Quantification and Morphological Analysis of Nanofibres for Material Characterisation Purposes using SEM and Advanced Image Processing

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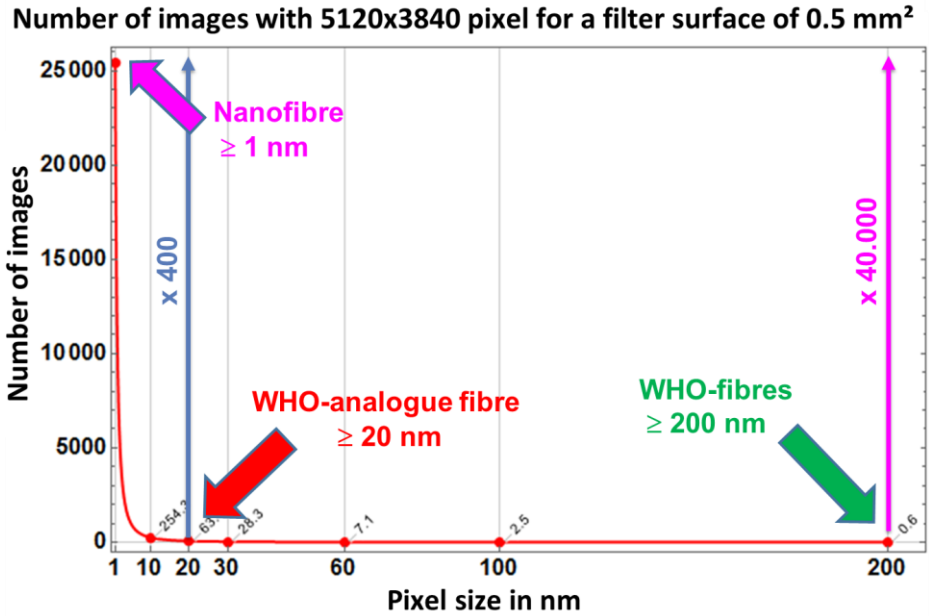
Automated evaluation for nanofibre exposure control

Recommended nanofibre exposure limit compliance testing requires the examination of a given air volume that corresponds to a specific filter area after air sampling and SEM/TEM imaging.

Number of images to be evaluated increases quadratically with decreasing fibre diameter.

Therefore, automated evaluation becomes necessary.



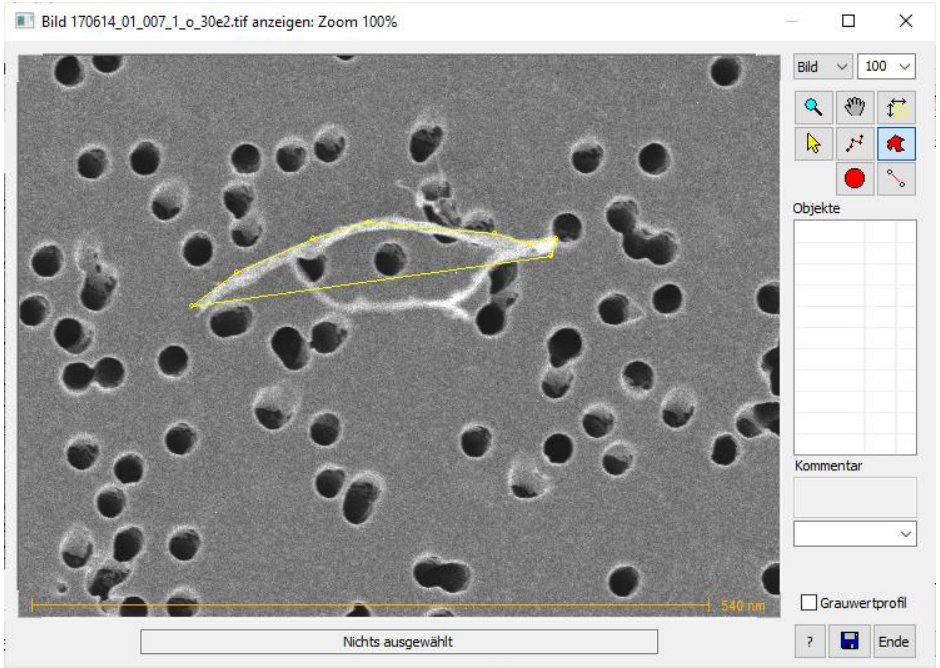
References: [TRGS 572], [doi: 10.3390/atmos11111254]

Manual evaluation using a computer-assisted measurement tool

Time spent for one workplace sample:
- 80-650 micrographs (20 MPX each)
- 150 micrographs on average
- about 3 min per micrograph

450 min. = 7.5 h

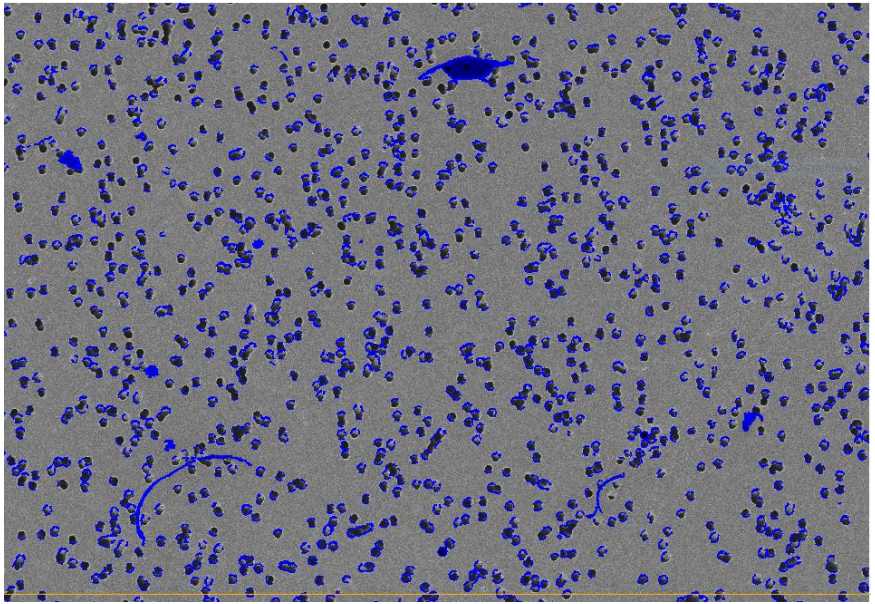
Very laborious &
Work load difficult to estimate!



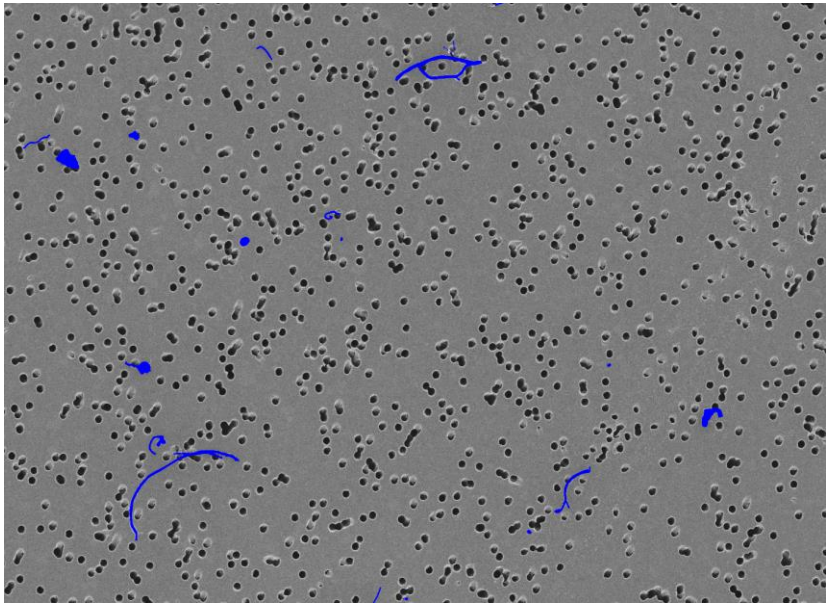
Classic image processing vs. convolutional neural networks (CNNs)

