CT scan preparation: nonwoven_scan

1 Question and setup

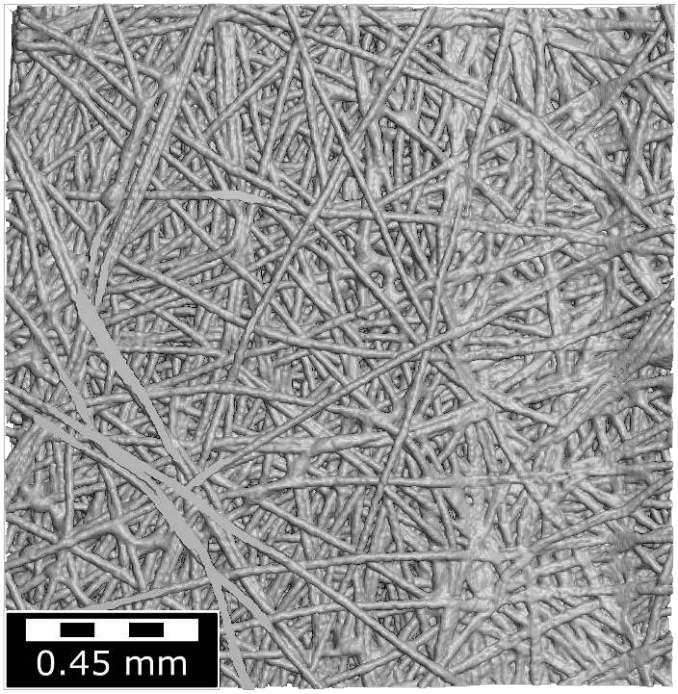
The segmented µCT scan `input/nonwoven_scan.gdt` (pore space on ID 0, one solid ID) is prepared for analysis: the thickness of the sheet is put on z, the tilt and the turn about z are removed, and the frayed x-y borders and the empty space in z are cut away. Every step is a macro of the project (`macros/`) that either measures or modifies; a modifying step writes a new file and never changes its input. Every number in this report is read from the result file of a step.

Two structures come out:

- **Structure 1** is the largest x-y rectangle of intact sheet, with only the empty space removed in z. The surface zones stay. It is the input for a through-plane flow simulation.
- **Structure 2** is structure 1 cut in z to the sheet region found by `MatDict:ThicknessEstimation`, without the surface zones. It is the input for geometric properties such as porosity and pore sizes.

All steps work in voxels and pass the voxel length of the scan file through unchanged. Lengths in metres inherit it. The voxel length of this file was set to 4 µm in the project before the preparation (`macros/02_fix_voxel_length.py`); it is plausible for a calendered spunbond web, and the sheet thickness in the Verification section, in metres, is the one number that depends on it.

2 Result



Structure 1, view along z (x-y plane)

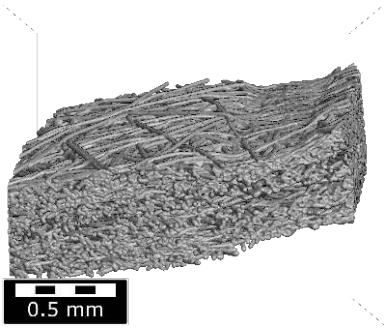
Structure	Voxels x (1)	Voxels y (1)	Voxels z (1)	Solid volume fraction (%)
nonwoven_scan_structure1	438	448	141	28.6
nonwoven_scan_structure2	438	448	126	31.1

Source: `report_src/nonwoven_scan_preparation/final/data/runs.csv` (collected by collect_study from report_src/nonwoven_scan_preparation/final/collect.yaml)

Every check of the procedure passed: the thickness axis was clear, the sheet is levelled and aligned, the crop limits were stable, and the verification of both structures found the thickness on z, no tilt above the limit, no remaining angle about z and no remaining crop on structure 1 (section Verification).

3 Raw scan

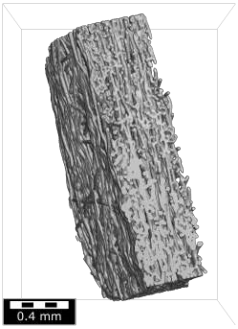
The scan as received. Whole-domain averages (solid volume fraction, porosity, density) are not shown here: the empty borders and the air in z dilute them.



view along z (x-y plane)

