POLITECNICO
MILANO 1863

# BIG DATA MINING, MODELING AND MONITORING FOR MANUFACTURING 4.0: OPPORTUNITIES AND CHALLENGES

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mecc
DIPARTIMENTO DI ECCELLENZA
MIUR 2018-2022

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## A lifelong journey


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2

## Special issue and call for papers




Special issue – AI and Statistics for quality technology – vol 5 2021



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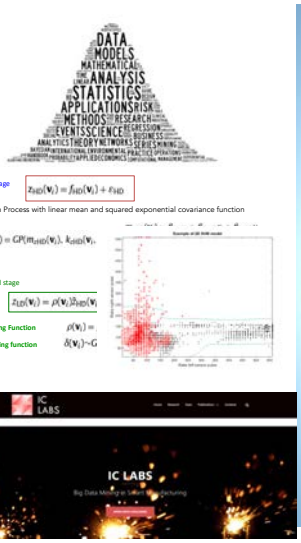
## A lifelong journey – connecting Manufacturing to Data Mining







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Politecnico di Milano (since 1863)
Largest technical university in Italy

Manufacturing (2022)
- 1st in Italy
- 5th in Europe
- **13th worldwide**

Engineering & Technology (2022)
- 1st in Italy
- 7th in Europe
- **13th worldwide**

Bianca M Colosimo - AddME, IC Labs and 3D cells lab

Full Professor - Deputy Head of the Department of Mechanical Engineering – Co-founder of the **AddMe Lab**, **IC Labs and 3D cell Lab**

Senior Editor- Department Editor:
**Progress in Additive Manufacturing- Additive Manufacturing Letters**
**Past Editor-in Chief Journal of Quality Technology**
**Informs Journal of Data Science – IISE Transactions**

Council members of **Enbis**, **ASQ**, **Informs QSR** and
Member of the European Commission's platform **Manufuture** Member of the SC of the **Vanguard Initiative on 3D Printing** - Board Member of the CLC South - **EIT Manufacturing**,

Included among the top 100 Italian woman scientists in **STEM** (https://100esperte.it/)

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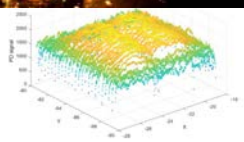
## AddME Lab & IC Lab @ POLIMI

https://www.ic.polimi.it/

AddMeLab

**Laser and EB Powder Bed Fusion**

**Direct Energy Deposition, Waam, BMD**

In-situ quality process monitoring in Additive Manufacturing

An Open Science project collaboration between Trumpf GmbH and Politecnico di Milano

TRUMPF

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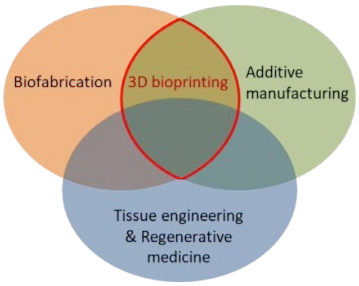
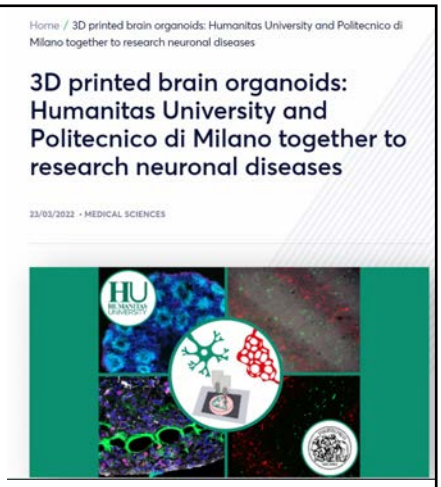
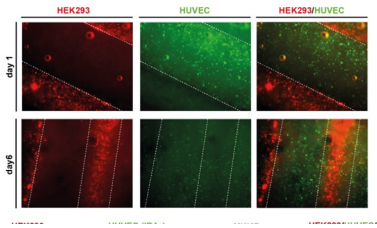
## 3D Cell Lab@ Polimi - Bioprinting

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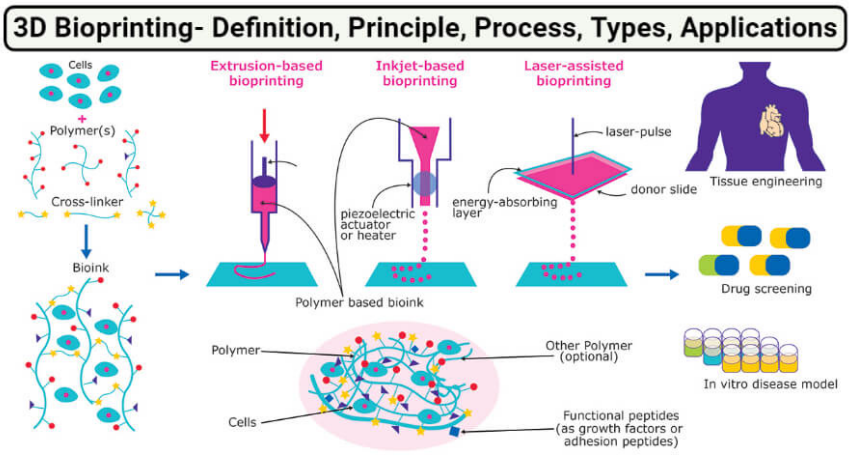
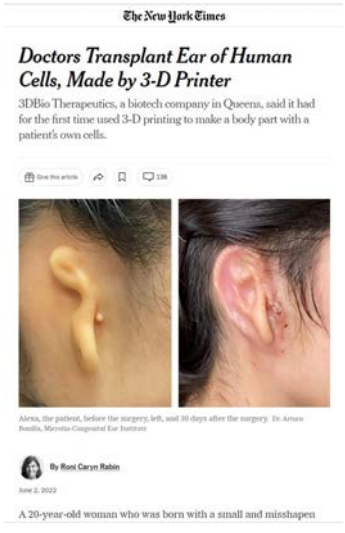
## 3D Cell Lab@ Polimi - Bioprinting the future of life sciencs

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## Agenda

- Manufacturing 4.0 and the twin transition
- Paradigm shifts for data science
  - From simple to complex product shapes
  - From ex-situ to in-situ (big) data monitoring
- Lessons learned and final comments

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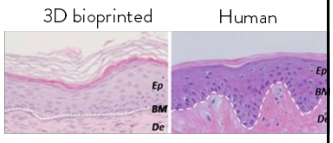
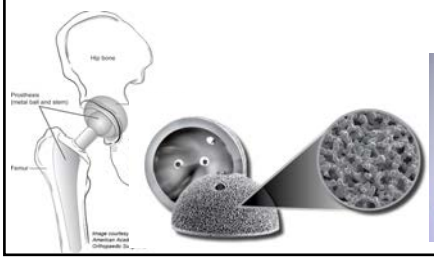
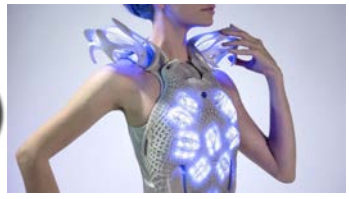
**Manufacturing 4.0:**
**ome paradigm shifts for data scientists**
**(and lessons learned)**




