Higher level spatial analysis of dead pixels on local grid geometry and applications to digital X-ray detector quality assessment

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9.12.2019

A tale of dead pixels

- *Inside-out*
- The birth of dead pixels
- Dead pixels geometry
- Spatial statistics for dead pixels
- Dead pixels go shiny: *DetectorChecker*
- Dead pixels make a deal
- Dead pixels alive

Engineering and Physical Sciences
Research Council

EPSRC
Investing in research for discovery and innovation

Inside-out

Statistical Methods for Computed Tomography Validation of Complex Structures in Additive Layer Manufacturing

3 years

10/2013 - 9/2016

PI: Prof W Kendall
Other investigators: Prof M A Williams, Dr G J Gibbons, Dr J Brettschneider, Prof T Nichols

EP/K031066/1

Warwick Statistics

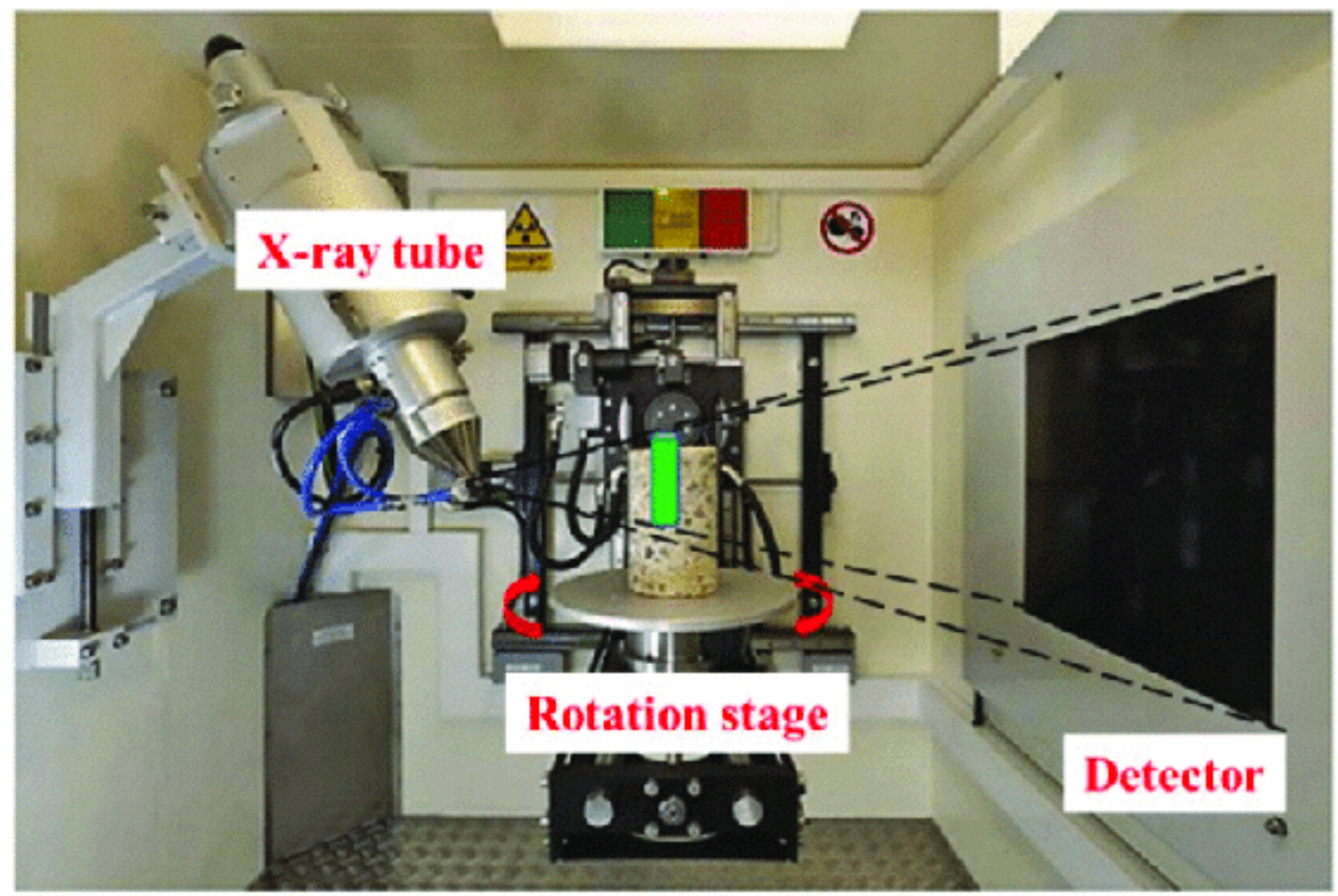
WMG

WARWICK
THE UNIVERSITY OF WARWICK

X-ray computed tomography

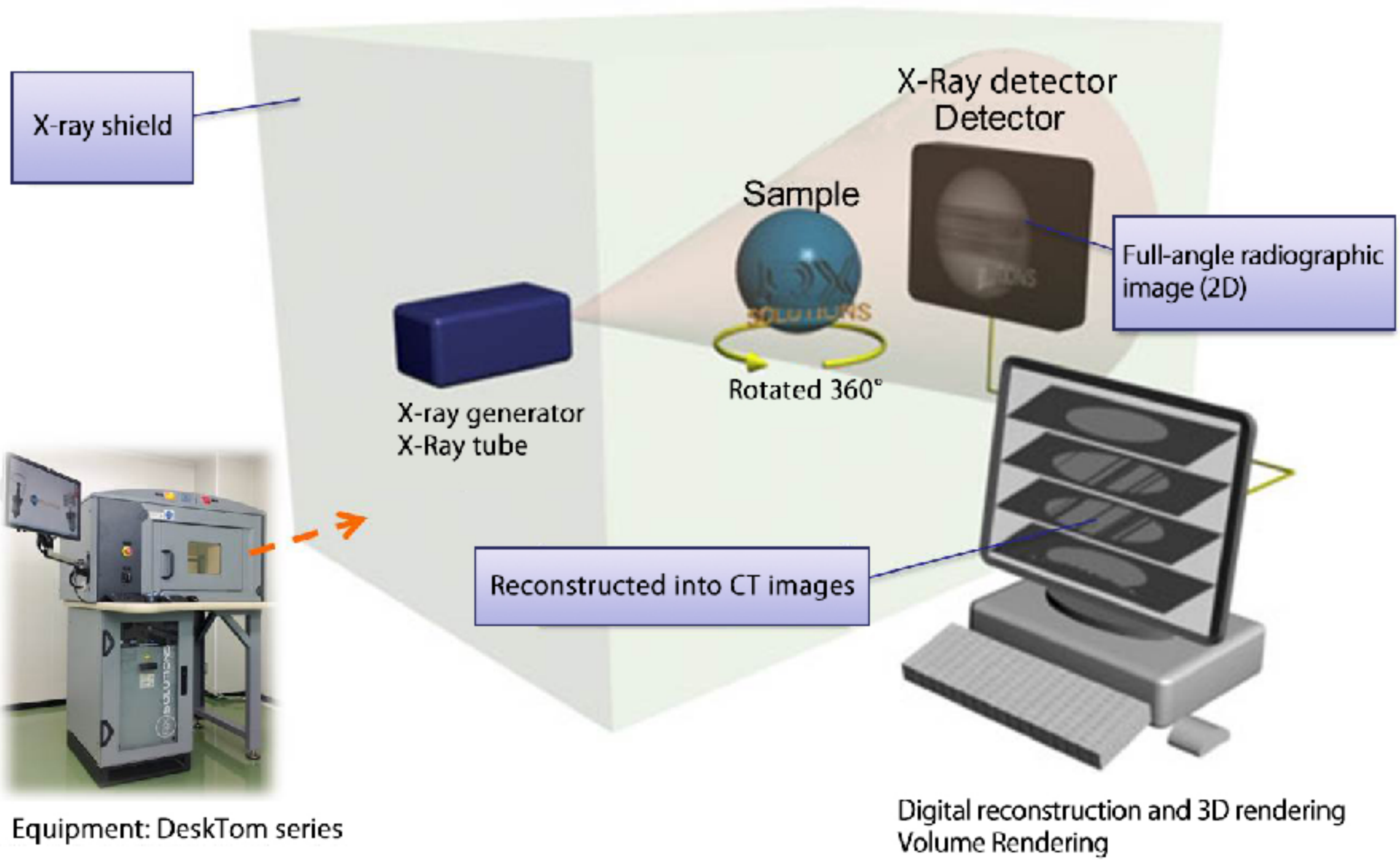
X-ray Computed Tomography (CT) is a nondestructive technique for visualising interior features within solid objects, and for obtaining digital information on their 3-D geometries and properties.

X-ray computed tomography



https://www.researchgate.net/figure/Example-of-an-industrial-computed-tomography-CT-system_fig1_324511614

X-ray computed tomography

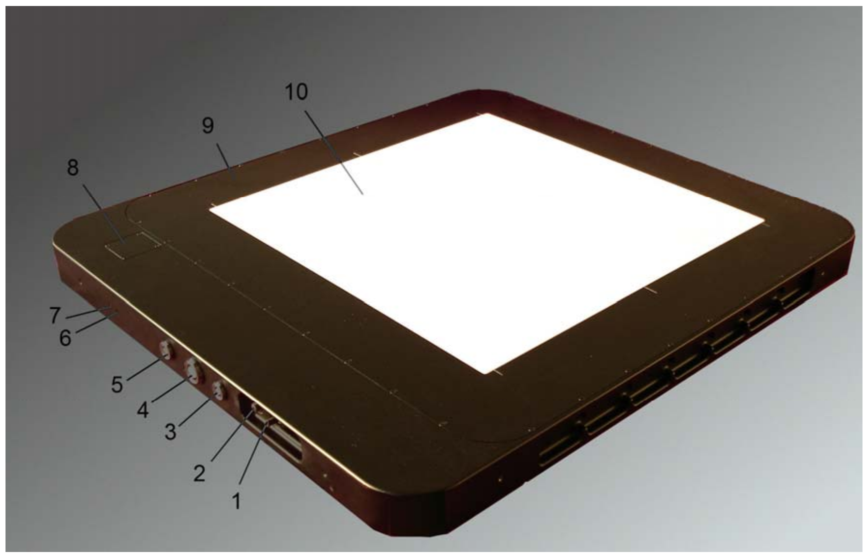


https://www.seikoh-giken.co.jp/en/products/xray.html

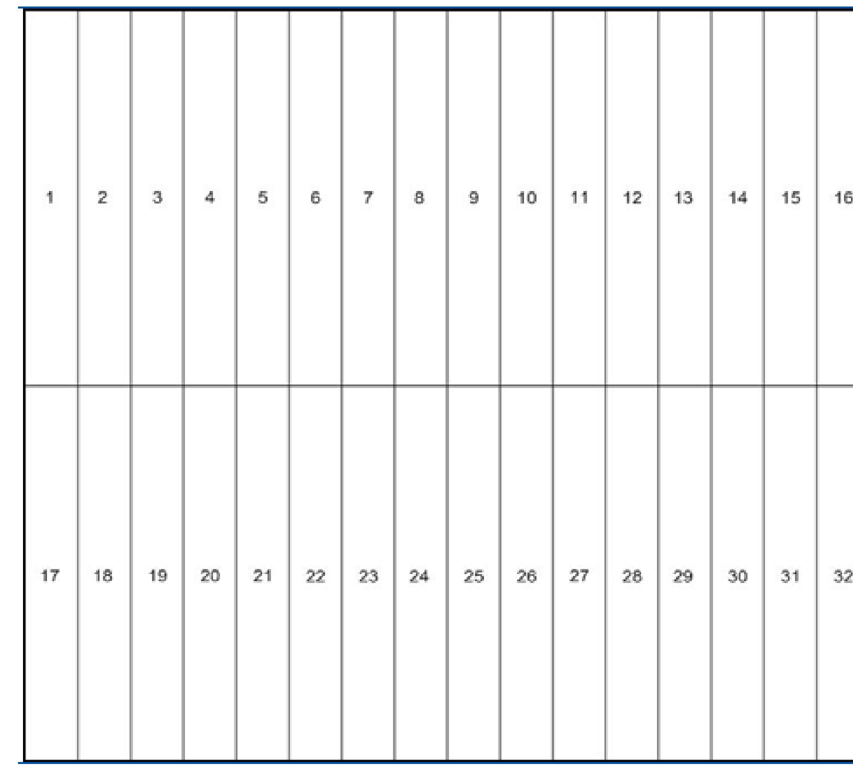
Projects (selection)

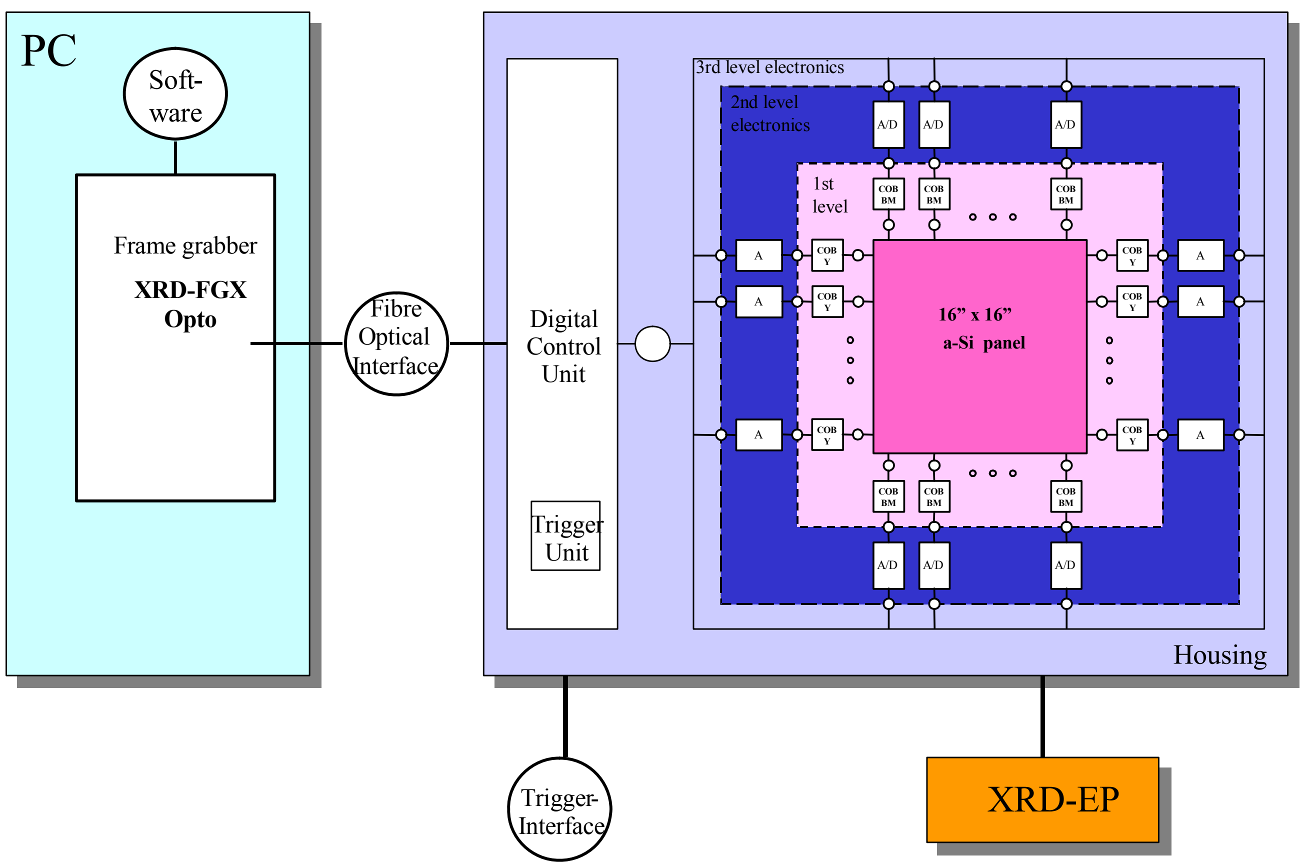
- Modelling the penumbra in Computed Tomography using a mixture model (Gauss + uniform) for estimating precision of radiographs from the penumbra effect in the image
- Modelling mean-variance relationship (compound Poisson for grey value, linear relationship for variance prediction)
- Detection of defects in additive manufacturing from a single x-ray projection using the empirical null filter
- Industrial uses for real-time tomography devices (e.g. airport security bag searches)
- …
- Dead pixels

X-ray detector



Perkin Elmer
XRD 1621





Readout groups (ROG):
Upper groups transferred first, starting read out from the upper row.
Lower groups starting from the last row.

Bad pixel maps

- Criteria for "underperforming" (Perkin Elmer):
  - Signal sensitivity (at different energies)
  - Noise observed in sequence of 100 bright/dark images
  - Uniformity (global, local)

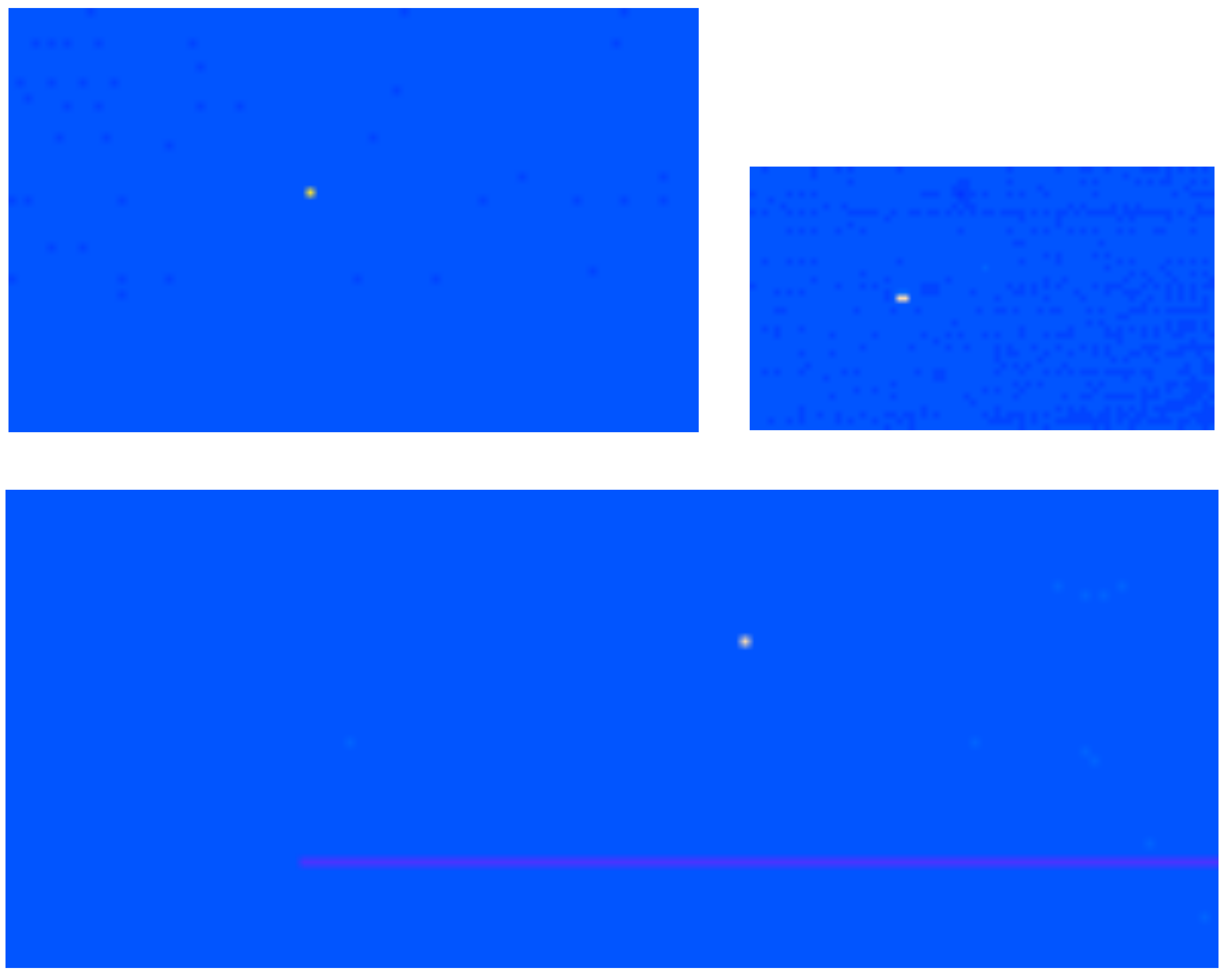
- Each bad pixel map consist of a total of 10 files:
  - White images: mean, min, max, sd (.tif)
  - Grey images: mean (.tif)
  - Black images: mean, min, max, sd (.tif)
  - Bad pixel list of locations (.xml)

Modeling and analysing dead pixels

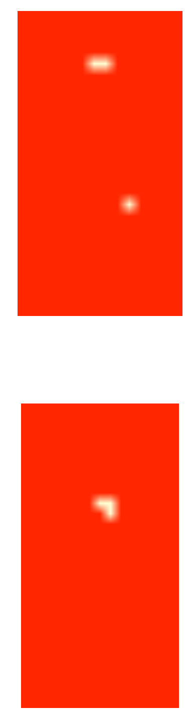
- **Spatial analysis of dead pixels:**
  - Exploratory analysis
  - Data structure for dead pixel data
  - Spatial statistics models and characteristics
- **Relationship to causes of damage:**
  - Change of perspective in the stochastic model: clusters
- **Refined analysis:**
  - Refined categories for dysfunctional pixels
  - Temporal development

Local defects: Isolated dead pixels

Singles, doubles, small clusters



A_0: Grey image [R]

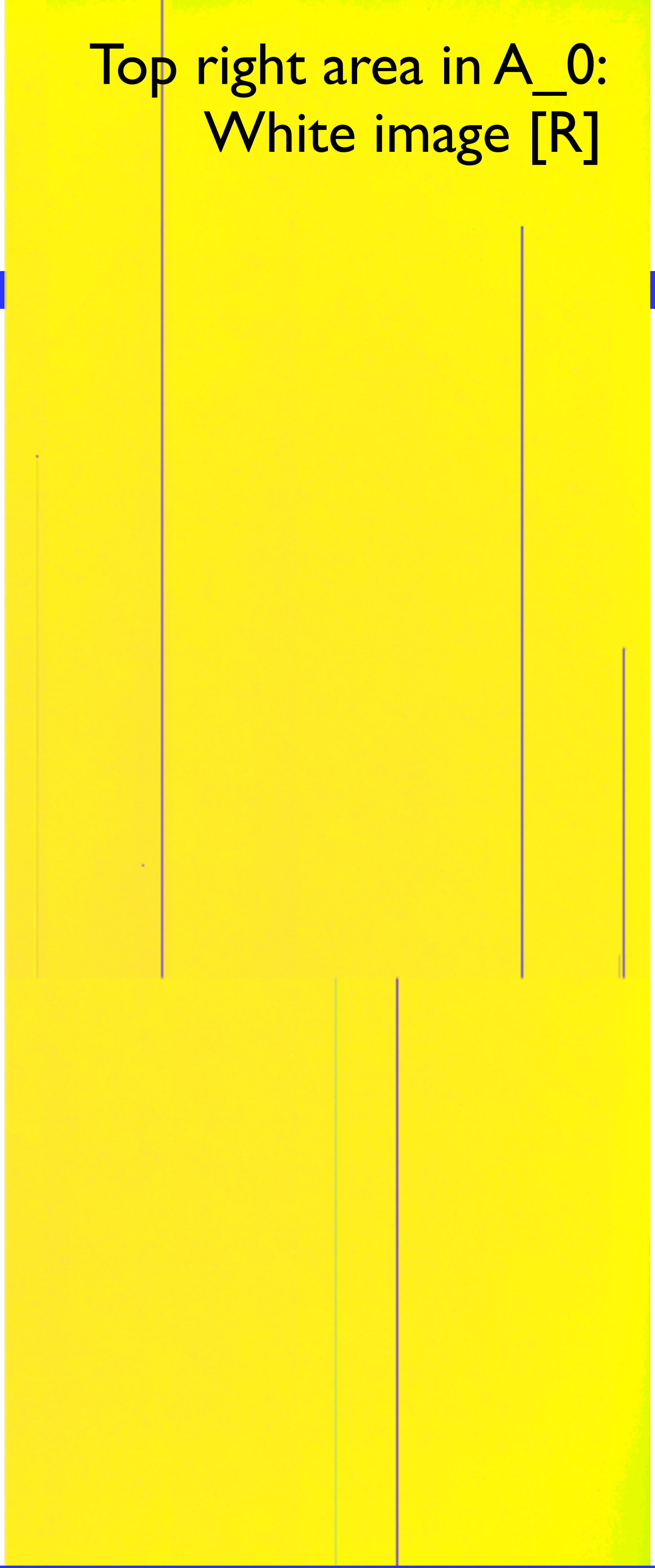


A_0:
bp binary
image [R]

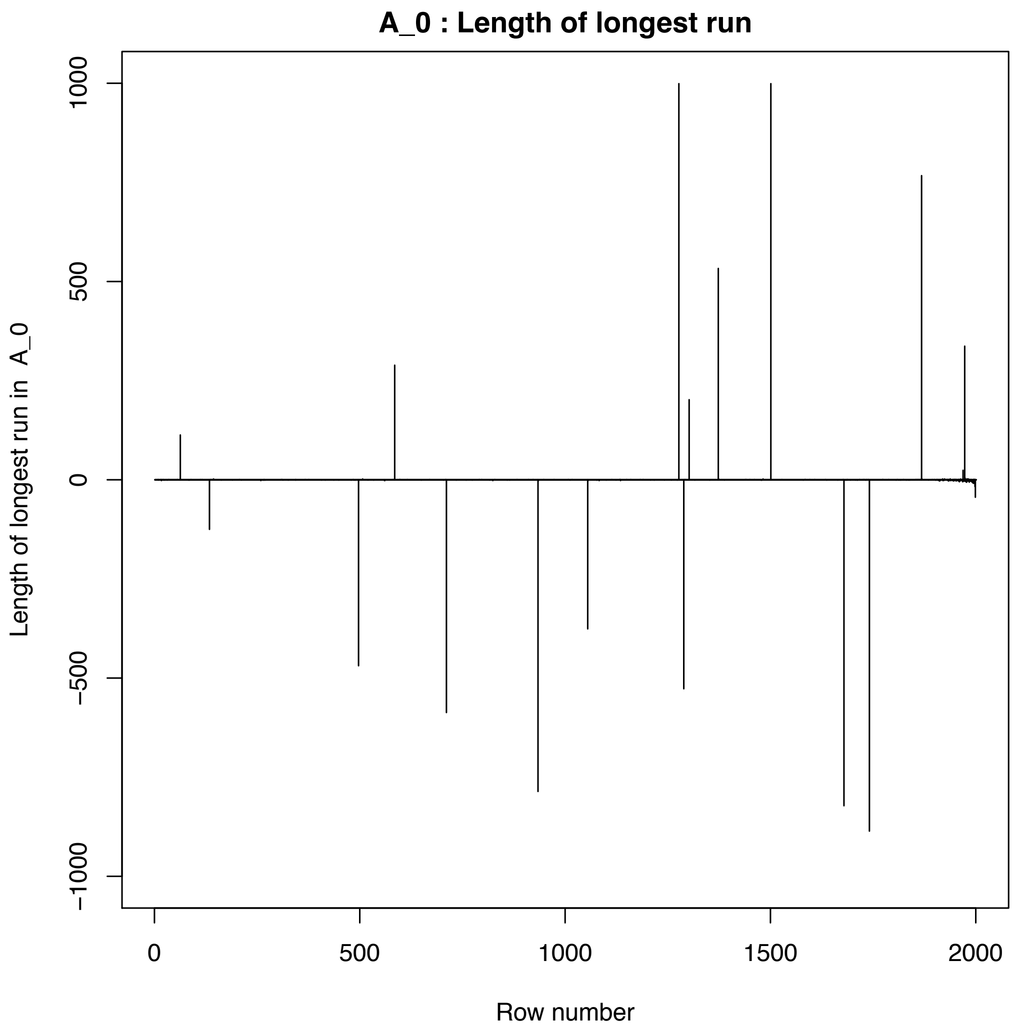
A_0: Black
image [R]

