OPEN SOURCE SOFTWARE AND OPEN DATA IN THE DEVELOPMENT OF SIMULATION METHODS FOR DIGITAL TWINS

17th World Congress on Computational Mechanics

10th European Congress on Computational Methods in Applied Sciences and Engineering

Jacopo Bonari,[1] Stefania Trentin,[1] Marco Mattuschka,[1] Lisa Kühn,[1] Philip Franz,[1] Max von Danwitz,[1] Alexander Popp[1,2]

1. German Aerospace Center (DLR), Institute for the Protection of Terrestrial Infrastructures
2. University of the Bundeswehr Munich, Institute for Mathematics and Computer-Based Simulation

PI-Institute and Department “Simulation Methods for Digital Twins”

Management

Administration

Resilience and Risk Methodology

Detection Systems

Simulation Methods for Digital Twins

Digital Twins for Infrastructures









High-Fidelity Simulation Methods

Reduced-Order Modelling

Physics-Informed Machine Learning

Algorithms for Inverse Problems

Responsive and Fast Planning in Case of Emergency

Chemical accident forward problem:

- Where will the contaminant be transported?

Chemical accident inverse problem:

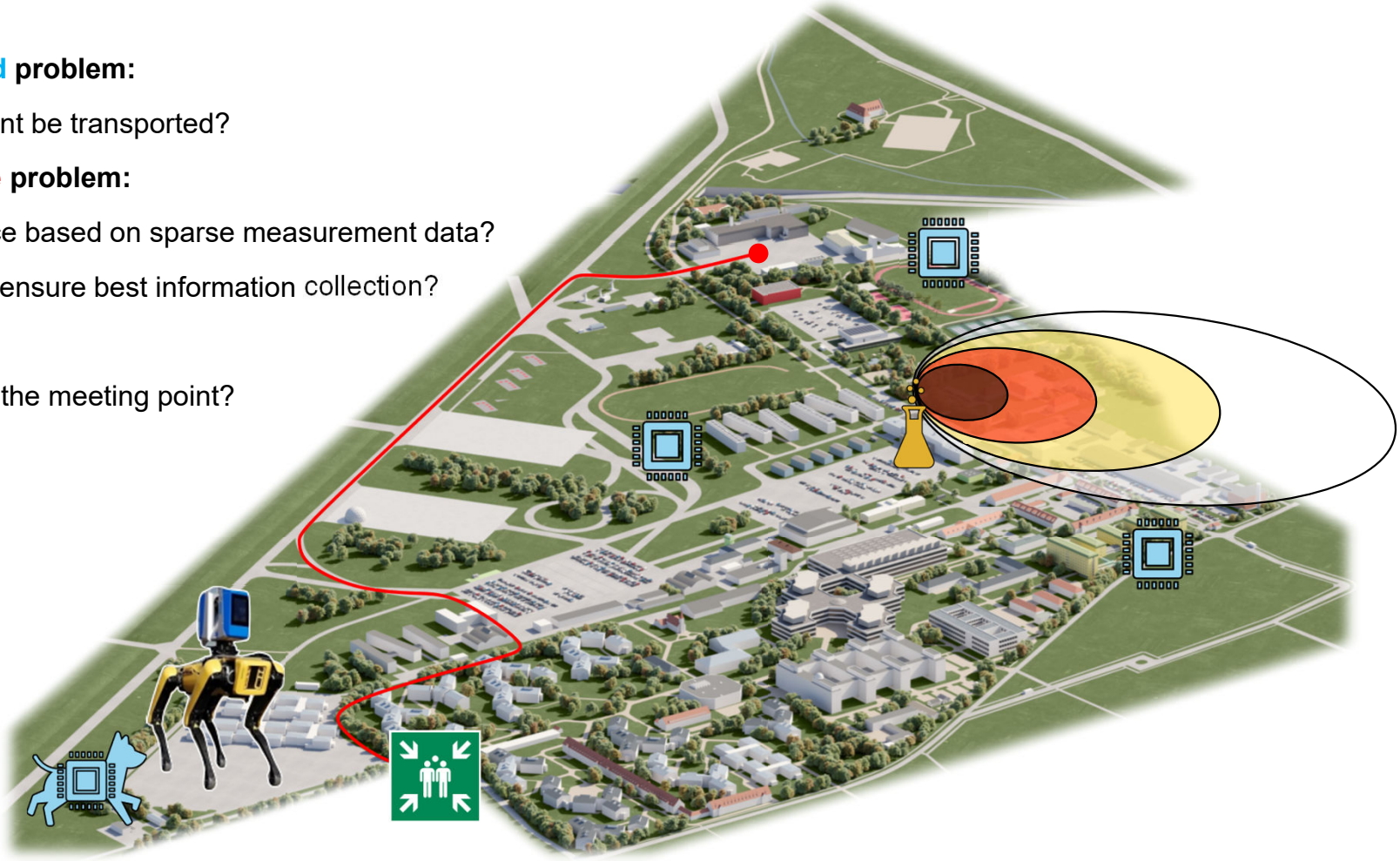
- Can we identify the source based on sparse measurement data?
- Where to add sensors to ensure best information collection?