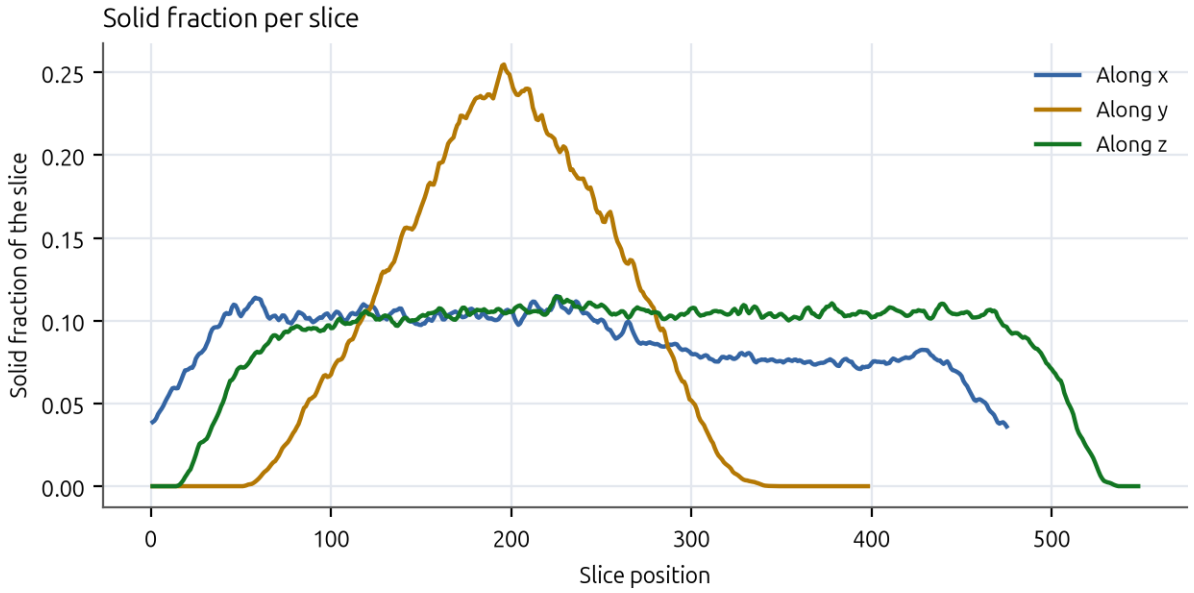


view along y (x-z plane)



view along x (y-z plane)

Measure (`measure_sheet.py`). The solid fraction of every slice along x, y and z shows where the material sits. The axis with the shortest extent of material is the thickness axis. The tilt is a plane fitted through the mid-height of blocks of columns.



Source: `models/nonwoven_scan/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

Axis	Domain (voxels)	Extent of material (voxels)	Tilt along the axis (degrees)	Thickness axis
x	475	475	11.18	
y	398	213	-	yes
z	548	493	−13.38	

Source: `models/nonwoven_scan/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

Operation	Value
Permutation (ProcessGeo:Permute)	FlipYZ
Rotation about X (degrees)	13.38
Rotation about Y (degrees)	11.18

Source: `models/nonwoven_scan/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

Quantity	Value	Unit
ThicknessAxis	y	
ThicknessOverNextExtent	0.45	
ThicknessAxisIsClear	yes	

Source: `models/nonwoven_scan/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

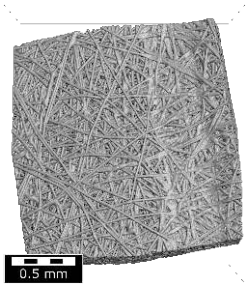
Rule. The thickness axis counts as clear when its extent is under 0.7 times the next shortest one; otherwise the procedure stops and asks. **Decision.** The thickness lies on y and is clear, so the procedure continued; `ProposedPermute` is FlipYZ, which puts y on z.

4 Step 1: Thickness onto z

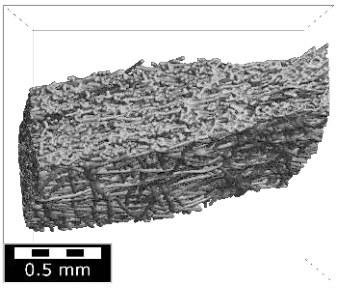
Modify (`permute.py`). `ProcessGeo:Permute` swaps two axes without mirroring, so voxel length, materials and values stay as they are.

Axis	Before (voxels)	After (voxels)
x	475	475
y	398	548
z	548	398

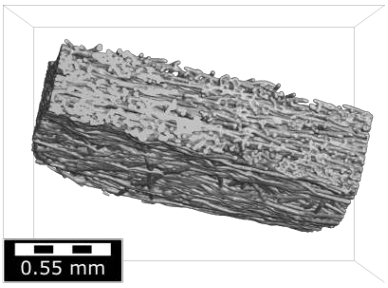
Source: `models/nonwoven_scan_permuted/Permute.gdr` (GeoDict:CustomAnalysis)



view along z (x-y plane)