Local defects: Dead lines

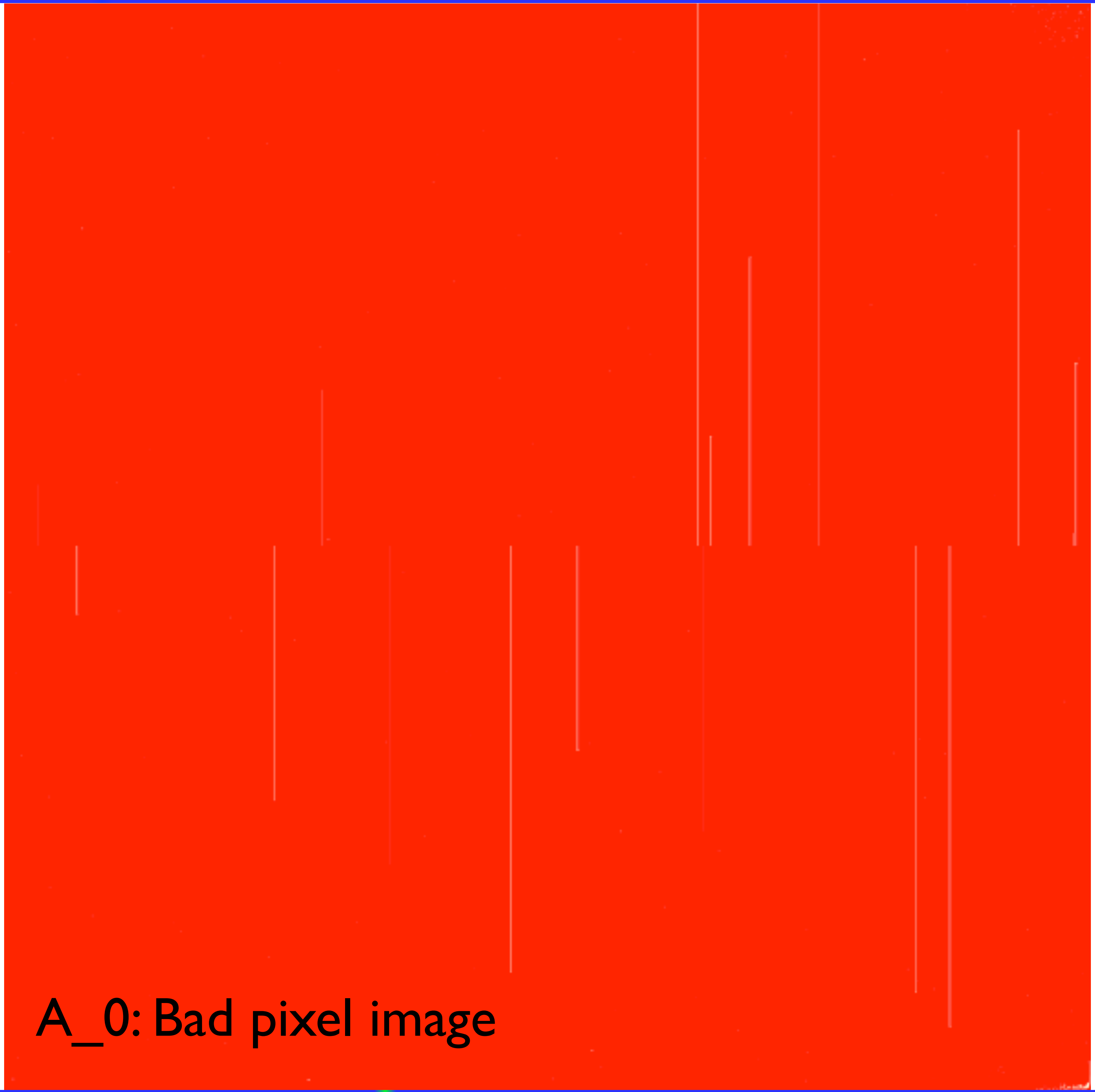
- Lines on bad pixel images
- From centre horizontal line outwards
- Visible on tif images of channel(s), too



Local defects: Locations of dead lines



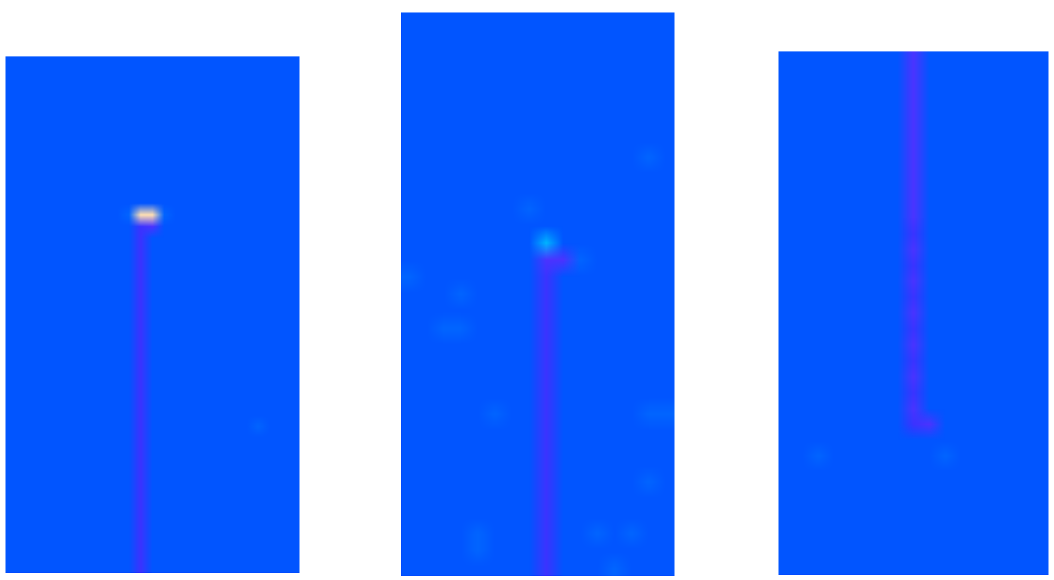
A_0: Graph of bad pixel images



A_0: Bad pixel image

Local defects: Ends of dead lines

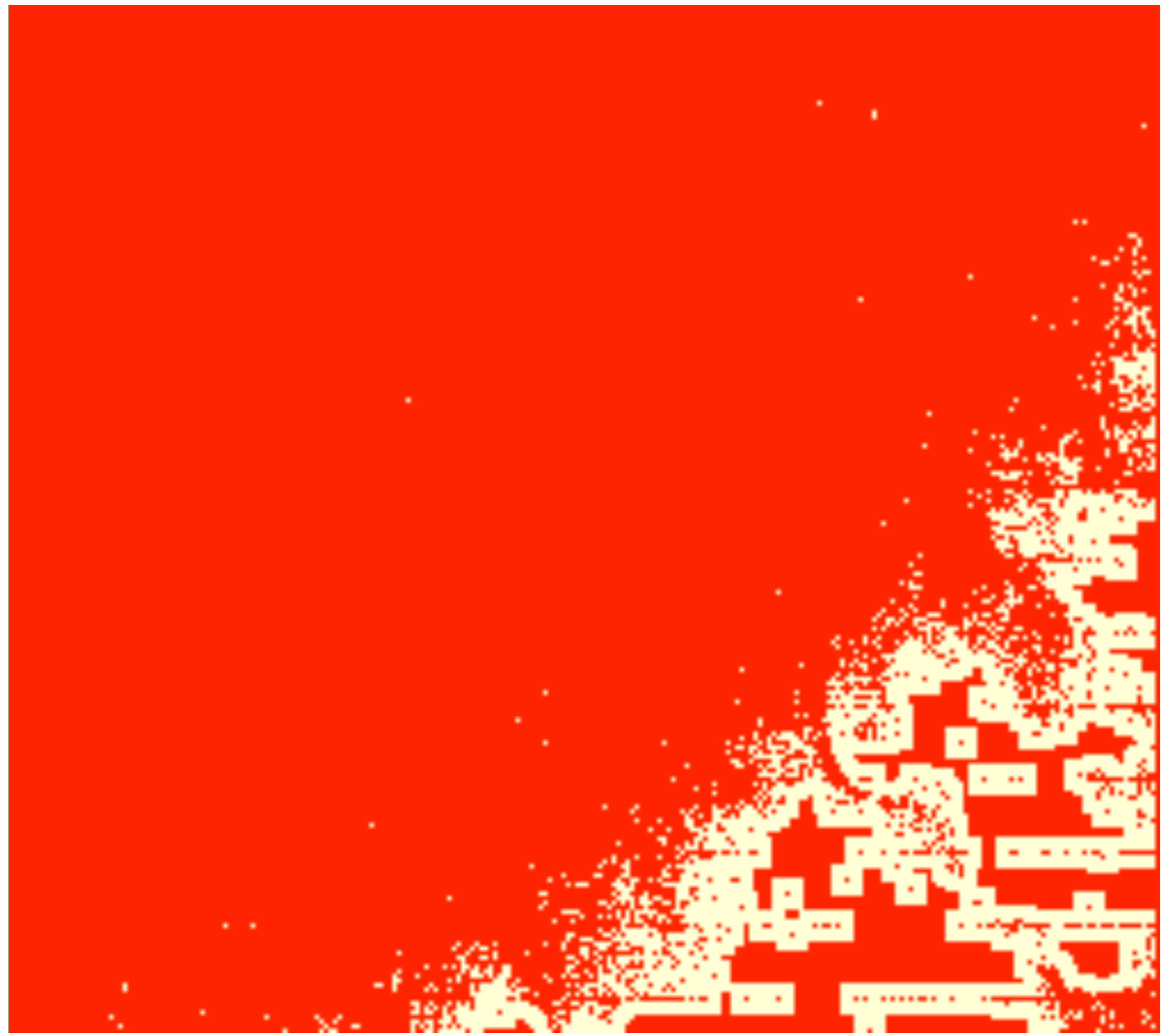
bmp binary image



Black image

- Most lines end in small cluster pointing to the right
- Lines are composed of dark pixels
- Lines have constant intensity, except end may differ

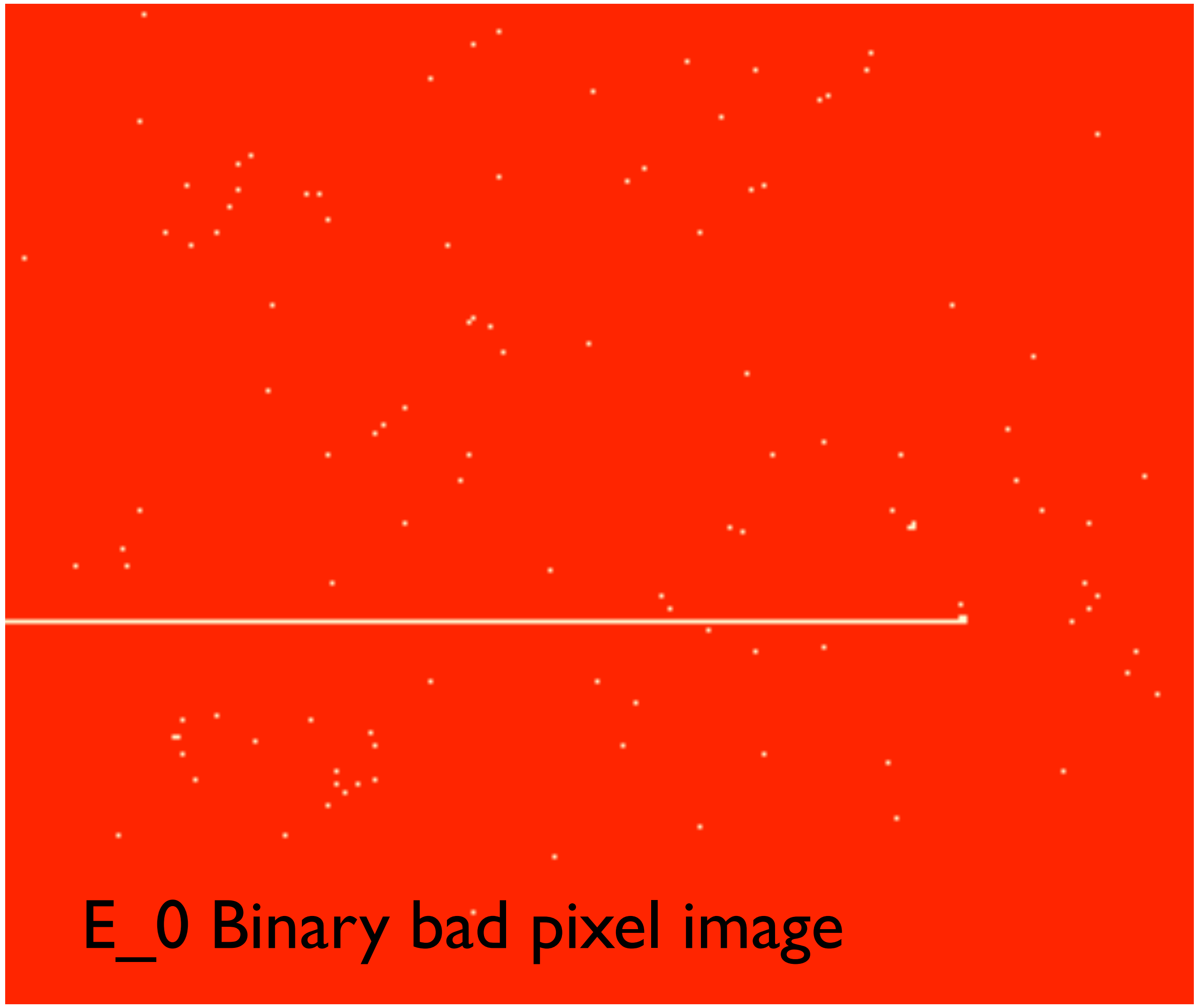
Local defects: Corners

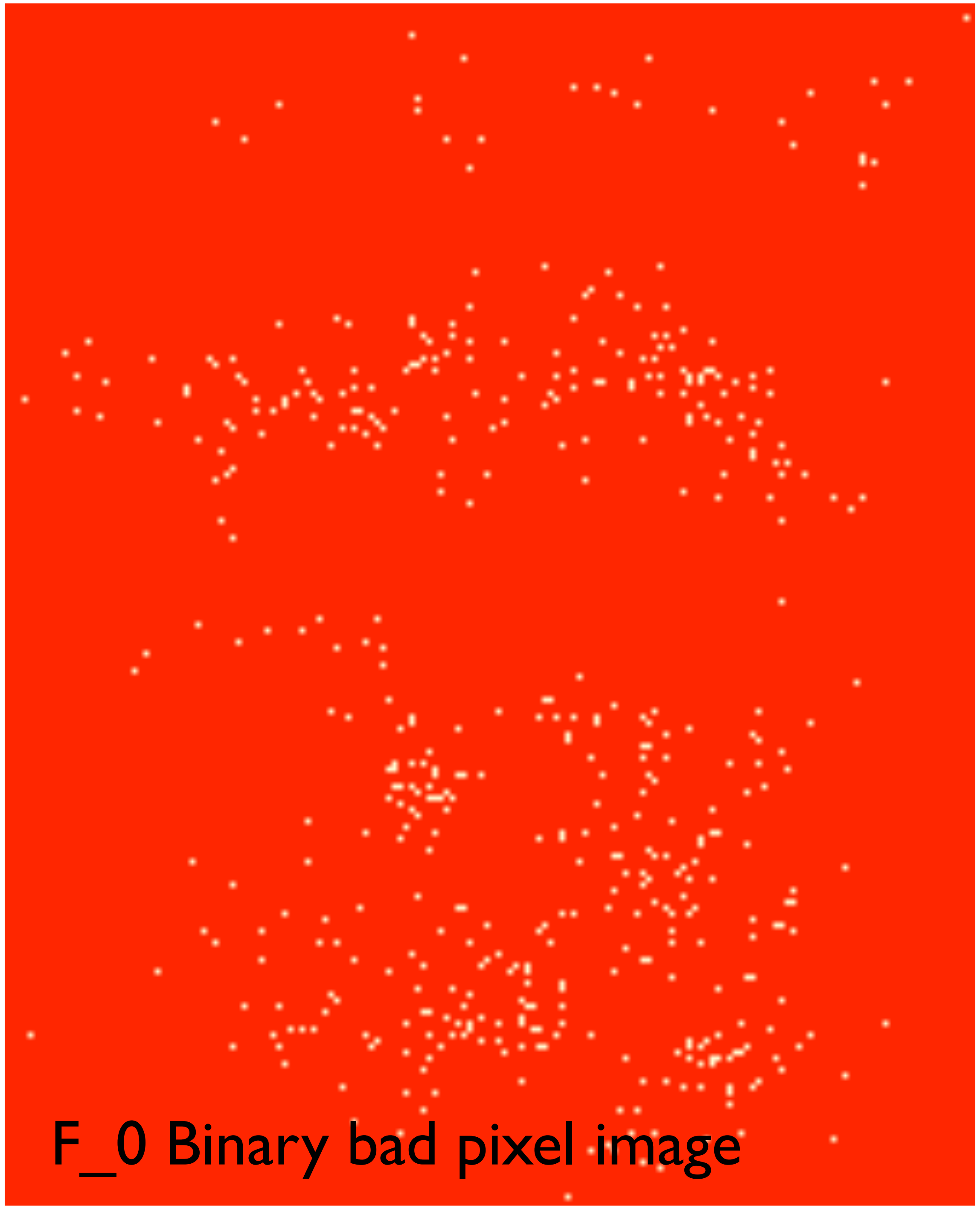


B_0: Binary bad pixel image [R]

Local defects: Patches

- Areas with high density area of bad pixels





Which spatial data structure?

Three common types described by Cressie (1993)

Geostatistical data:
Fixed study region with a random variable (observed or unobserved) in every location.
e.g. *UK with rainfall*

Lattice data:
Collection of fixed (nonrandom) set of points in study region with a random variable defined in each of them.
e.g. *Ising model on a lattice, crime in snap points*

Spatial point patterns:
Spatial locations of the observations are random, with observations itself deterministic (=1) or itself random variables.
e.g. *locations of bird nests, same with number of eggs in each nest*

Spatial model for dead pixels

Lattice or point pattern?

Detector is based on a lattice, but ***our interest*** is in ***locations*** *of dead pixels*. Hence, use a *spatial point pattern* model, but with reduced resolution (given by the detector lattice).

Point pattern X: random locations of dead pixels

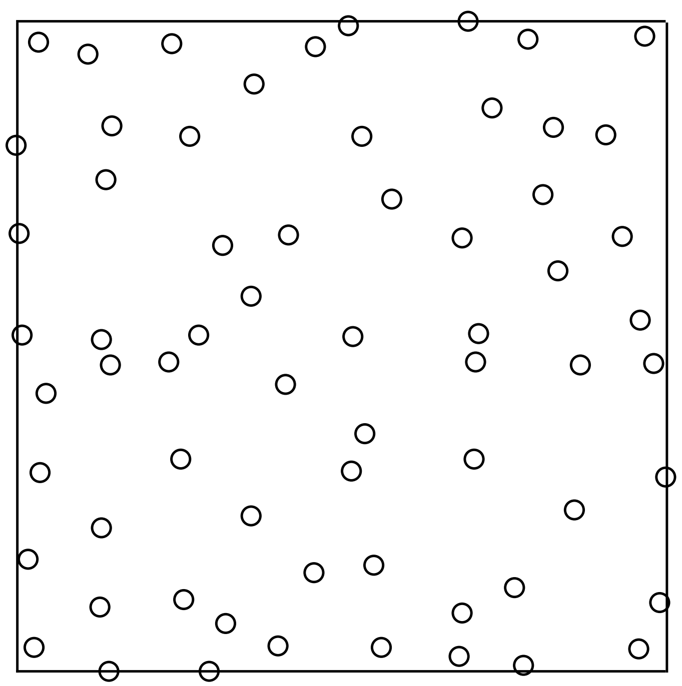
Objectives:

- describe spatial distribution of dead pixels
- hypothesise causes for dead pixels

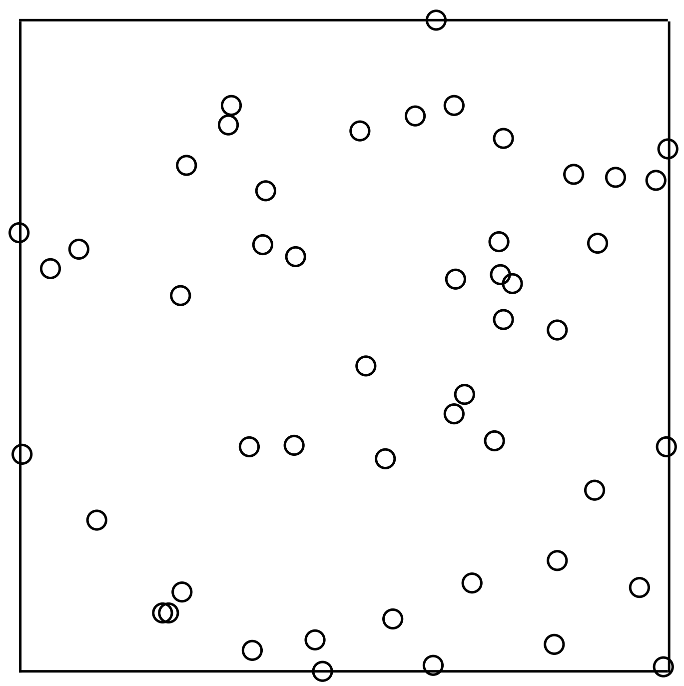
For example, look at CSR…

Complete spatial randomness (CSR)

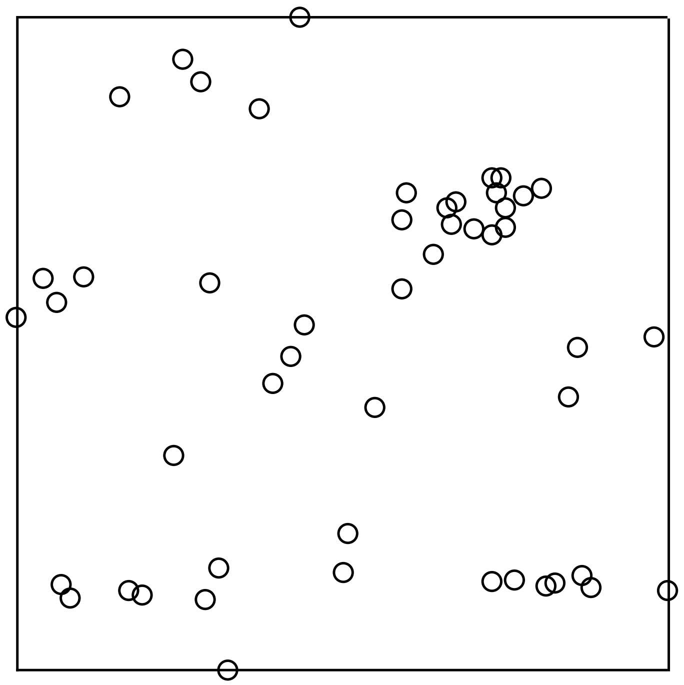
CSR: Points are distributed independently and homogeneously, as in a homogenous Poisson process.



