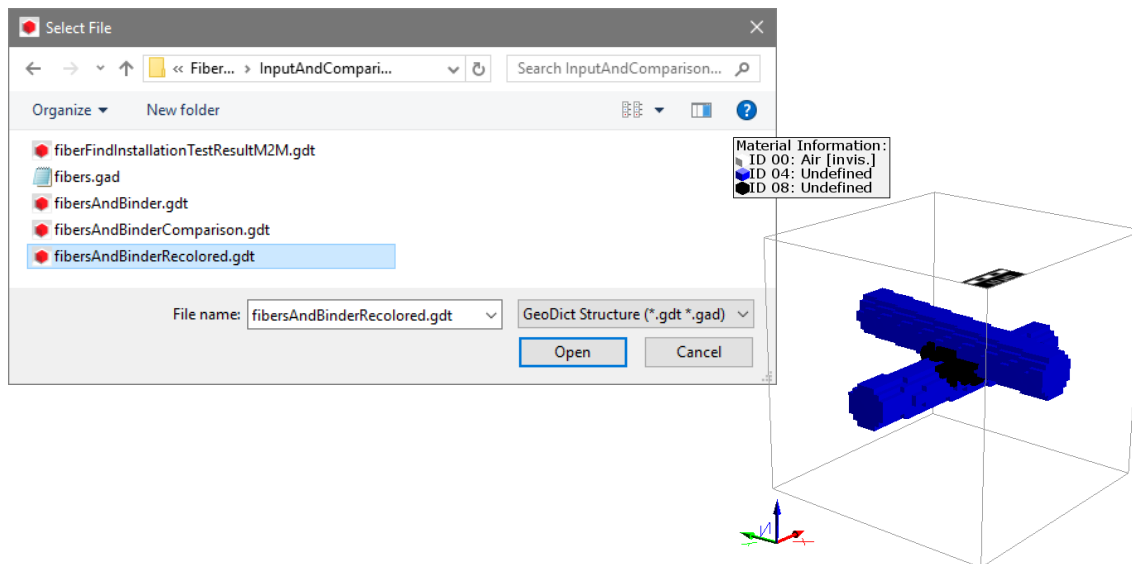
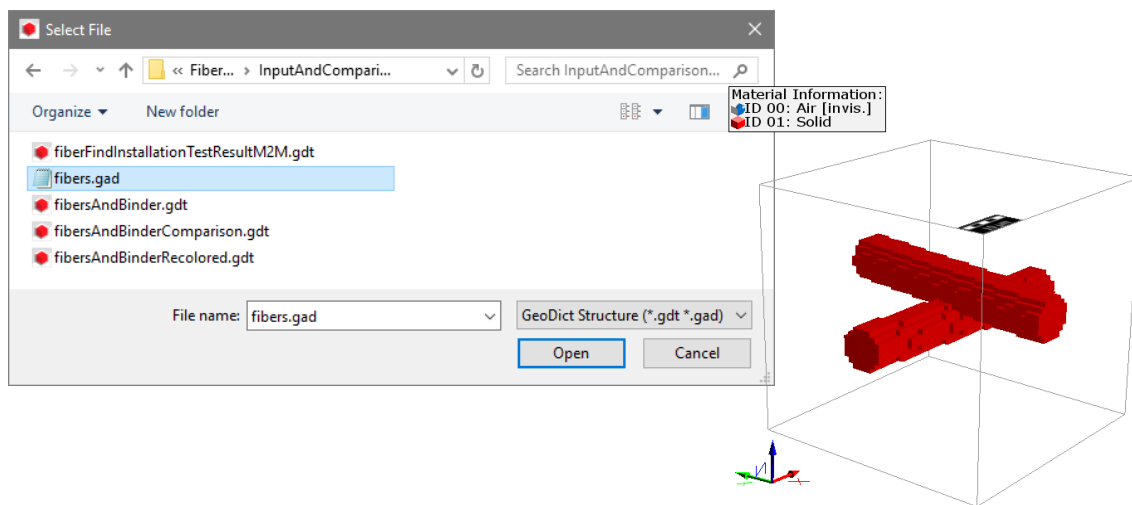
Save the structure as **fiberFindInstallationTestResult.gdt** in the project folder.