Optimization:

- Which is the best path to the meeting point?

Routing:

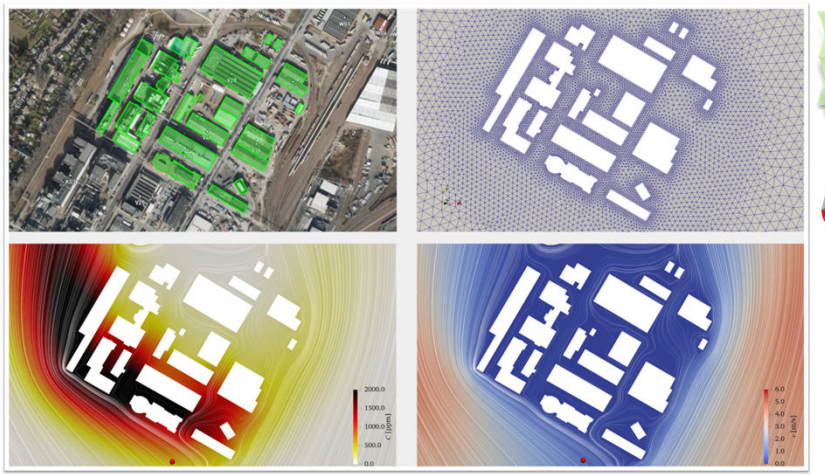
- Where do we send help?



Mesh Generation and Substance Transport Simulation

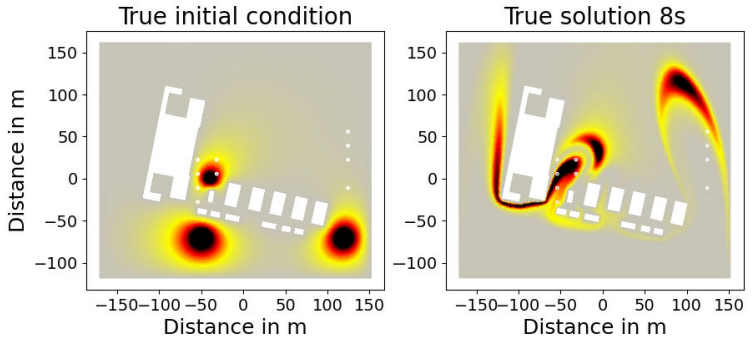
Mesh generation

- Automated mesh generation from OpenStreetMap (OSM) data;
- conversion of GIS data into polygons with refined boundary layer resolution.



Substance transport

- Approximation of flow around buildings;
- solution of the advection–diffusion equation using stabilized finite element methods in **FEniCS**.