Regular (nearly)



CSR



Clustering

Exploring CSR using Ripley's K-function

K-function:
expected number of extra points in circle of radius r rescaled by density

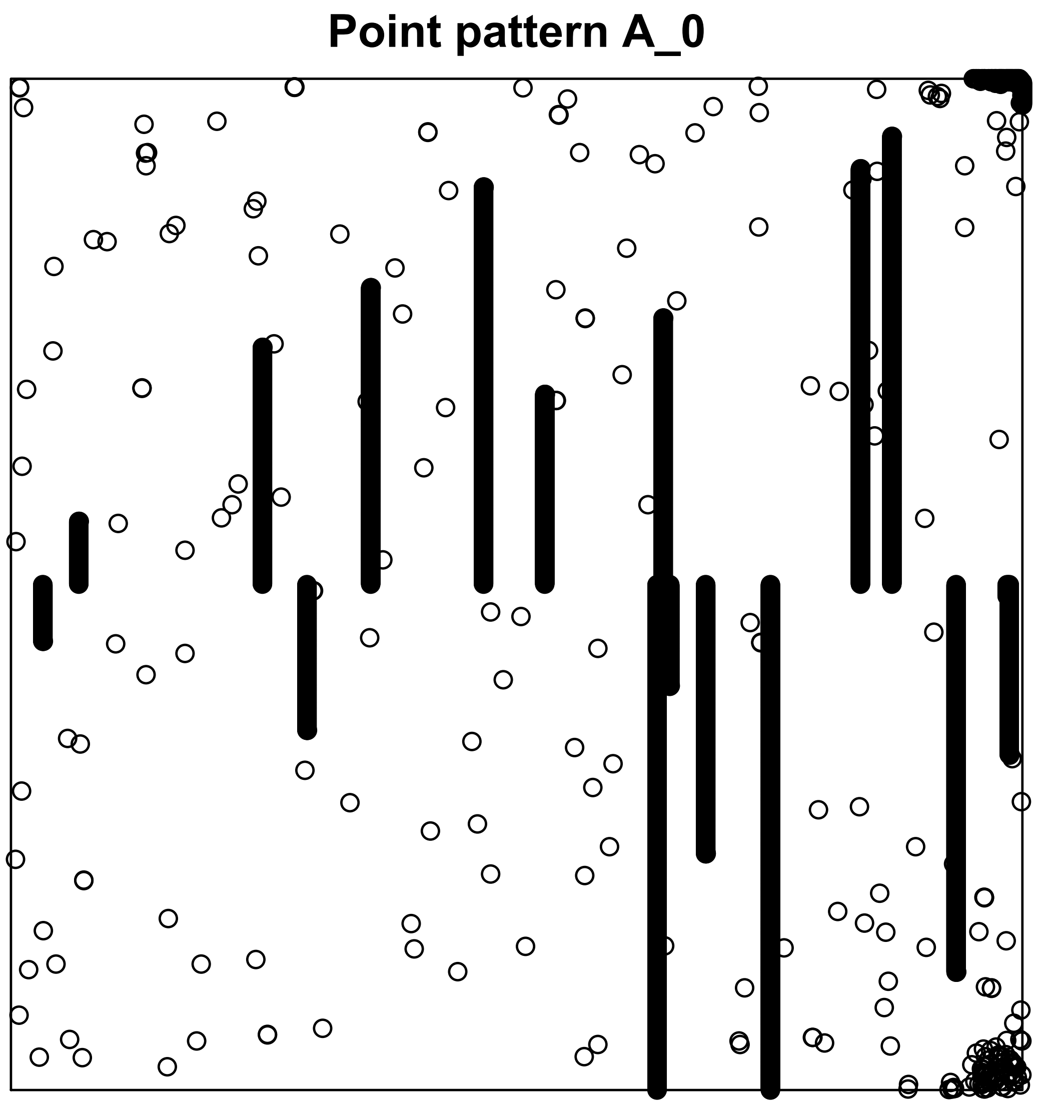
$$K(r) = \lambda^{-1} E[N_0(r)]$$

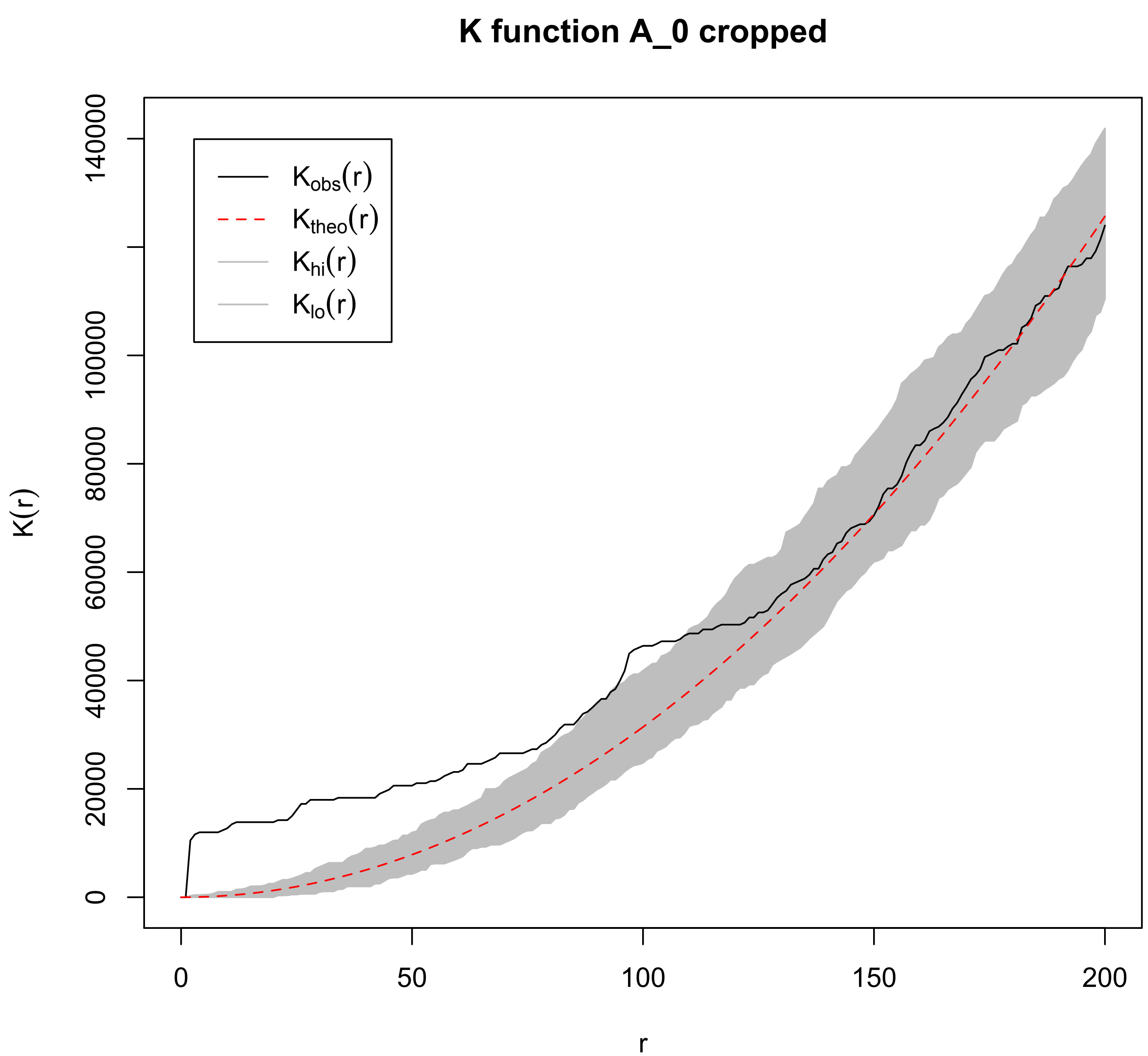
$N_0(r)$ number of points within distance r from arbitrary point

λ globally estimated density

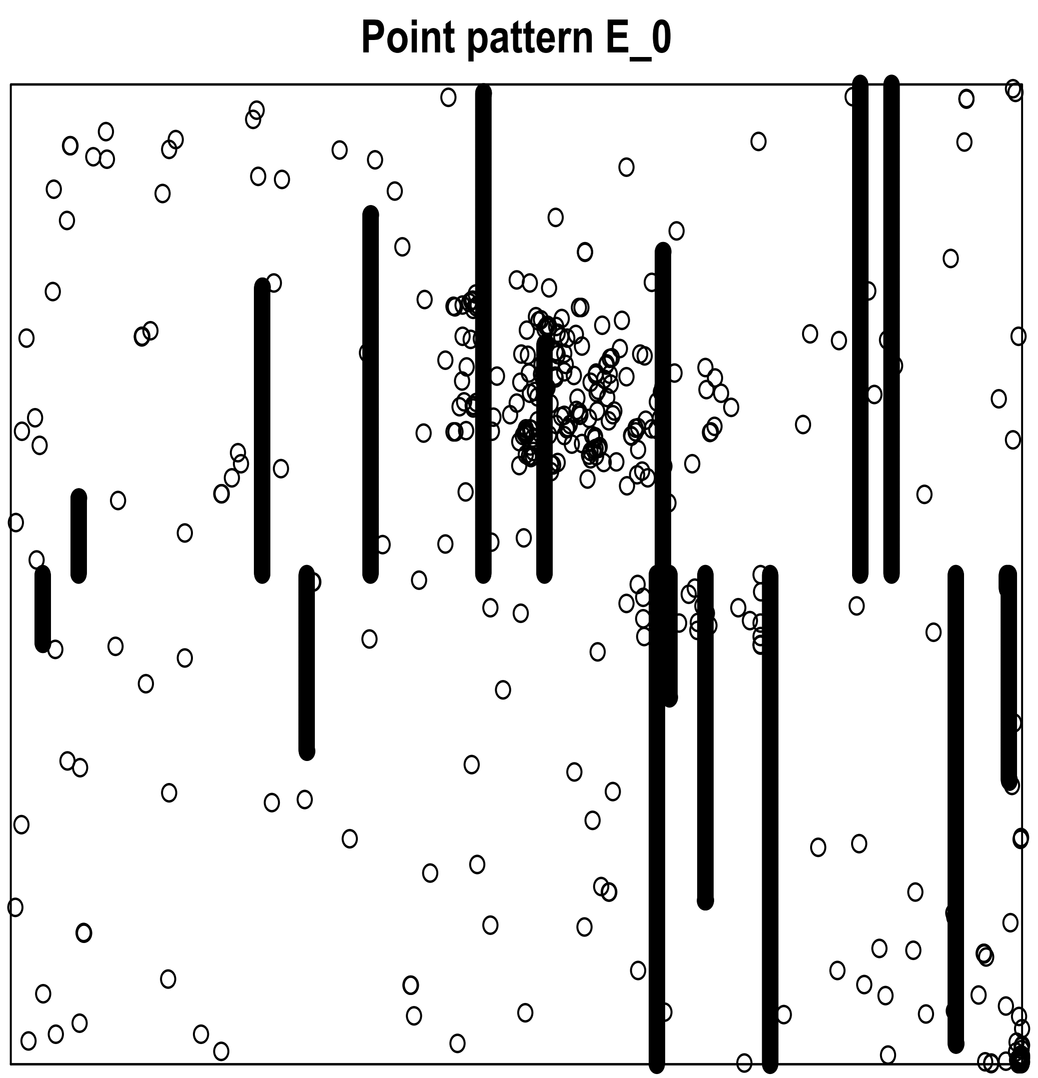
Under CSR: $K(r) = \pi r^2$

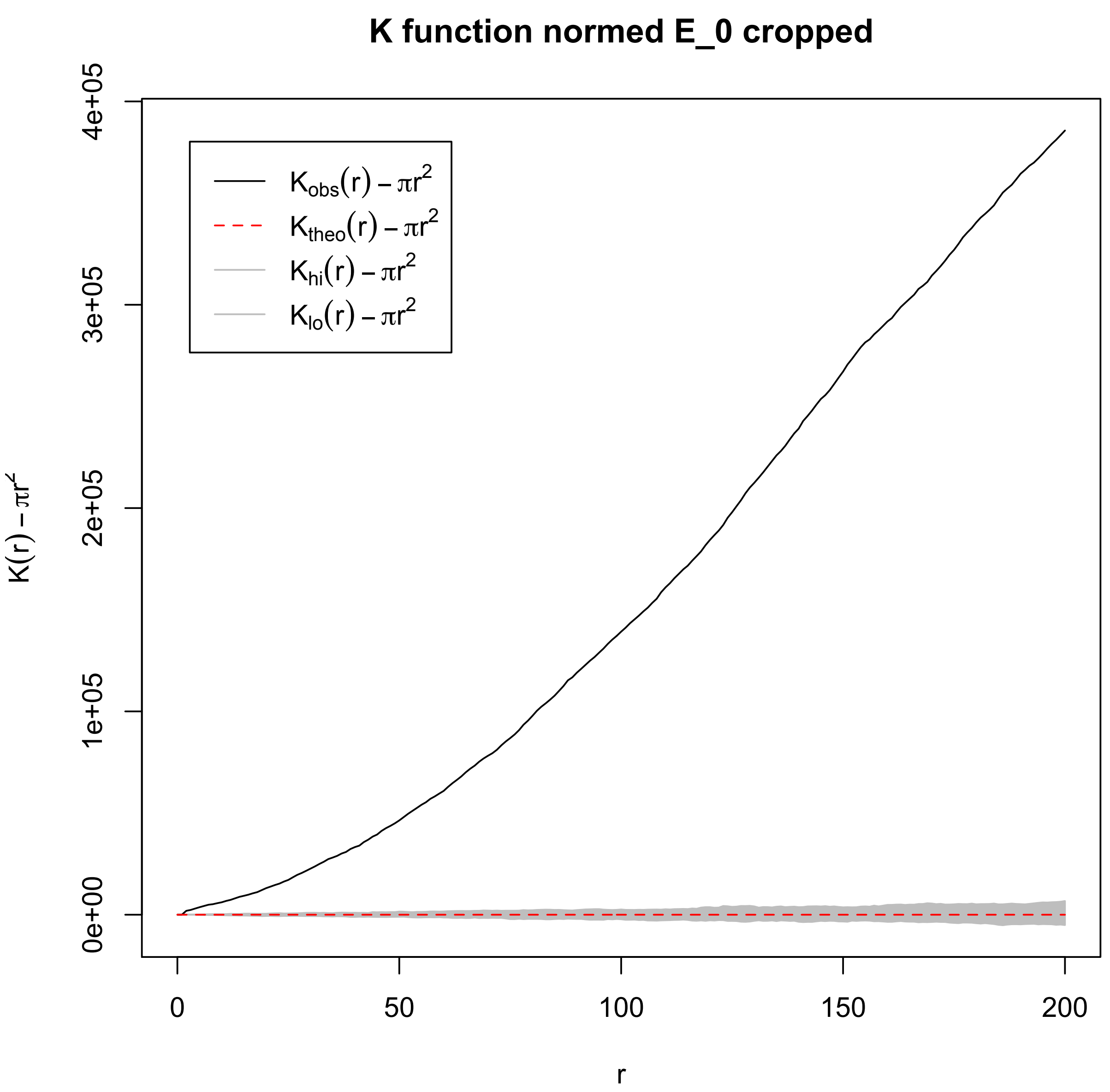
Point pattern and K-function





Point pattern and K-function





Exploring CSR using F- and G-functions

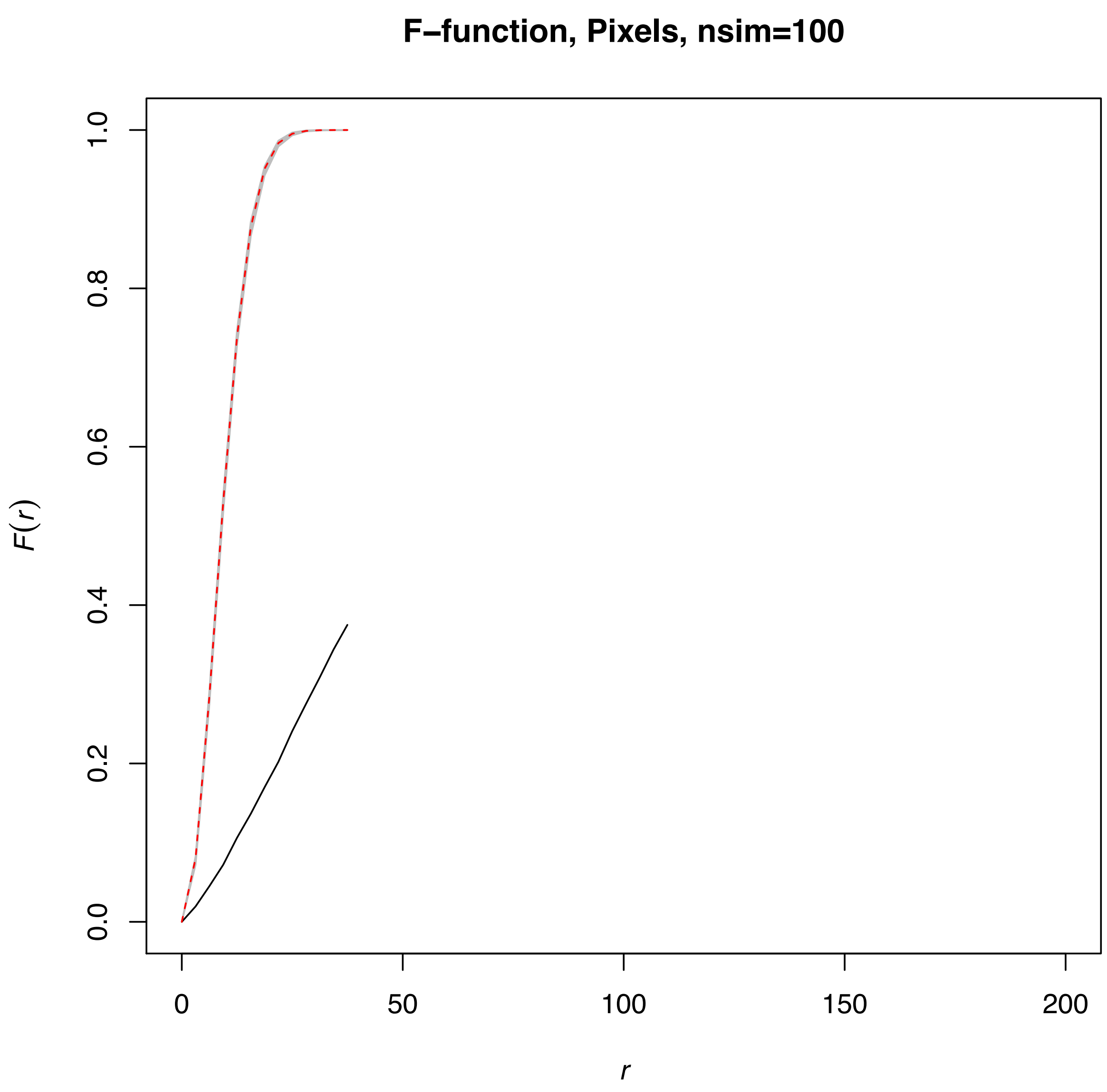
Nearest neighbour function G:
cumulative distribution function of the distance from an arbitrary point to its nearest point

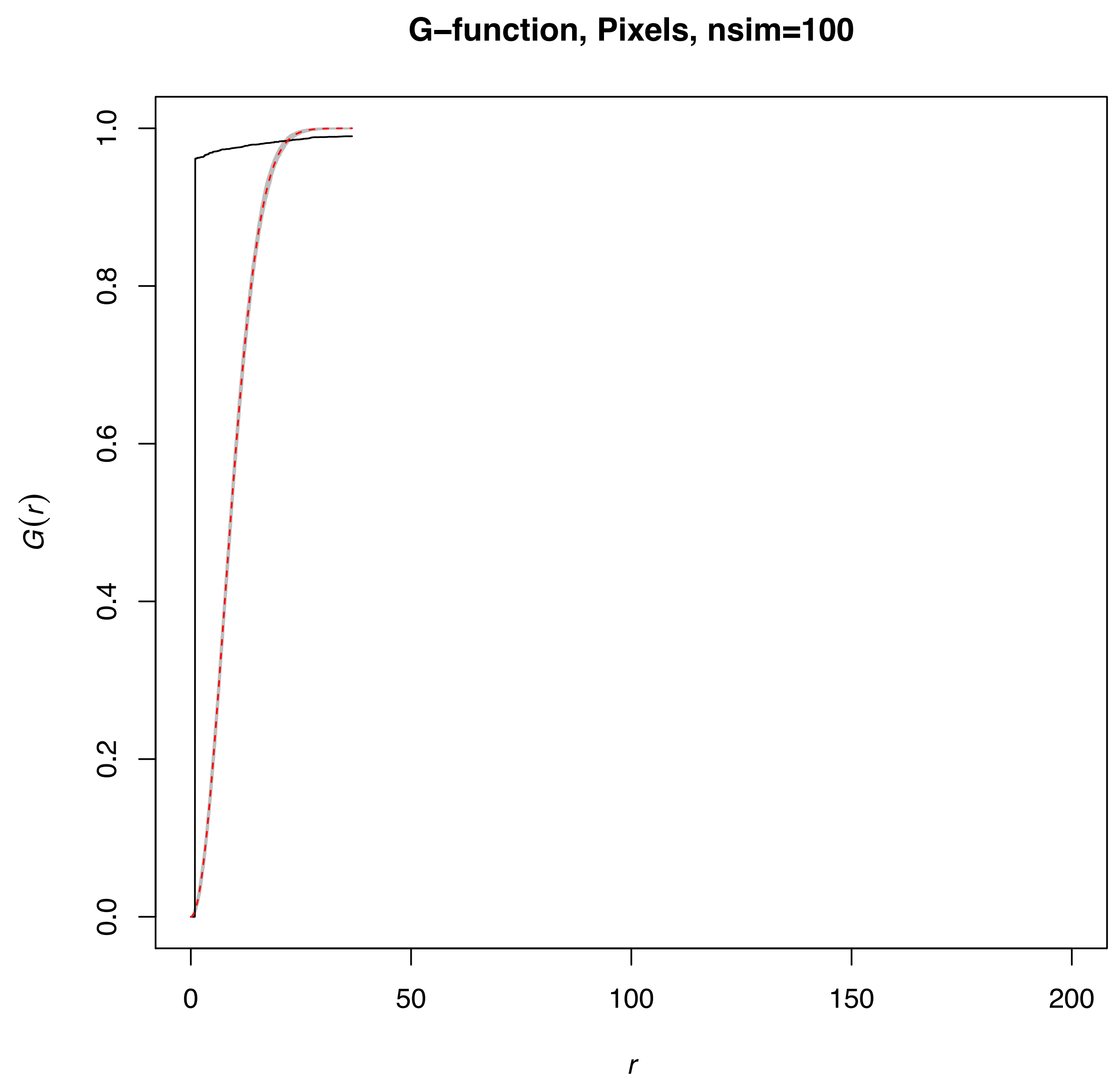
Under CSR: $G(r) = 1 - \exp(-\lambda \pi r^2)$

Empty space function F:
cumulative distribution function of the distance from an arbitrary location to its nearest point

Under CSR: $F(r) = 1 - \exp(-\lambda \pi r^2)$

Point pattern and F- and G-function





Are we asking the right question?

Modified question: Is it CSR after we remove all specific (known) problems?

Step 1:

Convert point process into *event process* by

- Reducing lines to their endpoint
- Reducing clusters to their centre point

Are we asking the right question?

Modified question: Is it CSR after we remove all specific (known) problems?

Step 1:

Convert point process into *event process* by

- Reducing lines to their endpoint
- Reducing clusters to their centre point

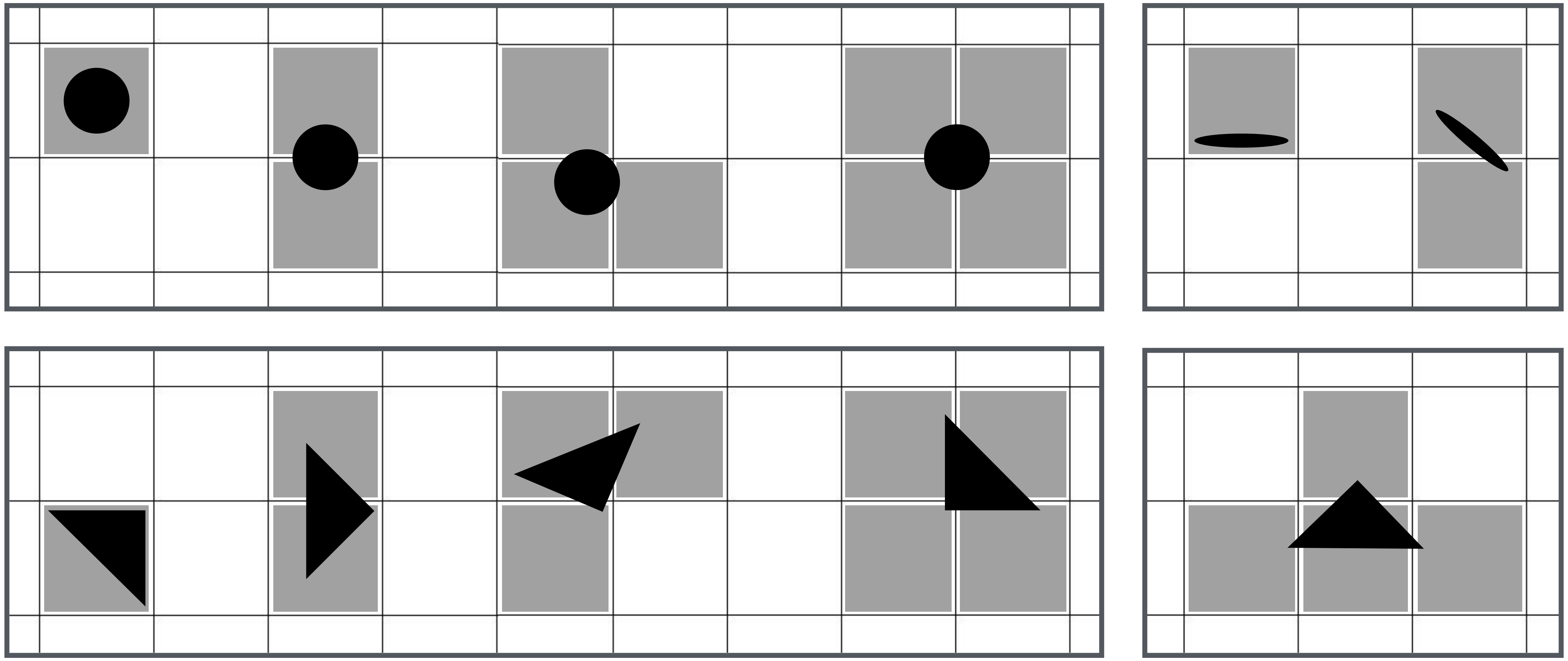
Step 2:

- Fit inhomogeneous density
- Cut out areas above threshold

Model for cause versus model for effect

Detector is based on a lattice, but damage occurs independently of the lattice structure.

The ***same cause for damage*** shape can hit 1, 2, 3 or 4 pixels, depending on position and orientation.



Higher level model: dead events

Solution: Model the damage by summarising neighbouring dead pixels into one dead event.