Classic image processing

by greylevel thresholding



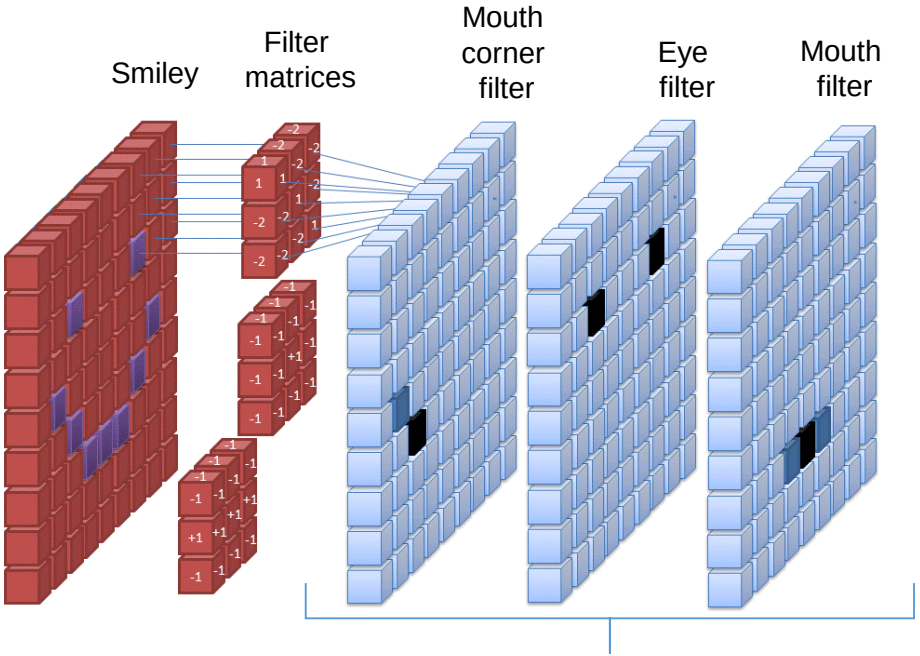
CNN

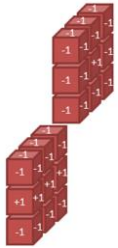


Computation time: ~1 second per micrograph (GPU)

How do CNNs work?

Convolutional image filter matrices in neural networks





Optimisation by training data!

Each convolutional filter matrix produces a „feature map“.
Training aims at optimising the filter matrix’ parameters to obtain “useful” feature maps.

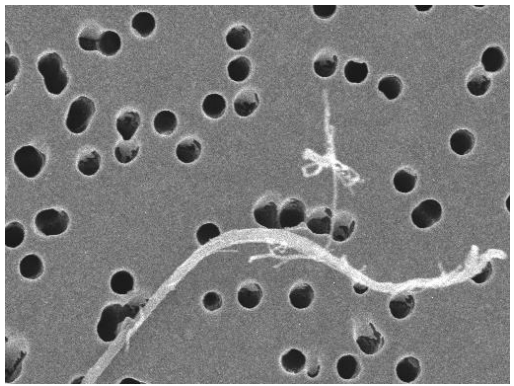
Picture: https://commons.wikimedia.org/wiki/File:3_filters_in_a_Convolutional_Neural_Network.gif

Training data set

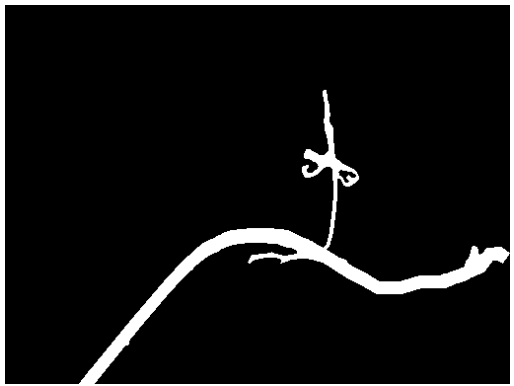
Data set used for supervised training

- 1080 manually evaluated and annotated SEM-micrographs (5120x3840 pixels)
- 108.000 training images (512x384 pixels)
- Mainly CNT-materials, few images of other fibre materials
- 7/8 of the data is used for training, the rest is used for validation