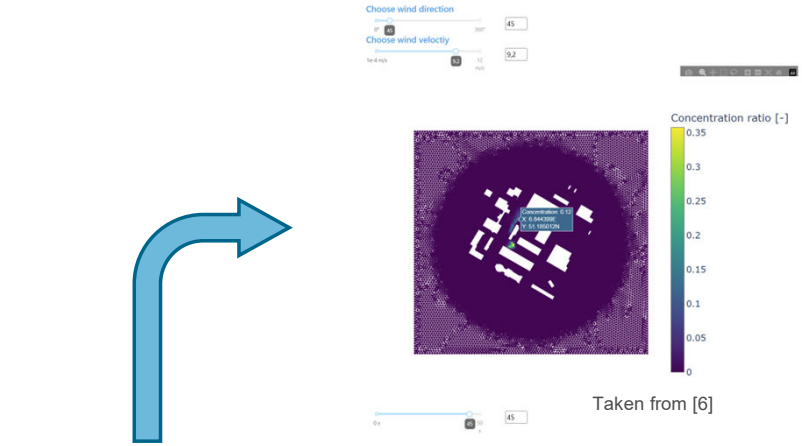
[1] Bonari, J., Kühn, L., von Danwitz, M., & Popp, A. Towards Real-Time Urban Physics Simulations with Digital Twins. In: Proceedings of the 28th IEEE/ACM International Symposium on Distributed Simulation and Real-Time Applications (DS-RT 2024), pp. 18–25, 2024

[2] Danwitz, M. von, Bonari, J., Franz, P., Kühn, L., Mattuschka, M., & Popp, A. Contaminant Dispersion Simulation in a Digital Twin Framework for Critical Infrastructure Protection. In *Proceedings of ECCOMAS Congress* https://doi.org/10.23967/eccomas.2024.301

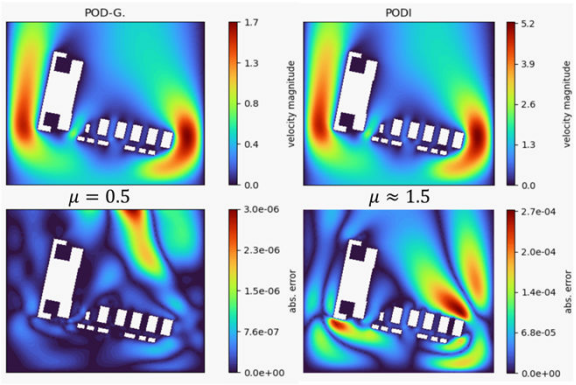
Tools for Reduced-Order Modeling and Uncertainty Quantification

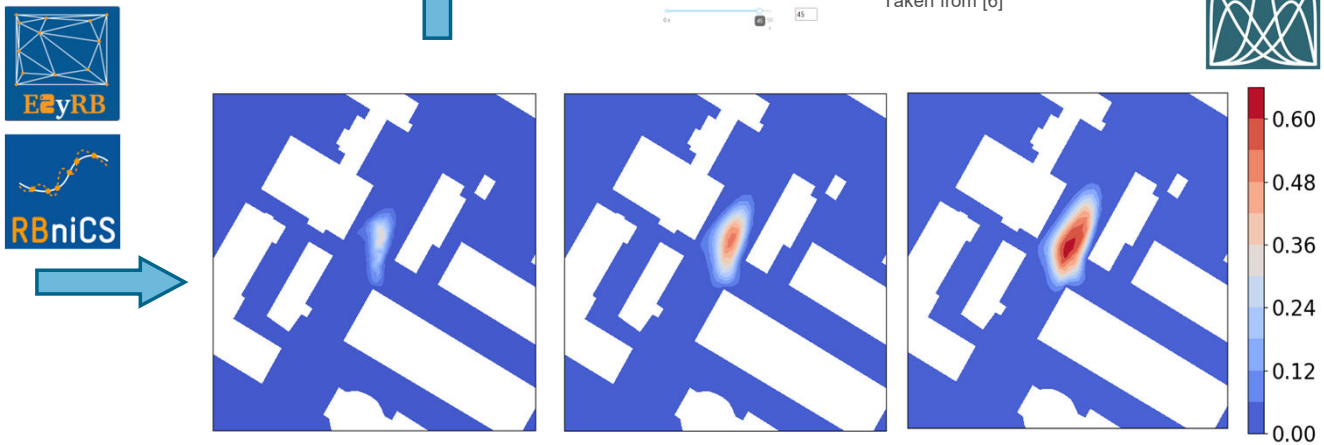
Model order reduction:

- fully implemented in **FeniCS**;
- online dashboard is under development;
- **EZyRB** [3] and **RBniCS** [4,5] for **ROM** evalution;
- **QUEENS** [6] for UQ.