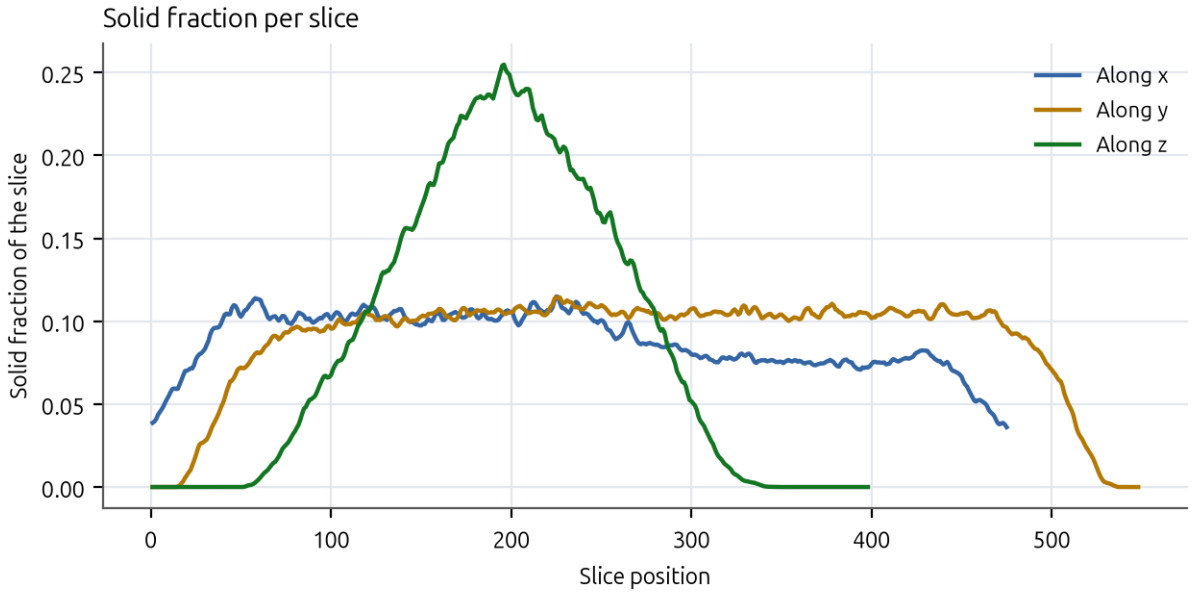


view along y (x-z plane)



view along x (y-z plane)

Measure (`measure_sheet.py`) on the permuted structure: if the swap worked, the profile along z is now the narrow one.



Source: `models/nonwoven_scan_permuted/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

Axis	Domain (voxels)	Extent of material (voxels)	Tilt along the axis (degrees)	Thickness axis
x	475	475	11.18	
y	548	493	−13.38	
z	398	213	-	yes

Source: `models/nonwoven_scan_permuted/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

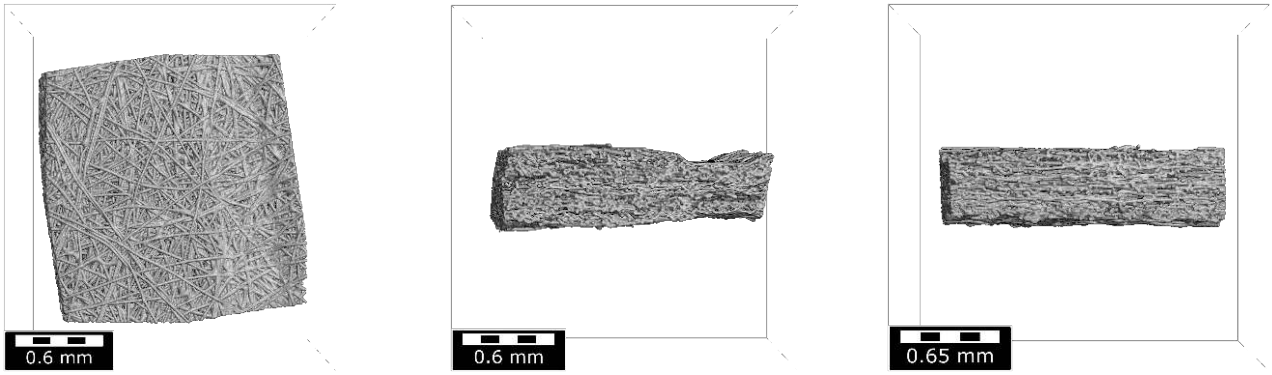
Rule. `ProposedPermute` from the raw scan names the swap; with the thickness already on z the step is skipped. **Decision.** FlipYZ was applied; the thickness lies on z now, and the rotation angles proposed on the permuted structure equal the ones proposed on the raw scan, as they should.

5 Step 2: Tilt

Modify (`rotate.py`). One rotation about x and one about y, by the angles proposed on the raw scan, through a grey-value round trip with `AutoResize`: the domain grows so nothing is clipped, and the empty corners it brings are cut away in step 4.

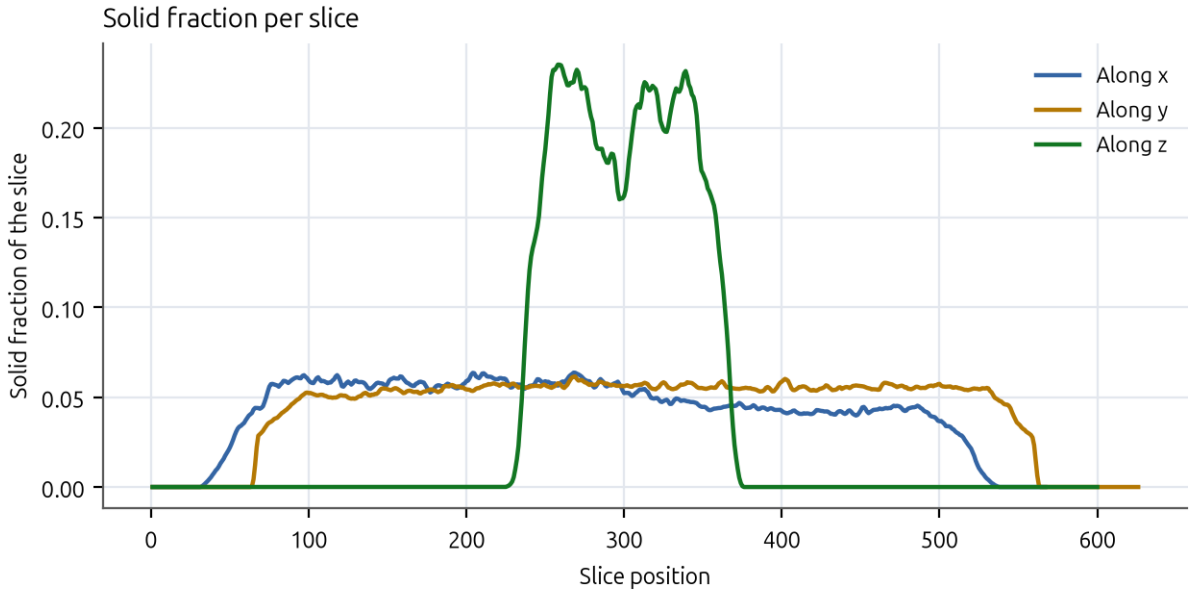
Axis	Angle (degrees)	Before (voxels)	After (voxels)
x	13.38	475	567
y	11.18	548	626
z	0.00	398	600