## MEASURE THE QUALITY OF THE ALGORITHM

The fibers and binder seen in **fiberFindInstallationTest.gdt** in [Step 4](#) above were generated in **GeoDict**, making it now possible to check how well the algorithm recovers the original data. The generation process was as follows:

First, **GadGeo** was used to generate two fibers that are oriented almost perfectly in the x-y plane. The generated fibers are saved in the **fibers.gad** file inside the **InputAndComparisonDataM2M** folder.

Next, binder was added by morphological operations with **Model** → **ProcessGeo** → **Add Binder**. The resulting structure can be found in the file **fibersAndBinder.gdt** in the **InputAndComparisonDataM2M** folder. To facilitate the comparison with the output of the algorithm, the fibers in this file have been recolored and the resulting structure is saved in the file **fibersAndBinderRecolored.gdt** in the same folder.



Finally, the result of **BinderFind** binder identification is compared with this structure by adding the structure **fibersAndBinderRecolored.gdt** with **LayerGeo** to the result structure **fiberFindInstallationTestResult.gdt**, i.e., the result of the installation test shown in [Step 17](#) above.

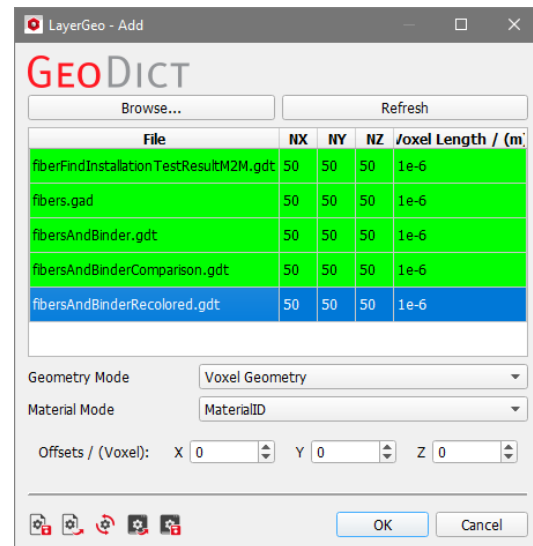
The result structure **fiberFindInstallationTestResult.gdt** needs to be loaded in **GeoDict**.

## Identification of binder and fibers, and analysis of fiber properties

Then, select **Model** → **LayerGeo** in the menu bar and choose **Add** in the **LayerGeo** section of the **GeoDict** main GUI.

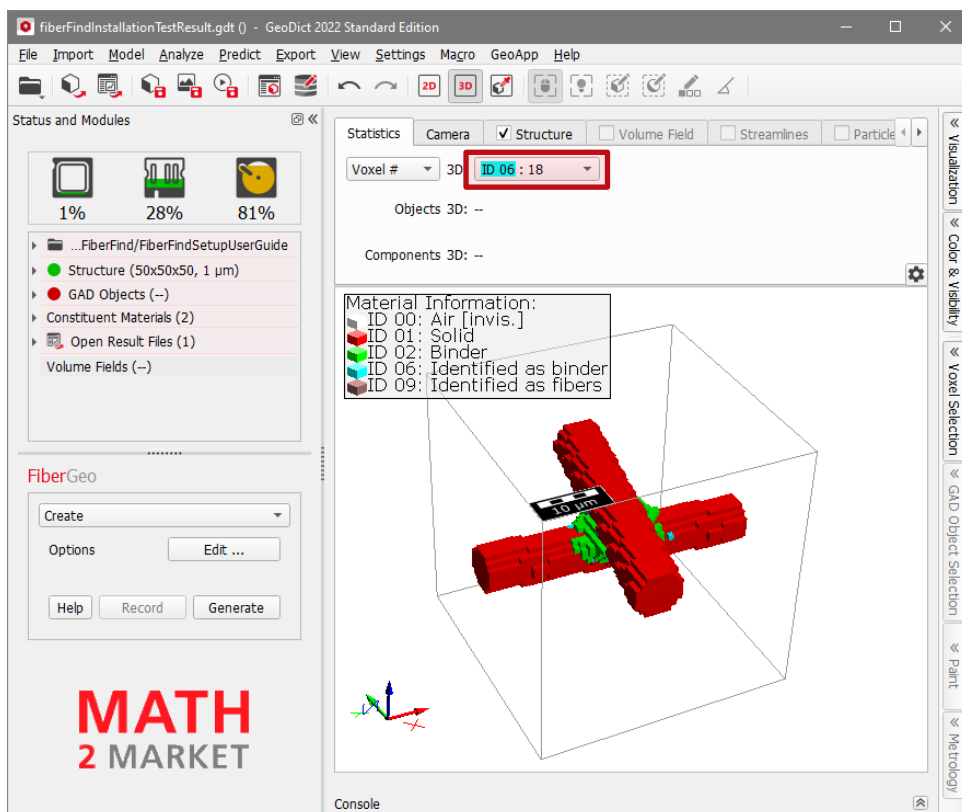
Click **Edit** and browse to the folder **InputAndComparisonDataM2M**. Select the **Voxel Geometry** as Geometry Mode. Then select **MaterialID** as the Material Mode for the addition and the file **fibersAndBinderRecolored.gdt**.