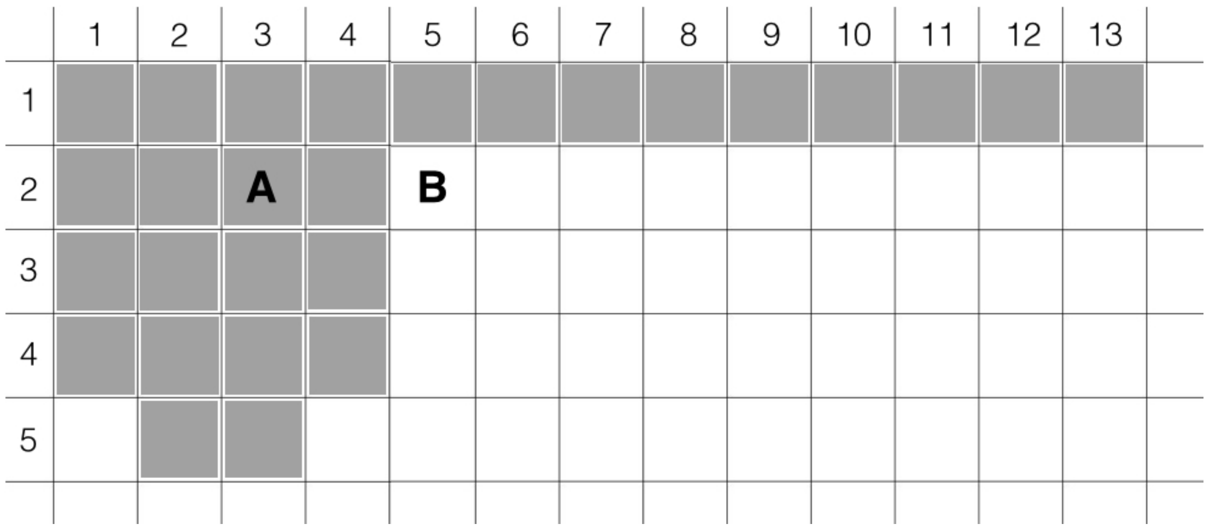
Convert pixel point pattern X into event point pattern Y by replacing each cluster of pixels $\mathcal{C}$ in X by

$$i^{\text{median}}(\mathcal{C}) = \big(\rho(\text{median}_1(\mathcal{C})), \rho(\text{median}_2(\mathcal{C}))\big)$$

Using median because of robustness:

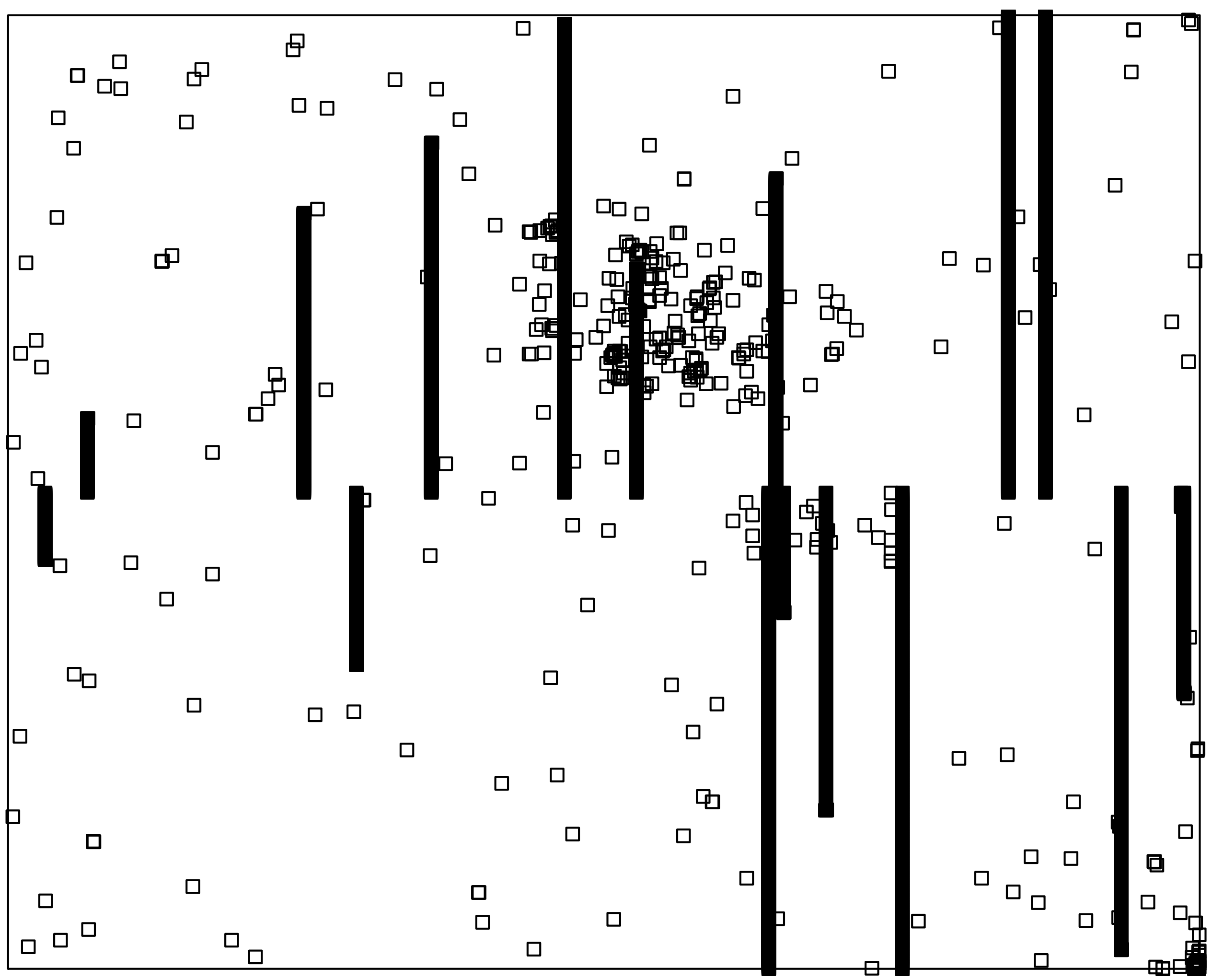
e.g. $i^{\text{mean}}(\mathcal{C}) = (5, 2)$

$i^{\text{median}}(\mathcal{C}) = (3, 2)$



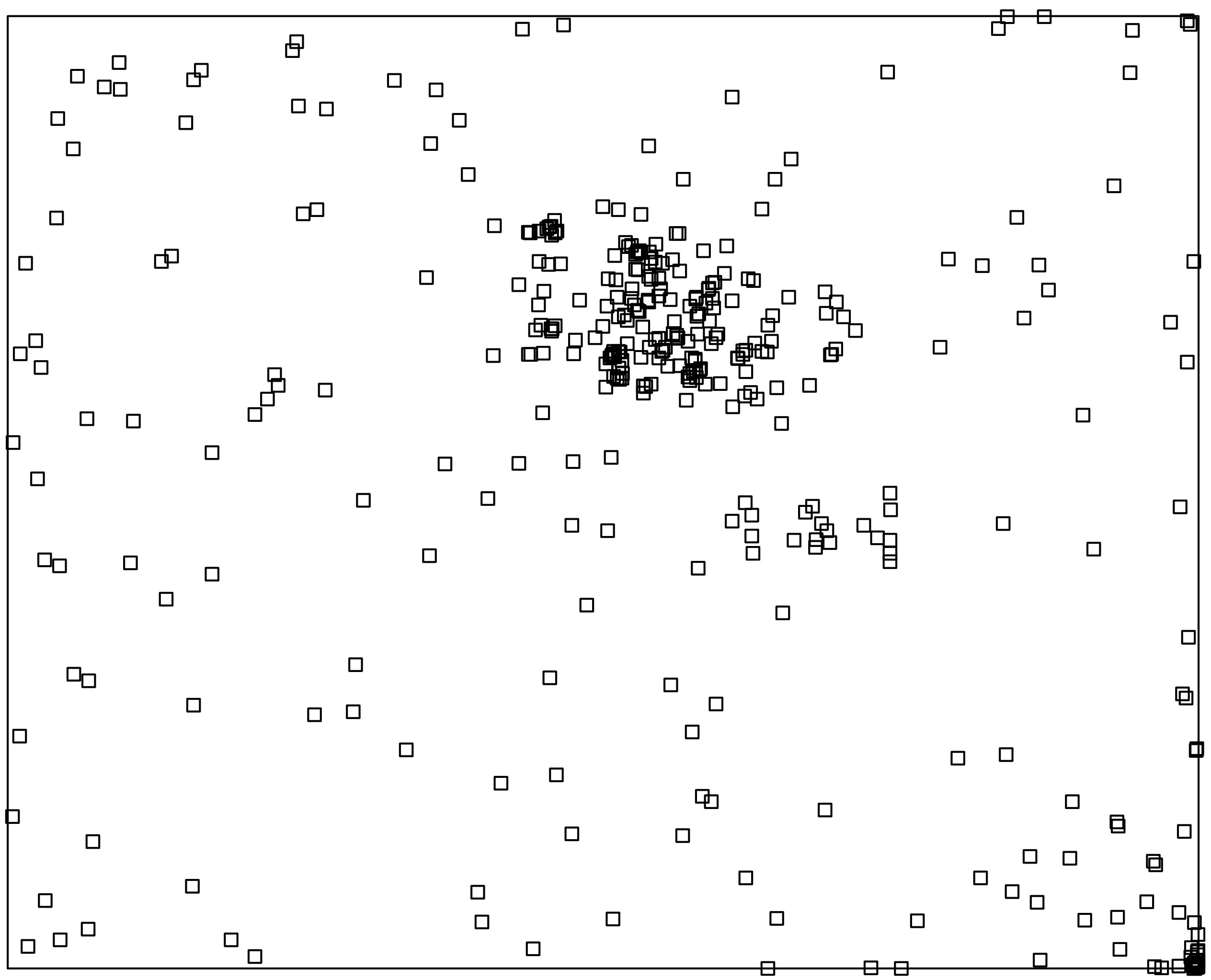
Dead pixels versus dead events

X (dead pixels)



(a) Pixel process

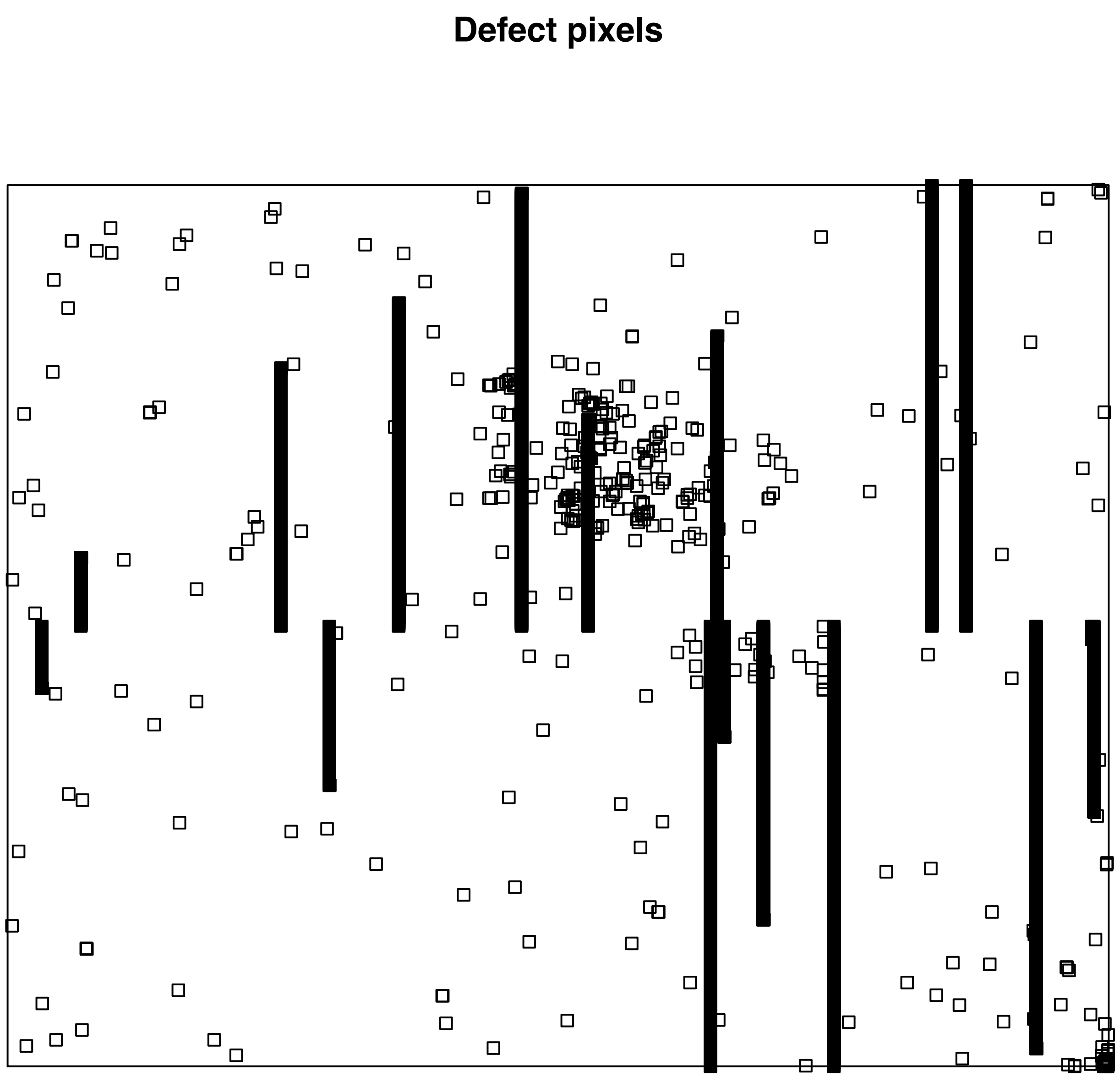
Y (dead events)

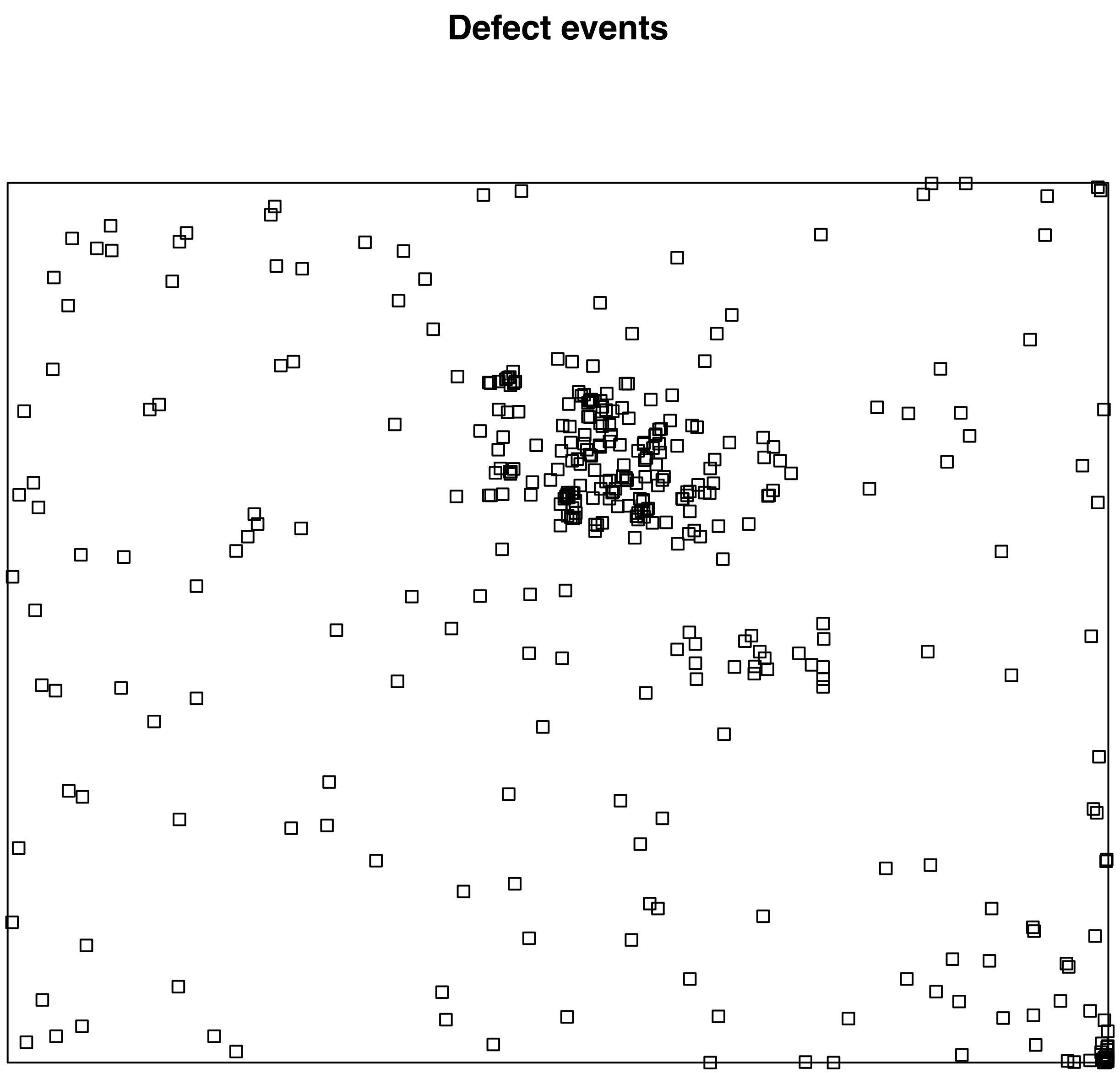


(b) Event process (marks not visualised)

Higher level defect model (Step 1)

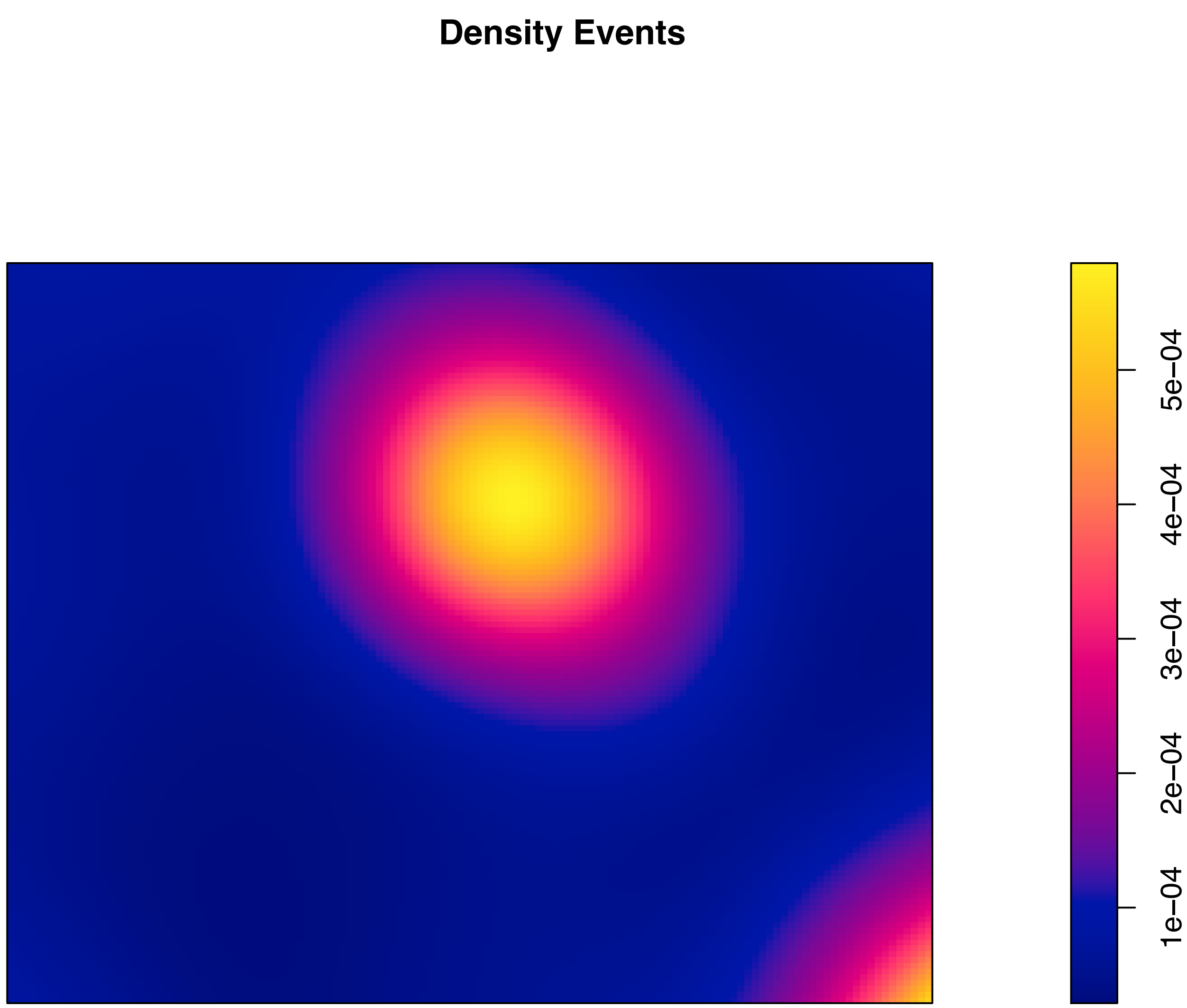
Conversion of point process to *event process*

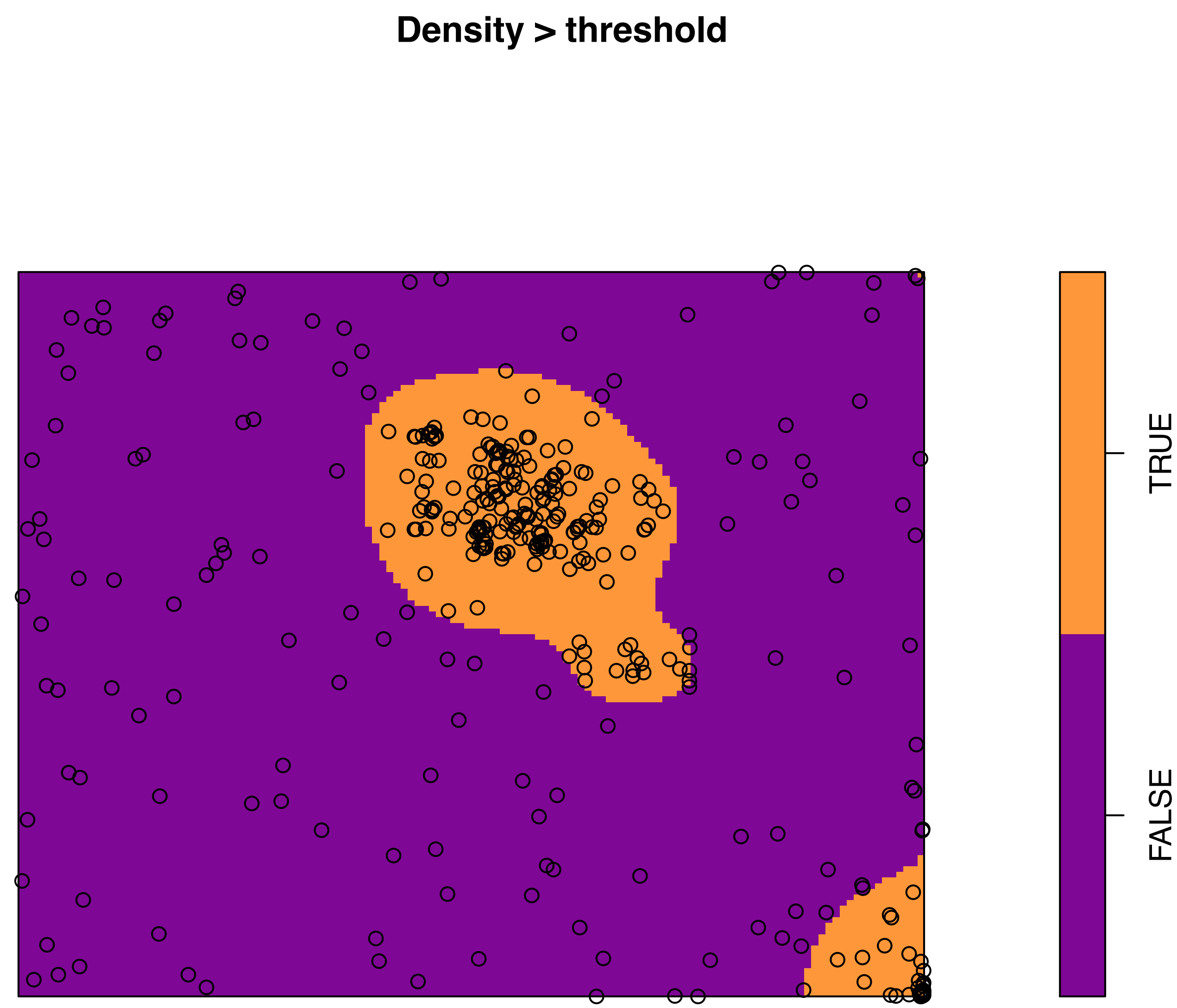




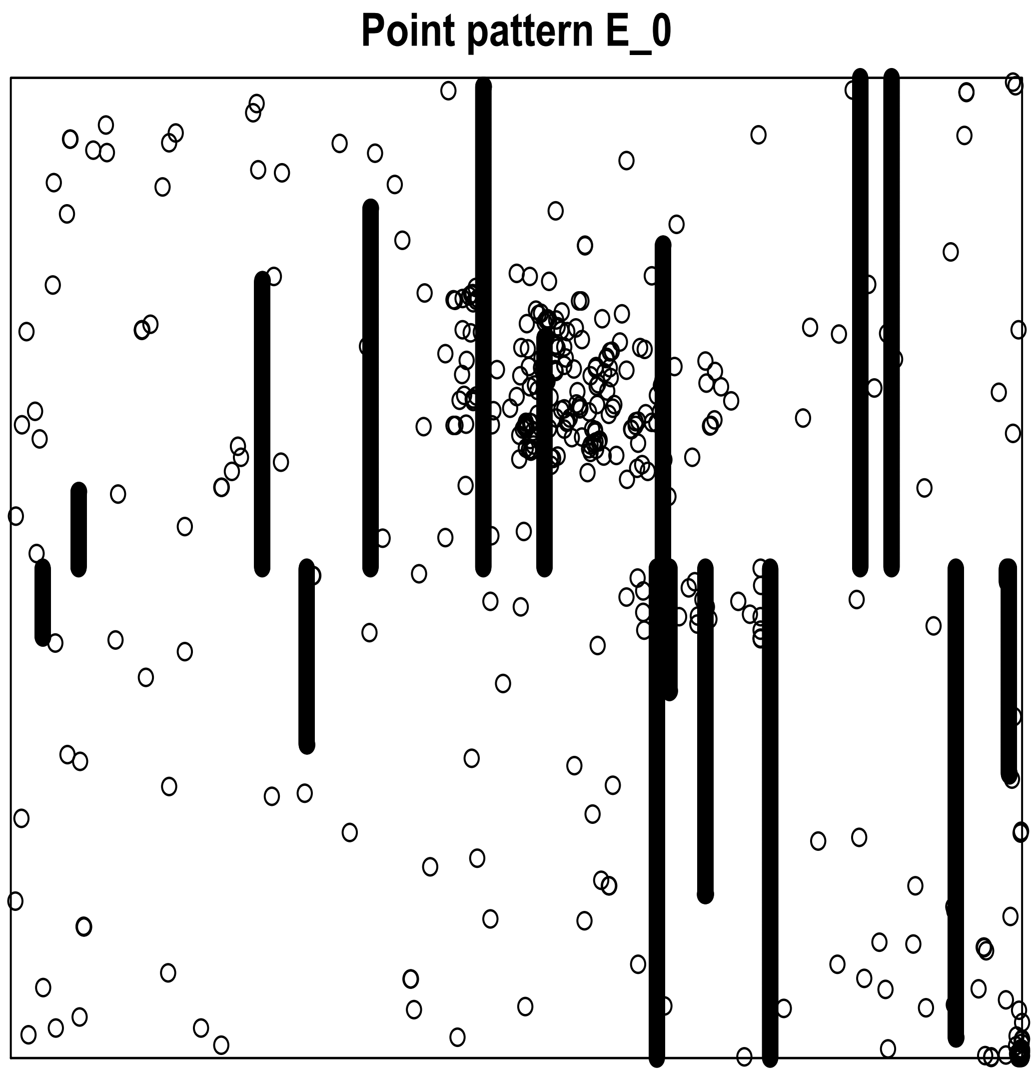
Density based thresholding (Step 2)