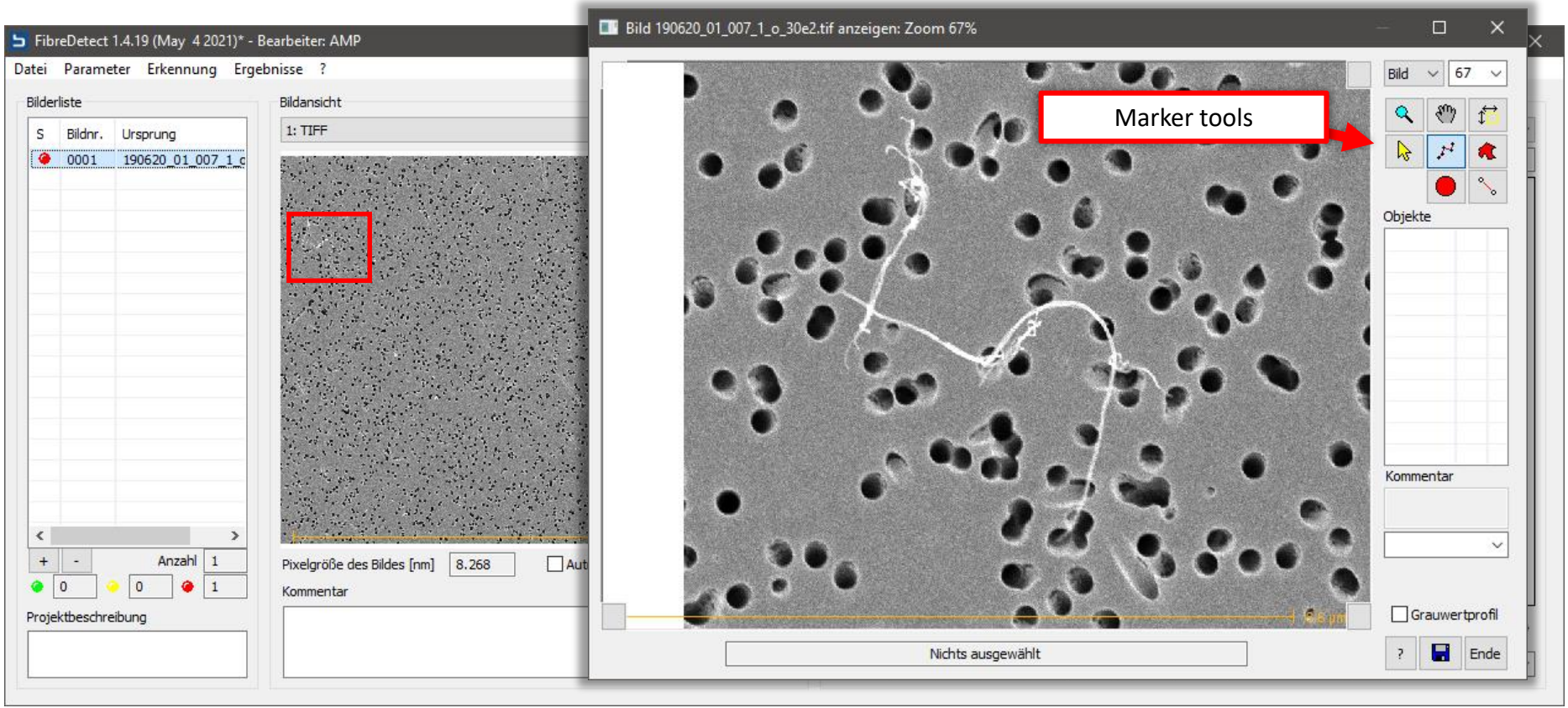
SEM image section



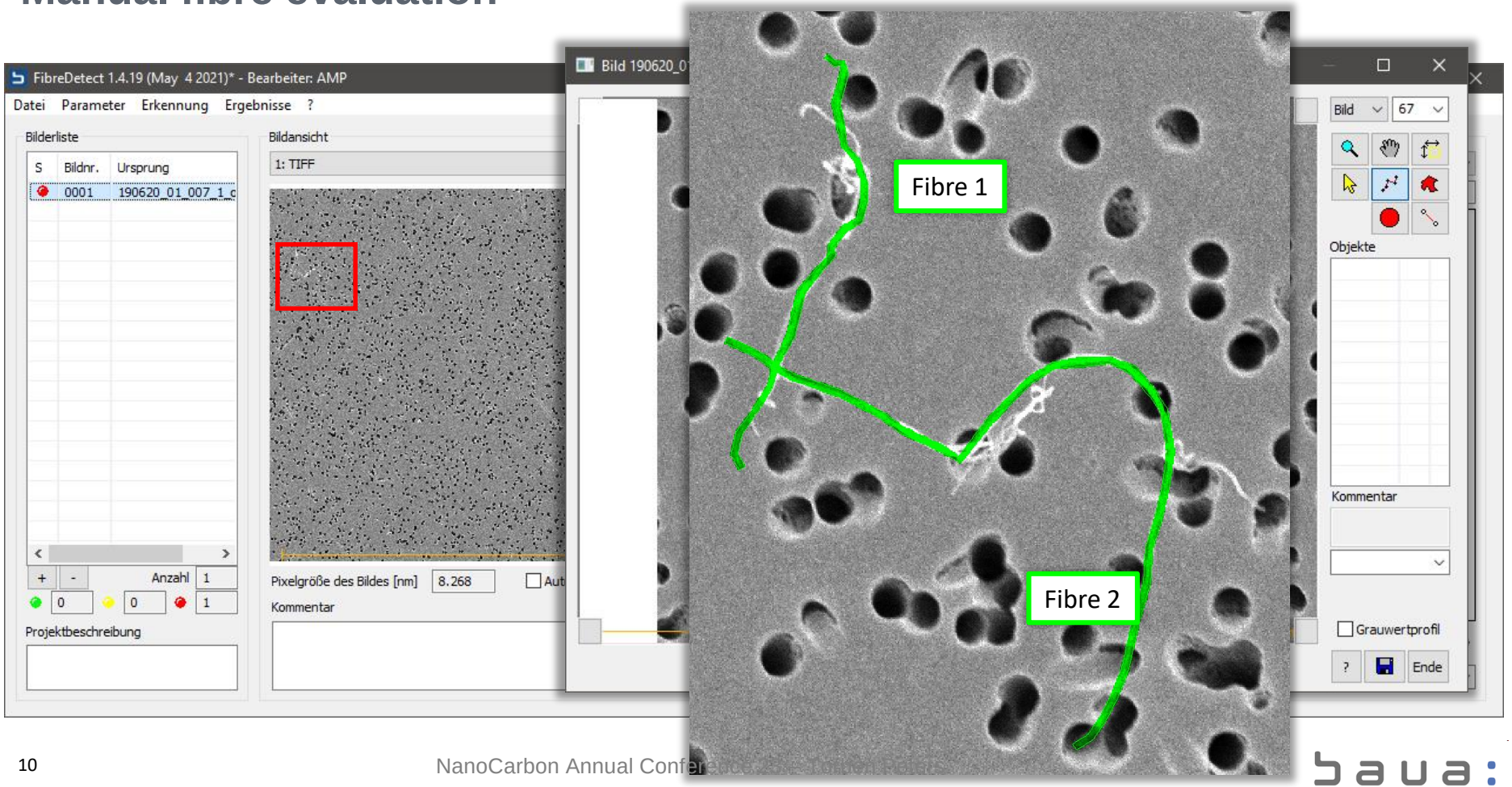
Ground Truth



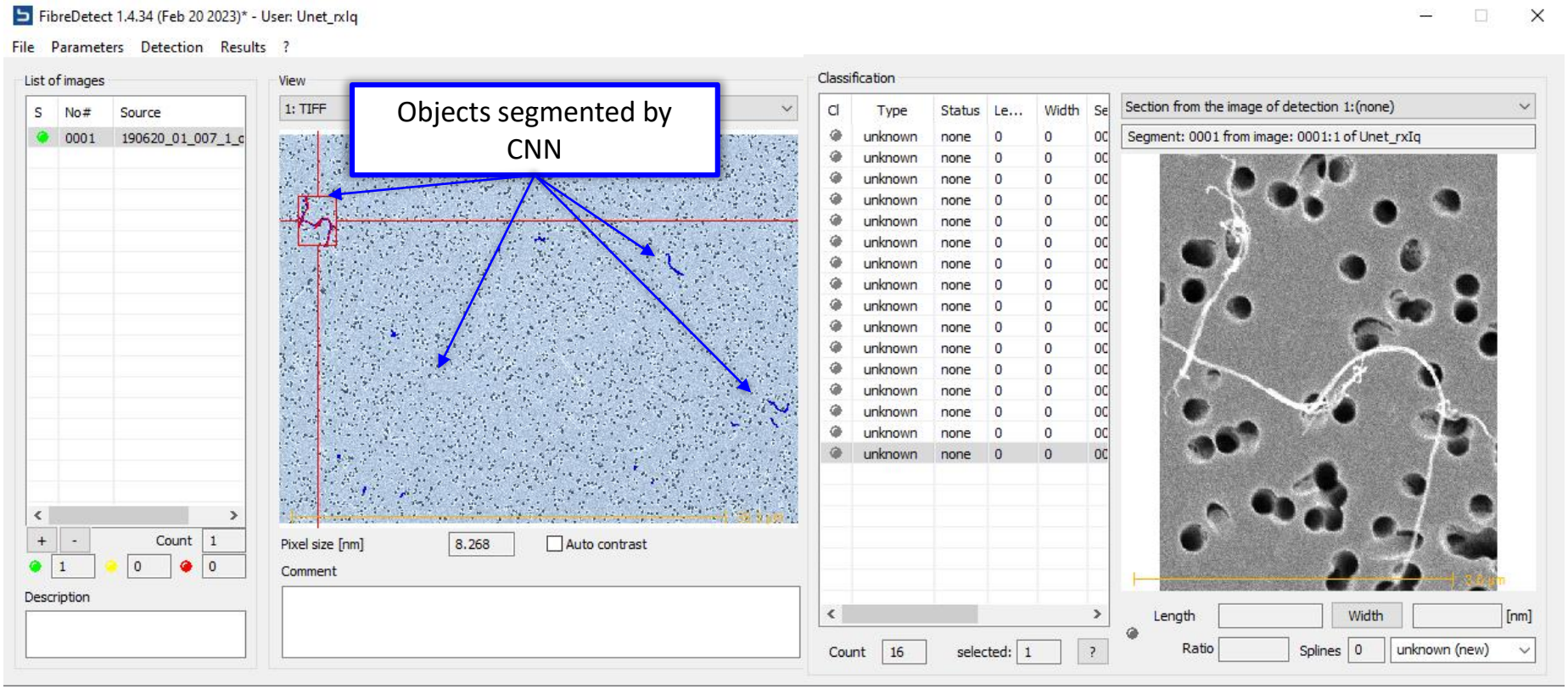
Manual fibre evaluation



Manual fibre evaluation



Automated fibre evaluation



Algorithmic fibre tracing - vectorisation