Source: `models/nonwoven_scan_levelled/Rotate.gdr` (GeoDict:CustomAnalysis)



view along z (x-y plane) | view along y (x-z plane) | view along x (y-z plane)

Measure (`measure_sheet.py`) on the levelled structure: if the sheet is level, the profile along z has a flat top and steep flanks.



Source: `models/nonwoven_scan_levelled/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

Axis	Domain (voxels)	Extent of material (voxels)	Tilt along the axis (degrees)	Thickness axis
x	567	480	−0.15	
y	626	496	−0.22	
z	600	133	-	yes

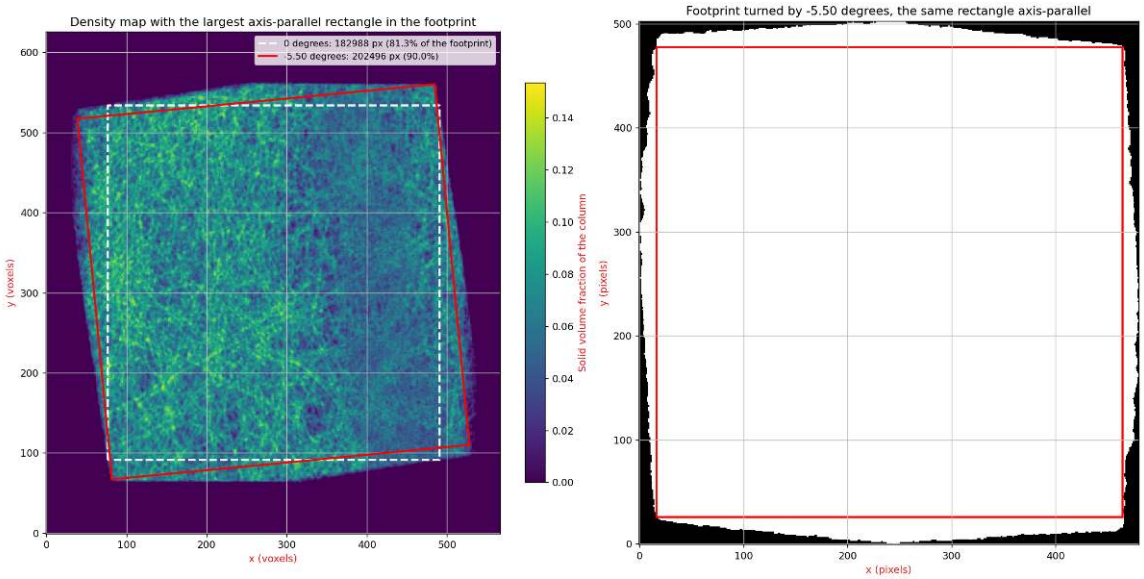
Source: `models/nonwoven_scan_levelled/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

Rule. Both remaining tilts must be under 0.5 degrees; otherwise rotate once more, and stop if that fails too.
Decision. One rotation was enough: both remaining tilts are under 0.5 degrees (table above), so no second rotation was made.

