Big data mining for industry 4.0:

the new pathway for the digital and green 'twin' transition

Bianca Maria Colosimo
Politecnico di Milano

Complementary discussion

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DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

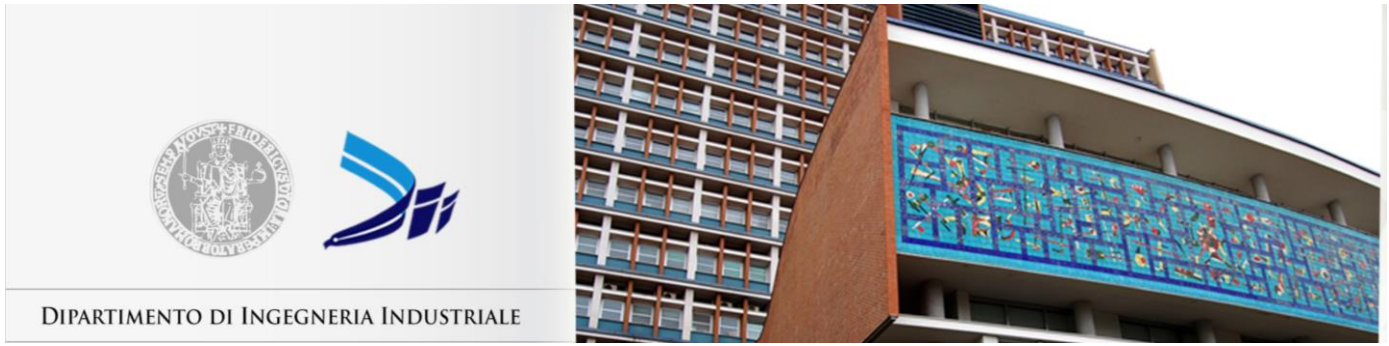
neapōlis

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
SCUOLA POLITECNICA E DELLE SCIENZE DI BASE

Introduction to the SFERe group I belong to

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

The University of Naples Federico II was founded by the emperor of the Holy Roman Empire Frederick II in 1224 and is now organized into 26 departments.



Università degli Studi di Napoli Federico II

Motto	*Ad Scientiarum Haustum et Seminarium Doctrinarum*
Motto in English	For the inculcation of the sciences and the dissemination of knowledge
Type	Public
Established	5 June 1224; 798 years ago
Endowment	€473 million
Rector	Prof. Matteo Lorito
Administrative staff	5,517 (2013)
Students	93,280 (2020)
Undergraduates	44,700
Postgraduates	33,600
Location	Naples, Italy
Campus	Urban
Sports teams	CUS Napoli
Affiliations	Campus Europae, UNIMED, PEGASUS
Website	www.unina.it/en_GB/home

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Statistics For Engineering Research (SFERe) group @dii.unina

Biagio Palumbo
biagio.palumbo@unina.it

Associate Professor in Statistics for experimental and technological research at the Department of Industrial Engineering of the University of Naples Federico II. His major research interests include reliability, design and analysis of experiments and statistical methods for process monitoring and optimization. He is President Elect of ENBIS.

Antonio Lepore
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Associate Professor in Statistics for experimental and technological research at the Department of Industrial Engineering of the University of Naples Federico II. PhD in Aerospace, Naval, and Quality Engineering.

Main research interests: the industrial application of statistical techniques to the analysis and monitoring of object-oriented data from high-frequency multi-sensor systems.

Fabio Centofanti, Post-doc researcher
fabio.centofanti@unina.it

Topic: Application of functional clustering and regression techniques to urban traffic context

Tutor: Antonio Lepore

PhD

Doctor Europaeus

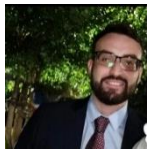
Christian Capezza, Researcher (RTD/A)
christian.capezza@unina.it

Research project title: Interpretable statistical learning methods for sustainable mobility.

Tutor: Biagio Palumbo

Visiting PhD student

Doctor Europaeus



Gianluca Sposito, PhD student
gianluca.sposito@unina.it

Topic: Artificial Intelligence and Statistics for Quality Technology

Tutor: Antonio Lepore

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B. M. Colosimo
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On-going industrial activity of SFERe group

in which statistical research (of interpretable methods) represents a crucial competition leverage

- Shipping
- Railway
- Manufacturing

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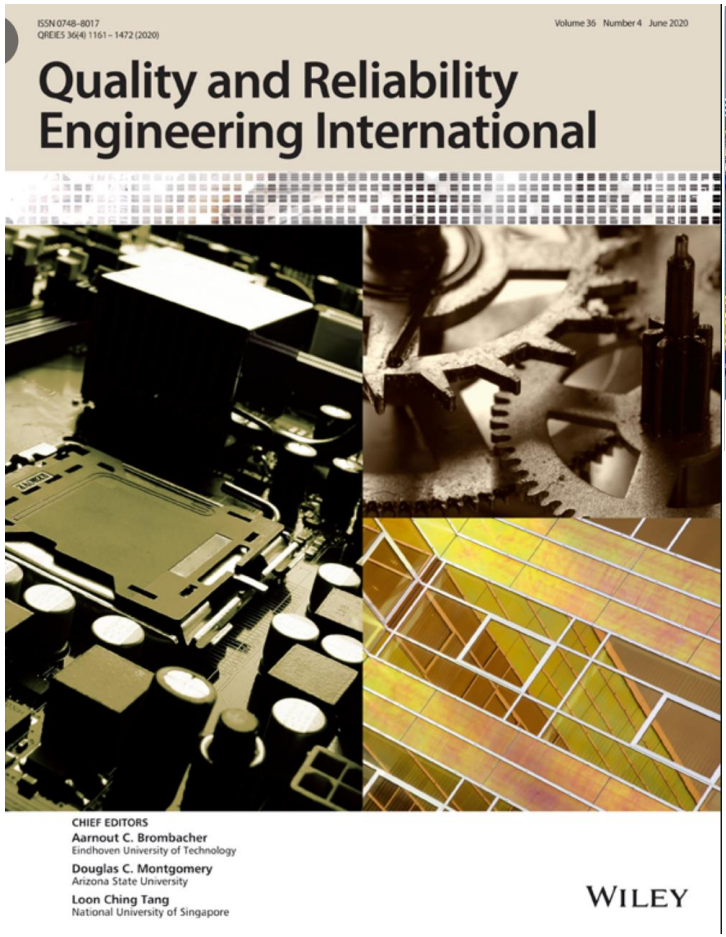
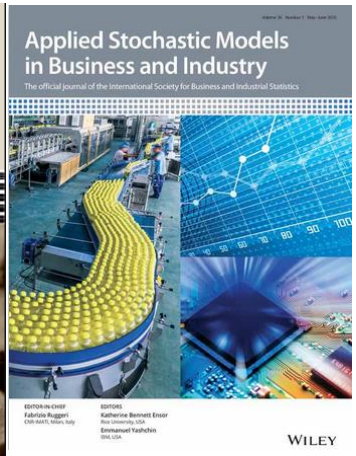
Research outcomes in International Journals