Bioprinted skin





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## Manufacturing 4.0 supporting the twin transition

**Green transition**

- Complexity for… green
  lightweight, energy-efficient, small number of components, material just where needed
- First-time-right
- Circular (Extend lifetime, repair, recycle)
- Produce when and where it is needed

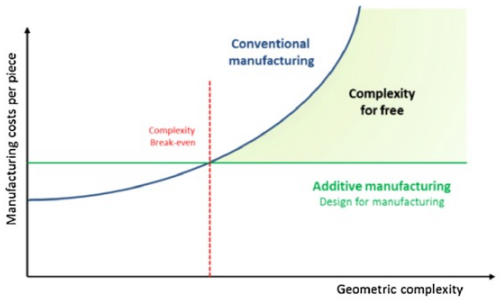
**Digital transition**

- From physical to digital
- From ex-situ to in-situ data
- From repeated production to customization
- Digital twin



## Manufacturing 4.0 - Additive Manufacturing or 3D printing for the twin transition

An example of metal AM – power bed fusion via EBM




Additive manufacturing:
"the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies."

## Additive Manufacturing & the green transition: A new generation of green products

AddMeLab

T. Ghidini – AM for Space and Aerospace – POLIMI
https://dmrc.uni-paderborn.de/content/innovation/am-for-satellites-reaction-wheel-bracket/

AM for satellites: Reaction Wheel Bracket

- Weight reduction: - 60 %
- Waste reduction: - 98 %
- Cost reduction: - 53 %

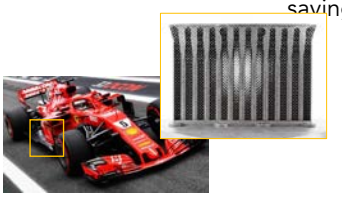
GE Fuel nozzle (Leap jet Engine)

- Reduce the number of subcomponents (20 to 1)
- 5X more durable
- 25% lighter (15% fuel savings)

Source: Renishaw.

- Energy-effient
- 20% reduction of cycle time

- 50% increase in the quality of tools



*Lightweight optimal exchange (https://altairenlighten.com*

Reduce material waste

Customization (improve fitness for purpose, reduce defective items)



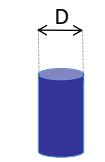


## 1st paradigm shift: Quality data and shape complexity

From simple to complex shapes

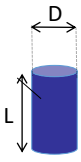
Traditional manufacturing

Additive manufacturing



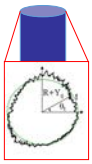

$X = D \in \mathbb{R}$

univariate



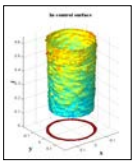

$\mathbf{X}=[D,L]'$
$\mathbf{X} \in \mathbb{R}^p$

multivariate



$X = f(\theta) + \varepsilon$

profiles



$X = f(\theta, z) + \varepsilon$

surfaces

?

?

volumes (manifold, lattice)

## SQM for complex shapes - lattice structure

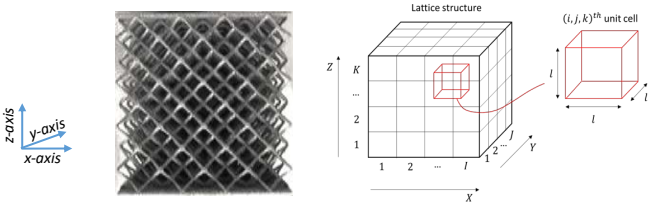
Colosimo and Grasso, 2021

*Main application:* Aerospace, Automotive and Medical sectors

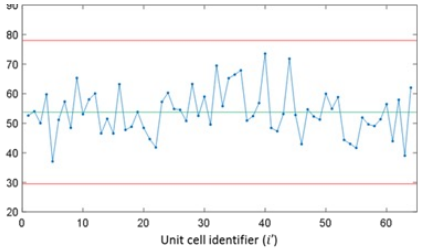
*Helicopter gas nozzle with cooling*

*Turbo intercooler for racing car*

*Hip implant*




Lattice – a regular grid of unit cells




benchmark: Individual control chart on cell porosity
"porosity" = ratio between the empty volume and the overall envelope volume of the unit cell

(Van Bael et al., 2011).

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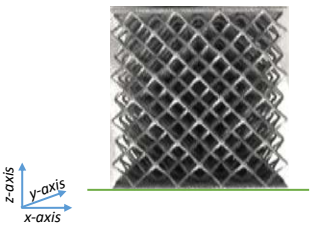
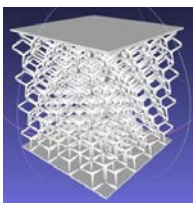
## Our newly developed approach

Colosimo and Grasso, 2021

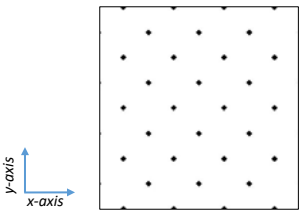
**Real** printed part (X-rays CT)



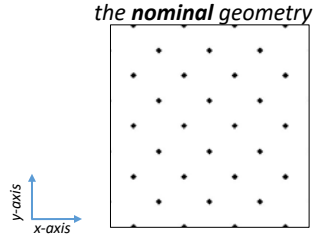

**Nominal** geometry (CAD)



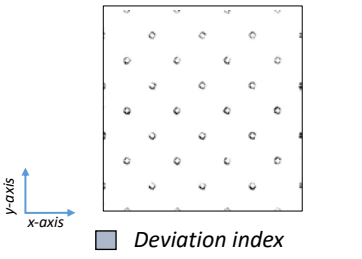
*Layerwise evolution of the **real** geometry (*Xray CT)




*Layerwise evolution of the **nominal** geometry (*CAD)