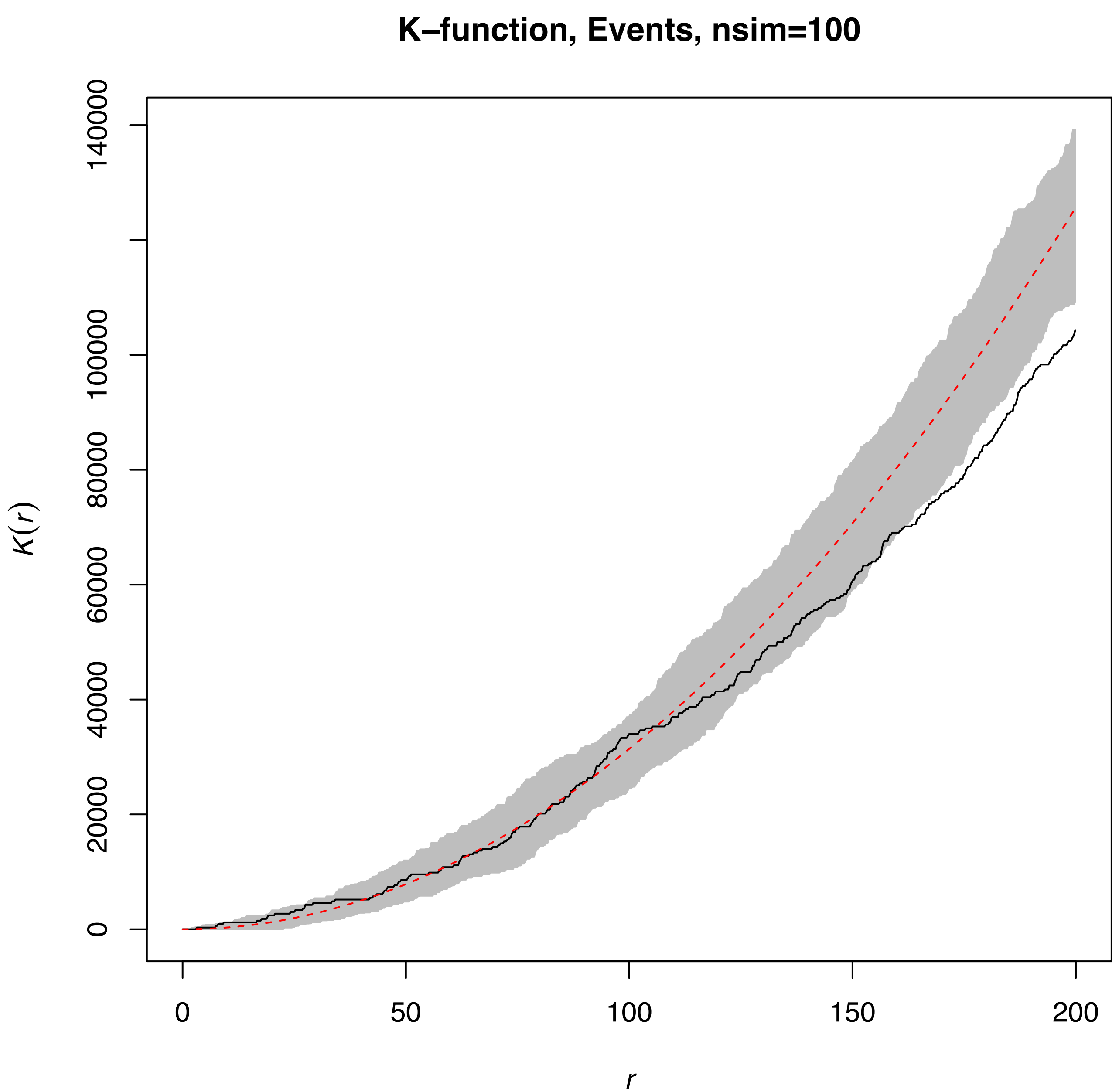
Remove areas with local density above threshold (median +1.5 IQR)





After modification: K-function





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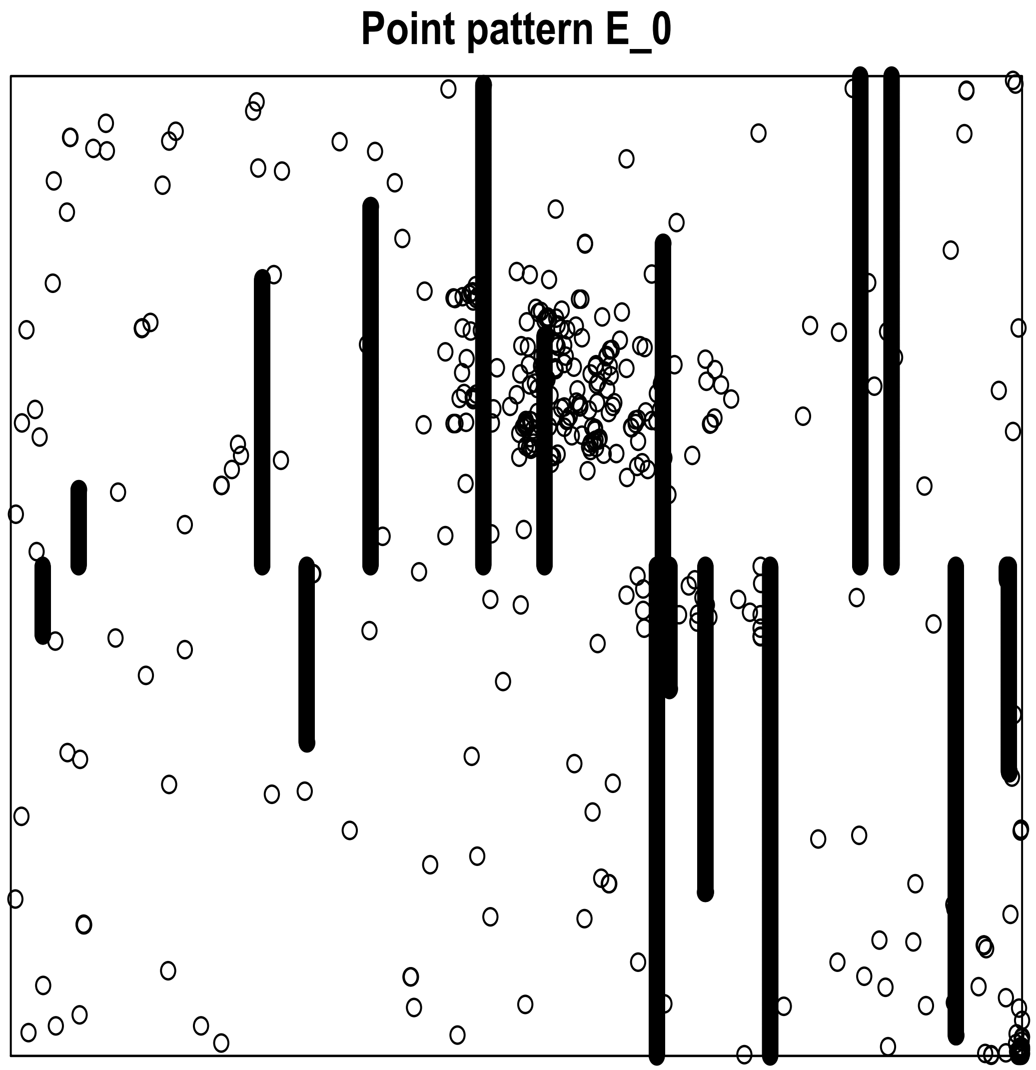
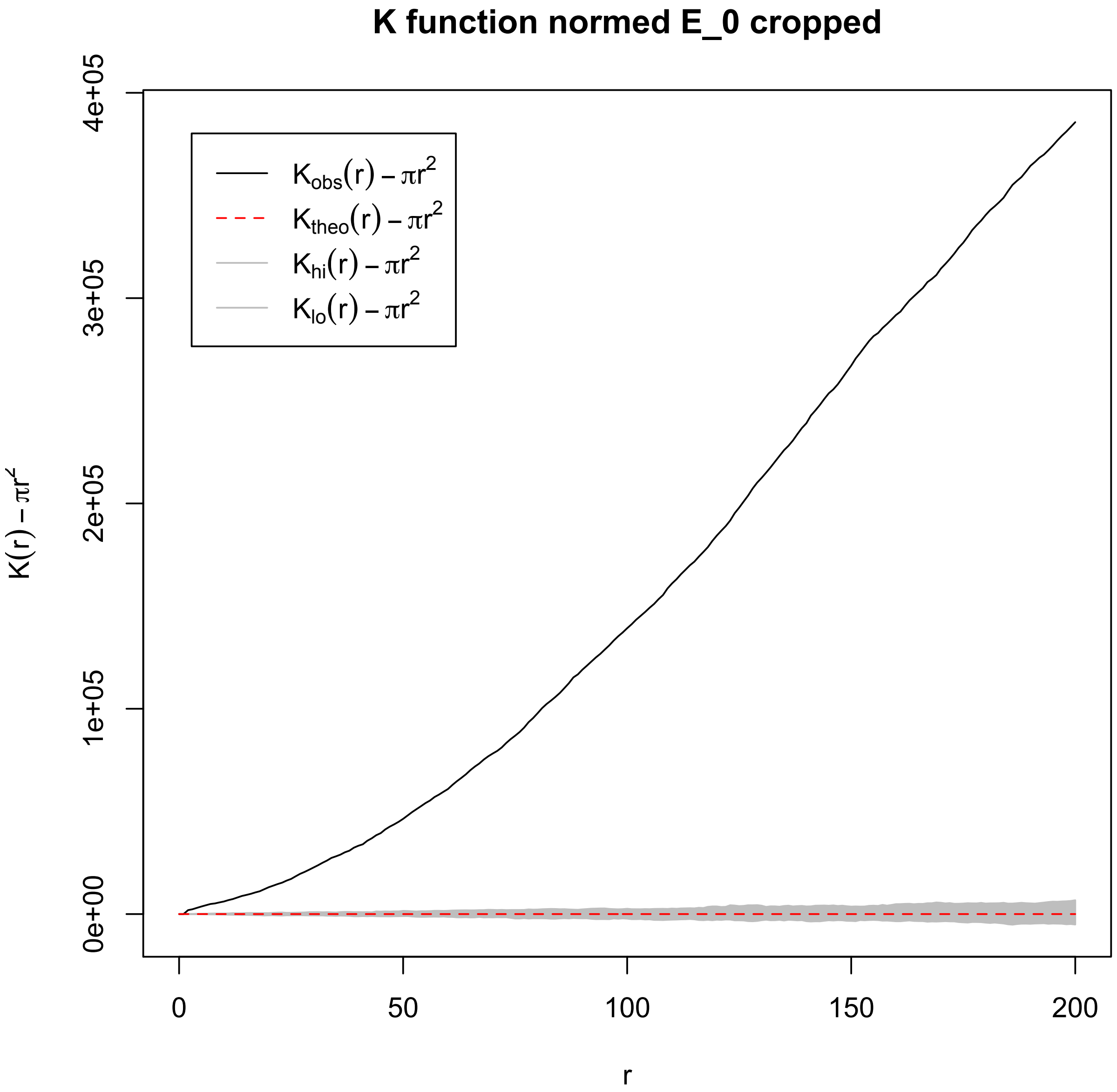
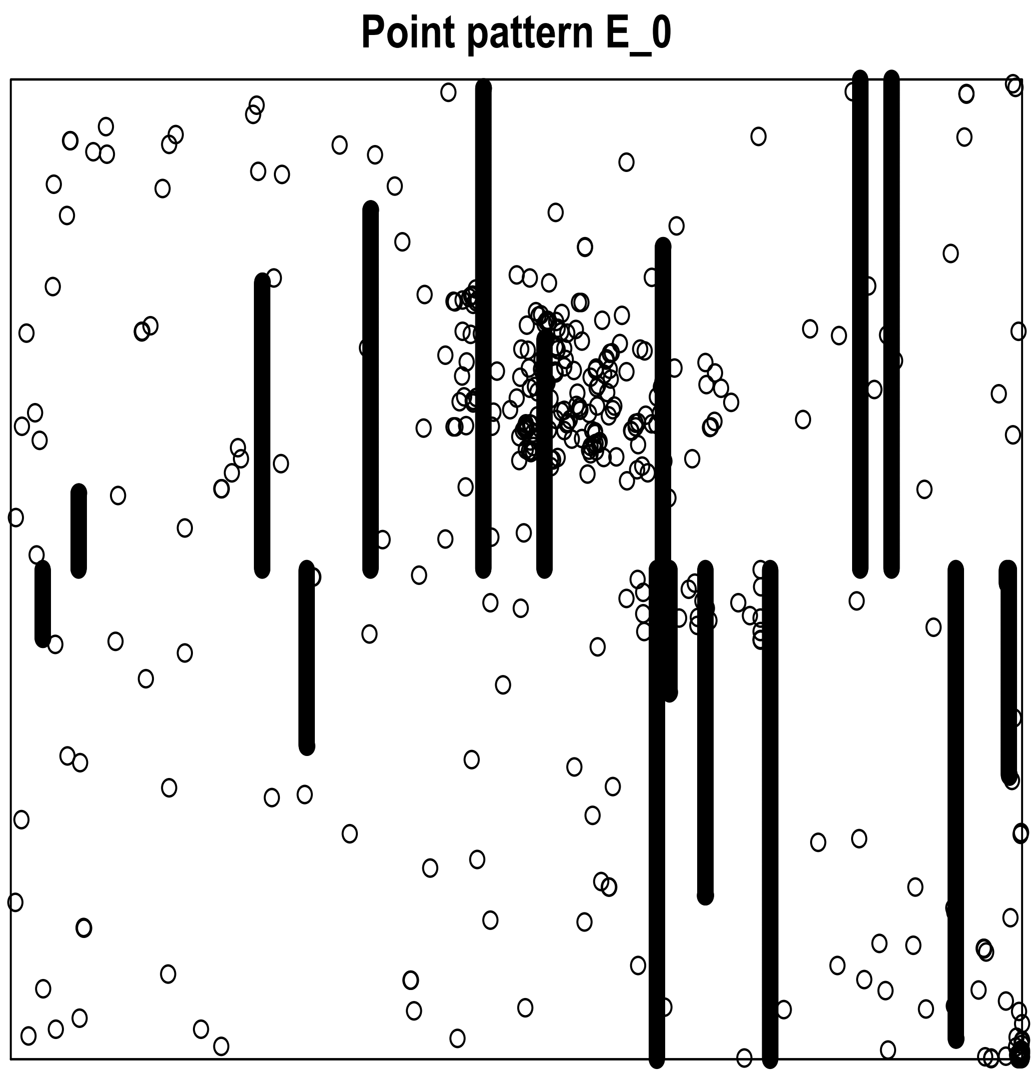
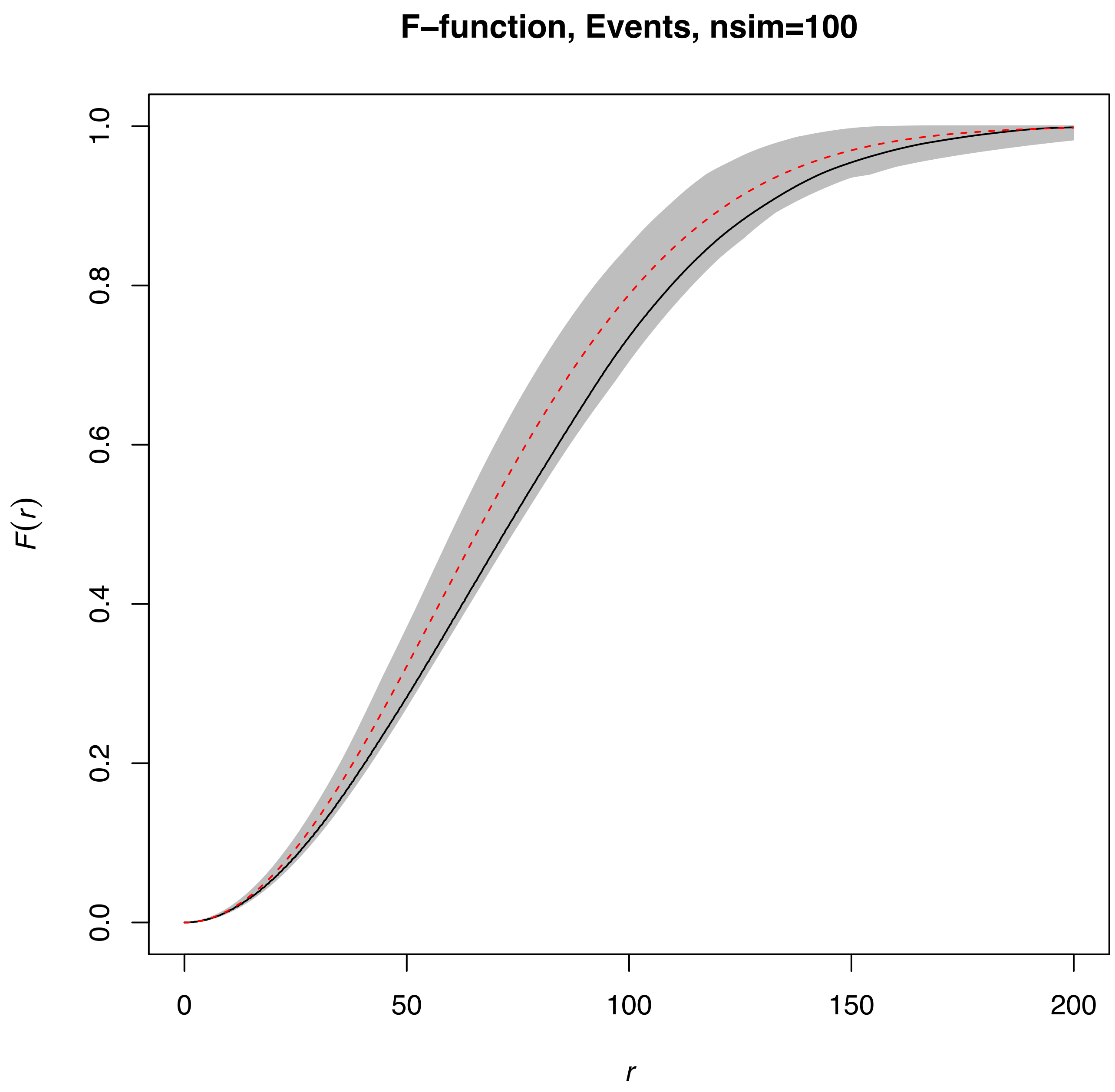