R packages (some including industrial datasets)

Capezza, C., Centofanti, F., Lepore, A., Menafoglio, A., Palumbo, B., Vantini, S. (2021) **`funcharts`**: Functional Control Charts. R package version 1.1.0, URL https://cran.r-project.org/web/packages/funcharts

Centofanti F., Lepore A., Palumbo B. (2021). **`sasfunclust`**: Sparse and Smooth Functional Clustering. R package version 1.0.0. https://CRAN.R–project.org/package=sasfunclust

Centofanti F., Lepore A., Menafoglio A., Palumbo B., Vantini S. (2021). **`adass`**: Adaptive Smoothing Spline (AdaSS) Estimator for the Function-on-Function Linear Regression. R package version 1.0.0. https://CRAN.R–project.org/package=adass

Centofanti F., Colosimo, B.M., Grasso, M.L., Lepore, A., Menafoglio A., Palumbo B., Vantini S. (2021). **`rofanova`**: Robust Functional Analysis of Variance. R package version 1.0.0. https://CRAN.R–project.org/package=rofanova

Centofanti F., Lepore A., Vantini, S., Fontana, M. (2021). **`slasso`**: S-LASSO Estimator for the Function-on-Function Linear Regression. R package version 1.0.0. https://CRAN.R–project.org/package=slasso

Big data mining for industry 4.0:

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Bianca Maria Colosimo
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A living experience of the extraordinary **evolution** of our **role** in science as **statisticians**

- The complexity of the **problems** presented at the **cutting edge** of innovation, and delivered to us statisticians, is frightening (… at first).
- Then, it essentially stimulates us to change the paradigm of a **statistician** as a one-man band toward **ensembles able to work together**.

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My role as an applied statistician in an Engineering School

- **Gather problems** from industries and select those that may potentially involve impactful data analysis, mining and data-driven testing of research answers/conjectures
  - Dealing with **real data** is per se always a big and time-consuming challenge
- Then I find myself with a very particular background **mix** between **science** (engineering in my case) and **data**, in the sense nicely covered by Statistics and Probability Letters special issue on *the role of Statistics in the era of big data* edited by professor Sangalli.
- My usual initial tasks when approaching a new industrial problem are to
  - **try and formalize the problem** from the domain information (science) perspective in a compact and structured way by translating the industrial conjectures into a more formal structure
  - make it **quickly accessible to** and facilitate the **interplay with a wider audience of scientists**, such as mathematicians, mathematical statisticians as well as IT and high-performance computing experts, and so on.
- Then, industrial problems we are engaged in represent the big arena where we **develop new methods and models** from a general perspective to the extent of
  - being inspired and not limited to the specific problem investigated
  - identifying the hidden **broader industrial need** and the **statistical literature gap** to possibly fill in.

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Some works from our research activity coherent with the paradigm shift envisaged by the keynote lecture

1. Ex-situ to in-situ (real-time) monitoring through functional data

- Functional regression control chart (FRCC)

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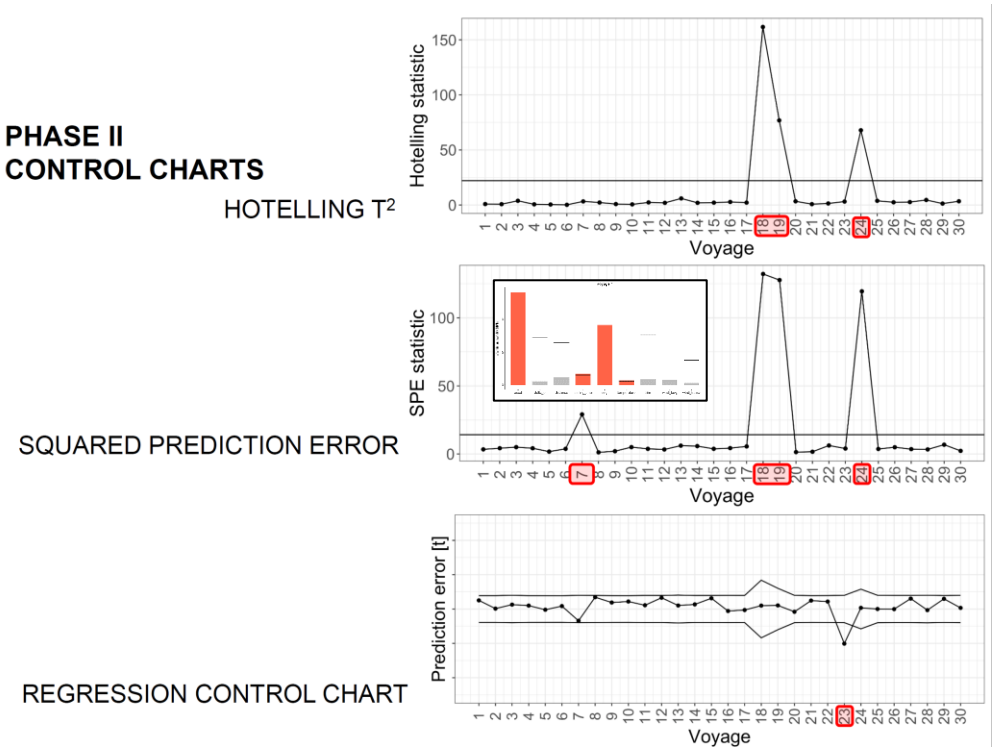
Ex-situ to in-situ (real-time) monitoring through functional data

Functional regression control chart (FRCC)

for the ex-situ monitoring of ship operating conditions and CO_2 emissions



Capezza, C., Lepore, A., Menafoglio, A., Palumbo, B., Vantini, S. (2020) Control charts for monitoring ship operating conditions and CO2 emissions based on scalar-on-function regression. Applied Stochastic Models in Business and Industry, 36(3):477-500, doi:10.1002/asmb.2507

Centofanti, F., A. Lepore, A. Menafoglio, B. Palumbo, and S. Vantini (2021). Functional regression control chart. Technometrics 63 (3), 281-294

Capezza, C., F. Centofanti, A. Lepore, A. Menafoglio, B. Palumbo, and S. Vantini (2022). `funcharts`: Control charts for multivariate functional data in R. arXiv preprint arXiv:2207.09321