***Layerwise evolution of the deviation***
*Real (printed) vs nominal shape (CAD)*

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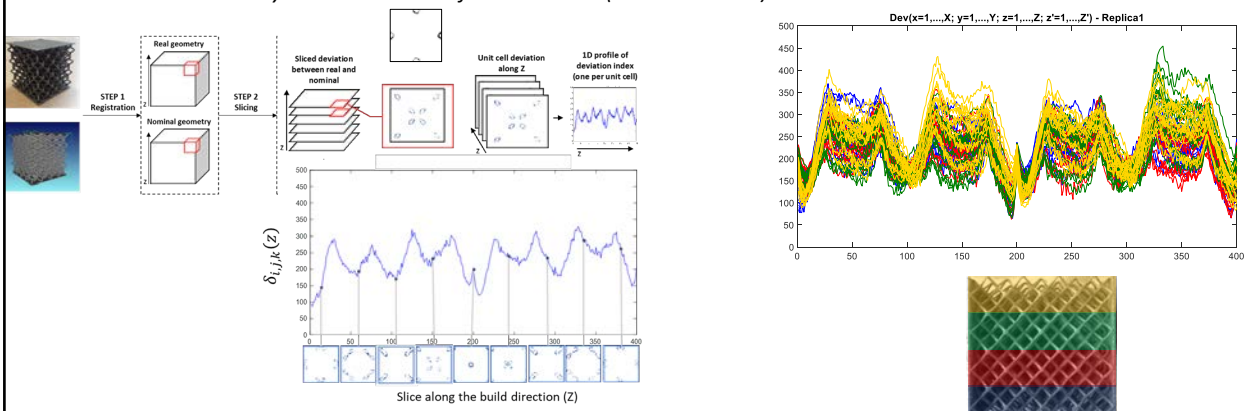
# Modelling and monitoring lattice structure: 3D Reconstruction

Colosimo and Grasso, 2021

*Layerwise evolution of the deviation (real vs nominal)*




Layerwise evolution of the deviation from nominal in one cell

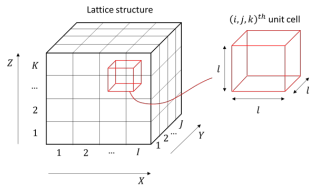




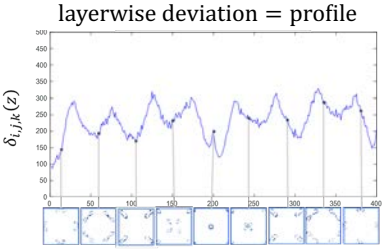
# Profile monitoring

Colosimo and Grasso, 2021

cell (i, j, k) = i′ − th cell



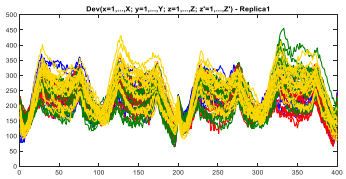

layerwise deviation = profile

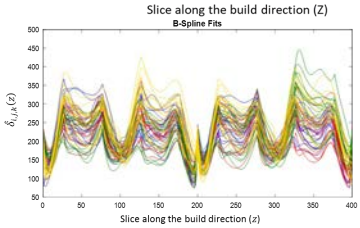


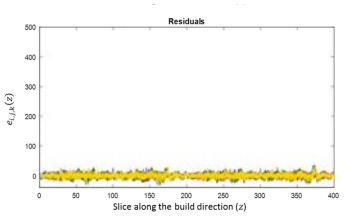

B-spline functions (cubic splines)

$$\hat{\delta}_{i,j,k}(z) = \sum_{q=1}^{Q+L-1} c_{i,j,k,q}\Phi_q(z,\boldsymbol{\tau}), \qquad MSE_{i'}$$

cell (i, j, k) = i′ cell, z = 1, … , n




$$\mathbf{X} = \begin{bmatrix} c_{1,1} & \cdots & c_{1,Q+L-1} & \delta_1 \\ c_{2,1} & \cdots & c_{2,Q+L-1} & \delta_2 \\ \cdots & & \cdots & \\ c_{N,1} & \cdots & c_{N,Q+L-1} & \delta_N \end{bmatrix} = \begin{bmatrix} \boldsymbol{x}_1{}^T \\ \boldsymbol{x}_2{}^T \\ \cdots \\ \boldsymbol{x}_N{}^T \end{bmatrix}$$

Multivariate control chart (profile)

$MSE_{i'}$

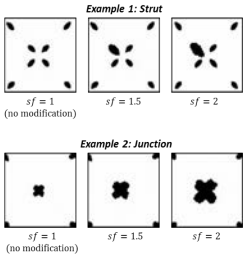
univariate cc (residual noise)

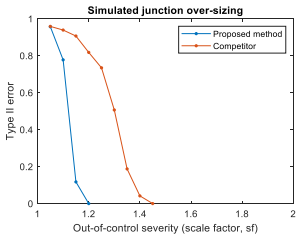
# Modelling out-of-control states

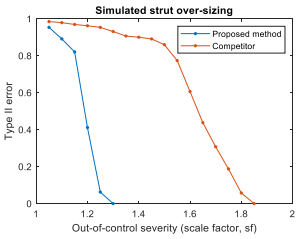
SIMULATIONS

Competitor method
- industrial practice:
*as-built porosity*
(Van Bael et al., 2011).

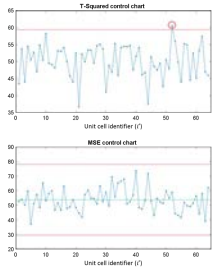
- Our newly developed approach

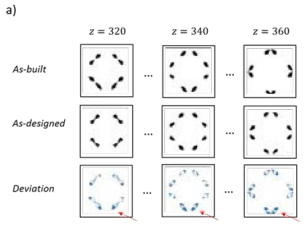


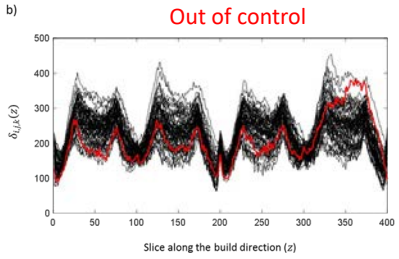




REAL DATA



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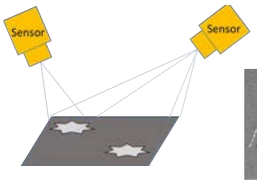
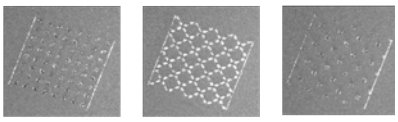
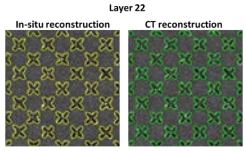
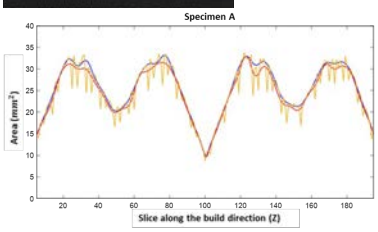
# From ex-situ to in-situ structures




Garghetti, Grasso, Pagani, Colosimo (2022)





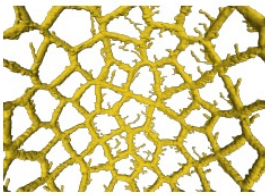



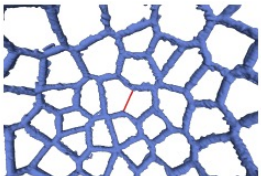

In-situ vs ex-situ

# From complex lattice

Scimone et al., Technometrics, (2021)

Hausdorff's distance and functional PCA







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## Manufacturing 4.0 supporting the twin transition