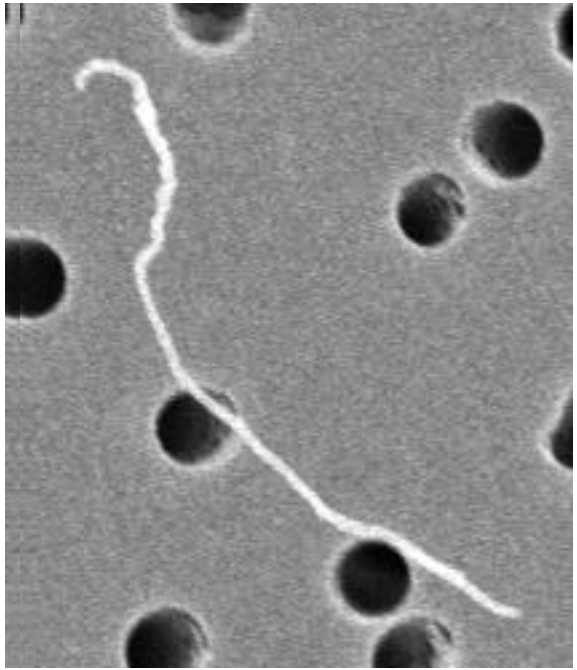
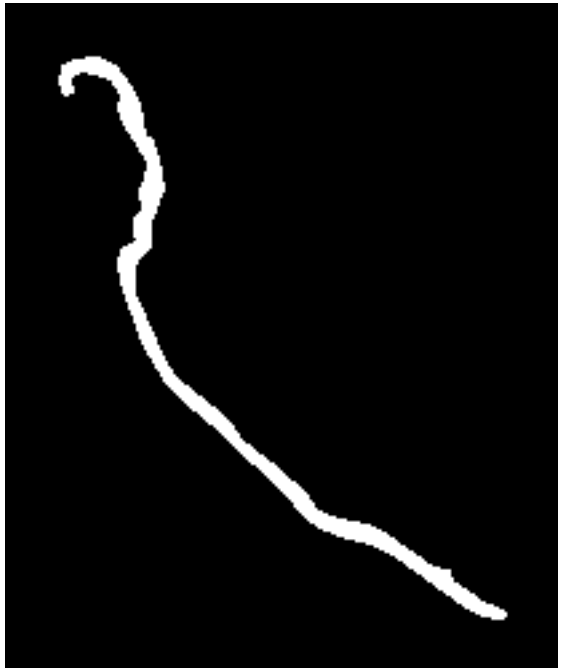
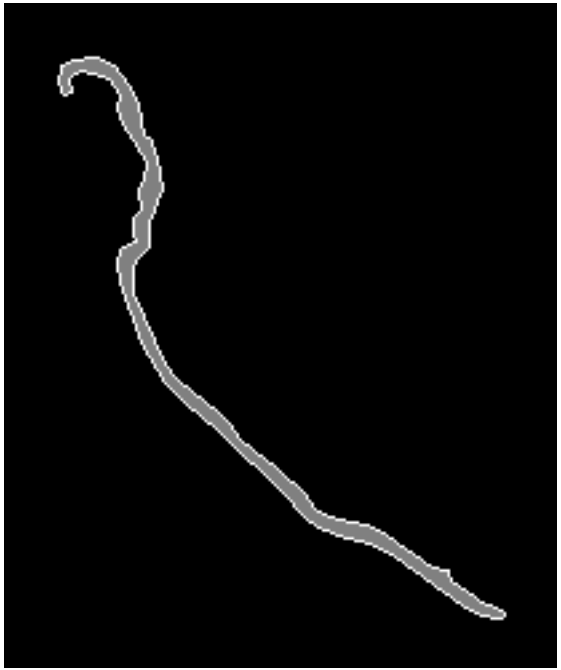


Image section

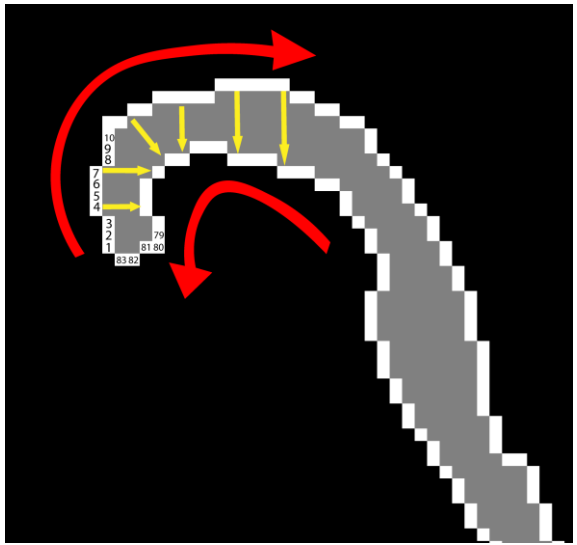


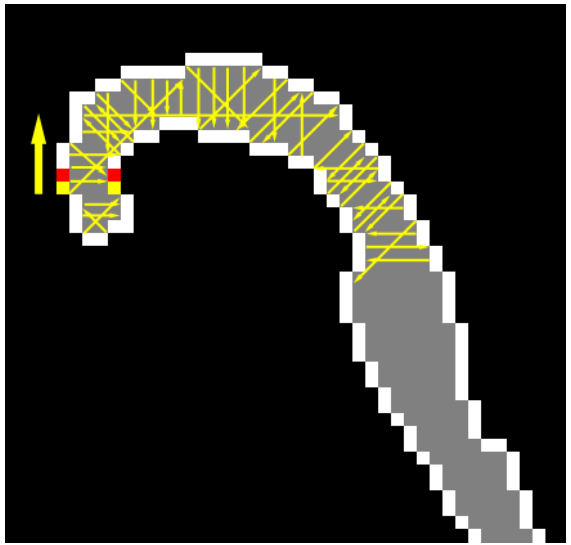
Binary Mask



Vectorisation (Polygon)