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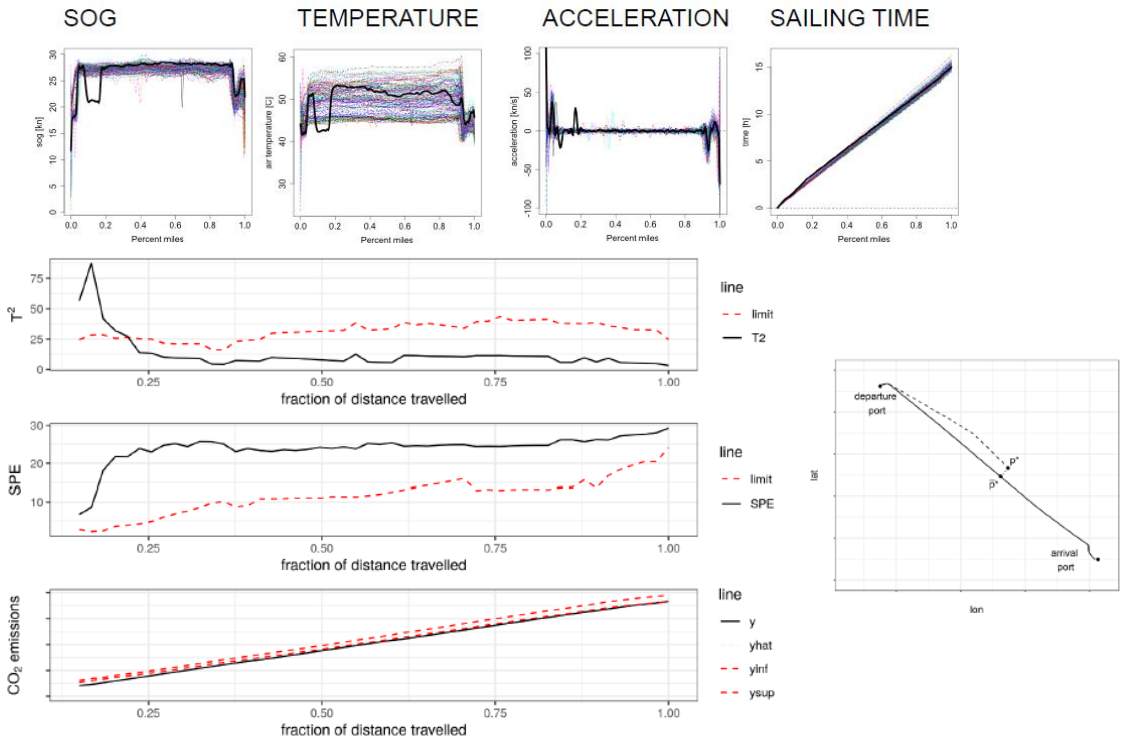
Ex-situ to in-situ (real-time) monitoring through functional data

Functional regression control chart (FRCC)

for the real-time monitoring of ship operating conditions and CO_2 emissions



Capezza, C., Lepore, A., Menafoglio, A., Palumbo, B., Vantini, S. (2020) Control charts for monitoring ship operating conditions and CO2 emissions based on scalar-on-function regression. Applied Stochastic Models in Business and Industry, 36(3):477-500, doi:10.1002/asmb.2507

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Capezza, C., F. Centofanti, A. Lepore, A. Menafoglio, B. Palumbo, and S. Vantini (2022). `funcharts`: Control charts for multivariate functional data in R. arXiv preprint arXiv:2207.09321

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1. Ex-situ to in-situ (real-time) monitoring through functional data

- Functional regression control chart (FRCC)
- Functional real-time monitoring (FRTM)

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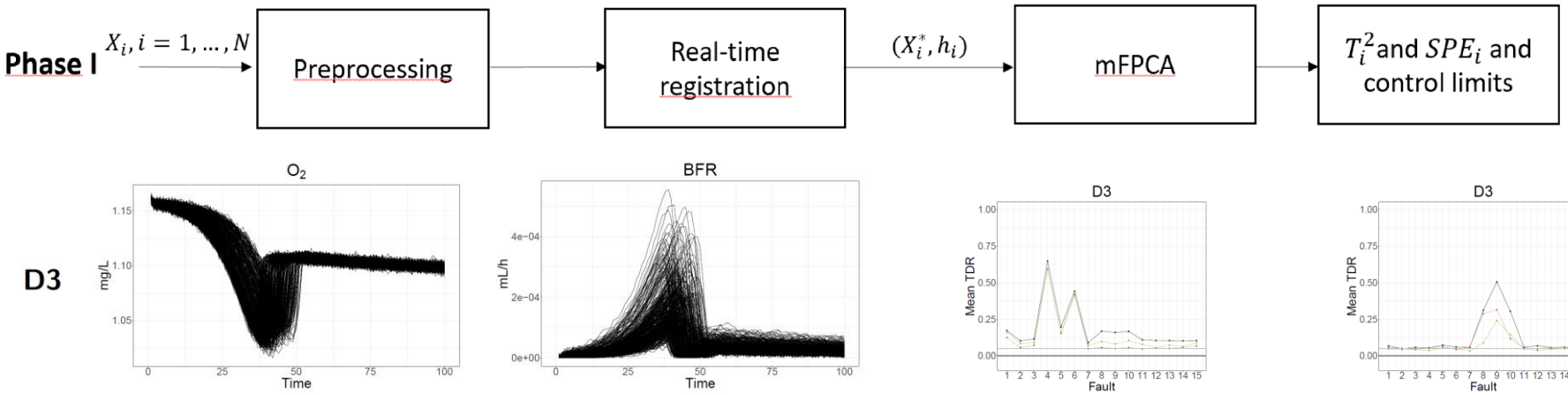
Ex-situ to in-situ (real-time) monitoring through functional data
Functional Real-Time Monitoring (FRTM)

The FRTM applies real-time a procedure consisting of:

i) registering the partially observed functional data to the appropriate reference curve;

ii) performing a dimensionality reduction through the mixed functional principal component analysis (mFPCA);

iii) monitoring the functional quality characteristic in the reduced space through an appropriate monitoring strategy.



Centofanti, F., A. Lepore, M. Kulahci, M. P. Spooner (2022). Real-time monitoring of functional data. arXiv preprint arXiv:2205.06256

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1. Ex-situ to in-situ (real-time) monitoring through functional data
   - Functional regression control chart (FRCC)
   - Functional real-time monitoring (FRTM)
2. **Interpretability**

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Interpretability

Even though there is a lack of consensus about the rigorous definition, ***interpretability*** is a key concept in statistical analysis and a broader issue to be faced in the development of insightful statistical approaches

- concerning the extraction of **relevant knowledge** about domain relationships contained in data;
- essentially refers to a profound cognitive process as the ability of a model or technique (or any element related to them, e.g., inputs, outputs, predictions) to **support human decisions based on them;**
- may have positive consequences on the acceptability of any proposed tool and its relative industrial deployment.