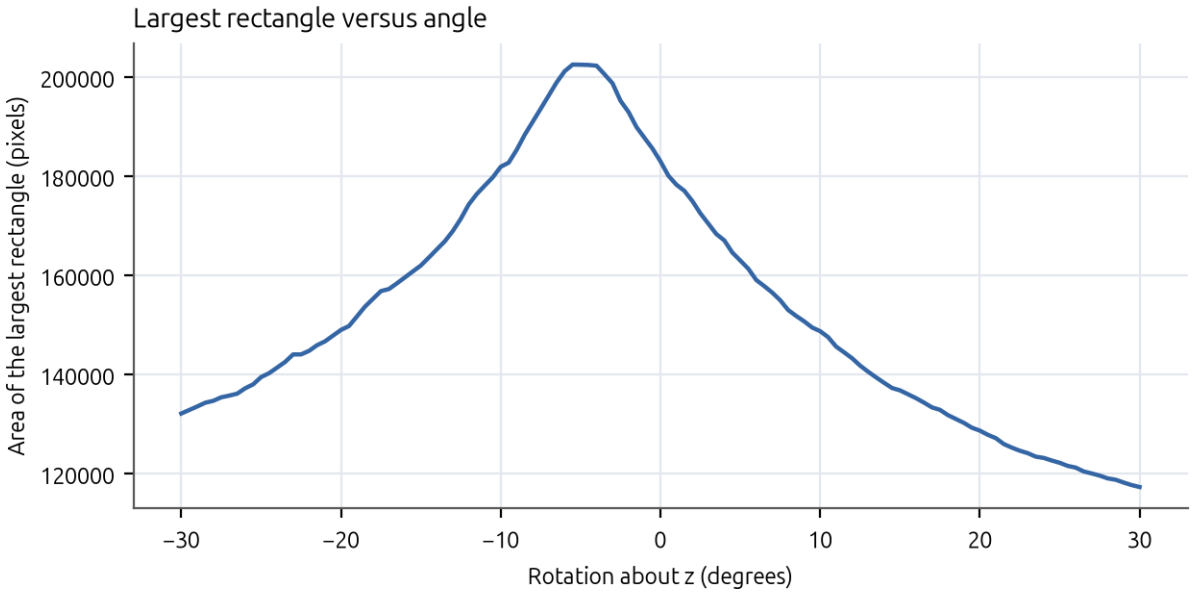
6 Step 3: Rotation about z

The scan axes x and y are not tied to the machine or cross direction of the web, so the angle about z is taken from the footprint of the sheet: the angle at which the largest axis-parallel rectangle fits into it. That rectangle is what the crop keeps.

Measure (`measure_z_angle.py`) on the levelled structure. Left: the density map (`MatDict:DensityMap`, solid volume fraction of each column) with the largest rectangle at 0 degrees and at the best angle. Right: the footprint turned by the best angle with the same rectangle.



Levelled structure: density map with the largest axis-parallel rectangle at 0 degrees and at the best angle



Source: `models/nonwoven_scan_levelled/MeasureZAngle.gdr` (GeoDict:CustomAnalysis)

Quantity	Value
Angle of the largest area (degrees)	−5.50
Angles within 1 % of it (degrees)	−6.0 to −3.5
Proposed rotation about z (degrees)	−5.50
Footprint (pixels)	225063
Largest area at that angle (pixels)	202496
Largest area at 0 degrees (pixels)	182988
Share of the footprint at that angle	0.900
Share of the footprint at 0 degrees	0.813

Source: `models/nonwoven_scan_levelled/MeasureZAngle.gdr` (GeoDict:CustomAnalysis)

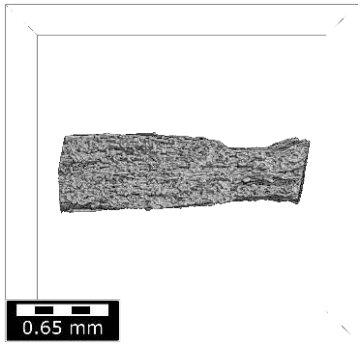
Modify (`rotate.py`) the levelled structure about z alone, by `ProposedRotateZ`.

Axis	Angle (degrees)	Before (voxels)	After (voxels)
x	0.00	567	625
y	0.00	626	678
z	−5.50	600	600

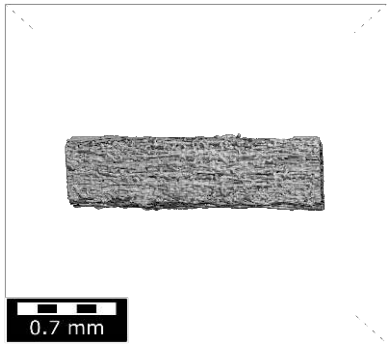
Source: `models/nonwoven_scan_aligned/Rotate.gdr` (GeoDict:CustomAnalysis)



view along z (x-y plane)

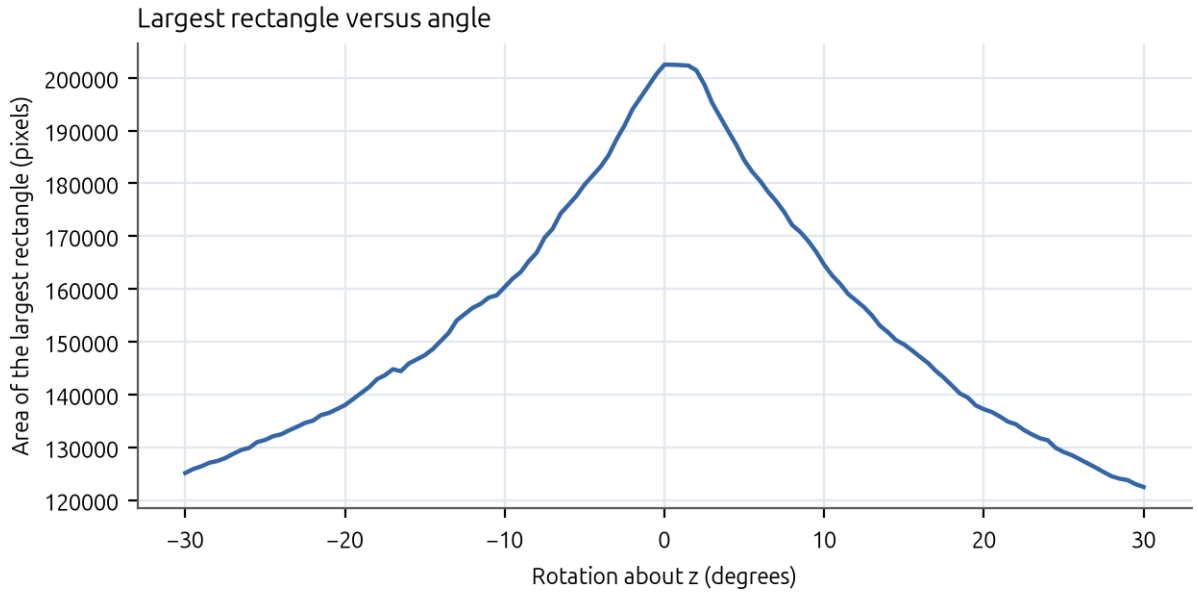


view along y (x-z plane)



view along x (y-z plane)

Check (`measure_z_angle.py` and `measure_sheet.py`) on the aligned structure: if angle and sign are right, the best rectangle now lies at 0 degrees, and the tilt has stayed under 0.5 degrees.