**Green transition**

- Complexity for… green
  lightweight, energy-efficient, small number of components, material just where needed
- First-time-right
- Circular (Extend lifetime, repair, recycle)
- Produce when and where it is needed

**Digital transition**

- From physical to digital
- From ex-situ to in-situ data
- From repeated production to customization
- Digital twin



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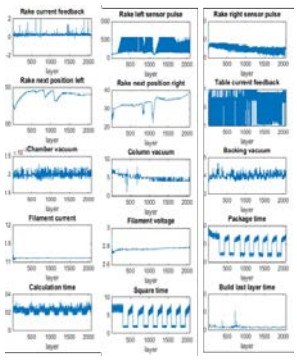
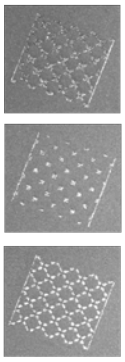
## 2nd paradigm shift: In-situ big data monitoring

From product quality to process quality data

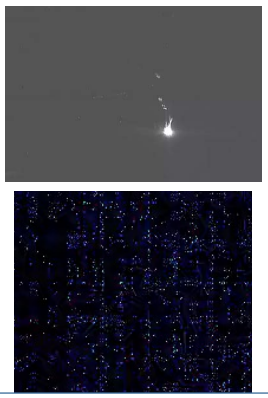
signals



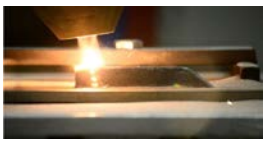
images



video



PROCESS





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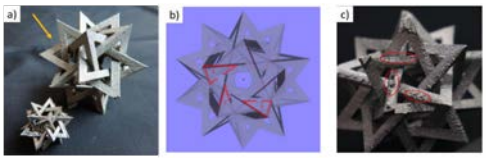
## Previous works: hot spot detection in videoimaging

A hot-spot is a local over-heating caused by a dimished heat flux towards surrounding material



- Spatially weighted PCA

Colosimo and Grasso, 2018 JQT

**(data available!)**

- Spatio-temporal statistical process monitoring

Yan, Grasso, Paynabar & Colosimo - IISE Trans, 2022

- Fast detection via NN and SVM

Bugatti and Colosimo - Journal of Intelligent Manufacturing, 2022

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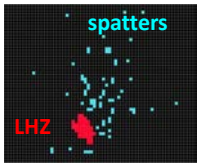
## Spatial point processes in video imaging

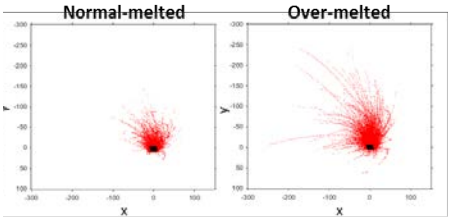
Edge detection




Classification (area&location)

*Repossini et al. (2017)*

### Spatter signature & part quality




**RED**: spatters
**BLACK**: Laser

Good quality of the final part (fully dense)

Bad quality of the final part (keyhole porosity)

The number of spatters has been used as indicator of density

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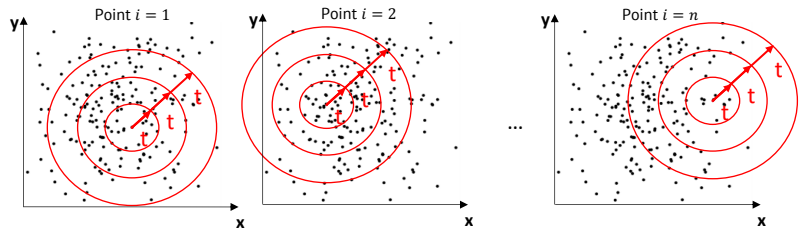
# Modeling Spattering via K-functions

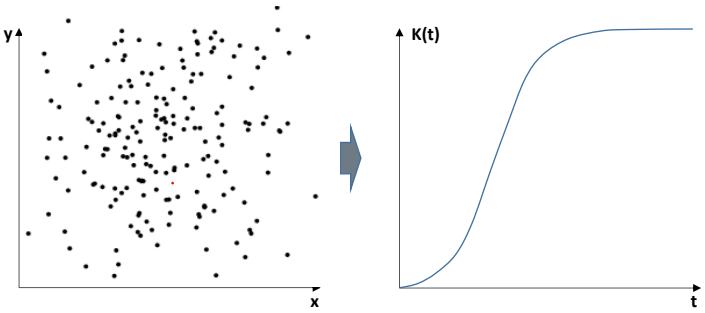
Colosimo et al, 2022




Ripley 1977,
Diggle et al. 2005

$$K(t) = \frac{1}{\lambda}\mathrm{E}\left(\begin{array}{c}\text{extra points within}\\ \text{distance}t\text{ of a}\\ \text{randomly chosen point}\end{array}\right)$$

λ is the spatial density of points, i.e., the number of points per unit area.




$$K(t) = \frac{1}{n^2}\sum_{(x,y)\in U} \mathrm{I}(0 < d(x,y) \le t)$$

$$K(t) = \frac{1}{n^2}\sum_{(x,y)\in U} w(x,y)\mathrm{I}(0 < d(x,y) \le t)$$

Edge correction (to cope with circles that may be not fully inside the domain U)

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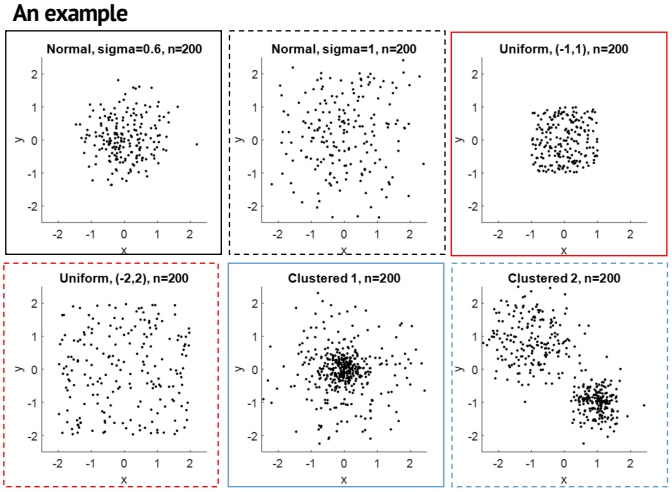
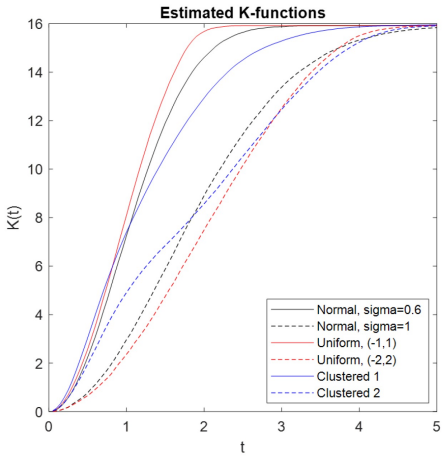
# Modeling Spattering via K-functions