This concept was recently discussed during the **ENBIS** (European Network for Business and Industrial Statistics) **Workshop "Interpretability for Industry 4.0"** that was held at the University of Naples Federico II (Italy) on July 12-13, 2021, and offered real-world industrial motivations and deep methodological insights on this topic.
https://conferences.enbis.org/event/8/

Lepore, A., Palumbo, B., Poggi, J.M. (eds.): Interpretability for Industry 4.0: Statistical and Machine Learning Approaches, to appear, Springer

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2. **Interpretability in functional data analysis**
   - Sparse and smooth functional clustering (sas-Funclust)

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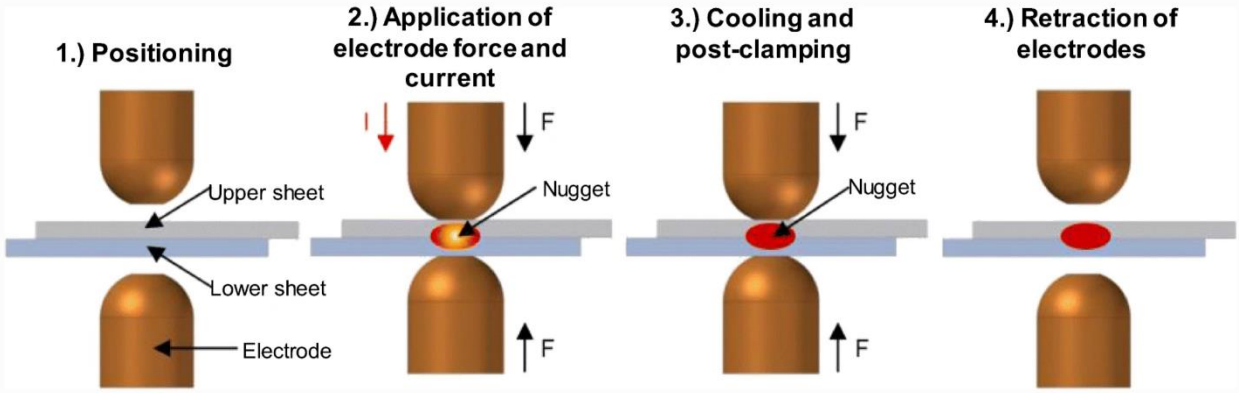
An industrial case study: Resistance Spot Welding (RSW) process in the automotive industry



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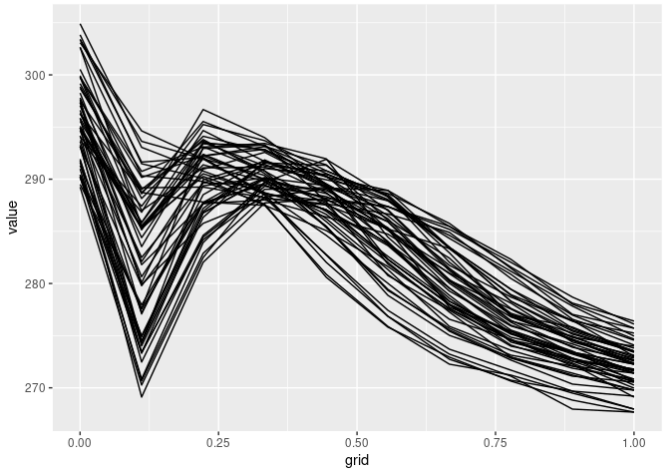
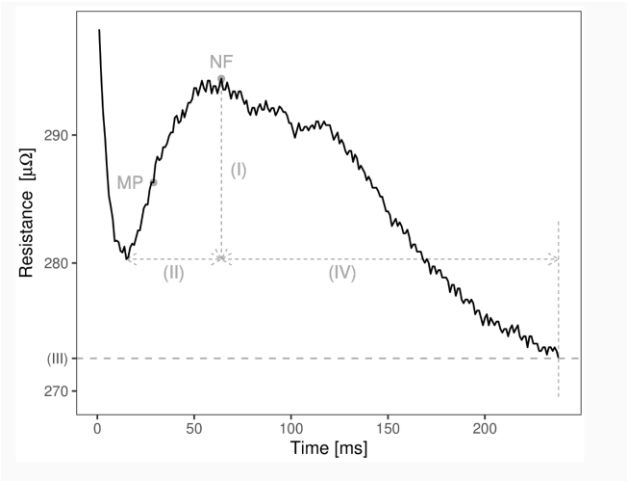
Interpretability in functional data analysis

An industrial case study: Resistance Spot Welding (RSW) process in the automotive industry at CRF

Dynamic resistance curve (**DRC**) is recognized as the **full technological in-situ process signature** in resistance spot welding (RSW) and **comes at no cost for each welded spot**, while off-line (ex-situ) inspection tests of the final quality of produced parts can be very expensive or destructive and not feasible on a large scale.





Challenge: find out **homogeneous groups** of DRCs that likely pertain to spot welds **sharing common mechanical and metallurgical properties**.

Capezza, C., Centofanti, F., Lepore, A., & Palumbo, B. (2021). *Functional clustering methods for resistance spot welding process data in the automotive industry*. Applied Stochastic Models in Business and Industry. 37:908-925 Data openly available at `https://github.com/unina-sfere/funclustRSW`

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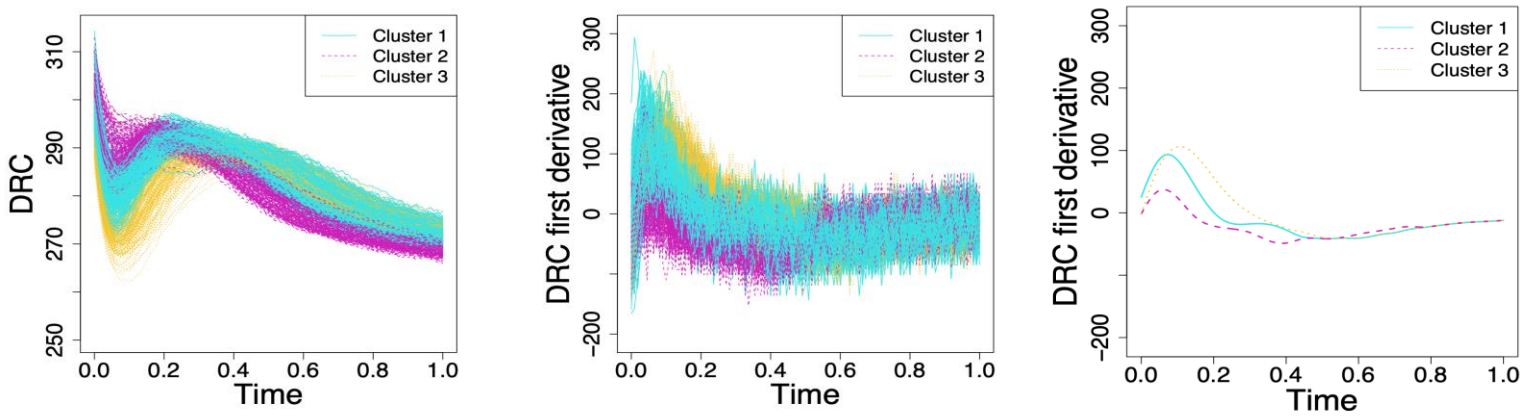
Interpretability in functional data analysis

Sparse and smooth functional clustering (sas-Funclust) - RSW



(a) (b) (c)

(a) 538 DRCs and (b) the corresponding derivative functions from the ICOSAF project data set colored by cluster identified by the SaS-Funclust method; (c) estimated cluster mean functions.