Source: `models/nonwoven_scan_aligned/MeasureZAngle.gdr` (GeoDict:CustomAnalysis)

Quantity	Value	Unit
RectangleAngle	0.00	deg
ProposedRotateZ	0.00	deg
RectangleShareBest	0.90	

Source: `models/nonwoven_scan_aligned/MeasureZAngle.gdr` (GeoDict:CustomAnalysis)

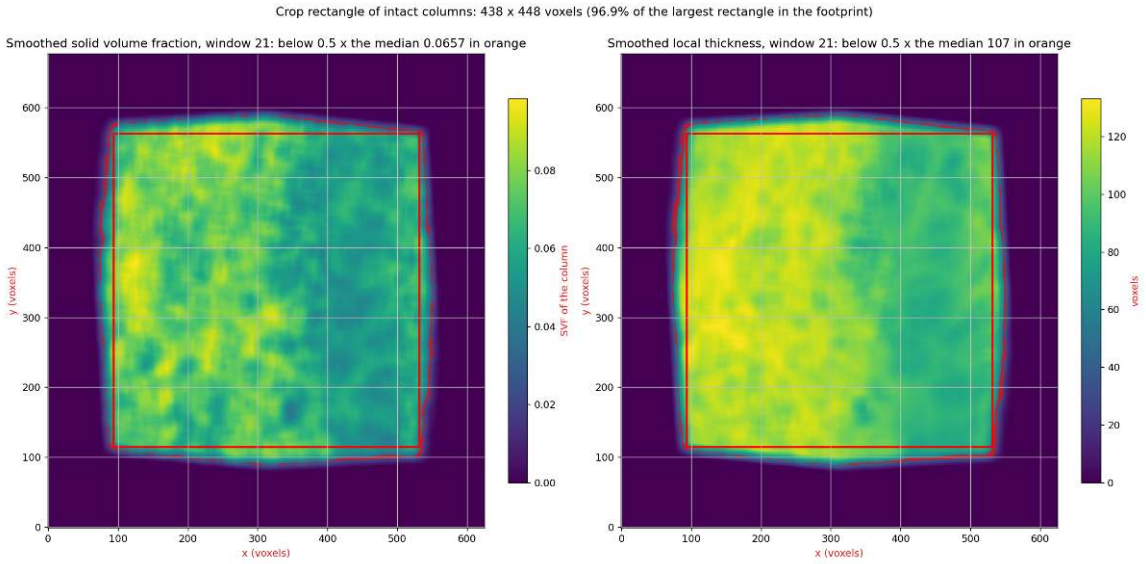
Quantity	Value	Unit
TiltX	−0.14	deg
TiltY	−0.19	deg

Source: `models/nonwoven_scan_aligned/MeasureSheet.gdr` (GeoDict:CustomAnalysis)

Rule. The angle is skipped when the 1 % band around the best area holds 0 degrees; after the rotation `ProposedRotateZ` must come back 0. **Decision.** The band around the best angle did not hold 0 degrees, so the levelled structure was rotated about z by `ProposedRotateZ`; on the aligned structure `ProposedRotateZ` comes back 0, the best rectangle lies at 0 degrees, and the tilt stayed under 0.5 degrees. The sign of the rotation is therefore correct.

7 Step 4: Crop limits

Measure (`measure_crop_limits.py`) on the aligned structure. A column along z is intact when its solid volume fraction and its local thickness, both smoothed over a window of columns, reach a fraction of their medians over the footprint. x and y are the largest axis-parallel rectangle of intact columns; z keeps the sheet and removes only the empty space. Left: the smoothed solid volume fraction, right: the smoothed thickness, each with the failing columns and the crop rectangle.



Aligned structure: smoothed solid volume fraction and local thickness with the crop rectangle

Axis	Removed at the minus side (voxels)	Removed at the plus side (voxels)	Remaining (voxels)
x	94	93	438
y	115	115	448
z	231	228	141