Algorithmic fibre tracing – width determination

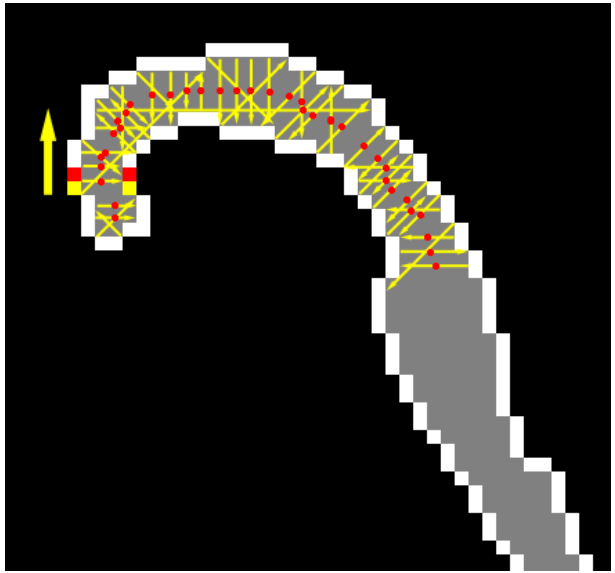


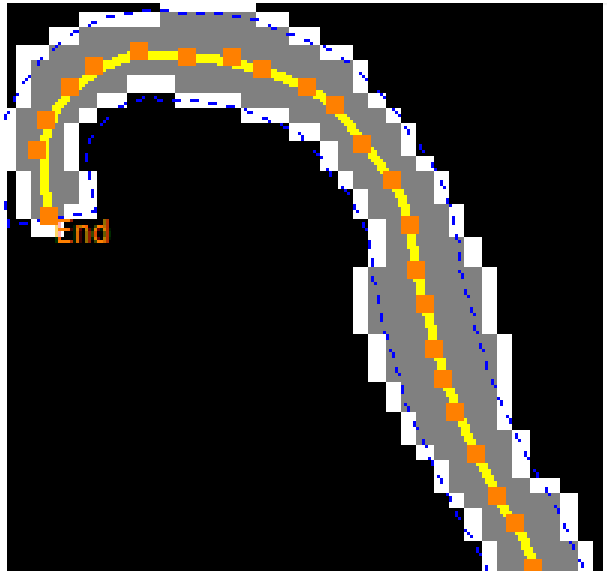


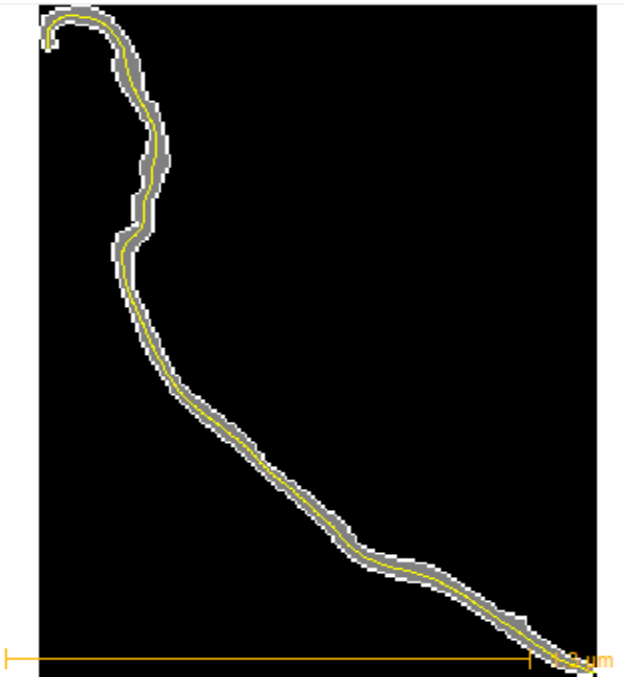
Adjacent points: Orthometric distances to opposite edge

Width histogram:
maximum = fibre width
Green area = width tolerance

Algorithmic fibre tracing – spline computation





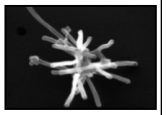
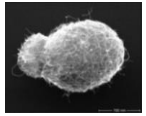
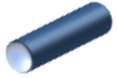
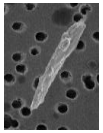
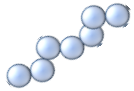
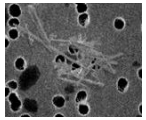
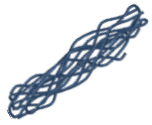
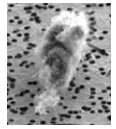
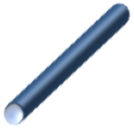
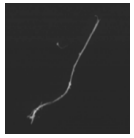
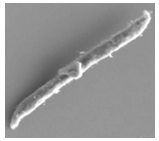


Half distances to the edge: Support points of the fibre axis within width tolerance

Compute support points of spline

Fibre length and width

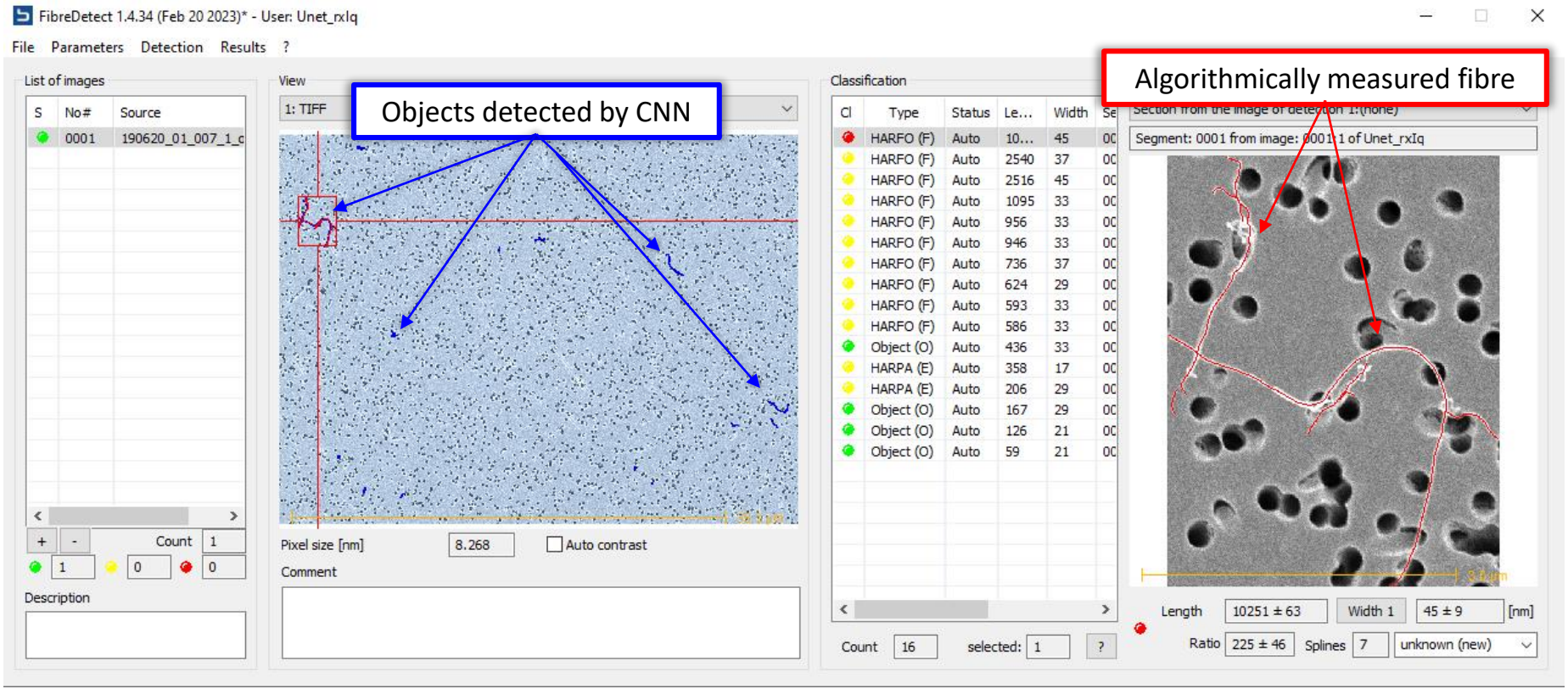
General morphological classification scheme for particles and fibres

	Individual Object	Cluster		Agglomerate		
		Particulate	Fibrous	Particulate	Fibrous	
Low-Aspect Ratio	**LARPO** Individual Particle Object	**LARC (GBS-Cluster)** Agglomerated and Countable		**LARA (GBS-Agglomerate)** Agglomerated and Un-countable		Low-Aspect Ratio
		**LARPC** 	**LARFC**  	**LARPA** 	**LARFA**  	
High-Aspect Ratio	**HARFO** Individual Fibre Object	**HARC** HAR-Cluster		**HARA** HAR-Agglomerate		High-Aspect Ratio
	 	**HARPC** 	**HARFC**  	**HARPA** 	**HARFA**  	
Satisfies WHO-Definition	**WHOFO** Individual WHO-Fibre Object	**WHOC** WHO-Cluster		**WHOA** WHO-Agglomerate		Satisfies WHO-Definition
	 	**WHOPC** 	**WHOFC**  	**WHOPA** 	**WHOFA**  	