- The specific application to the RSW process data collected at CRF identified homogenous groups of DRCs with different rates of change in the first part of the process alone.
- The **identification** of this behaviour, i.e., an **informative portion of the DRC domain** has been confirmed by CRF experts as a novel insight into the resistance spot welding process characterization
- This can naturally guide practitioners to define the most effective proxy of the final quality of spot welds produced in a later stage of process learning and **thus optimize future data collection and compression (active learning)**.

Centofanti, F., Lepore, A., Palumbo, B. (2021). *Sparse and Smooth Functional Data Clustering*. arXiv preprint arXiv:2103.15224.

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   - Estimators for the function-on-function Linear Regression Model
     - Smooth LASSO estimator

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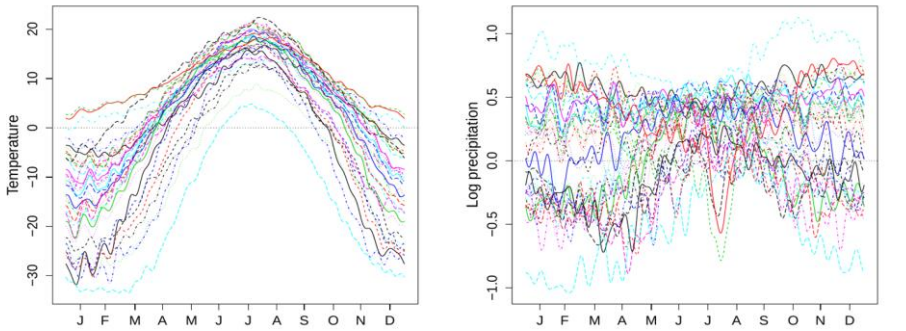
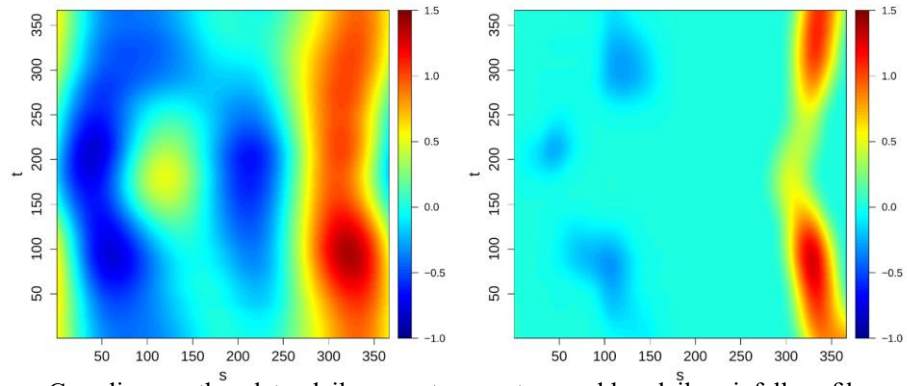
Smooth LASSO Estimator
for the Function-on-Function Linear Regression Model

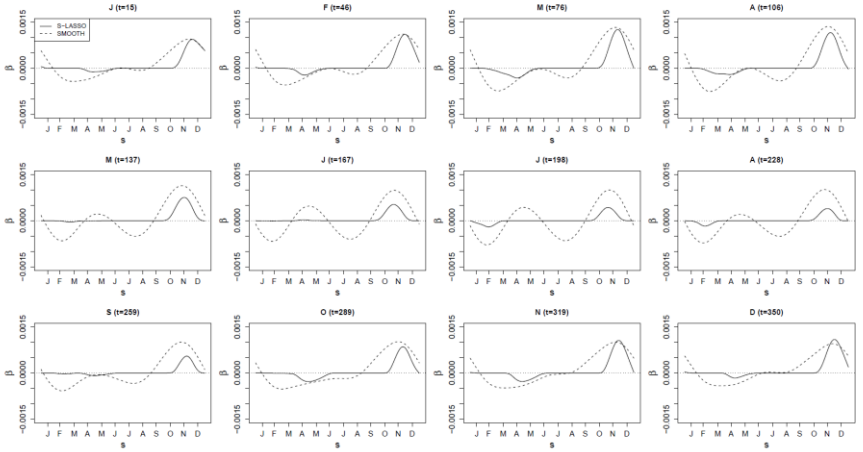


The aim is to predict the log daily rainfall based on the daily temperature using model

$$Y_i(t) = \int_{\mathcal{S}} X_i(s)\,\beta(s,t)\,ds + \varepsilon_i(t) \quad t \in \mathcal{T}$$



Canadian weather data: daily mean temperature and log daily rainfall profiles at 35 cities in Canada over the year.



Centofanti, F., Fontana, M., Lepore, A., & Vantini, S. (2022). *Smooth Lasso Estimator for the Function-on-Function Linear Regression Model*. Computational statistics and data analysis

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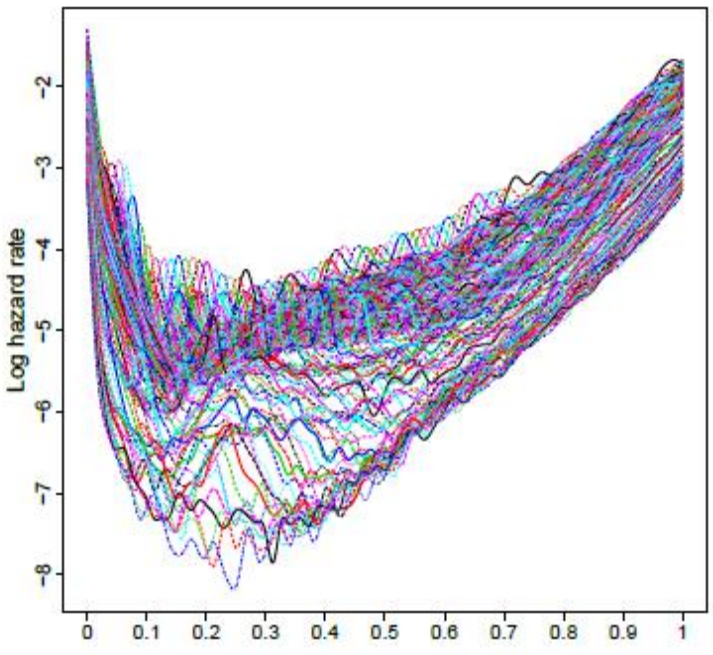
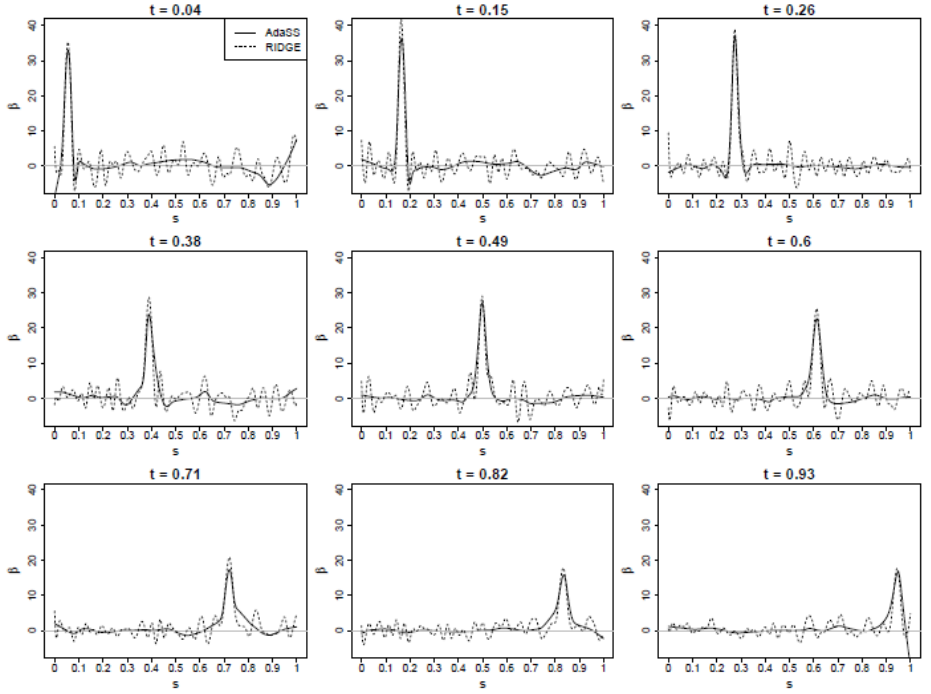
Adaptive Smoothing Spline Estimator (AdaSS)
for the Function-on-Function Linear Regression Model