Colosimo et al, 2022

An example

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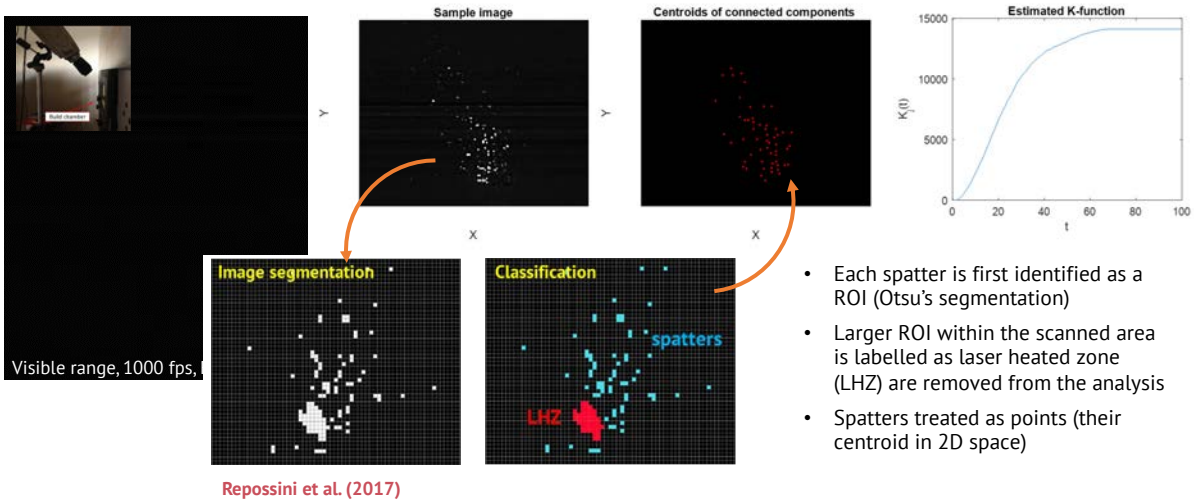
## In-line spatter analysis via K-function modelling

**From high-speed video to functional data representation**




- Each spatter is first identified as a ROI (Otsu's segmentation)
- Larger ROI within the scanned area is labelled as laser heated zone (LHZ) are removed from the analysis
- Spatters treated as points (their centroid in 2D space)

Repossini et al. (2017)





## In-line spatter analysis via K-function modelling

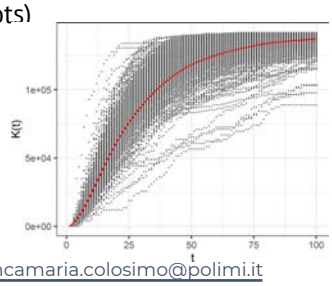
Aim: *investigate whether spattering (via K-functions) is statistically affected by the process conditions*

### K-function fitting…

A parametric model for ***non-decreasing*** functions was applied in the form:

$$K(t) = \beta_0 + \beta_1 \exp\left\{\int_{t_0}^{t} W(u)du\right\}$$

with $W(u) = \boldsymbol{\alpha} \boldsymbol{f}^T(t)$, where $\boldsymbol{f}(t)$ was fitted by means of 3° degree B-spline basis (equispaced knots)

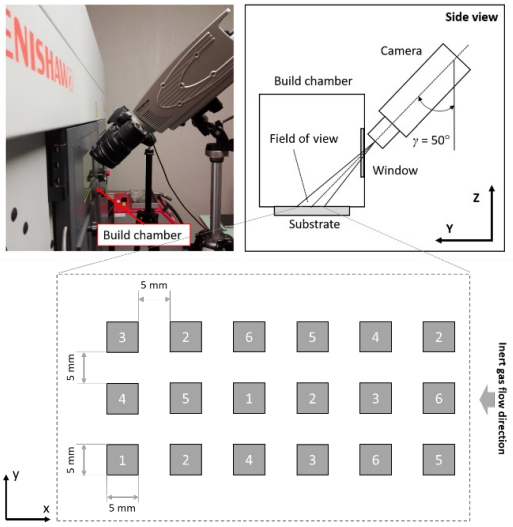


### Functional ANOVA (Ramsay, 2004)

$$\begin{cases} H_0: \mu_1(t) = \mu_2(t) = \cdots = \mu_l\ (t), t \in T \\ H_1: \exists (i,j): \mu_i(t) \neq \mu_j(t), t \in T \end{cases}$$

where $\mu_1(t), \mu_2(t), \ldots, \mu_l(t)$ are the **functional mean responses** (mean K-functions)

## Experimental settings




**L-PBF of 5 x 5 x 12 mm specimens of 18Ni(300) maraging steel on Renishaw AM250**

Gas atomized powder with average particle size of 25 – 35 µm

6 different sets of process parameters, 3 replicates per treatment (18 specimens printed in one single build)

**High-speed video acquisition @ 1000 fps**
**Spatial resolution: 250 µm/pixel**

| Energy density level | Volumetric energy density ($kJ/cm^3$) | Exposure time $\tau$ ($ms$) | Distance between scan point $d_p$ ($\mu m$) |
|---|---|---|---|
| 1 | 30 | 39 | 65 |
| 2 | 50 | 85 | 85 |
| 3 | 80 | 104 | 65 |
| 4 | 100 | 125 | 62.5 |
| 5 | 115 | 115 | 50 |
| 6 | 130 | 104 | 40 |

(other fixed parameters: distance between adjacent tracks: 80 $\mu m$; laser power: 200 W, layer thickness: 50 $\mu m$)

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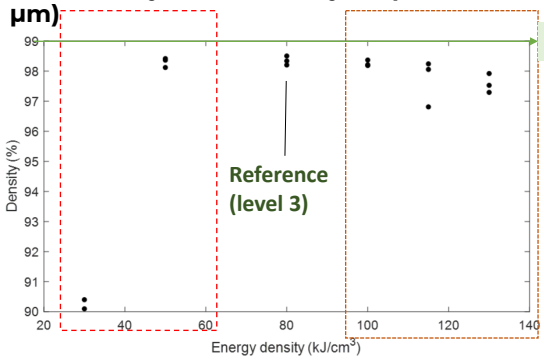
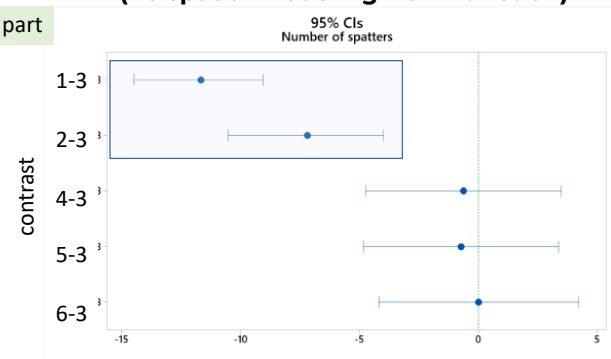
## Part quality (density(