Taken from [6]





[3] F. Ballarin, A. Sartori, and G. Rozza, “Rbnics – reduced order modelling in fenics,” 2015. url: https://www.rbnicsproject.org/
[4] G. Rozza, F. Ballarin, L. Scandurra, and F. Pichi, Real Time Reduced Order Computational Mechanics, ser. SISSA Springer Series. Springer Cham, 2024
[5] J. Biehler, J. Nitzler, S. Brandstaeter, M. Dinkel, V. Gravemeier, L. J. Haeusel, G. Robalo Rei, H. Willmann, B. Wirthl & W. A. Wall, “QUEENS: An Open-Source Python Framework for Solver-Independen
Computational Models“, 2025. doi: https://arxiv.org/abs/2508.16316

Source Identification and Sensor Placement

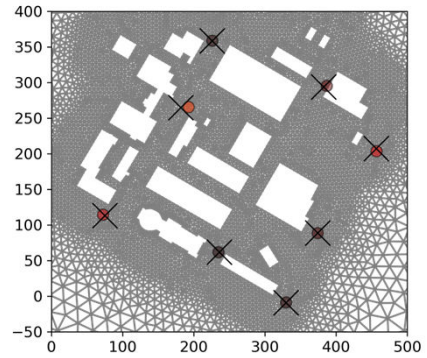
Sparse source identification

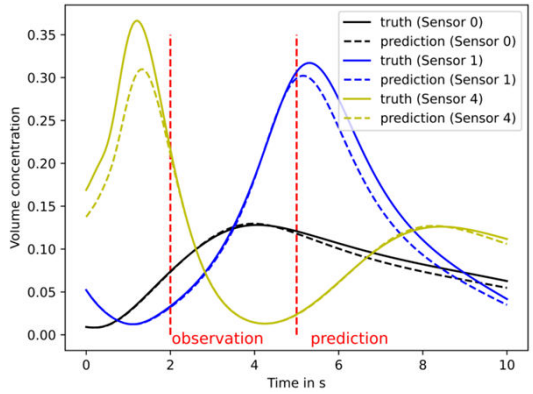
- Estimation of the location and intensity of point sources;
- computationally efficient solution of the inverse problem.

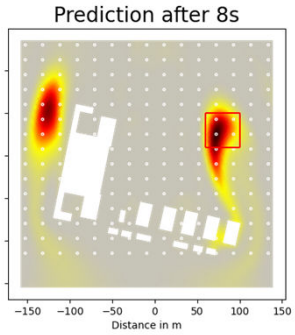


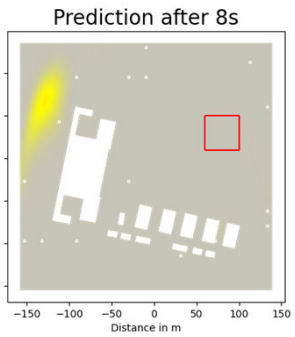
Sensor placement and path planning

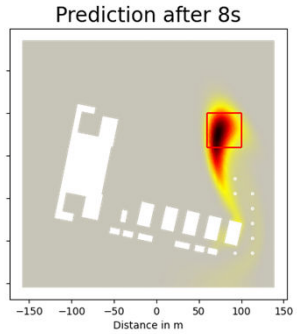
- Selection of 8 out of 202 candidate sensor locations by maximizing the expected information gain for the region of interest using **hIPPYlib - Inverse Problem PYthon library**





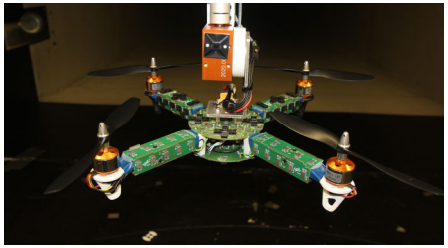






[6] Mattuschka, M., Walter, D., von Danwitz, M., & Popp, A. Sparse Source Identification in Transient Advection-Diffusion Problems with a Primal-Dual-Active-Point Strategy. Computer Methods in Applied Mechanics and Engineering, 2026.
[7] Danwitz, M. von, Bonari, J., Franz, P., Kühn, L., Mattuschka, M., & Popp, A. Contaminant Dispersion Simulation in a Digital Twin Framework for Critical Infrastructure Protection. In *Proceedings of ECCOMAS Congress.* DOI: 10.23967/eccomas.2024.301
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Sensor Placement and Path Planning