Swedish female mortality data: log-hazard rate functions of the for year-of-birth cohorts that refer to females born in the years 1751-1935 with ages 0-80.



Centofanti, F., Lepore, A., Menafoglio, A., Palumbo, B., Vantini, S. (2022). *Adaptive Smoothing Spline Estimator for the Function-on-Function Linear Regression Model*. Computational Statistics. doi: 10.1007/s00180-022-01223-6

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3. **Robustness to functional data outliers**
   - Functional ANOVA (RoFANOVA)

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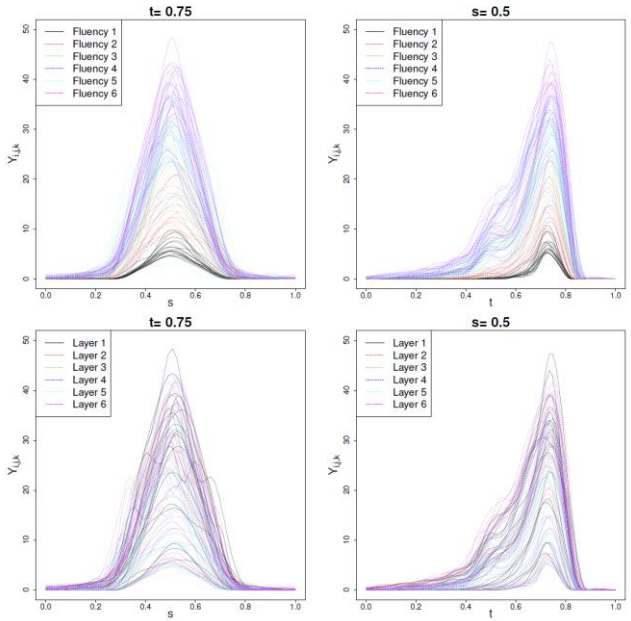
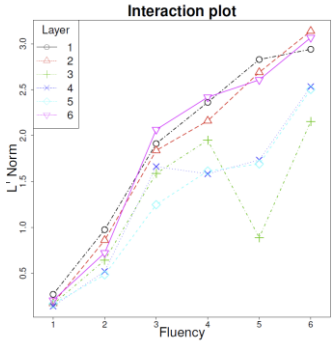
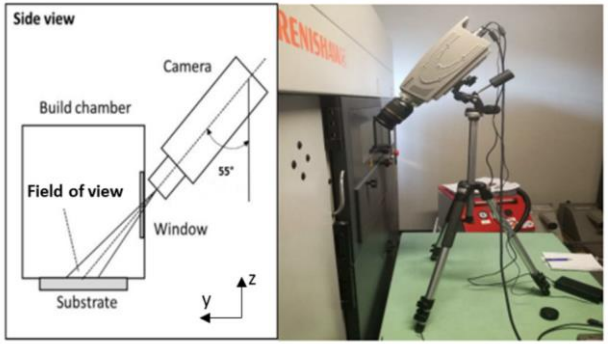
Robustness to functional data outliers

Robust functional ANOVA (RoFANOVA) – spatter analysis





	FNDP	TGPF
$H_{0,FluLay}$	0.72	0.23
$H_{0,Flu}$	0.00	0.00
$H_{0,Lay}$	0.00	0.00



- By comparing the RoFANOVA tests with competitors, they disagree in considering **significant** the **interaction** between the **energy density** and the **layer on the spatter intensity**.
- Outlying patterns represent a nuisance for the analysis results, as they may in ate the variability and mask effects of potential interest.

Centofanti, F., B. M. Colosimo, M. L. Grasso, A. Menafoglio, B. Palumbo, and S. Vantini (2021). Robust functional ANOVA with application to additive manufacturing. arXiv preprint arXiv:2112.10643

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   - Functional ANOVA (RoFANOVA)
   - Robust multivariate functional control chart (RoMFCC)