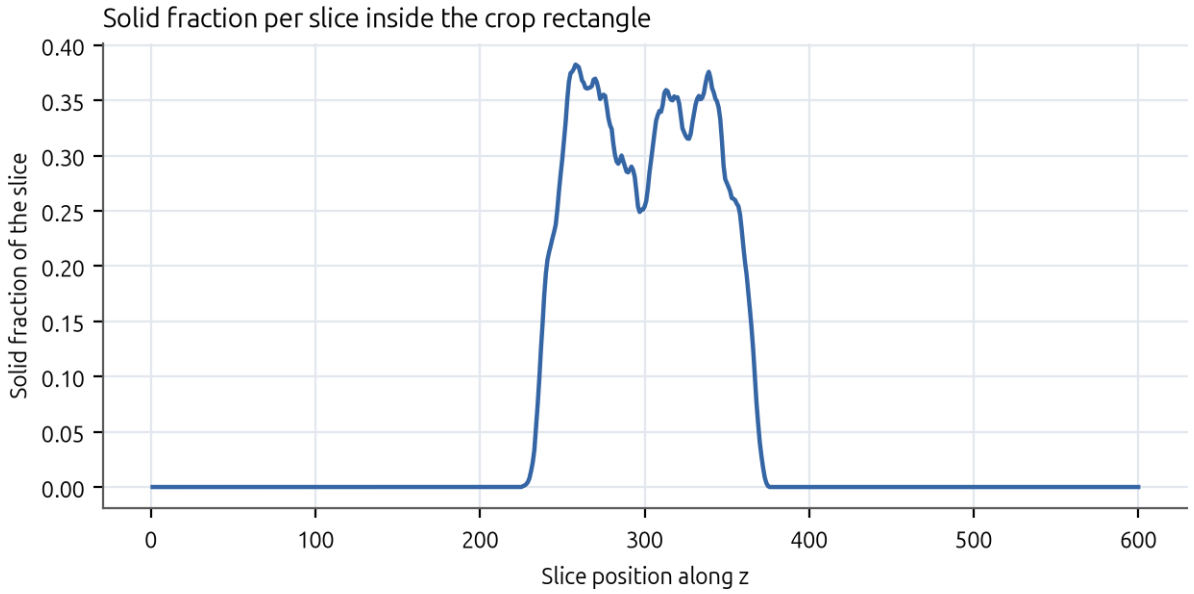
Source: `models/nonwoven_scan_aligned/MeasureCropLimits.gdr` (GeoDict:CustomAnalysis)

The size of the rectangle for other levels shows whether the chosen levels sit on a plateau or cut into a zone of the web:

Density level	Thickness level	Rectangle (pixels)	Share of the largest rectangle in the footprint
0.25	0.5	196224	0.969
0.25	0.6	193564	0.956
0.25	0.75	141750	0.700
0.5	0.5	196224	0.969
0.5	0.6	193564	0.956
0.5	0.75	141750	0.700
0.75	0.5	108480	0.536
0.75	0.6	108480	0.536
0.75	0.75	107550	0.531

Source: `models/nonwoven_scan_aligned/MeasureCropLimits.gdr` (GeoDict:CustomAnalysis)

The z window inside the rectangle cuts at a small fraction of the plateau of the slice profile, not at the first solid voxel, so a stray voxel cannot widen it:



Source: `models/nonwoven_scan_aligned/MeasureCropLimits.gdr` (GeoDict:CustomAnalysis)

Quantity	Value	Unit
Window	21	
IntactShare	0.97	
LargerWindow	31	
IntactShareLargerWindow	0.96	
CropLimitsStable	yes	

Source: `models/nonwoven_scan_aligned/MeasureCropLimits.gdr` (GeoDict:CustomAnalysis)

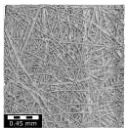
Rule. The limits count as stable when a window half as large again gives the same rectangle, and `IntactShare` must be at least 0.8 (the share of the footprint that is intact); otherwise the procedure stops and asks. **Decision.** The limits are stable and the intact share reaches the rule, so the six counts of the first table were used for structure 1.

8 Step 5: Structure 1

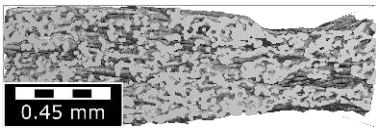
Modify (`crop.py`) the aligned structure with the six counts of step 4.

Axis	Removed at the minus side (voxels)	Removed at the plus side (voxels)	Before (voxels)	After (voxels)
x	94	93	625	438
y	115	115	678	448
z	231	228	600	141

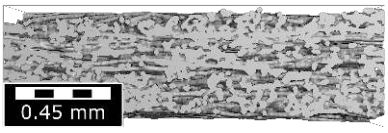
Source: `models/nonwoven_scan_structure1/Crop.gdr` (GeoDict:CustomAnalysis)



view along z (x-y plane)



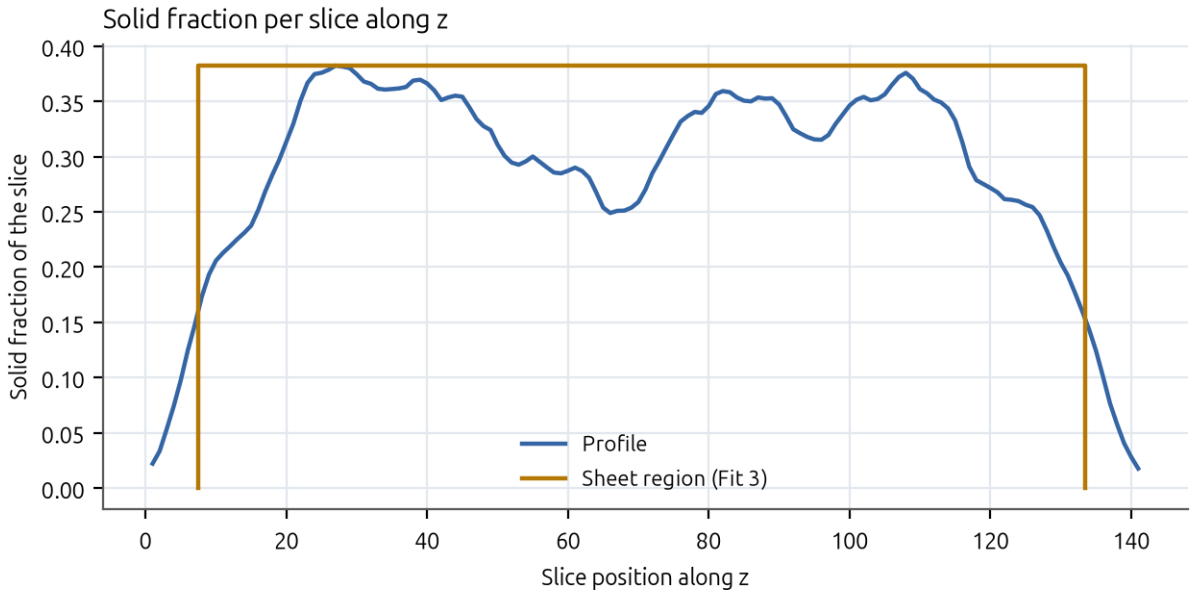
view along y (x-z plane)