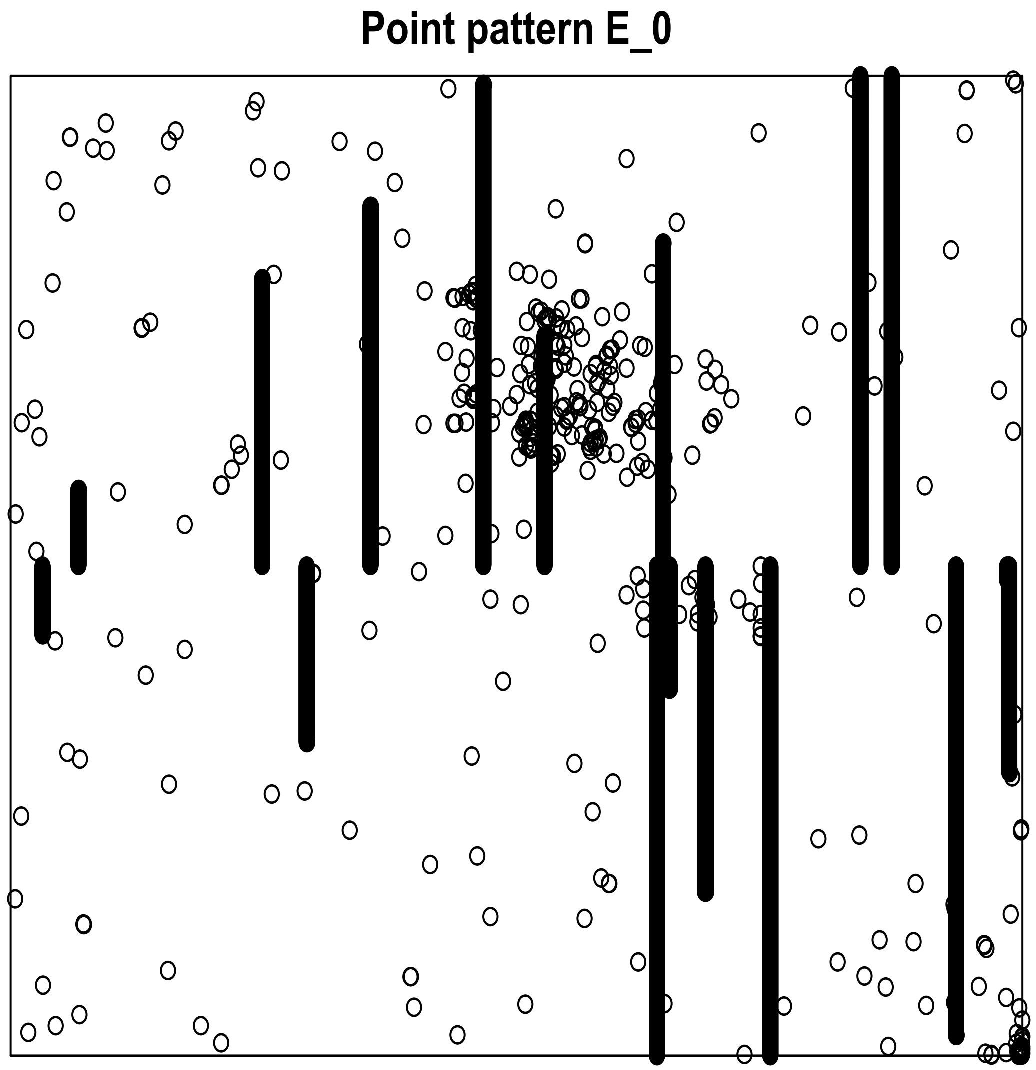


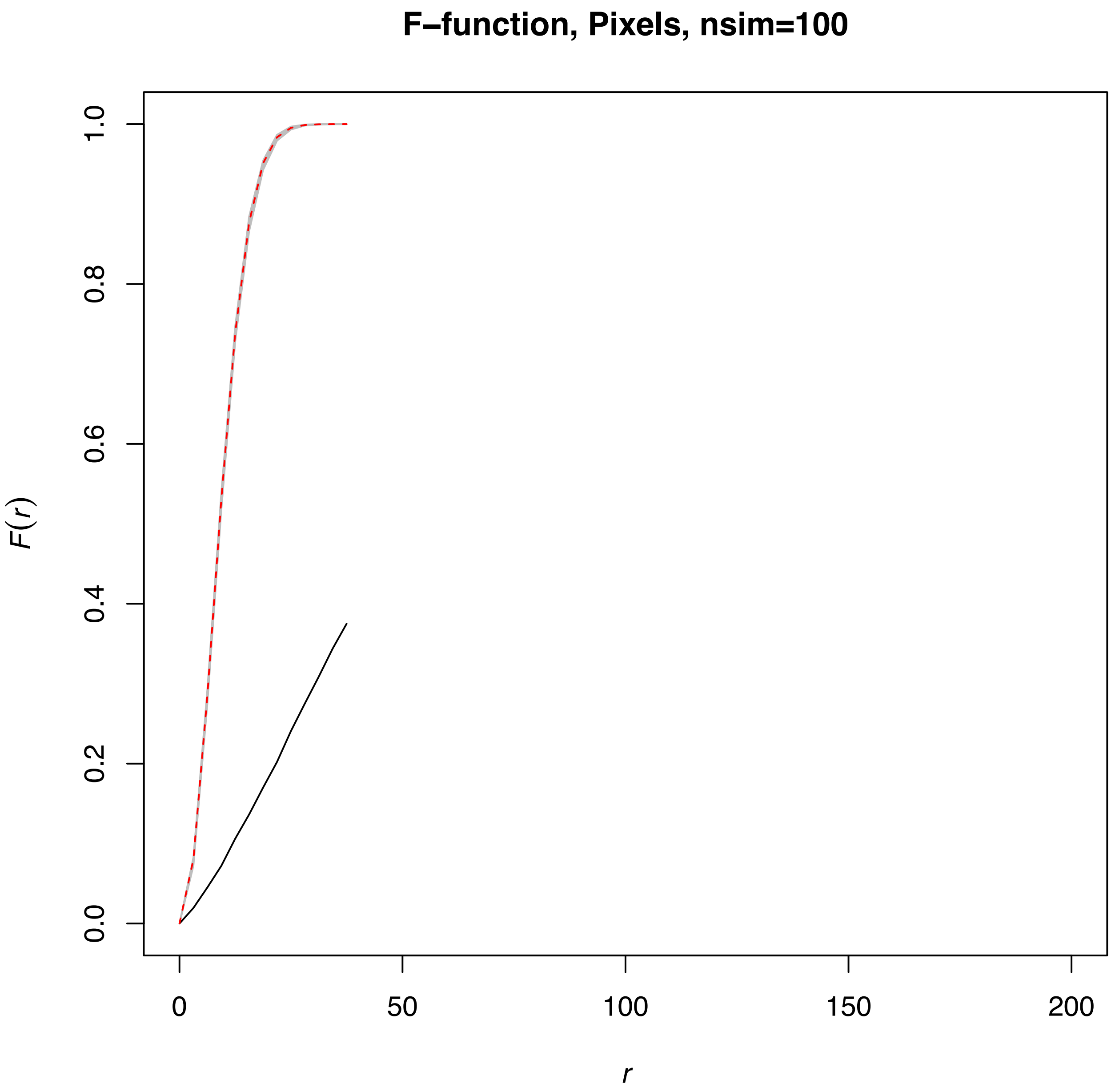
After modification: F-function



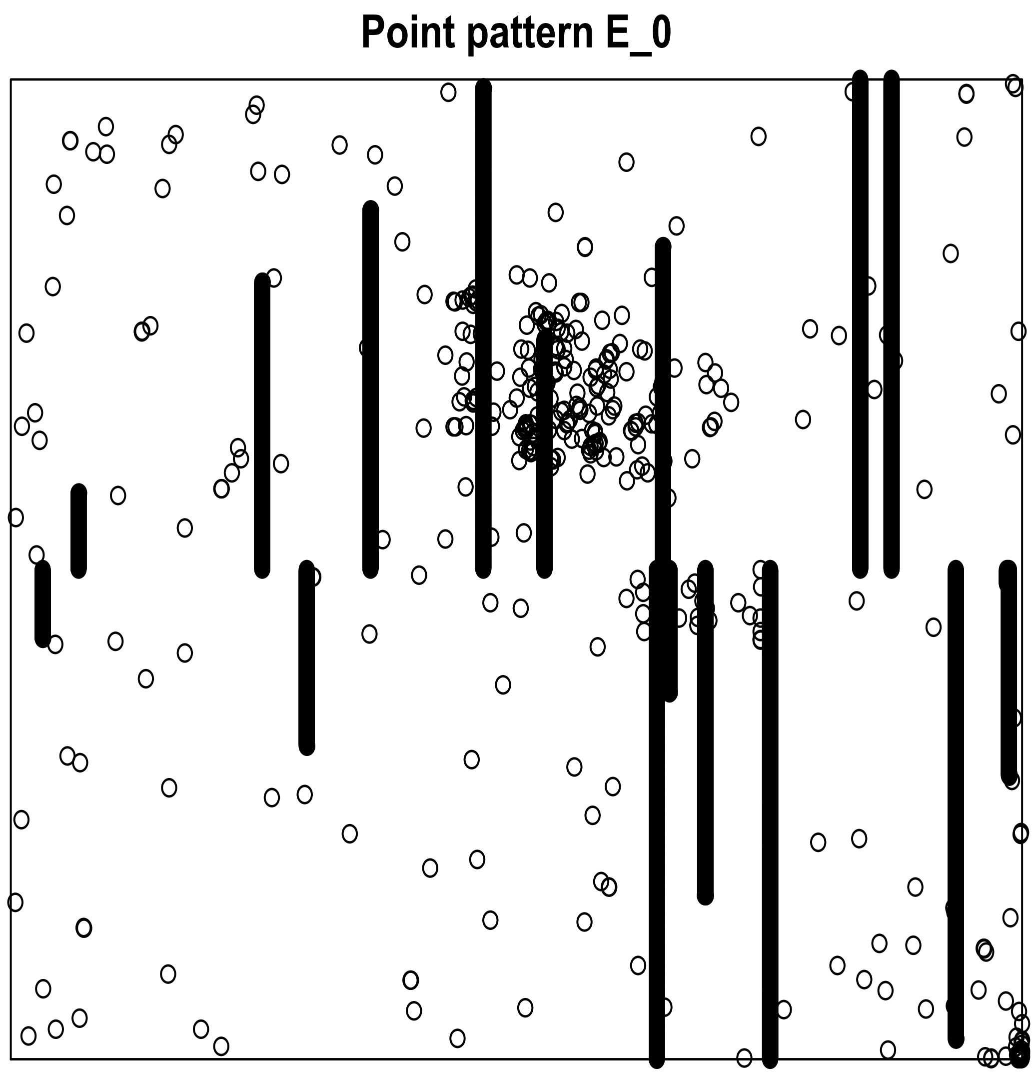


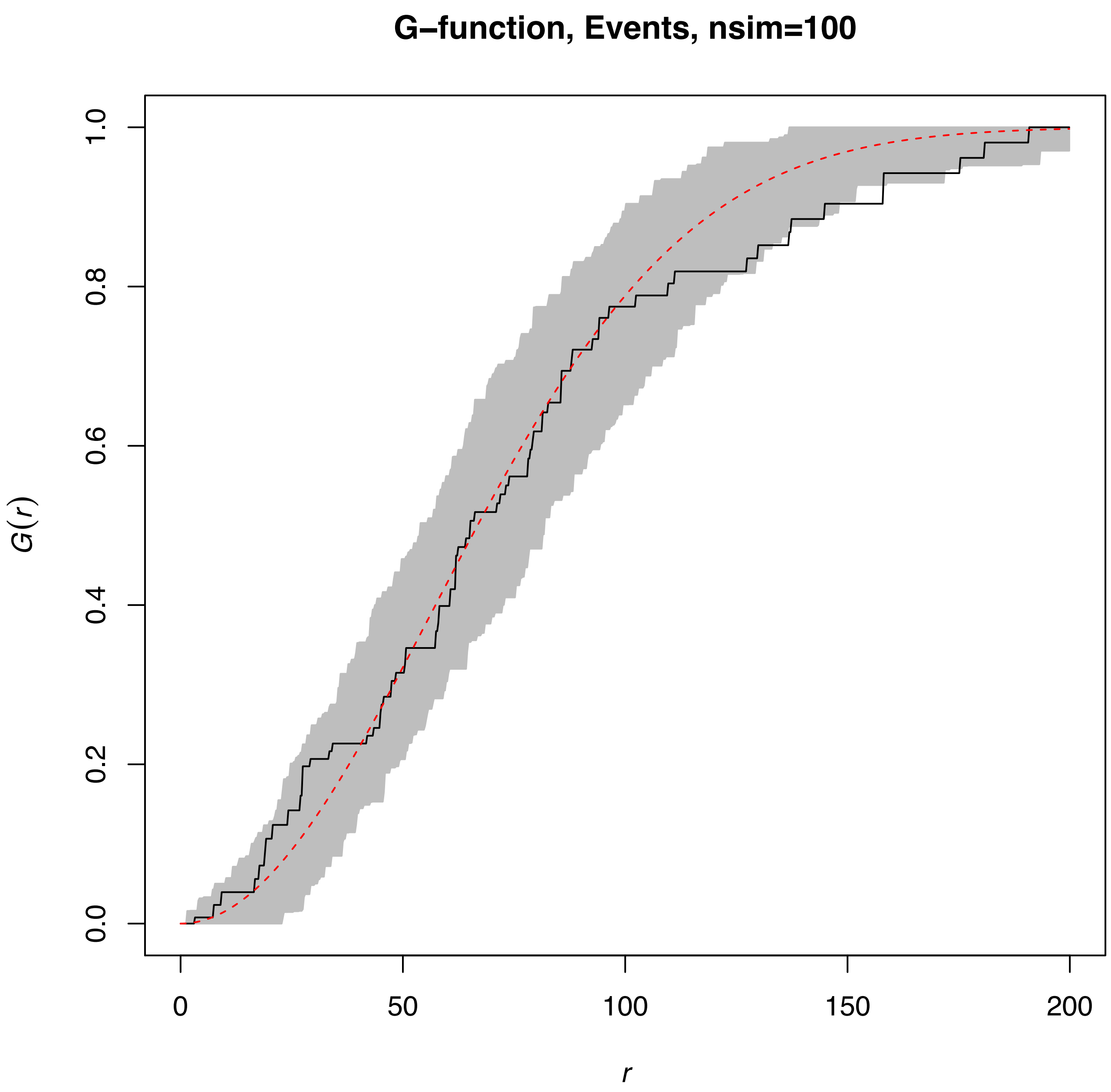
Before modification: F-function



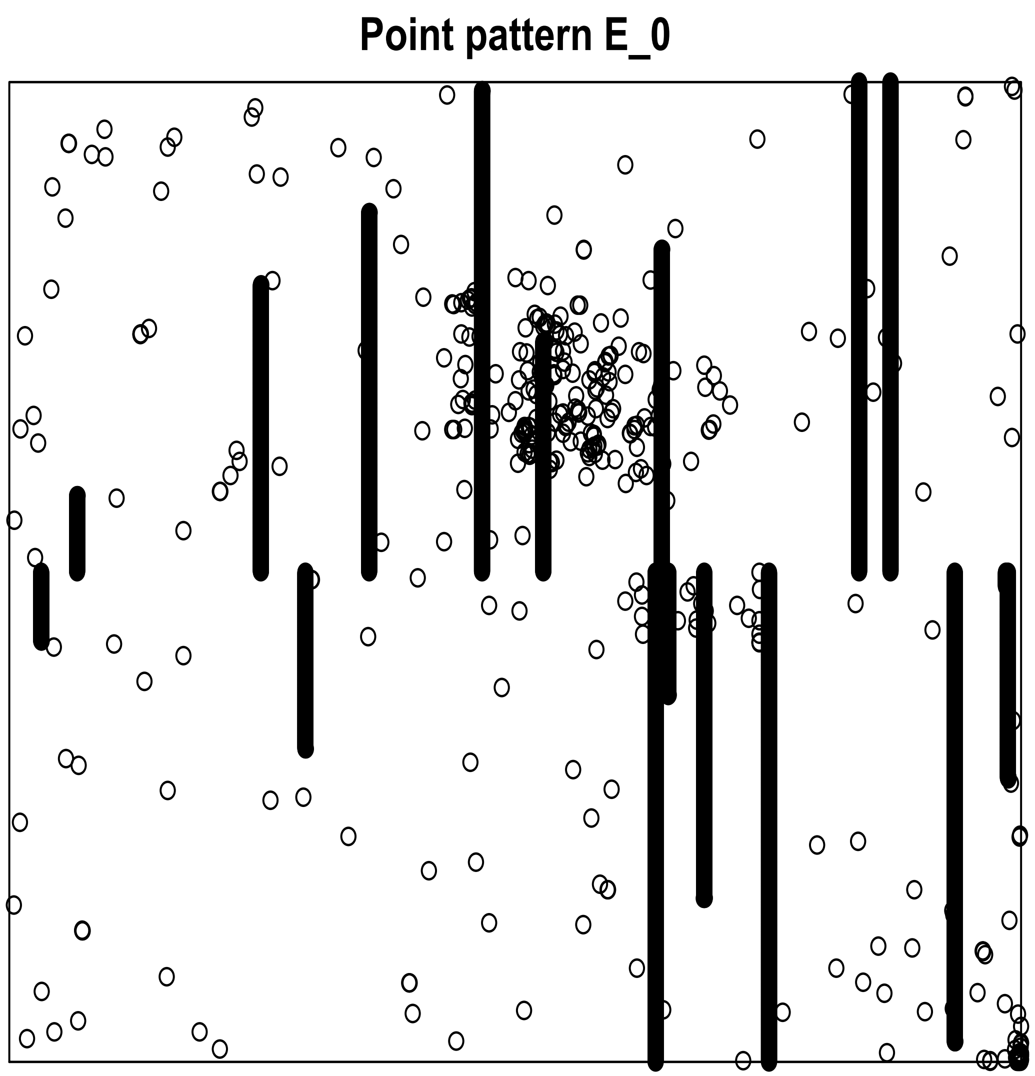


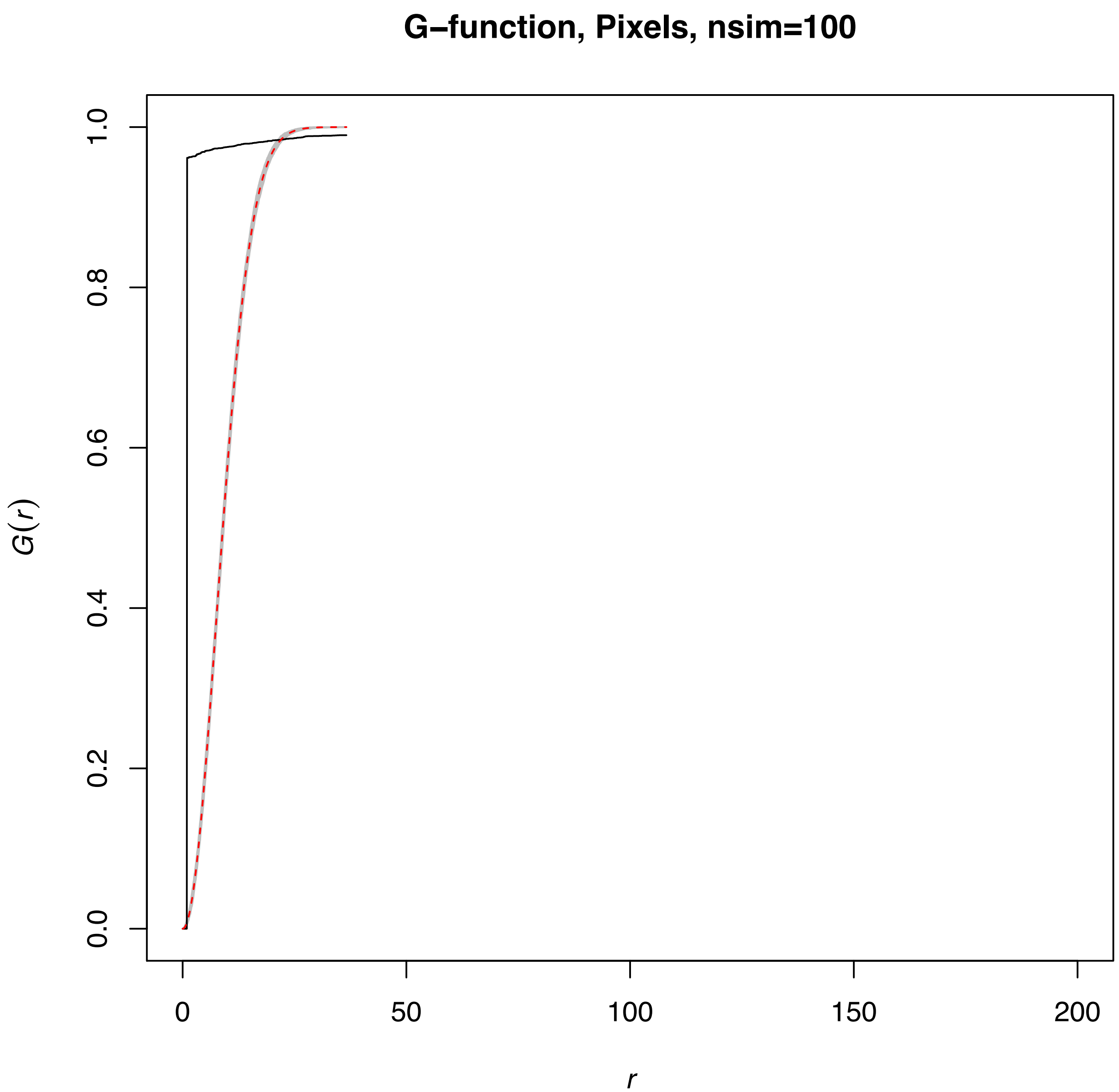
After modification: G-function





Before modification: G-function





Measurement quality assessment/improvement

- Identify poor quality regions (patches with high dead pixels density) through density thresholding
- Remaining area CSR means no special causes of poor quality
- Identify causes of poor quality
- Monitor over time
- Conclusions for usage modes

Software project with the Alan Turing Institute

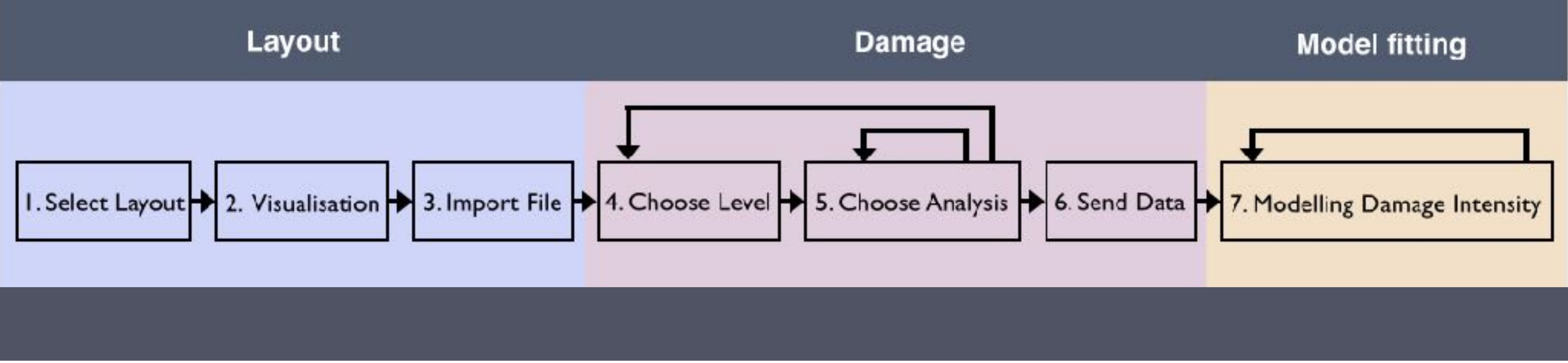
Objectives:

Web application “DetectorChecker”

- Feedback about state of detector through pixel damage analysis
- Detector data repository

Seed funded project:

- Working with Turing Research Software Engineer Group
- *DetectorChecker* R package for statistical analysis of pixel damage in CT scanners
- *DetectorCheckerWebApp* for useful initial graphical/analysis
- Facility to upload data in different formats (crowd sourcing)
- Hosted by *Azure*



https://detectorchecker.azurewebsites.net

Team

Dr Julia Brettschneider (University of Warwick)
Dr Oscar Giles (The Alan Turing Institute)
Dr Tomas Lazauskas (The Alan Turing Institute)
Prof Wilfrid Kendall (University of Warwick)

Contacts

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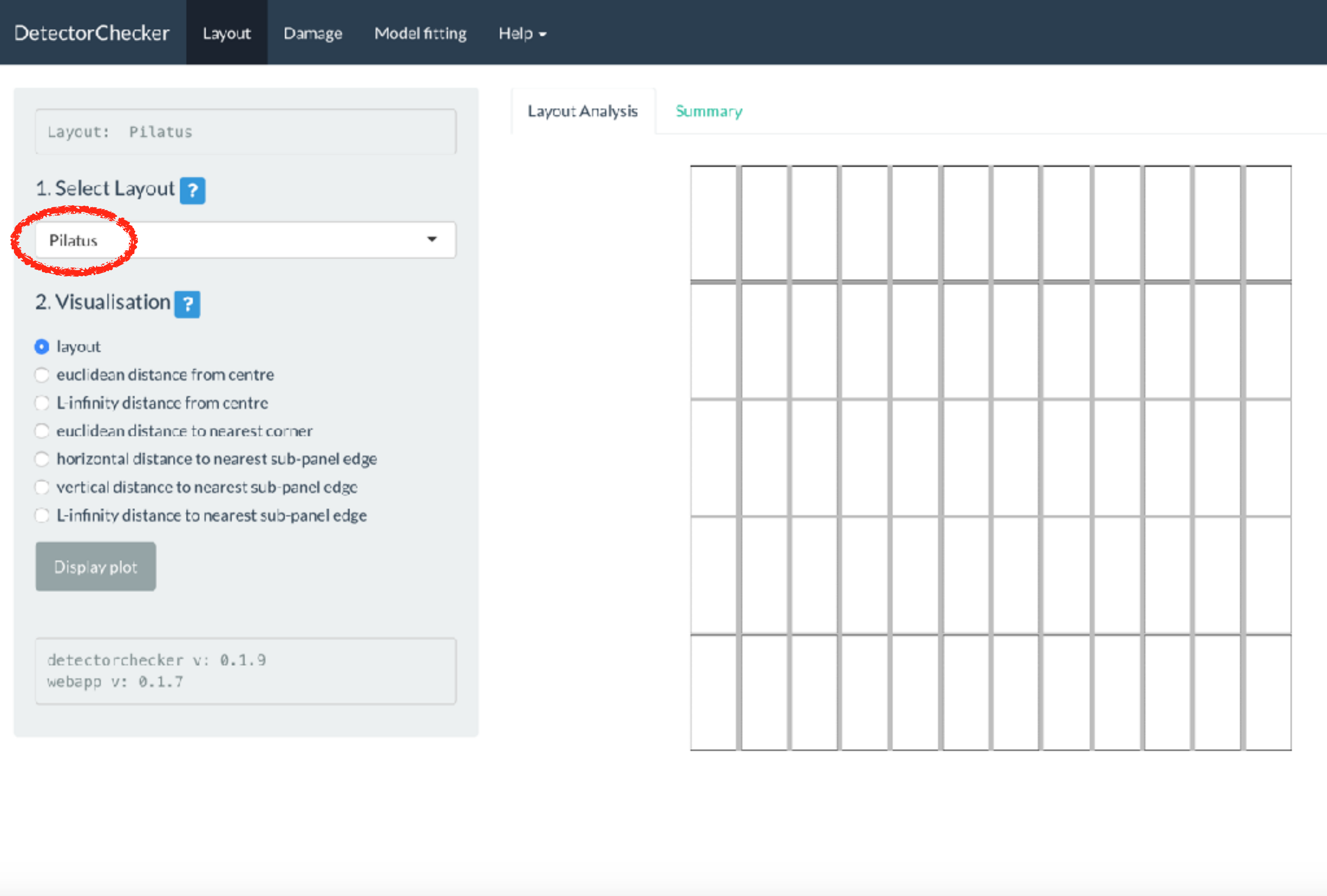
W.S.Kendall@warwick.ac.uk

Timeline

1.9.2018 - 29.3.2019

Warwick Statistics



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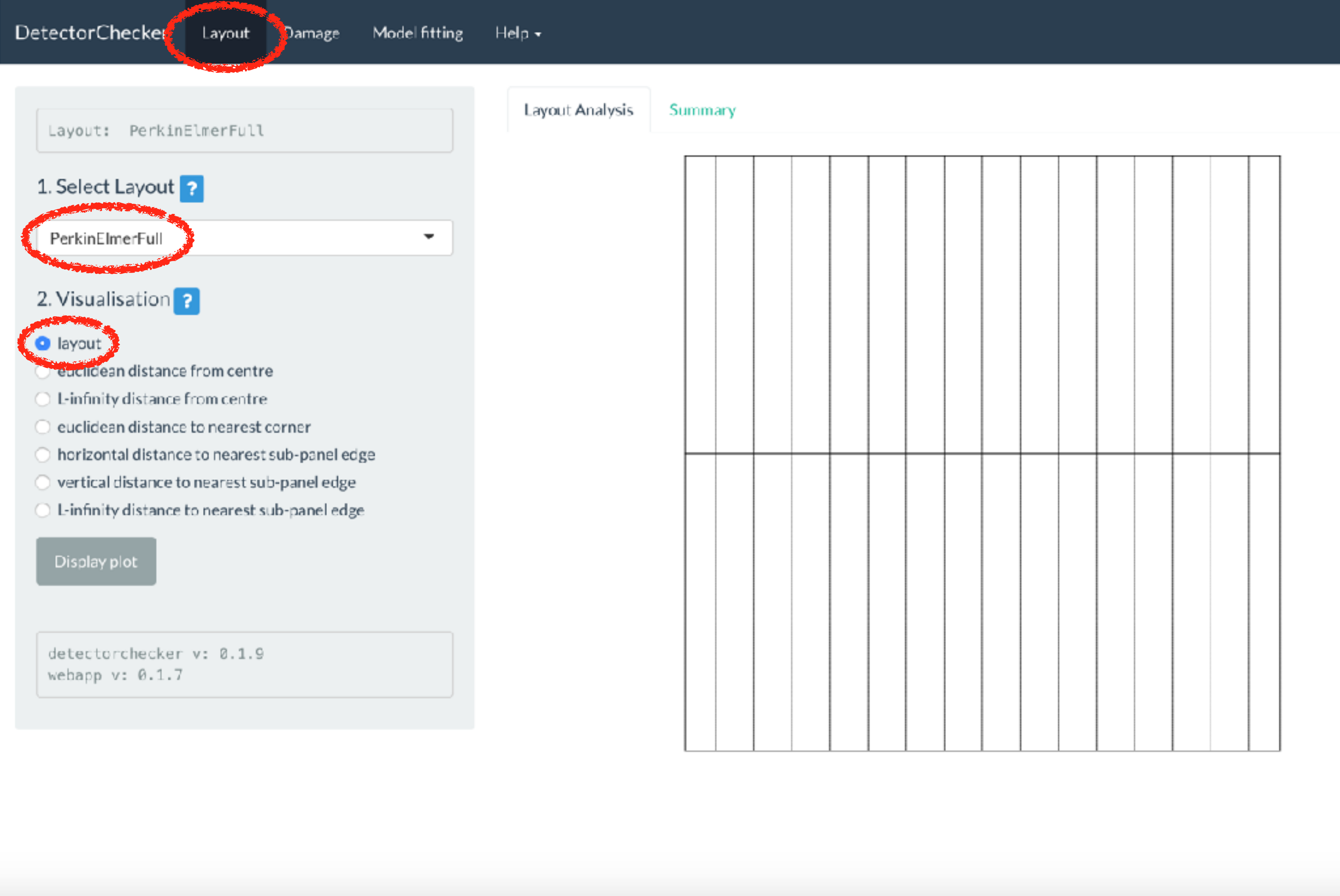
Warwick Statistics



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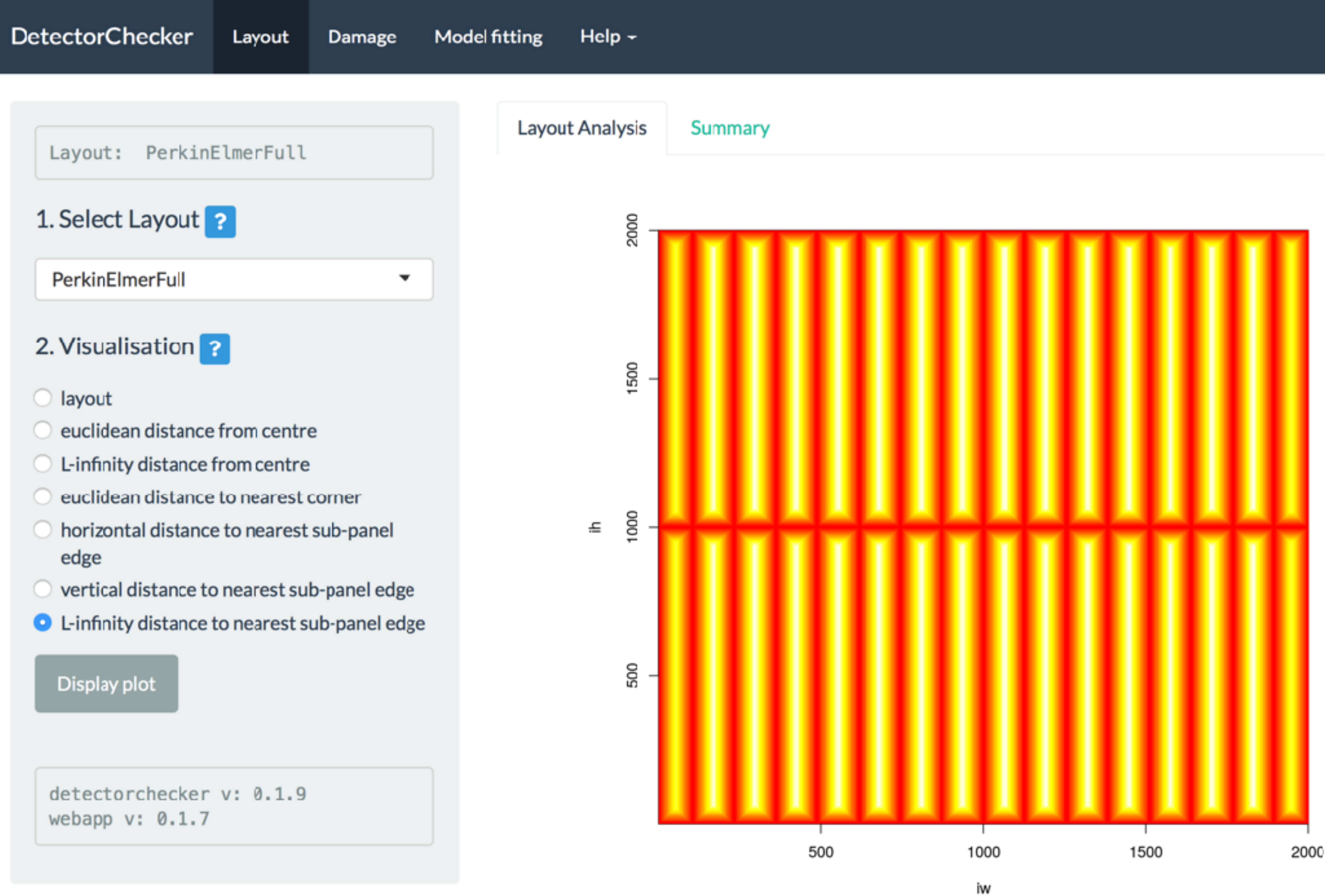
Warwick Statistics