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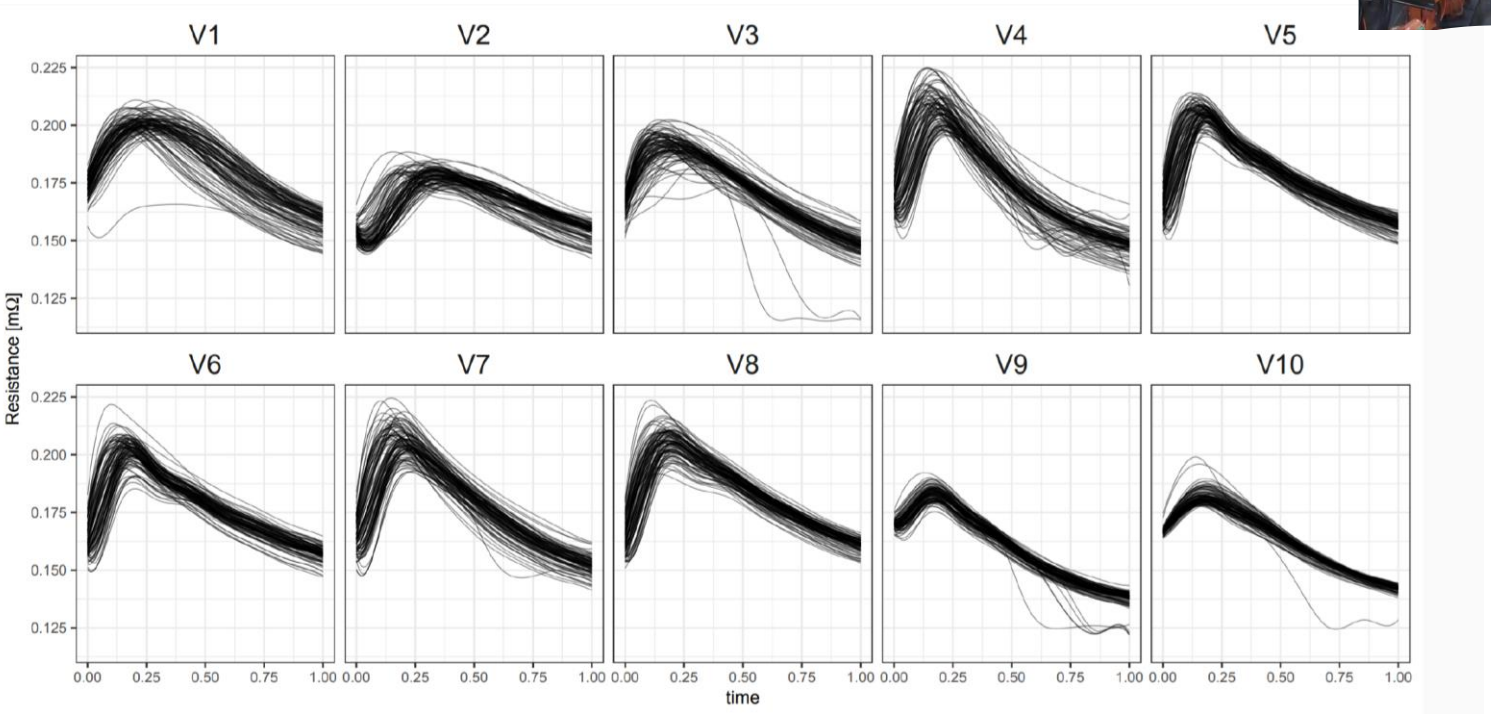
Robustness to functional data outliers

Robust multivariate functional control charts (RoMFCC) for RSW process quality monitoring and control



Capezza, C., F. Centofanti, A. Lepore, and B. Palumbo (2022). Robust multivariate functional control charts. arXiv preprint arXiv:2207.07978

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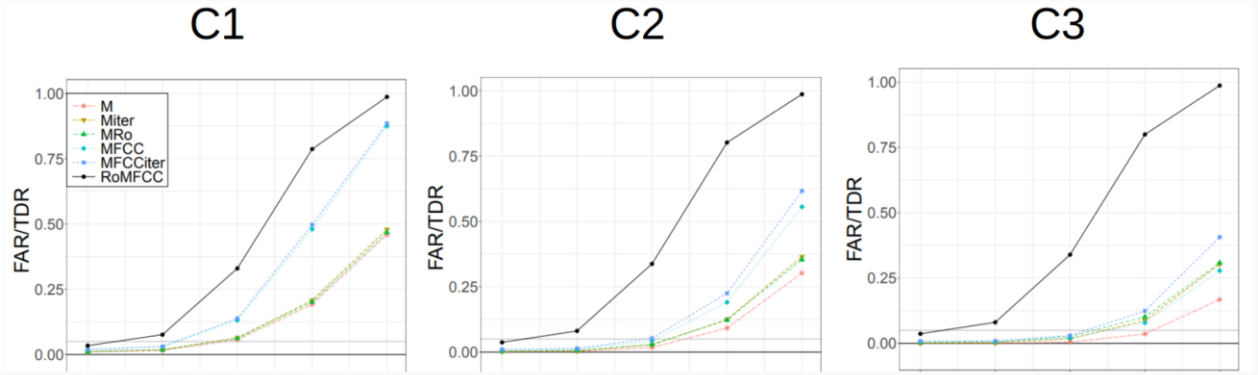
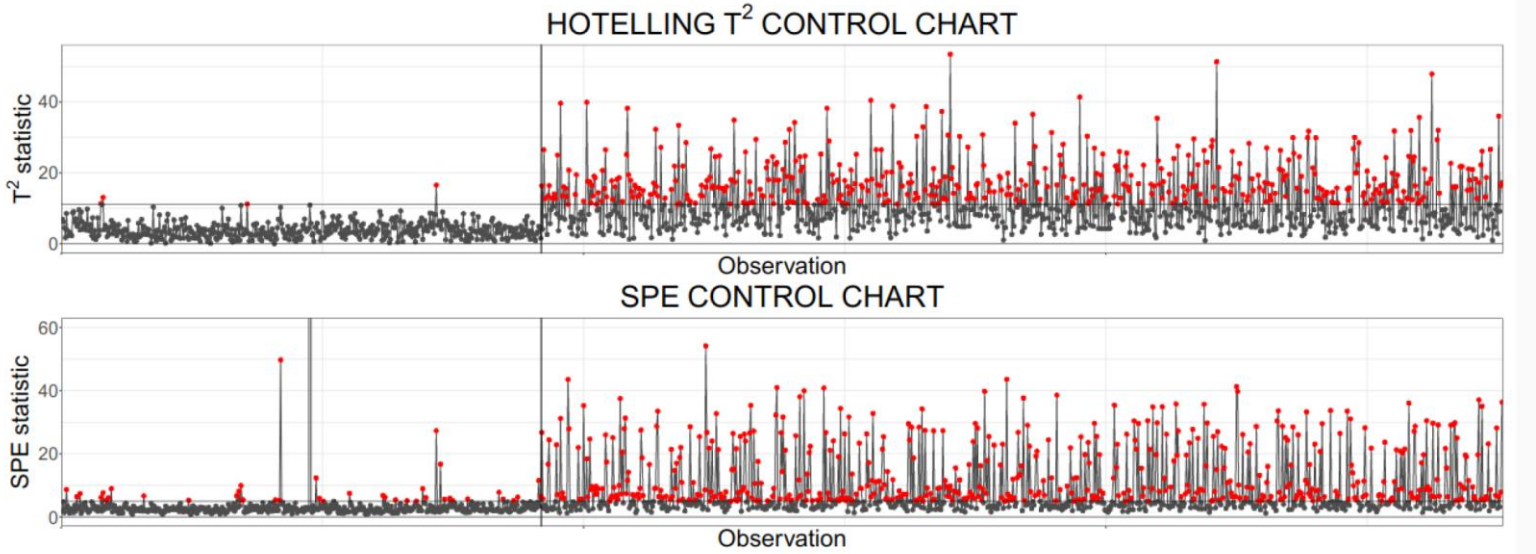


	$\widehat{TDR}$	$\overline{TDR}$	CI
M	0.336	0.335	[0.305,0.368]
Miter	0.462	0.461	[0.428,0.496]
MRo	0.513	0.512	[0.481,0.547]
MFCC	0.541	0.541	[0.511,0.574]
MFCCiter	0.632	0.632	[0.595,0.664]
RoMFCC	0.723	0.723	[0.695,0.753]