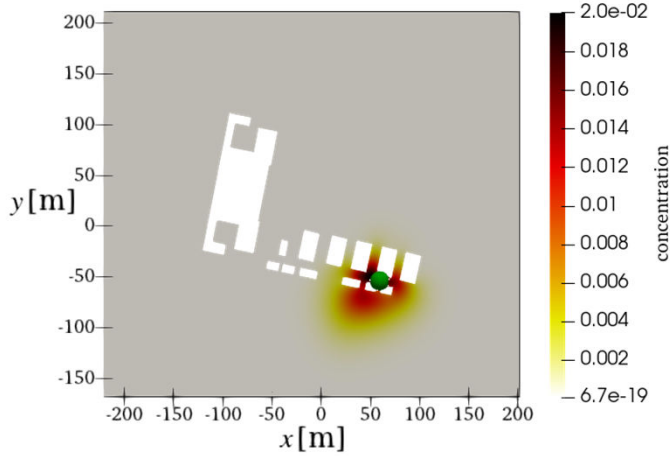




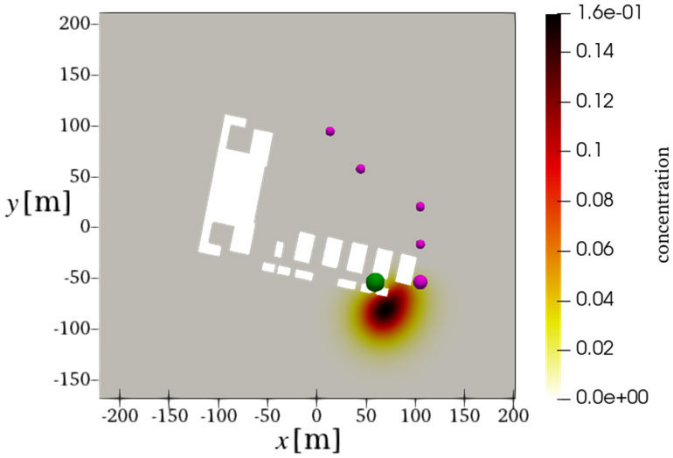
Sensorplattformen entwickelt u.a. von KN, MI, TP, PI

- Goal-oriented optimal sensor placement for concentration measurements using **hIPPYlib - Inverse Problem PYthon library**;
- extension toward dynamic sensor steering.

Concentration reconstruction using a stationary sensor [2s,12s]

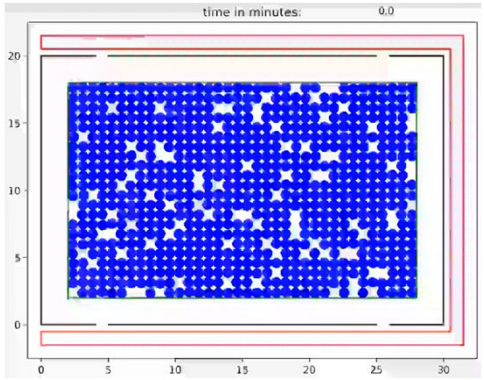


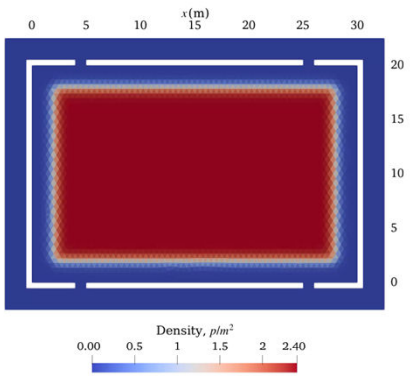
Additional measurements from a mobile sensor [2 s, 4 s]