view along x (y-z plane)

9 Step 6: Sheet region in z

Measure (`measure_sheet_region.py`) on structure 1. `MatDict:ThicknessEstimation` Fit 3 (sharp faces, uniform density) splits z into the low-z surface zone, the sheet and the high-z surface zone. The two zones are the counts structure 2 removes.



Source: `models/nonwoven_scan_structure1/MeasureSheetRegion.gdr` (GeoDict:CustomAnalysis)

Zone	Thickness (voxels)	Thickness (m)
Surface zone at z minus (inlet)	7.0	2.8e-05
Sheet (medium)	126.0	0.000504
Surface zone at z plus (outlet)	8.0	3.204e-05

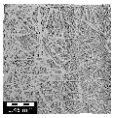
Source: `models/nonwoven_scan_structure1/MeasureSheetRegion.gdr` (GeoDict:CustomAnalysis)

10 Step 7: Structure 2

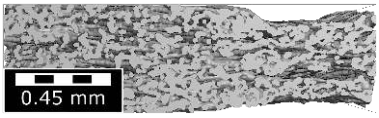
Modify (`crop.py`) structure 1 with the two z counts of step 6 only.

Axis	Removed at the minus side (voxels)	Removed at the plus side (voxels)	Before (voxels)	After (voxels)
x	0	0	438	438
y	0	0	448	448
z	7	8	141	126

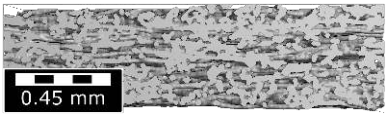
Source: `models/nonwoven_scan_structure2/Crop.gdr` (GeoDict:CustomAnalysis)



view along z (x-y plane)



view along y (x-z plane)



view along x (y-z plane)

11 Verification

Both structures are measured again with the same macros. The checks: the thickness lies on z, the tilt is under 0.5 degrees, the angle about z is 0, and on structure 1 all six crop counts are 0. A count that is not 0 means the crop missed.

Every measured structure, in the order of the steps:

Structure	Voxels x (1)	Voxels y (1)	Voxels z (1)	Thickness axis	Thickness / next extent (1)
nonwoven_scan	475	398	548	y	0.45
nonwoven_scan_permuted	475	548	398	z	0.45
nonwoven_scan_levelled	567	626	600	z	0.28
nonwoven_scan_aligned	625	678	600	z	0.28
nonwoven_scan_structure1	438	448	141	z	0.30
nonwoven_scan_structure2	438	448	126	z	0.29

Source: `report_src/nonwoven_scan_preparation/geometry/data/runs.csv` (collected by collect_study from report_src/nonwoven_scan_preparation/geometry/collect.yaml)

The tilt of every structure whose thickness lies on z:

Structure	Tilt along x (deg)	Tilt along y (deg)
nonwoven_scan_permuted	11.18	−13.38
nonwoven_scan_levelled	−0.15	−0.22
nonwoven_scan_aligned	−0.14	−0.19
nonwoven_scan_structure1	−0.28	−0.17
nonwoven_scan_structure2	−0.20	−0.01

Source: `report_src/nonwoven_scan_preparation/tilt/data/runs.csv` (collected by collect_study from report_src/nonwoven_scan_preparation/tilt/collect.yaml)

Angle about z and crop counts measured on structure 1:

Quantity	Value	Unit
RectangleAngle	0.00	deg
ProposedRotateZ	0.00	deg

Source: `models/nonwoven_scan_structure1/MeasureZAngle.gdr` (GeoDict:CustomAnalysis)

Axis	Removed at the minus side (voxels)	Removed at the plus side (voxels)	Remaining (voxels)
x	0	0	438
y	0	0	448
z	0	0	141

Source: `models/nonwoven_scan_structure1/MeasureCropLimits.gdr` (GeoDict:CustomAnalysis)

The thickness of the sheet (Fit 3 of step 6), in voxels and, with the voxel length of the file, in metres:

Quantity	Value	Unit
ThicknessMediumVoxels	126	
ThicknessMedium	504	µm

Source: `models/nonwoven_scan_structure1/MeasureSheetRegion.gdr` (GeoDict:CustomAnalysis)