**Part density and and x-ray CT (voxel size 10 µm)**

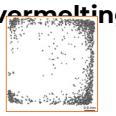



**Number of spatters only (no spatial modeling via k-function)**




**Lack of fusion – highly irregular pores**

**Plateau condition with slow decay to overmelting**



only lack-of-fusion condition (energy density 1 and 2) can be distingushed

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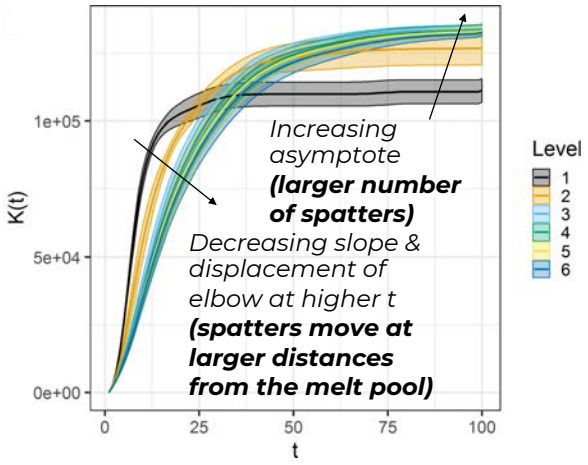
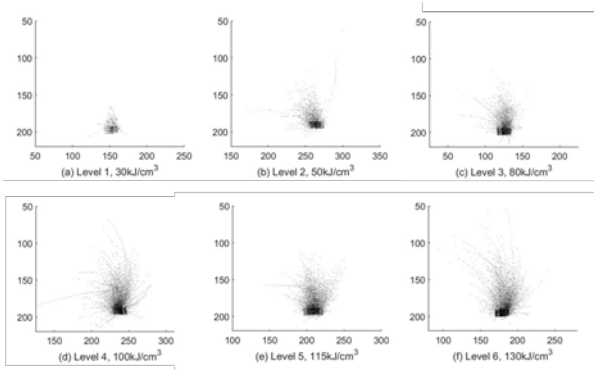
# Result

**95% CIs for the mean k-functions associated to different energy density levels**




**Superimposition of spatters ejected in one layer for each energy density level**

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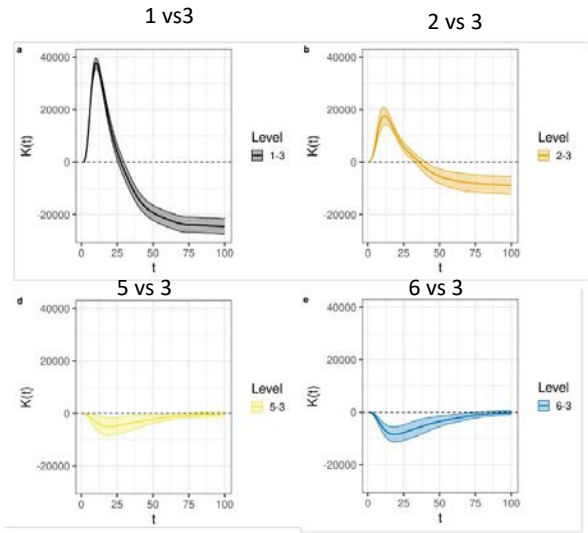
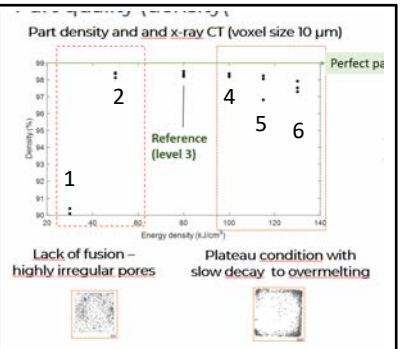
# Results




The spatial signature of spattering (via **k-functions**) allowed us to detect **all the departures** from the optimal condition

**Contrast plot** of k-functions (level 3 as reference)

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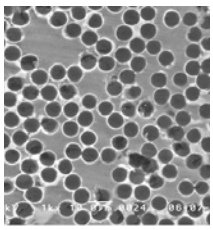
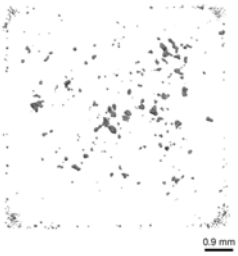
## Extensions and other applications

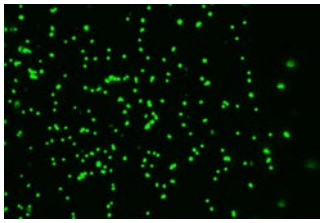
- **Extensions** of the K-function methodology include size, multiparticle, dynamic)
- Other possible applications

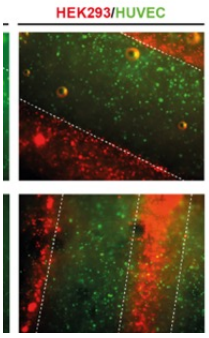


Example of CFRP (Carbon-Fiber-Reinforced Polymer)




Example of porosity structure in x-ray CT scan






Cells in bioprinting

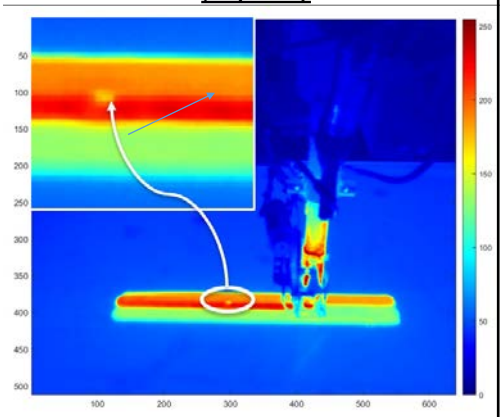




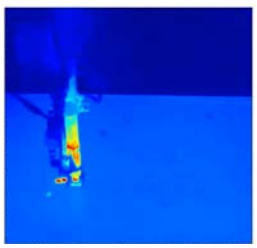
## Spatio-temporal modeling in thermal video imaging – application to BAAM