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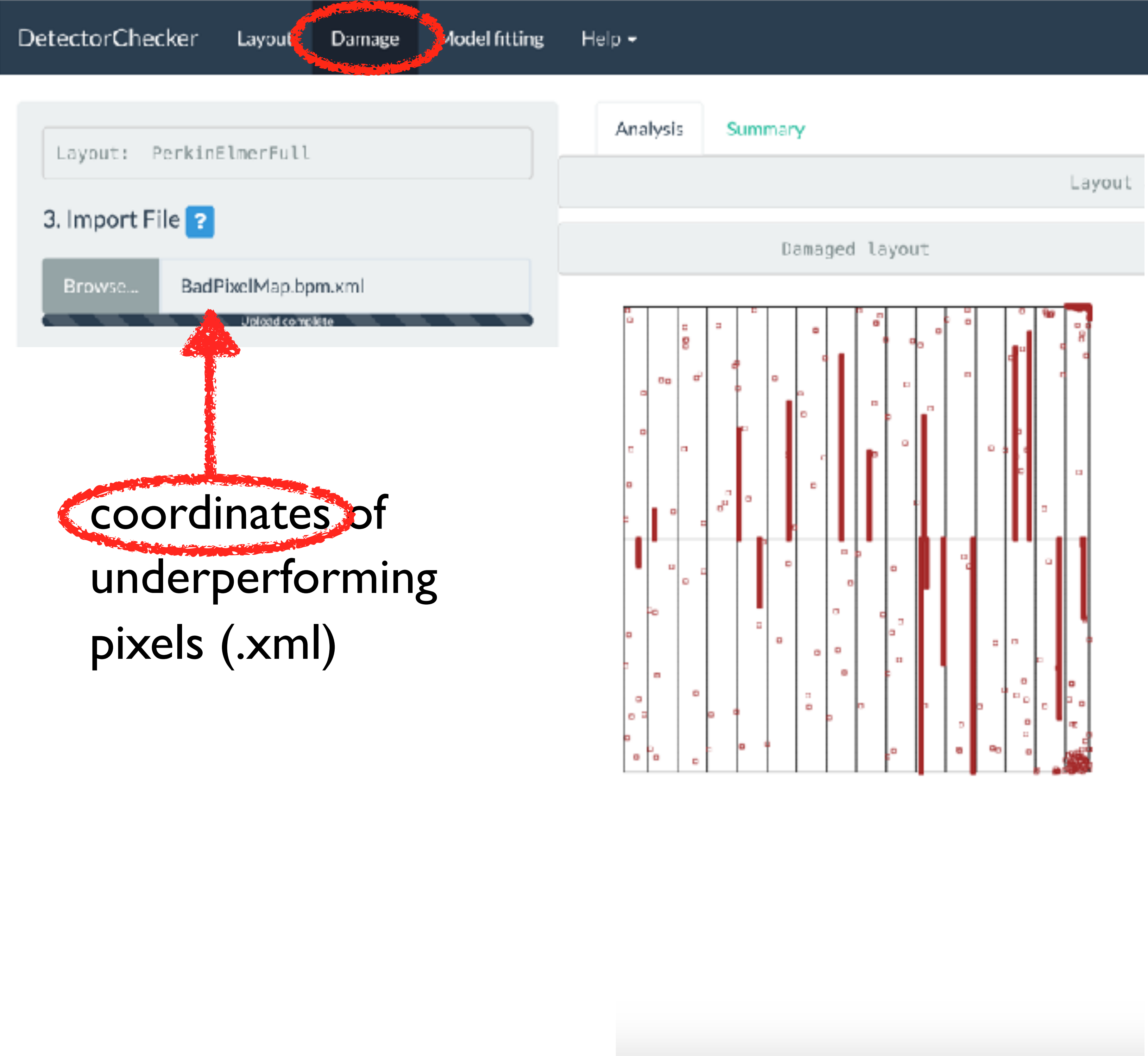
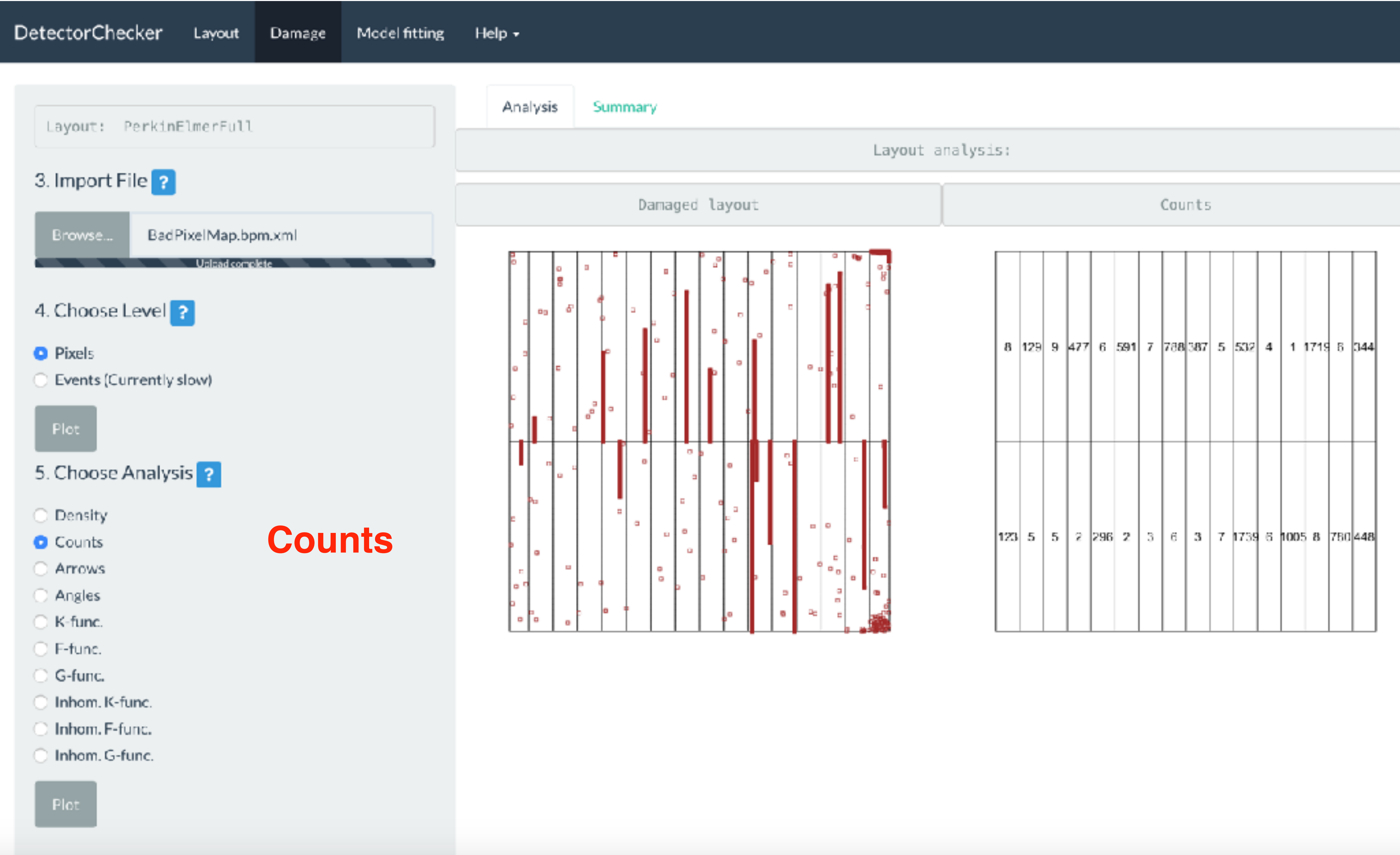


coordinates of underperforming pixels (.xml)

https://detectorchecker.azurewebsites.net

Warwick Statistics



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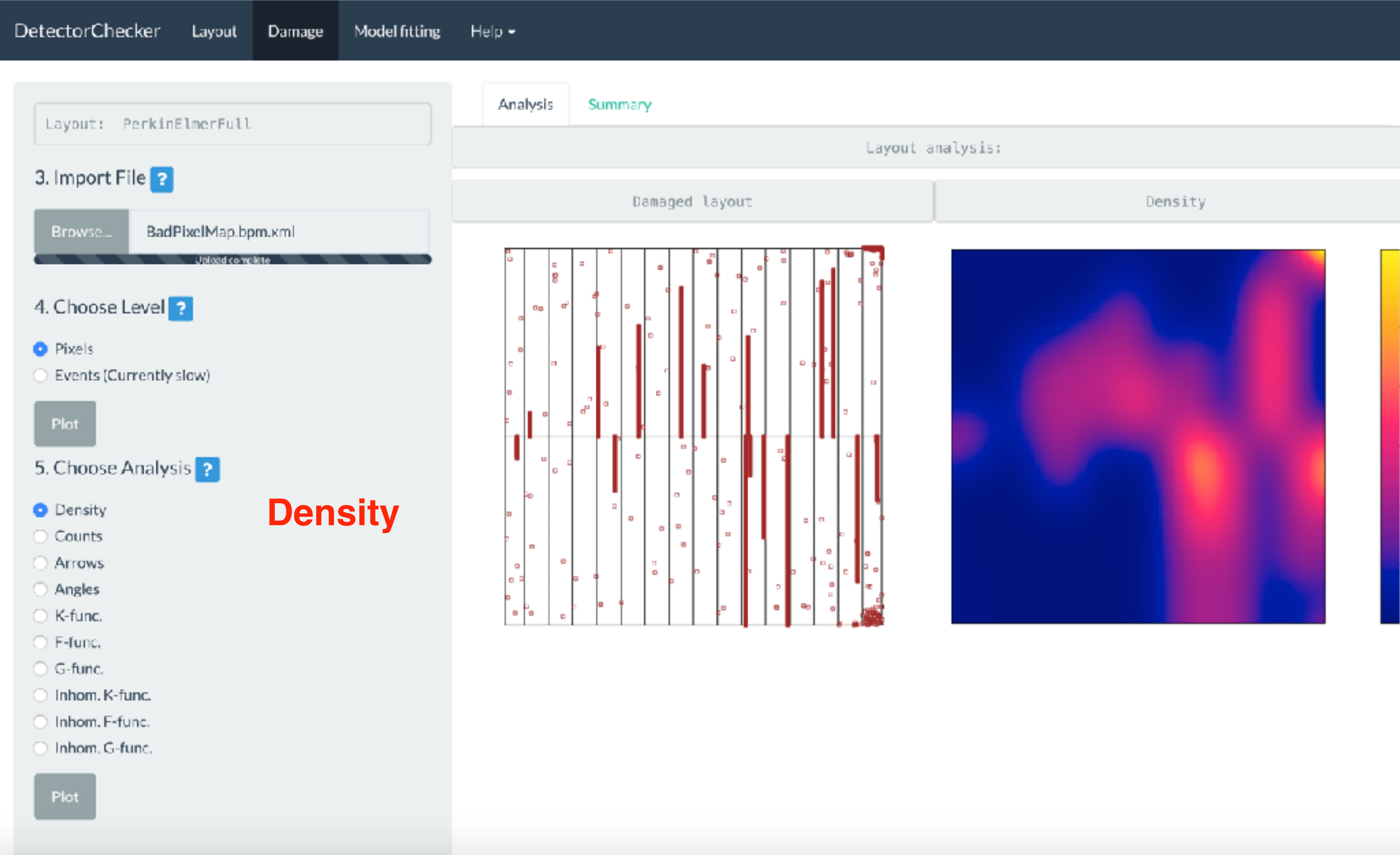

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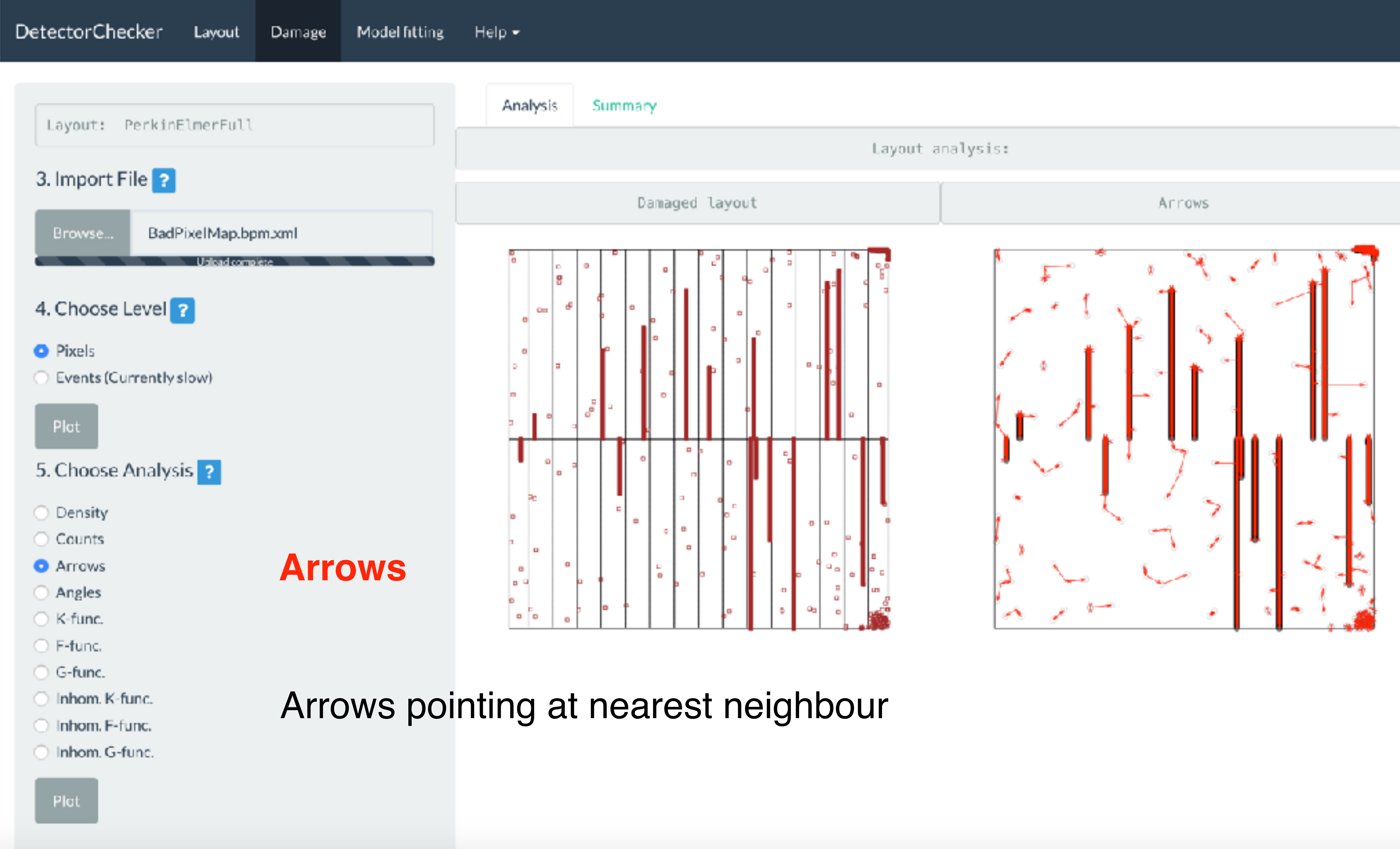
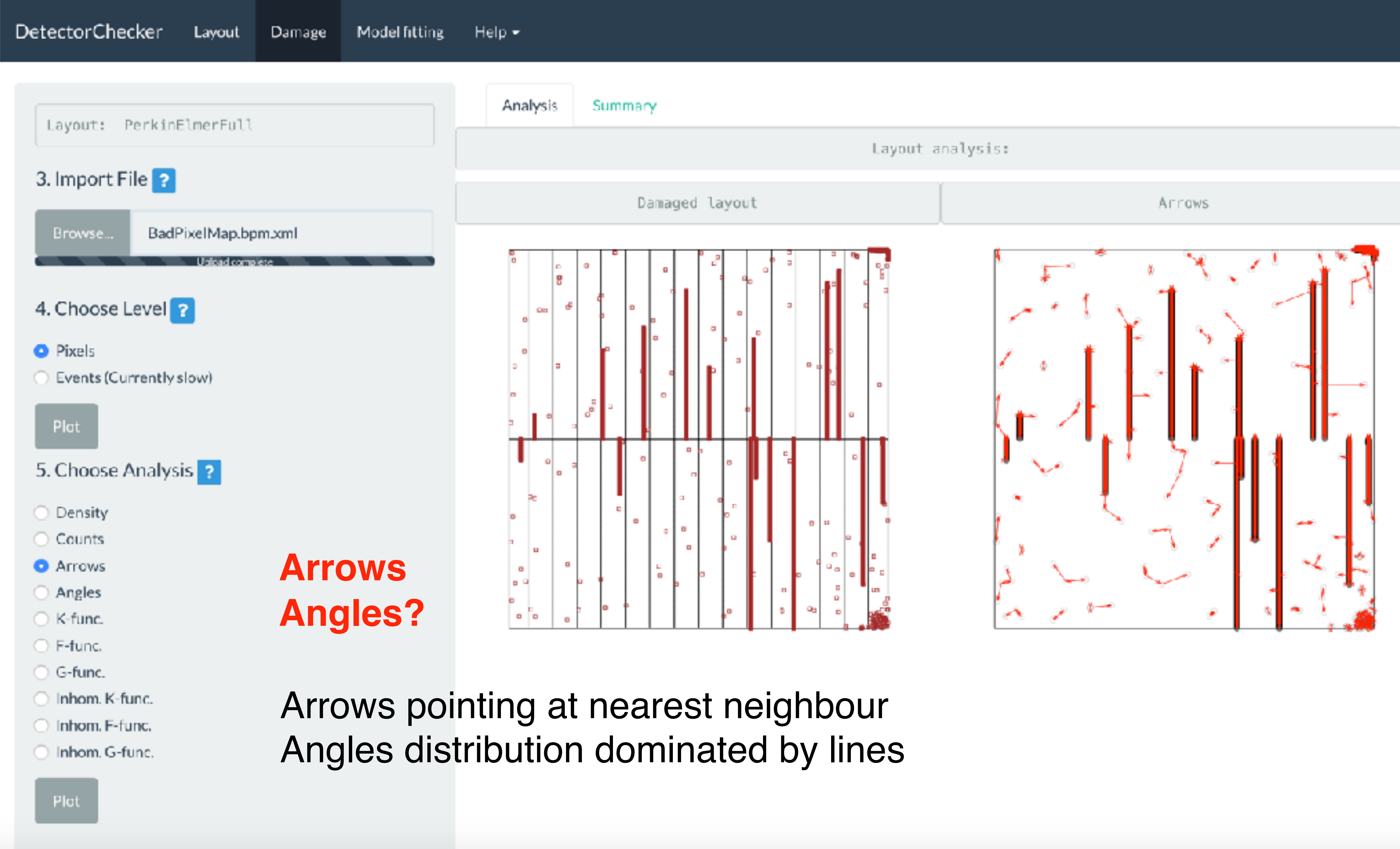


Arrows

Arrows pointing at nearest neighbour

https://detectorchecker.azurewebsites.net

Warwick Statistics

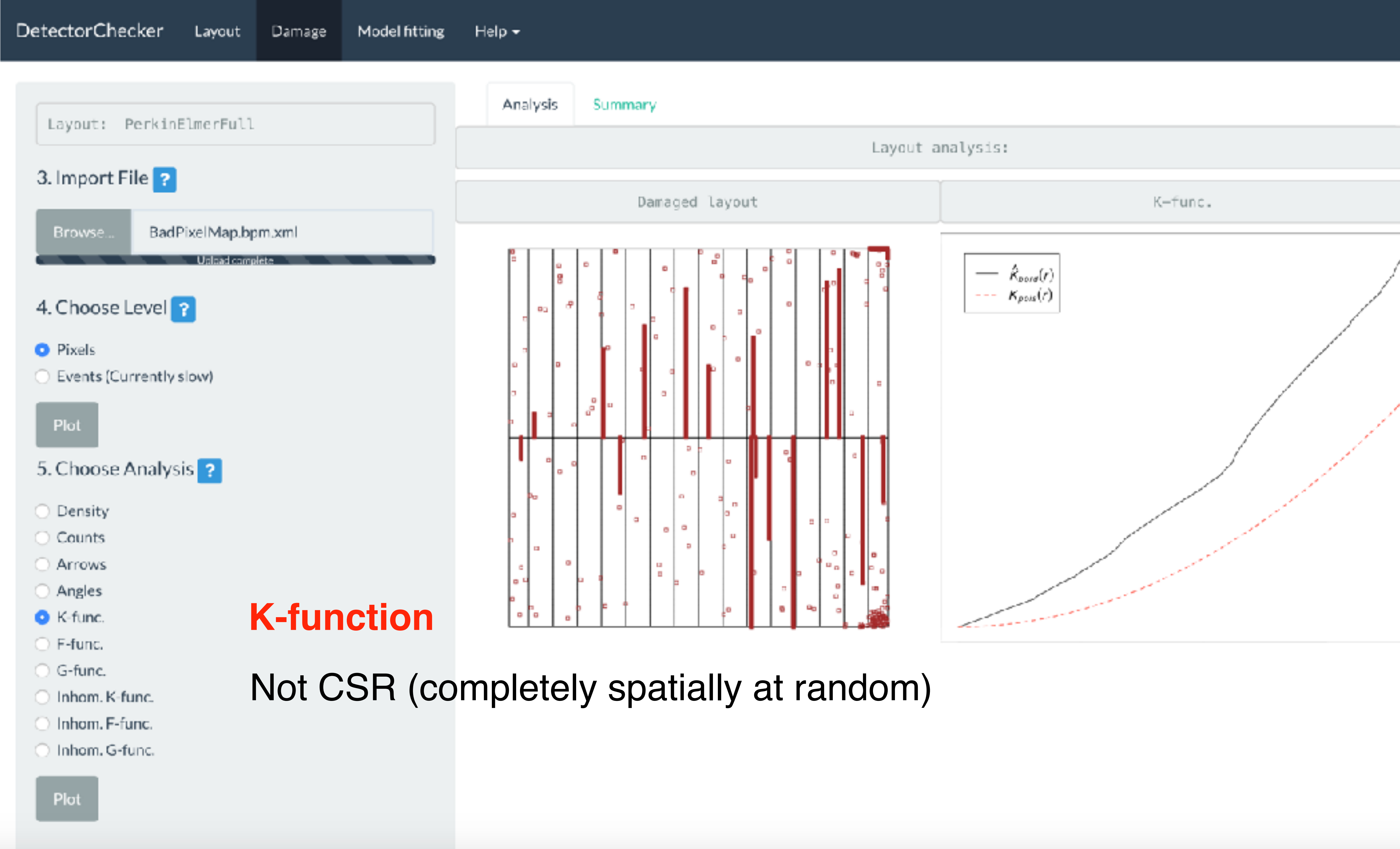


Arrows
Angles?

Arrows pointing at nearest neighbour
Angles distribution dominated by lines

https://detectorchecker.azurewebsites.net

Warwick Statistics



K-function

Not CSR (completely spatially at random)

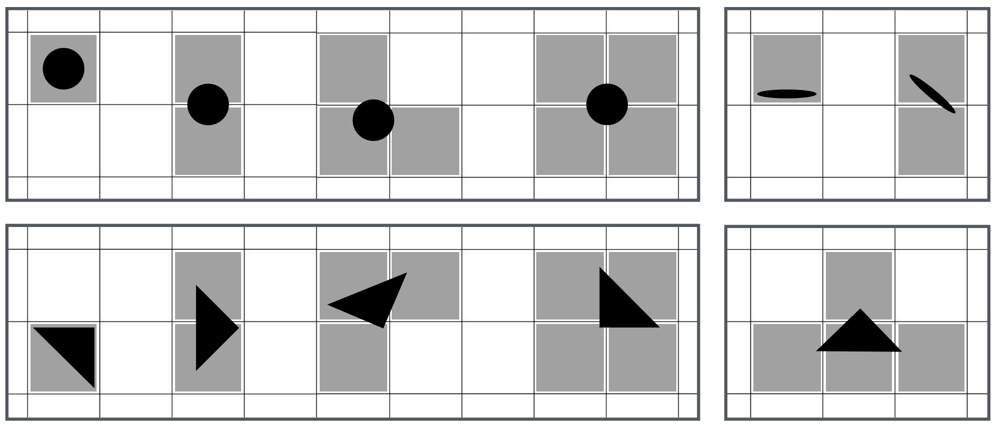
https://detectorchecker.azurewebsites.net

Warwick Statistics

Levels: Pixels or Events?

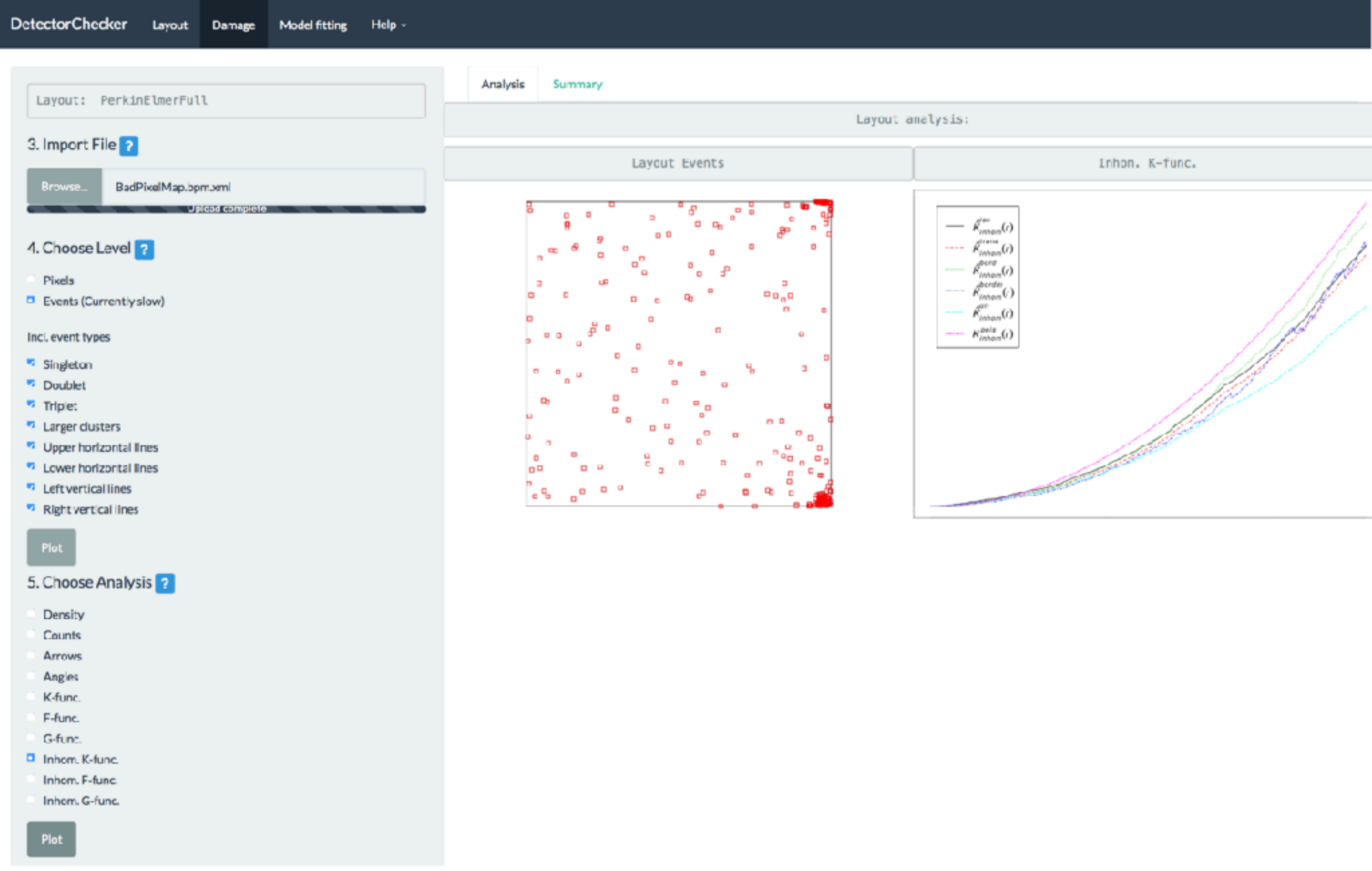
Detector is based on a lattice, but damage occurs independently of the lattice structure.

The ***same cause for damage*** shape can hit 1, 2, 3 or 4 pixels, depending on position and orientation.