The obtained RoMFCC



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Big data mining for industry 4.0:

the new pathway for the digital and green 'twin' transition

Bianca Maria Colosimo
Politecnico di Milano

Legacy of the keynote lecture

a living experience of the extraordinary evolution of our role in science as statisticians

Embrace the increasing **data dimensionality and complexity**

- Ex-situ to in-situ (real-time) monitoring

with parsimony

- Green transition may happen through "dietary" data reduction
  - the right model/method can guide in-situ data collection, storing and real-time transfer ex-situ.
- Interpretability

robustness

- Industrial real data (ex-situ or in-situ) often still come at a high cost and, especially when dimensionality diverges, they are easily contaminated by outliers, which hampers the collection of a clean reference sample, and violate standard assumptions.

and integration of existing science/knowledge

- PDE, Physics-informed approaches
- Bayesian approaches

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List of recent publications on referred journal

Capezza C., Coleman S., Lepore A., Palumbo B., Vitiello L. (2019) Ship fuel consumption monitoring and fault detection via partial least squares and control charts of navigation data. Transportation Research Part D: Transport and Environment, 67:375-387, doi:10.1016/j.trd.2018.11.009

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Centofanti, F., M. Fontana, A. Lepore, and S. Vantini (2022). Smooth LASSO estimator for the function-on-function linear regression model. Computational Statistics & Data Analysis

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Lepore, A., Reis, M.S., Palumbo, B., Rendall, R., Capezza, C. (2017) A comparison of advanced regression techniques for predicting ship CO2 emissions. Quality and Reliability Engineering International, 33:1281-1292, doi:10.1002/qre.2171

Palumbo, B., F. Centofanti, and F. Del Re (2020). Function-on-function regression for assessing production quality in industrial manufacturing. Quality and Reliability Engineering International 36 (8), 2738-2753

Reis, M. S., Rendall, R., Palumbo, B., Lepore, A., Capezza, C. (2020) Predicting ships' CO2 emissions using feature-oriented methods. Applied Stochastic Models in Business and Industry, 36(1):110-123, doi:10.1002/asmb.2477

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List of recent publications on preprint archives

Capezza, C., F. Centofanti, A. Lepore, A. Menafoglio, B. Palumbo, and S. Vantini (2022). `funcharts`: Control charts for multivariate functional data in R. arXiv preprint arXiv:2207.09321

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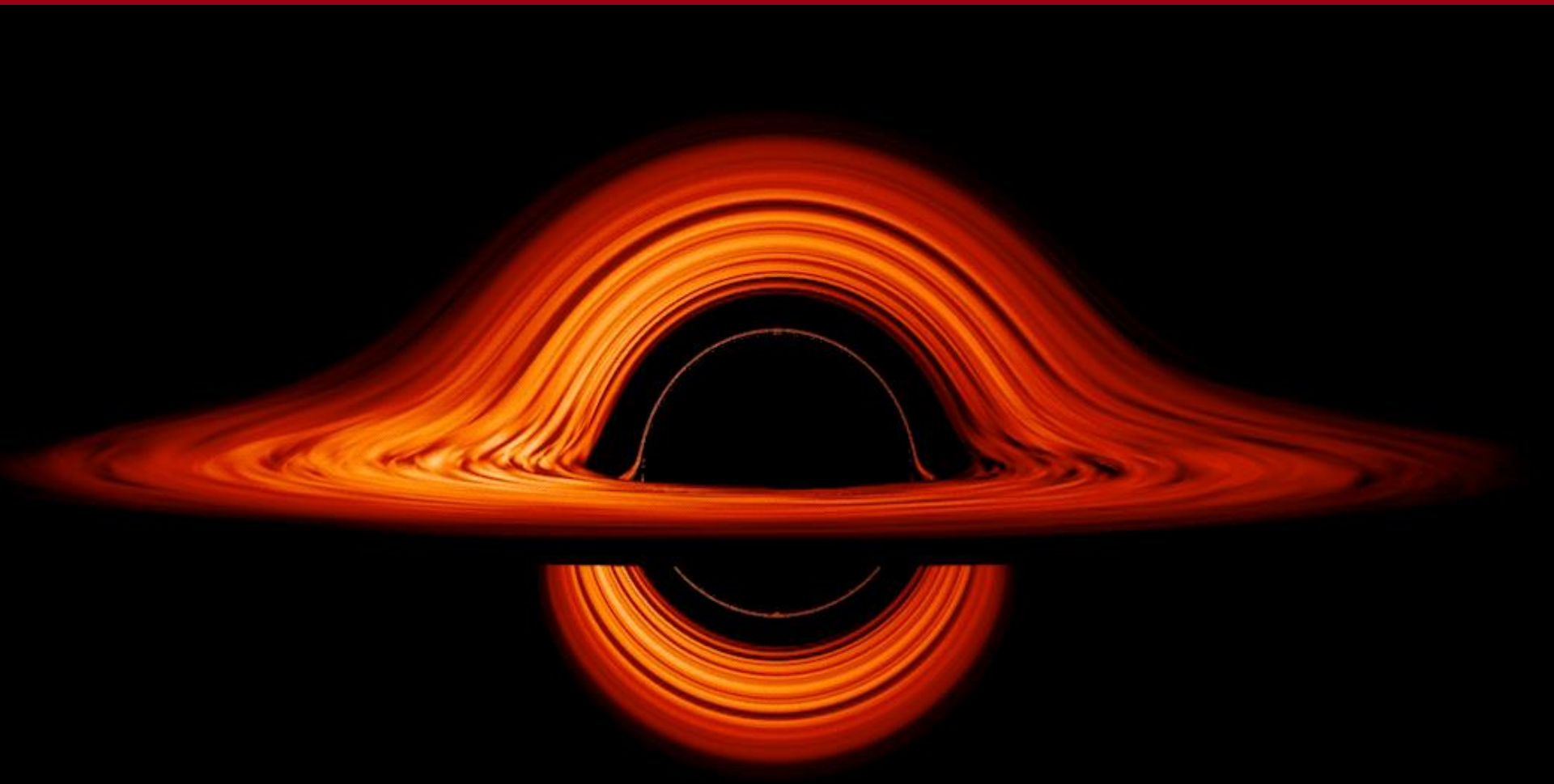
Centofanti, F., B. M. Colosimo, M. L. Grasso, A. Menafoglio, B. Palumbo, and S. Vantini (2021). Robust functional ANOVA with application to additive manufacturing. arXiv preprint arXiv:2112.10643



It's space beyond our three dimensions.
Without the right model, all you can do is record and observe.
(altered from Interstellar, 2014 - science fiction film)

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B. M. Colosimo
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the new pathway for the digital and green 'twin' transition

Bianca Maria Colosimo
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Complementary discussion

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DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

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