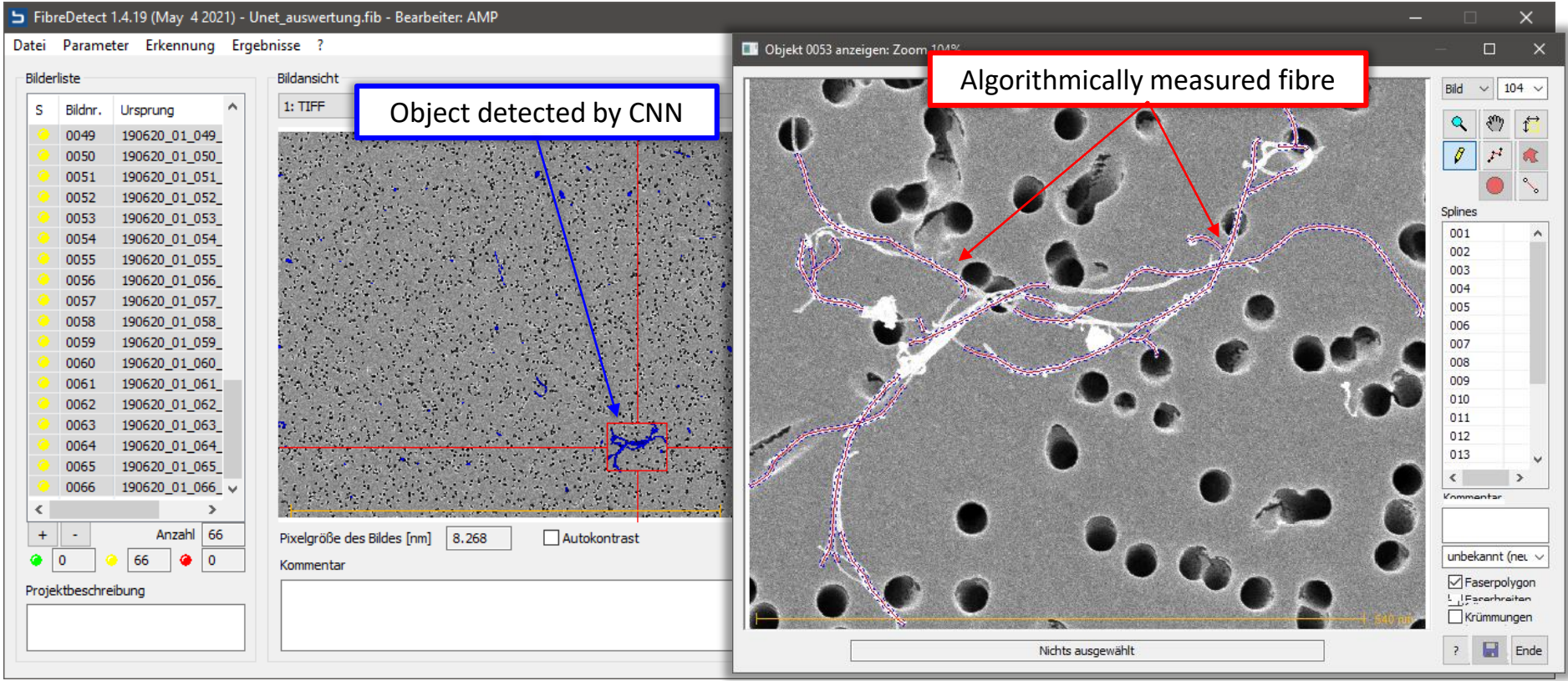
LAR stands for **L**ow-**A**spect **R**atio and is defined by a longitudinal to lateral dimension smaller than 3.
HAR stands for **H**igh-**A**spect **R**atio and is defined by a longitudinal to lateral dimension greater than 3.
WHO stands for HAR longitudinal dimensions greater than 5 µm and lateral dimensions smaller than 3 µm.
O stands for **O**bject, i.e., particle, tube, rod or fibre. **C** for **C**luster. **A** for **A**gglomerate.
Clusters are characterized by a low number of objects that could be individually distinguished,
whereas **Agglomerates** contain objects in a higher concentration such that they overlap and can predominantly not be distinguished individually.

baua:

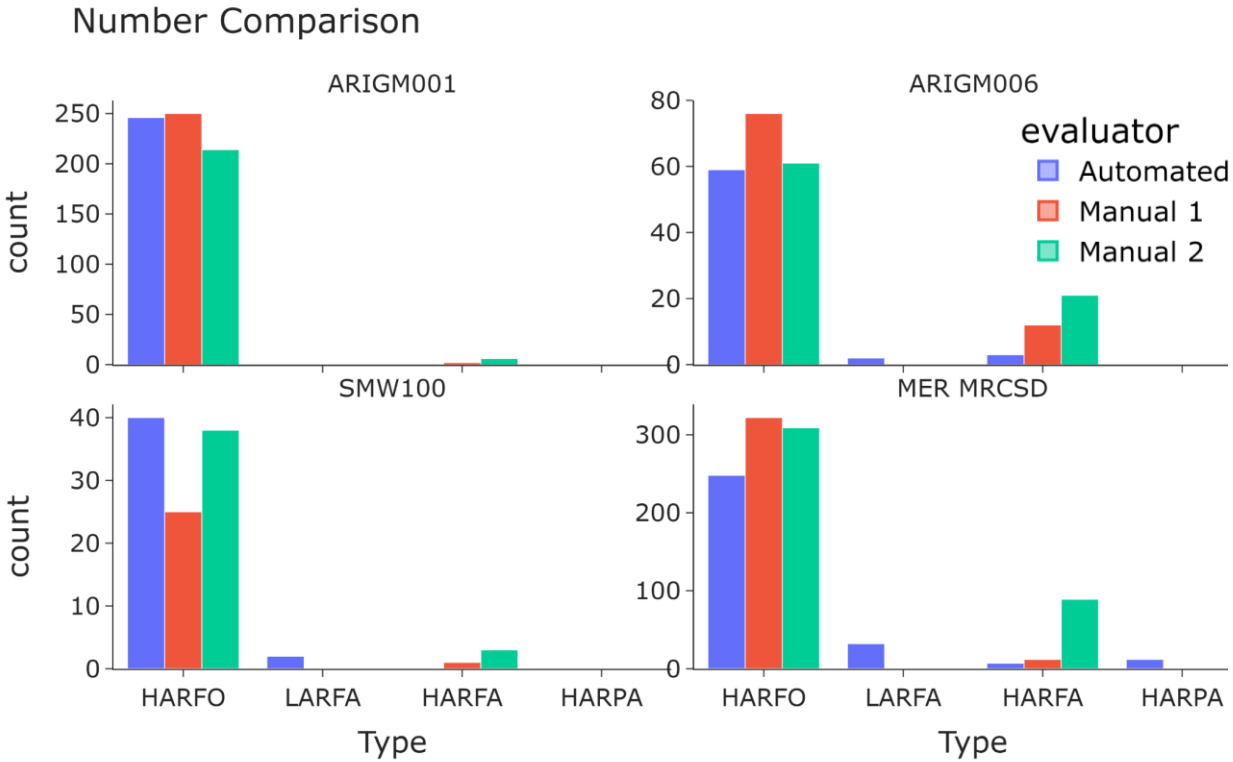
Algorithmic measurement of CNN-detected objects