Click **OK** and then click **Add** in the **LayerGeo** section of the **GeoDict** main GUI.



Then, in the resulting structure (which is available also as **fibersAndBinderComparison.gdt** in the folder **InputAndComparisonDataM2M**), Material ID numbers are changed through **Model** → **ProcessGeo** → **Reassign** (from the pull-down menu) to facilitate comparison with the original structure created in **GeoDict**. Reassign Material ID 5 to Material ID 1 and Material ID 10 to Material ID 2. Now, the original colors (red, green) match at the voxels where both original data and analyzed data agree.

All voxels with IDs 1 and 6 were fiber voxels in the original structure, voxels with IDs 2 and 9 were binder voxels in the original structure. Reassign a solid material to both ID 06 and ID 09 with the information **Identified as binder** and **Identified as fibers**.



As it is shown in the Visualization panel, above the Visualization area, 18 original fiber voxels (ID 06) were labeled as binder by the algorithm. By extending this pull-down menu, we also find that 16 original binder voxels (ID 09) were classified as fibers. All other voxels were labeled correctly: 5583 fiber voxels (red, ID 01) and 276 binder voxels (green, ID 02).

Formally, the volume fractions can be evaluated after selecting **Analyze → MatDict Material Statistics → Structure Information** in the menu bar. The results are shown below.

Volume Fraction:
Material Pore: 0.952856
Material Manual: 0.047144
MaterialID 0: 0.952856
MaterialID 1: 0.044808
MaterialID 2: 0.002336

Volume Fraction:
Material Pore: 0.952856
Material Manual: 0.047144
MaterialID 0: 0.952856
MaterialID 1: 0.044664
MaterialID 2: 0.002208
MaterialID 6: 0.000144
MaterialID 9: 0.000128

On the left, observe the data for the original structure with only two solid materials (**fibersAndBinder.gdt**). On the right, the data for the comparison with the result of the binder identification shows four materials.

The volume fractions for Pore and Manual agree exactly because **BinderFind** will not change a pore to a solid or vice-versa.

**MaterialID 1** and **MaterialID 2** are assigned to fibers and binder in both cases. **MaterialID 6** indicates fiber voxels mistakenly labeled as binder voxels and **MaterialID 9** indicates binder voxels mistakenly labeled as fiber voxels.

In summary, we see that:

1. **BinderFind-AI** recognizes 99.7% of the fiber voxels as fiber voxels correctly and recognizes about 94.5% ( $0.002208/(0.002208+0.000128)$ ) of the binder voxels correctly as binder.
2. **BinderFind-AI** almost never classifies a fiber voxel falsely as a binder voxel, but classifies the remaining 5.5% ( $0.000128/(0.002208+0.000128)$ ) of the binder voxels incorrectly as fibers.



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