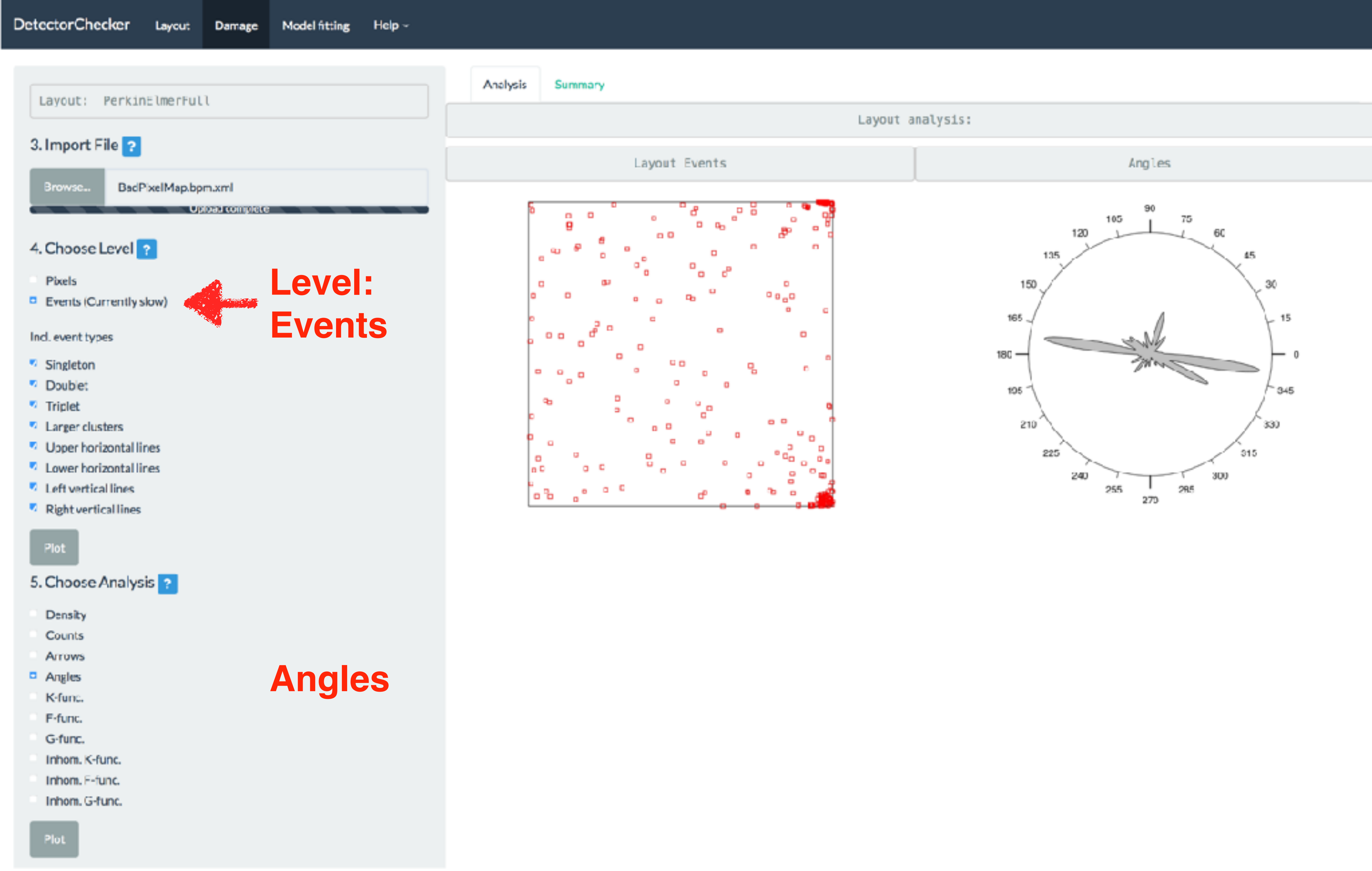
Solution: Model the damage by summarising neighbouring dead pixels into one dead event.

Convert point process into *event process* by



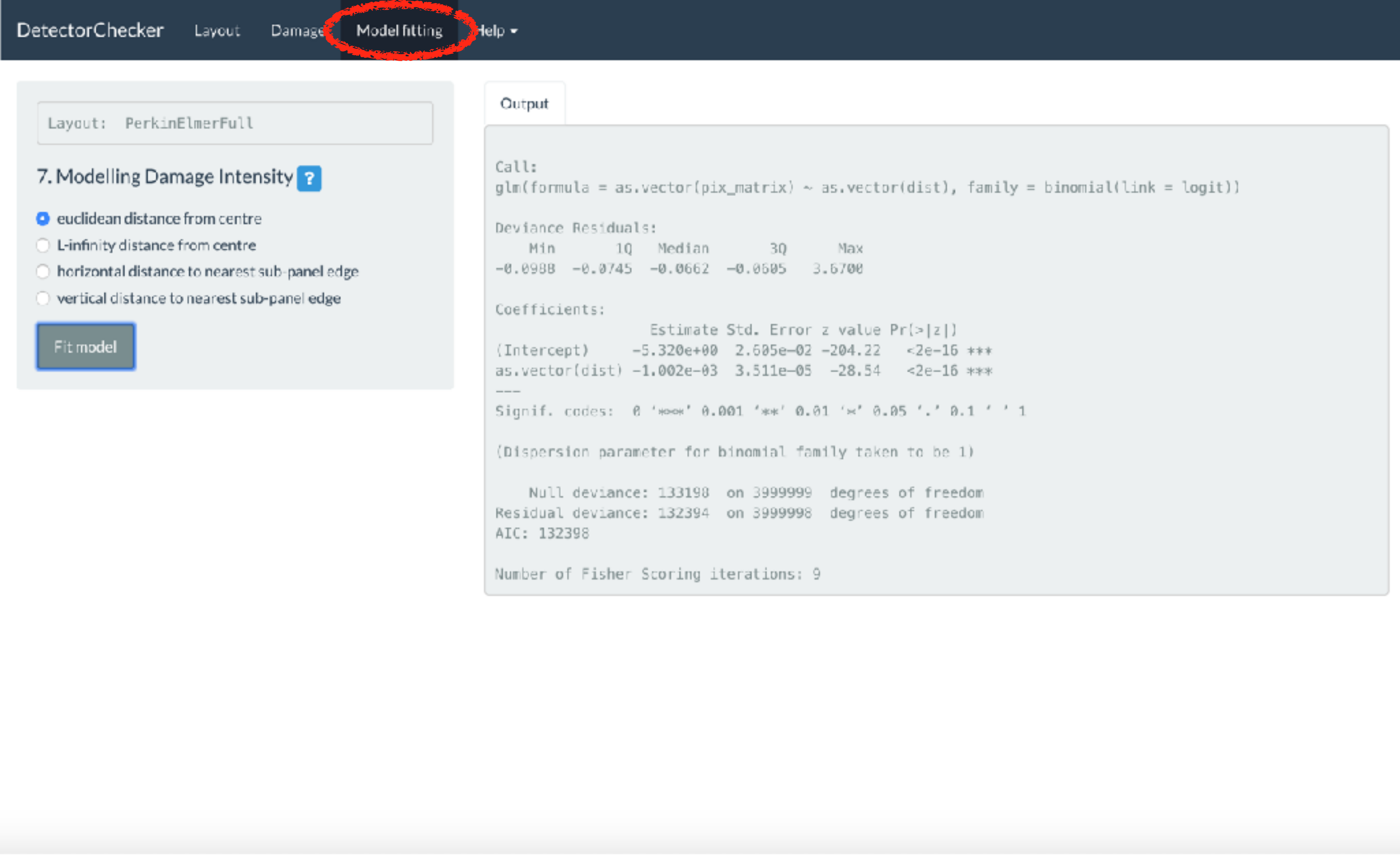
https://detectorchecker.azurewebsites.net

Warwick Statistics



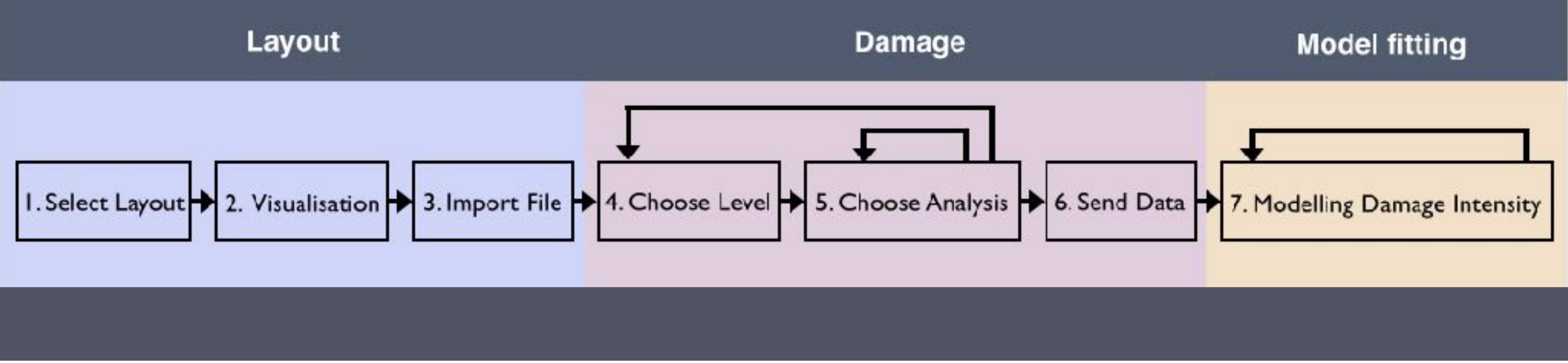
https://detectorchecker.azurewebsites.net

Warwick Statistics



https://detectorchecker.azurewebsites.net

Warwick Statistics



https://detectorchecker.azurewebsites.net

Team

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Dr Oscar Giles (The Alan Turing Institute)
Dr Tomas Lazauskas (The Alan Turing Institute)
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Contacts

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Timeline

1.9.2018 - 29.3.2019

Warwick Statistics

Brexit on 29.3. after all: dead pixel deal approved at 11pm in PM surprise move

30.3.2019 | UK Politics

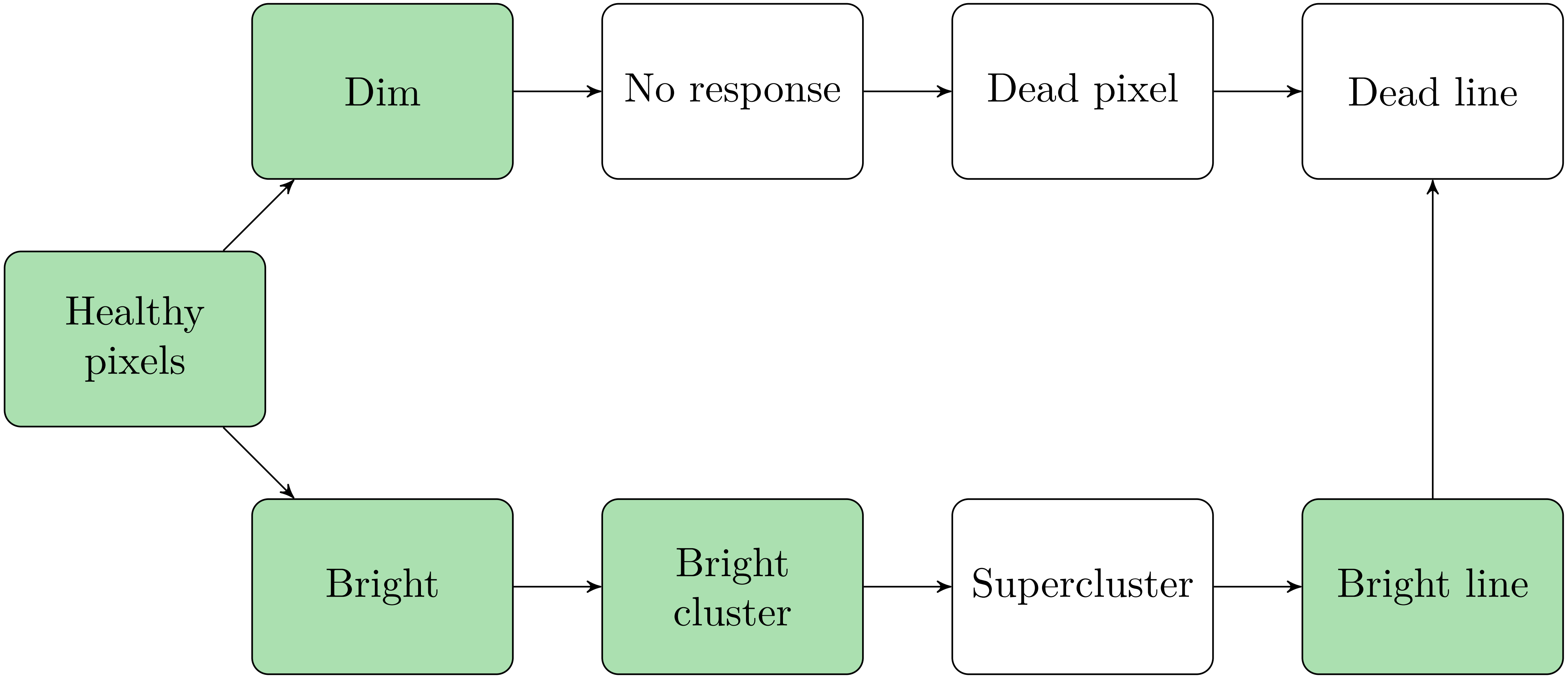
Deal approved by narrow majority of Conservative and Labour MPs without DUP.

- **Corbyn: British workers make dead pixels here in UK**
- **Rees-Mogg: I have never had an X-ray, no**
- **Farage: Greatest day in British history**
- **DUP: N. Ireland doesn't recognise pixels of any sort**
- **Business: Optimistic about digital economy**
- **Tusk's special place in hell better with dead pixels**

- **PM: Pixel means pixel**
- **Gove: Dead pixels key to Irish border IT solution**
- **Merkel and Macron seen waltzing in Brussels**

Refined states (more than just dead)

Using grey, white and black images define a variety of dysfunctional states and look at transitions.



Model for temporal development

Markov model with transition probabilities estimated from data:

		New state										
		Normal	No response	Dead	Hot	V. bright	Bright	Bright line	Screen spot	Edge	V. dim	Dim
Initial state	normal	99.91	-	-	0	0	0	0	0.1	0	-	0
	no response	-	98.83	-	-	-	-	-	-	-	1.17	-
	dead	-	-	100	-	-	-	-	-	-	-	-
	hot	-	-	-	96.72	3.28	-	-	-	-	-	-
	v.bright	0.89	-	-	2.74	88.62	7.69	-	-	0.06	-	-
	bright	18.07	-	-	-	8.44	73.44	0.05	-	-	-	-
	line.b	-	-	-	-	-	-	100	-	-	-	-
	screen spot	84.7	-	-	-	-	-	-	16.59	0.56	-	-
	edge	0.06	-	-	-	0	-	0	0.06	99.89	-	-
	v.dim	-	10	-	-	-	-	-	-	-	90	-
	dim	15	-	-	-	-	-	-	-	-	-	94.44

Markov decision process

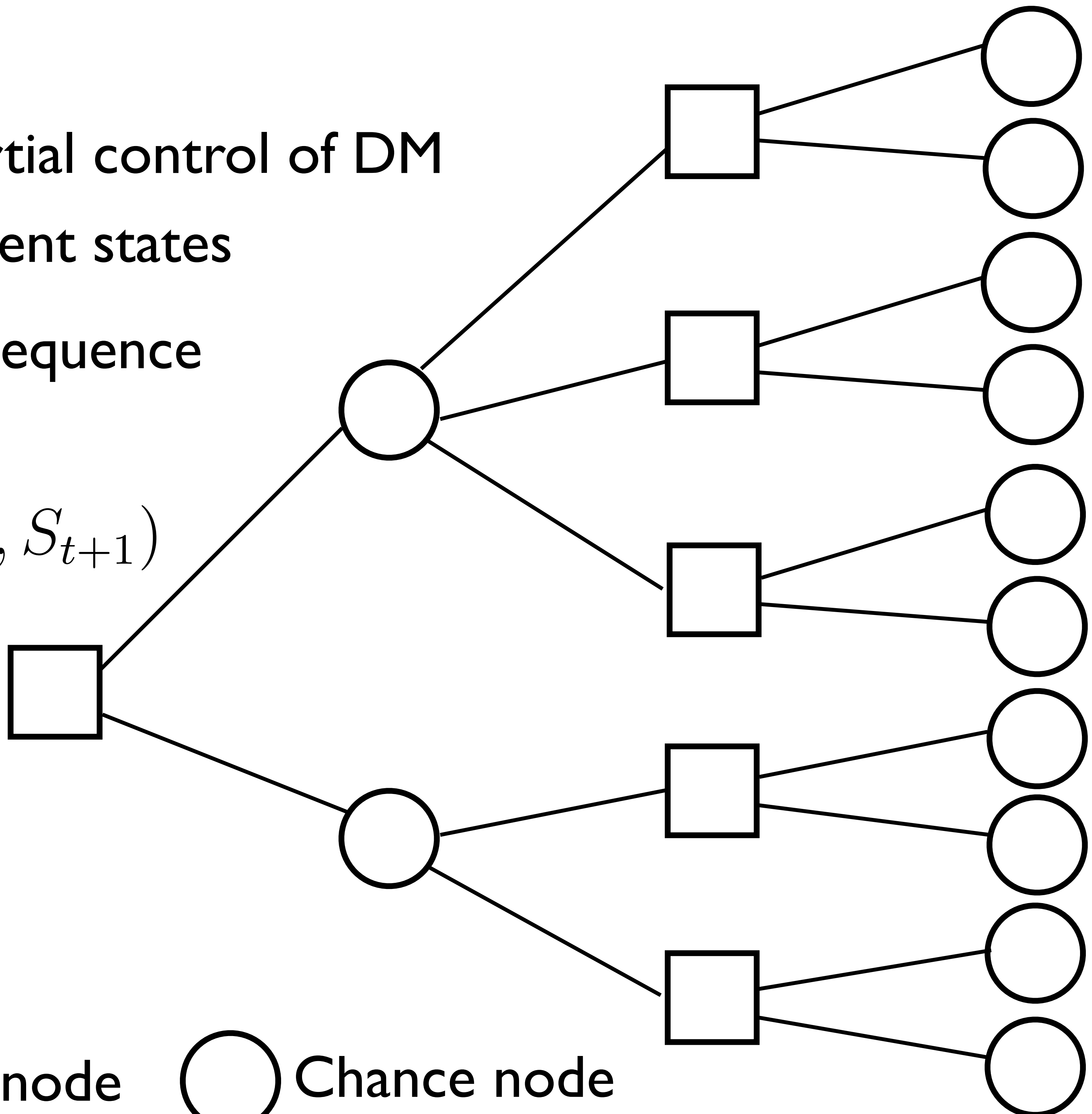
$\mathcal{M} = (T, A, \Theta, R)$

X Dynamic system under partial control of DM

$\sigma = S_0, \ldots, S_\tau$ Subsequent states

$\alpha = a_0, a_1, \ldots, a_\tau$ Action sequence

$$P_\tau^{(S,\alpha)}(\sigma) = \prod_{t=0}^{\tau-1} \theta_t(S_t, a_t, S_{t+1})$$



Decision node

Chance node

Markov decision process evaluation

$\mathcal{M} = (T, A, \Theta, R)$

X Dynamic system under partial control of DM

$\sigma = S_0, \ldots, S_\tau$ Subsequent states

$\alpha = a_0, a_1, \ldots, a_\tau$ Action sequence

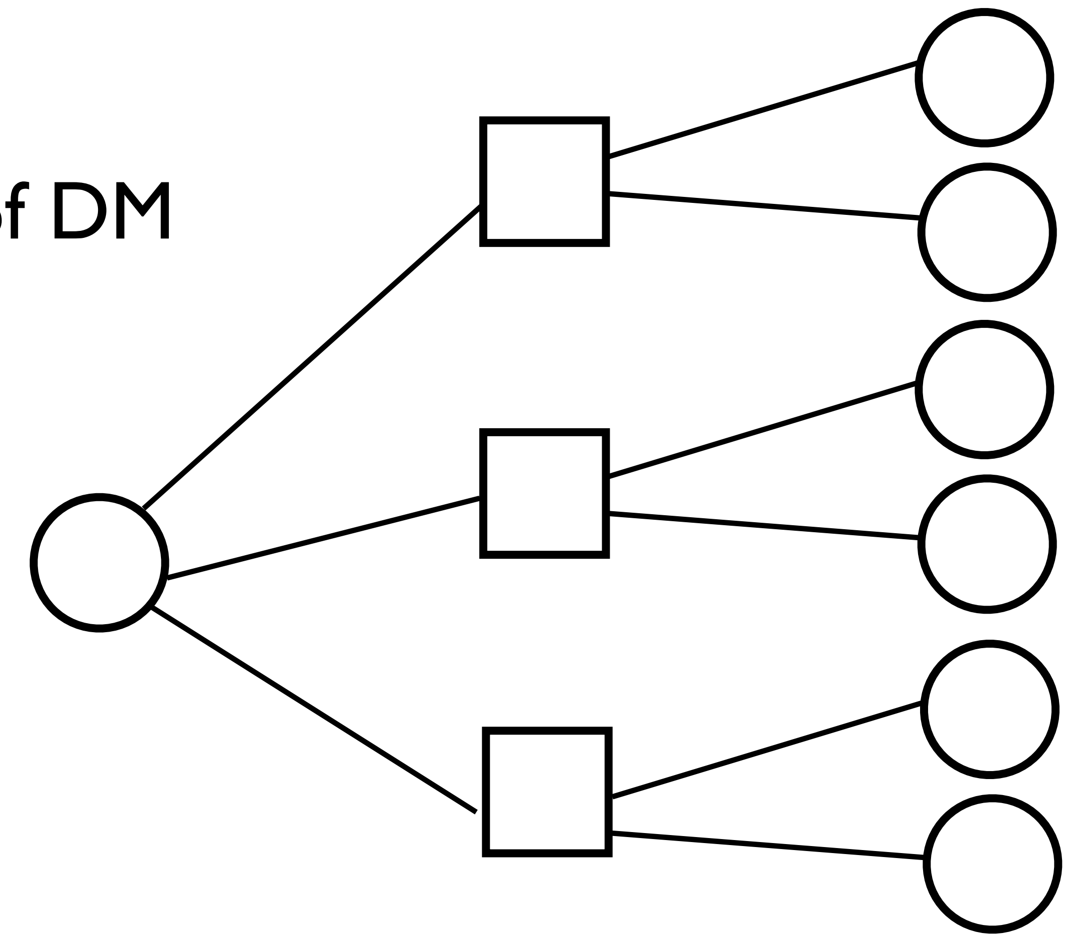
$$P_\tau^{(S,\alpha)}(\sigma) = \prod_{t=0}^{\tau-1} \theta_t(S_t, a_t, S_{t+1})$$

$h = (S_0, \ldots, S_N, a_0, \ldots, a_N)$

$$u(h) = \sum_{t=0}^{N} \lambda^t r_t(S_t, a_t)$$ Utility

$S_0 = S$ and $\delta_t(S_t) = a_t$ Usage policies

$$P_\tau^{(S,\pi)}(h) = \prod_{t=0}^{\tau-1} \theta_t(S_t, a_t, S_{t+1})$$



$$\begin{aligned} \tilde{u}_\pi(S) &= E_{P_N^{(S,\pi)}}(u) \\ &= \sum_{h \in H_N} u(h) \cdot P_N^{(S,\pi)}(h) \end{aligned}$$

Engineering and Physical Sciences
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Investing in research for discovery and innovation

Thanks to the team!

Inside-out

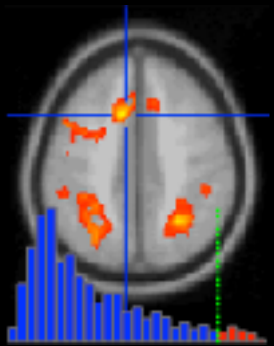
Statistical Methods for Computed Tomography Validation of Complex Structures in Additive Layer Manufacturing

3 years

10/2013 - 9/2016

PI: Prof W Kendall
Other investigators: Prof M A Williams, Dr G J Gibbons, Dr J Brettschneider, Prof T Nichols

EP/K031066/1


Project partners:
EOS systems, Nikon, Renishaw

PDRAs:
Audrey Kueh, Jay Warnett, David Garcia

Clair Barnes (Intern)
Sherman Ip (PhD student)
Tom Suchen (Masters student

Goals

EPSRC
Investing in research for discovery and innovation

Bottlenecks in Additive Layer Manufacturing (ALM) (a "3D printing" technique) is quality control. Direct verification typically involves lengthy analysis of individual manufactured objects using Computed Tomography (CT) scans. Statistical methods are key to enabling engineers to do that.

- **Image quality for CT scanners**: We analysed penumbra effects and demonstrated that they can be mitigated by careful filter design (published paper, impact case).
- **Characterisation of CT noise:** We modeled of the greyvalue of each pixel as a compound Possion random variance to capture the behaviour of x-ray photons and use the resulting linear relationship between the mean and variance for variance prediction (ongoing work by an EPSRC-funded research student).
- **Defect detection in ALM structures:** We have been developping a procedure for rapid assessment and location of collections of small defects in 3D-printed objects (paper in preparation).
- **Real-time tomography performance:** Industrial uses for real-time tomography devices developed in the context of airport baggage searches (published and ongoing).
- **Dead pixels and other detector damages**: We introduced a taxonomy for dysfunctional pixels based on local grid geometry. We methods from spatial statistics to establish decision rules distinguishing special causes of poor quality from common causes, which helps removing damage and avoided future problems (two technical reports online, paper in preparation).

Key outcomes

EPSRC
Investing in research for discovery and innovation

- **Research:**
    1. Kueh, A., Warnett, J. W., Gibbons, G. J., Brettschneider, J., Nichols, T. E., Williams, M. A., & Kendall, W. S. (2016). Modelling the Penumbra in Computed Tomography. Journal of X-Ray Science and Technology, 24(4).
    2. Warnett, J. M., Titarenko, V., Kiraci, E., Attridge, A., Lionheart, W. R. B., Withers, P. J., & Williams, M. A. (2016). Towards in-process x-ray CT for dimensional metrology. Measurement Science and Technology, 27(3).
    3. Kueh, A., Warnett, J. W., Gibbons, G. J., Brettschneider, J., Nichols, T. E., Williams, M. A., & Kendall, W. S. (in preparation). Sinogram Analysis.
    4. Ip, S., Brettschneider, J., Nichols, T., Characterisation of CT Noise in Projection and Image Space with Applications to 3D Printing (2017), poster prize at Dimensional X-ray CT conference 2017. Continuing work from Masters thesis by Tom Suchen Jin 2013.
    5. Brettschneider, J., Barnes, C., Warnett, J., Gibbons, G.J., Williams, M. A., Nichols, T. E., Kendall, W. (in preparation), Life and Death of Pixels. (CRISM reports 2014, 2017 online.)
- **Collaborations (New academics/industry):** RA Warnett now Assistant Professor at WMG, RA Kueh now Teaching Associate at Cambridge, Crevillen-Garcia now research associate at Warwick Engineering Department, Master student Jin now PhD student at OxWaSP (EPSRC funded), intern Barnes now statistics PhD student at UCL.
- **Impact:** Formal impact case relating to publication 1 above with industrial support (Nikon).