Algorithmic measurement of CNN-detected objects



Evaluation comparison – Counted objects

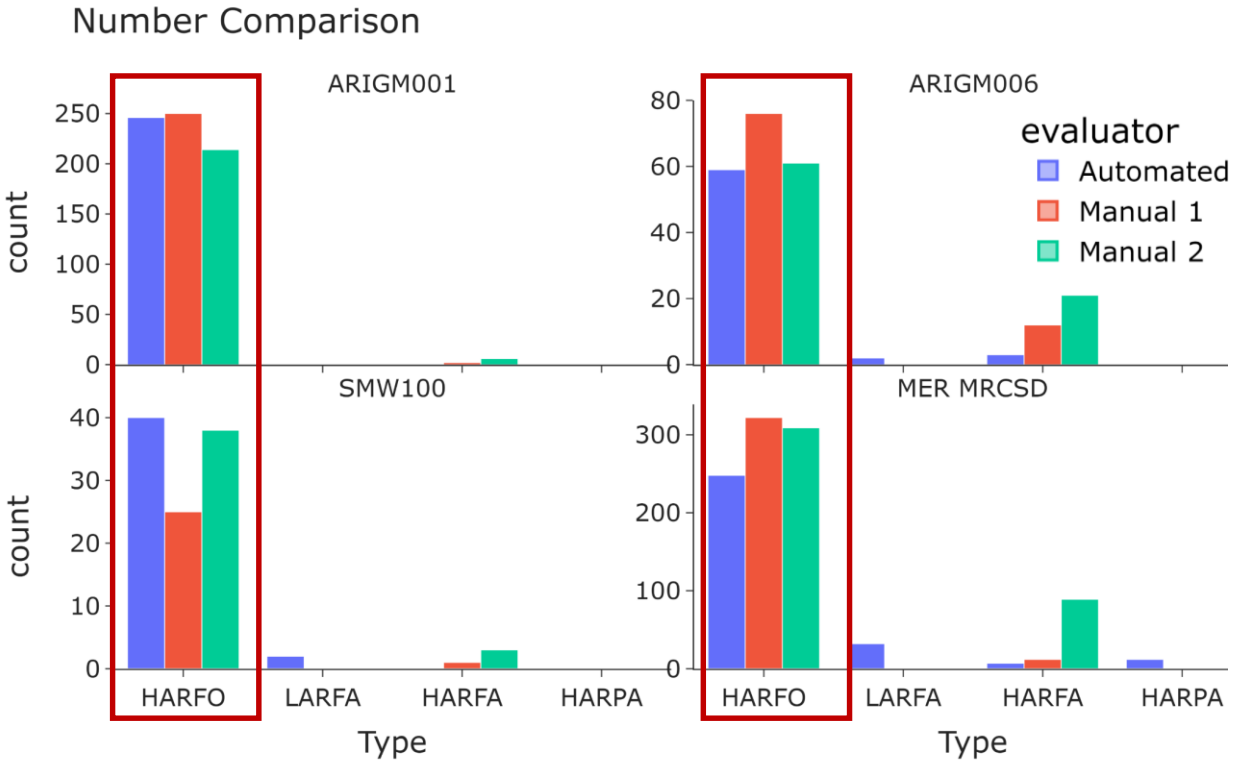


ARIGM006:
- wide length distribution
- often agglomerated

MER MRSCD:
- very long fibres
- often agglomerated

SMW 100:
- short fibres
- low filter occupancy

Evaluation comparison – Counted objects



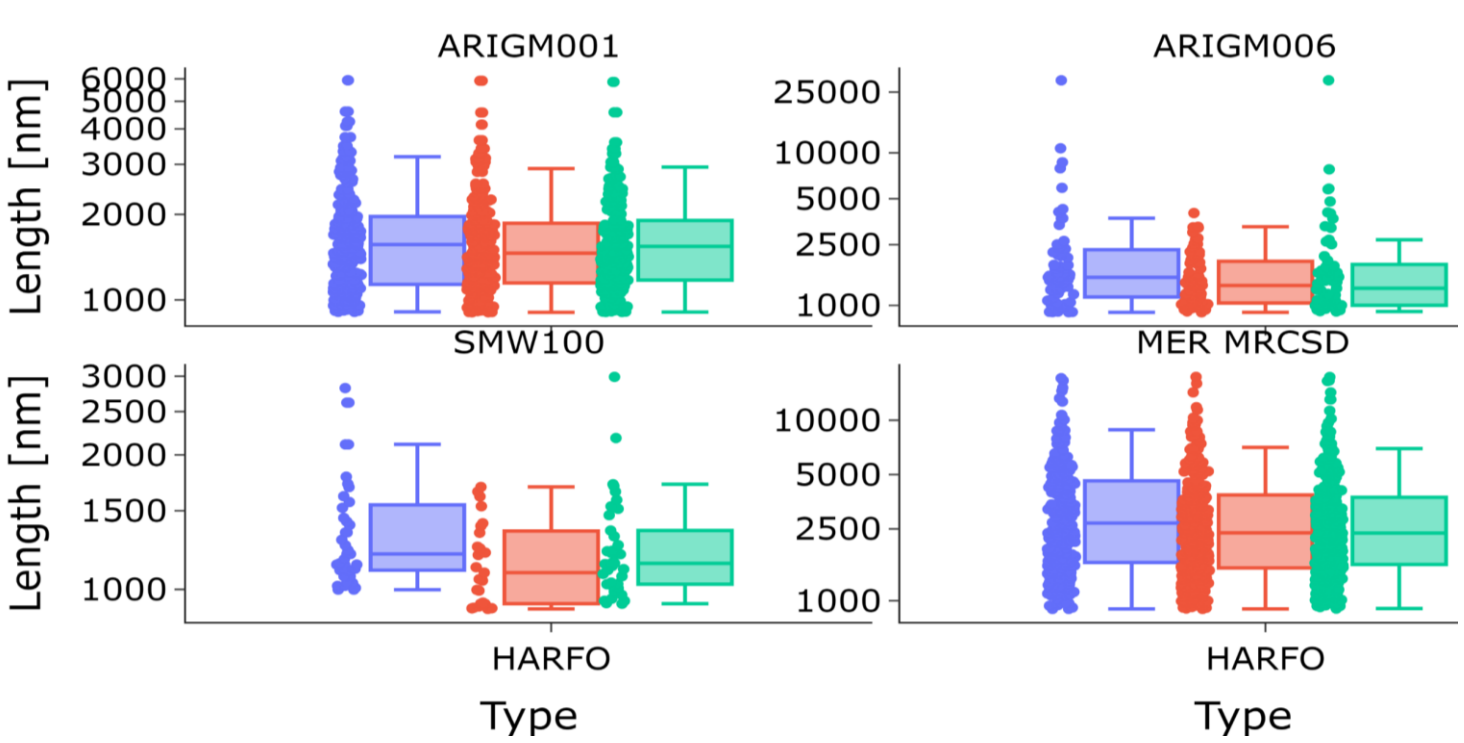
ARIGM006:
- wide length distribution
- often agglomerated