Caltanissetta et al., 2022

*Potential lack of material bonding (layer 3)*



*In collaboration with:*
*John Anastasios Hart , Gregory Dreifus*

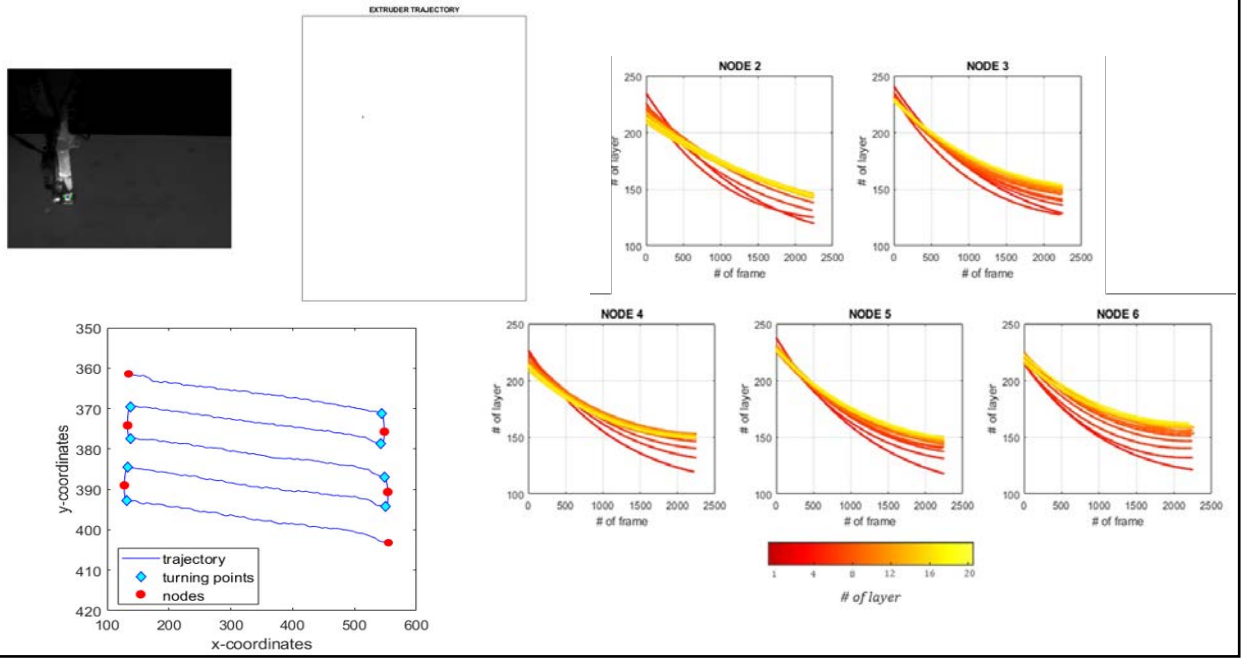


ABS +20% of carbon fibers; acquisition frequency= 30 Hz; temperature range: 20-250 °C

**OBJECTIVES:**

- **Thermal profiles (as a function of location and time)**
- **In-line Cold/hot spot detections**

## Cooling profiles change as a function of the location

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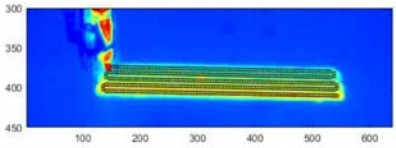
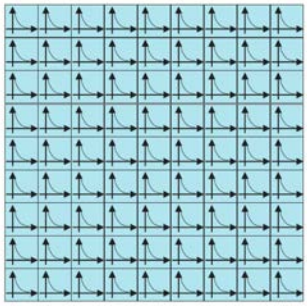
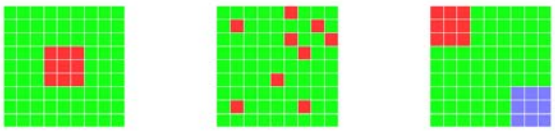
## Spatial-temporal indicator



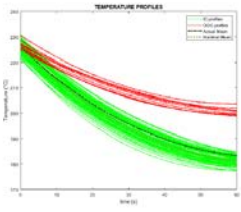


9x9 Matrix of Temperature profiles

3 defective scenarios:

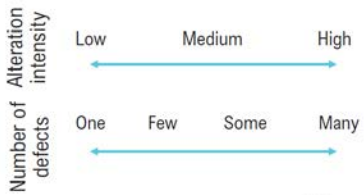


Single cluster  Sparse Defects  Two Clusters



Defect = alteration of cooling rate

Sensitivity analysis

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## Moran index (spatial association) for profiles similarities

Colosimo, Caltanissetta, Carraro, 2022

### Z index (Gao 2019)

Expresses deviation of a profile from average profile

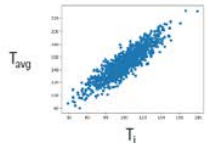
$$Z_i = \varphi\left(CORT(\overrightarrow{T_i}, \overrightarrow{T_{avg}})\right) * (area(\overrightarrow{T_i})\text{-area}(\overrightarrow{T_{avg}}))$$

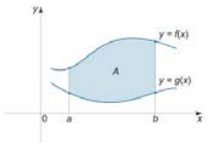
Deviation in terms of profile shape

Deviation in terms of magnitude

"CORT component"

"Area difference component"



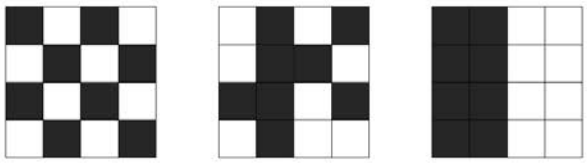




Similarity of profile pattern

Similarity of profile location

### Local Moran's I (Anselin 1995)

Expresses association between neighboring elements



Moran's I < 0 | Moran's I ≈ 0 | Moran's I > 0

Inputs:

- Spatial coordinates of each cell
- Indicator of deviation from mean (Z INDEX)

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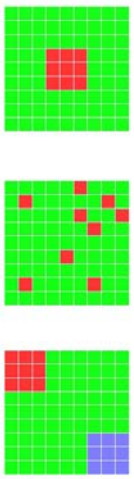
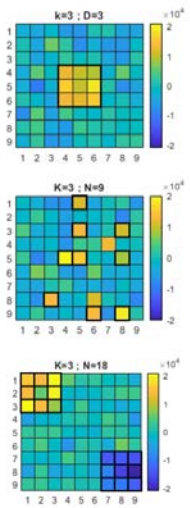
## Monitoring Spatio-temporal profiles

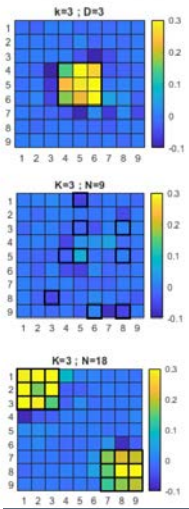
Scenario:



Z index




Local Moran's I




Both the metrics highlight defective profiles when they are clustered

Only the Z-index can detect randomly sparse anomalies of the cooling profiles

Moran index can clearly highlight clustered events on cooling profiles

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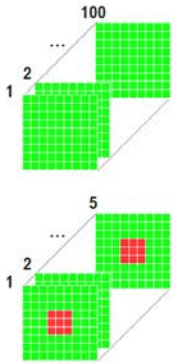
## Control charting

Approach

Global Metrics:

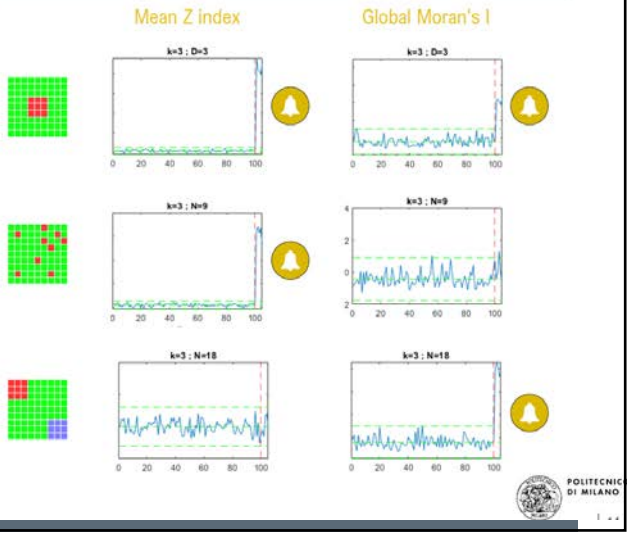
- Global Moran's I *(mean of all Local Moran's I)*
- Mean Z index *(mean of all Z indexes)*




Build CC for global metrics on 100 IC matrices

Test CC performance on 5 defective runs

Results

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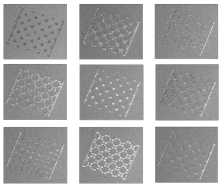
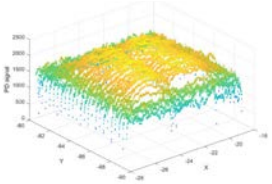
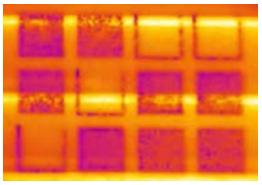
## Conclusions and final remarks

### 1 DIGITAL AGAINST GREEN

The Digital transition is not green per se:
computation and data gathering ARE energy consuming tasks

***Example**: data storage need for in-situ monitoring of a 24h build (2000 layers)*

| Layer Images | Co-axial photodiode | Off-axis high speed video (8 bit) | Off-axis high speed IR video |
|---|---|---|---|
|  |  |  |  |
| 5 - 10 Gbyte | 10 – 30 Gbyte | 5 – 10 Tbyte | 50 – 100 Tbyte |

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## Conclusions and final remarks

1 "DIETARY" data analysis:

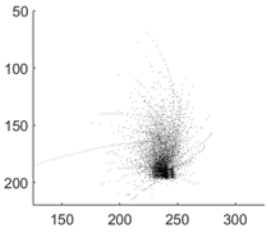
- Data reduction- Sensor and variate selection
- the simpler the better (Edge computing)
- Data science of the artificial: embed process knowledge

The spattering example

**High-speed video**

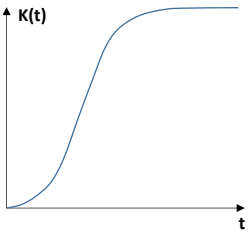
**3.12 Gbyte**

**Spattering image from superimposed frames**




**432 Mbyte**

**K-function modeling**




**<1 Mbyte**

(txt file with fitted function + estimated coefficients)



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## Conclusions and final remarks

2. DATA IS NOT INFORMATION, INFORMATION IS NOT KNOWLEDGE

- Robustness
- Interpretability
- Include existing knowledge


ESA benchmarck center – on structural integrity and in-situ monitoring

AMATHO - *Additive MAnufacturing Tdrotor HOusing* - https://www.amatho.org H2020- CleanSky 2 -


Funded by the Italian Space agency

Some of our current research partners (running research contracts):

TRUMPF

Lima Corporate

Avio Aero

Baker Hughes

INGERSOLL Machine Tools



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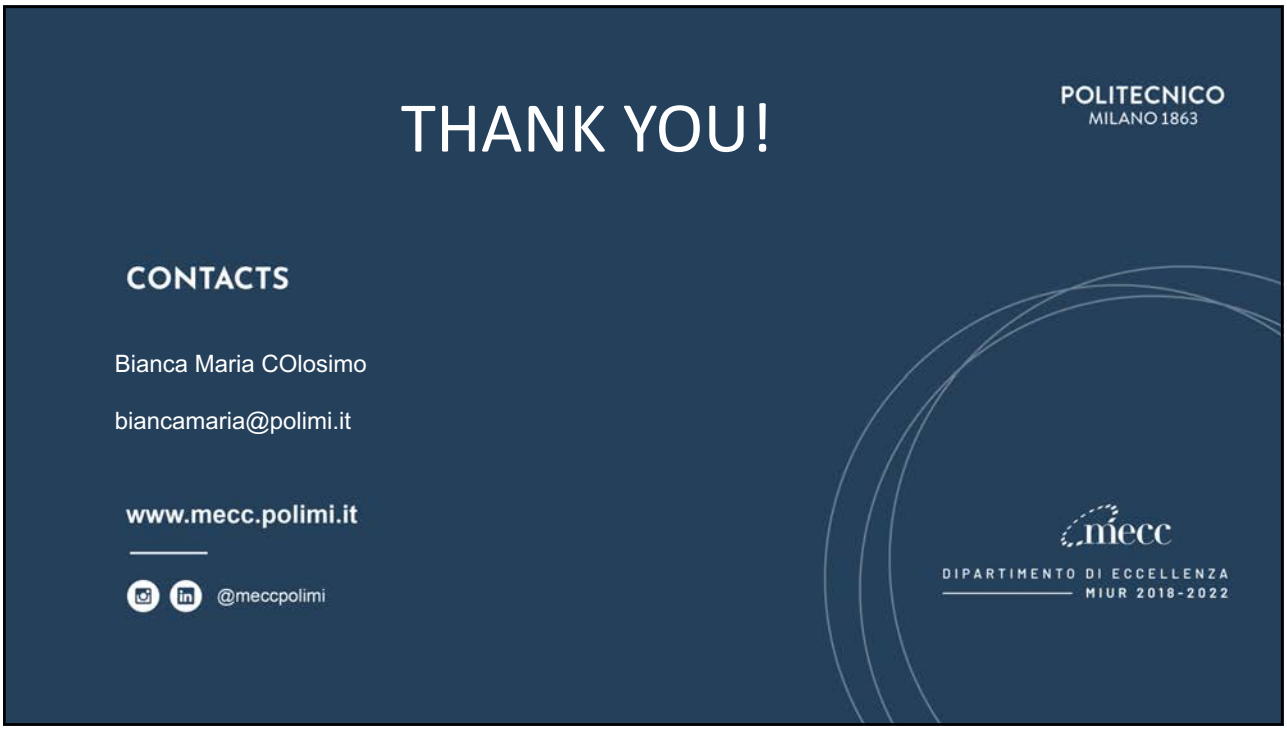
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MIUR 2018-2022

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