MER MRSCD:
- very long fibres
- often agglomerated

SMW 100:
- short fibres
- low filter occupancy

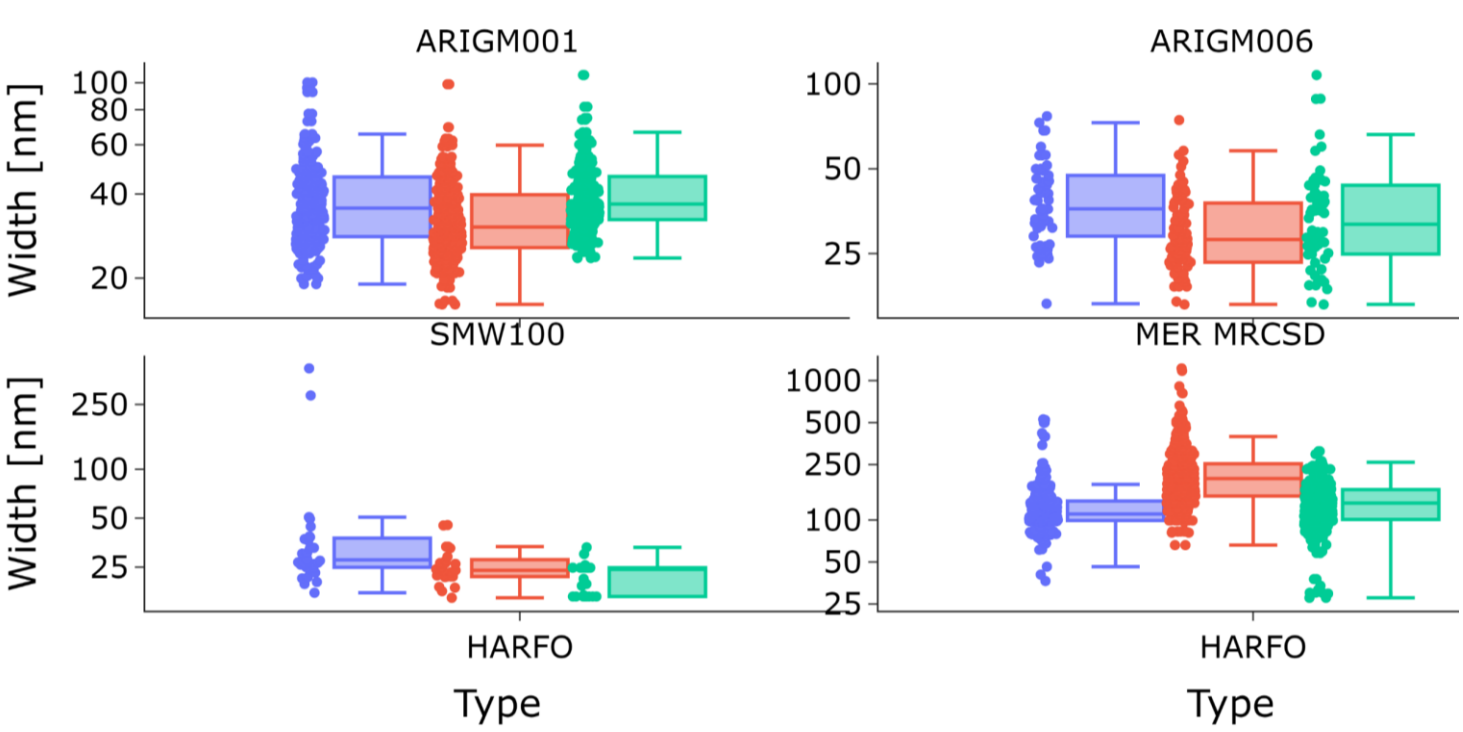
The number of counted HARFOs agrees with the manual evaluation.

Evaluation comparison - length



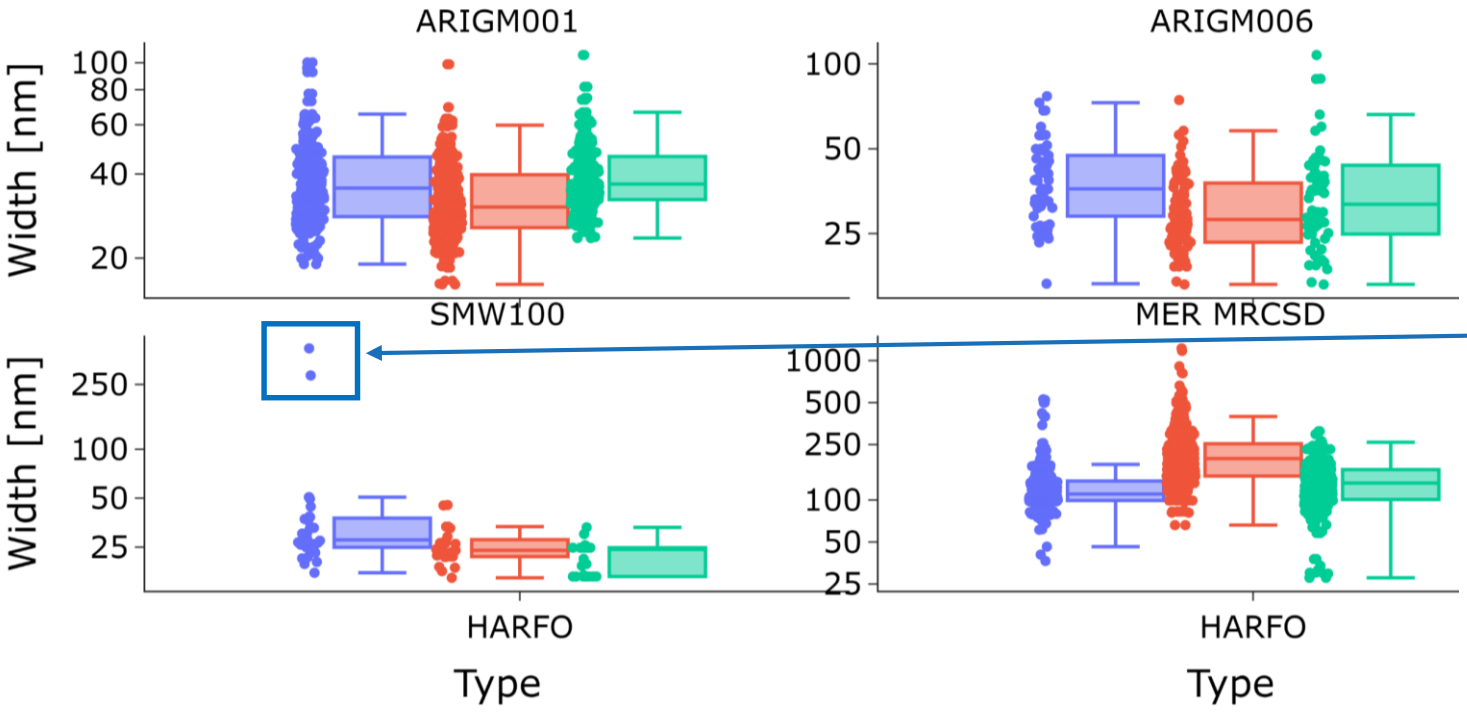
Automated evaluation is in agreement with manual evaluation.

Evaluation comparison - width

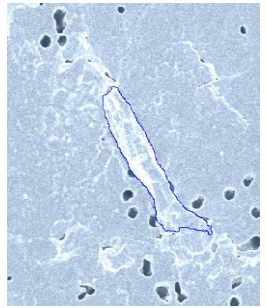


Automated evaluation is in agreement with manual evaluation.

Evaluation comparison - width



Background evaluated as fibre



Automated evaluation is in agreement with manual evaluation.

Summary

- Counts comparison (HARFOs): fits
- Length comparison (HARFOs): fits
- Width comparison (HARFOs): fits

Recommended compliance testing for nanofibre limits becomes feasible!

- Algorithmic classification of object morphology is not always reliable
  - Can a neural network do a better job?

Thank you for your attention!

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Bundesanstalt für Arbeitsschutz
und Arbeitsmedizin

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