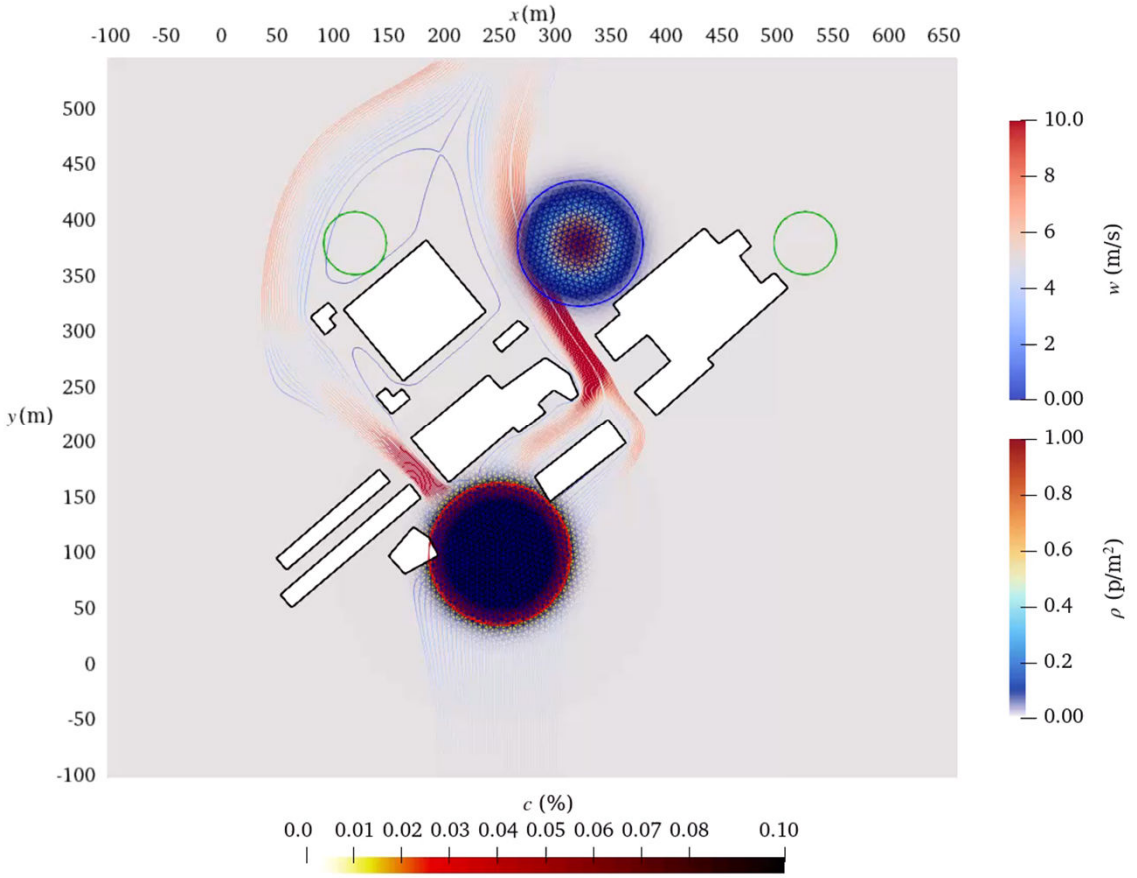


[9] Mattuschka, M., An der Lan, N., von Danwitz, M., Wolff, D., & Popp, A. Goal-Oriented Optimal Sensor Placement for PDE-Constrained Inverse Problems in Crisis Management. Computer Assisted Methods in Engineering and Science, 2026

Multiphysics Continuum Modeling of Evacuation Dynamics







- ✓ Fit for the analysis of large and/or complex domains;
- ✓ easier integration of additional physics;
- ✓ computational intensity does not directly scale with crowd's dimension;
- • estimate of crowd density everywhere in the domain;
- × discretization does not reflect individual human movement;
- × psychological effects are very difficult to be included in the n
- × difficult to validate and benchmark for small crowds.

[10] Hughes, R. L. (2000). The flow of large crowds of pedestrians. *Mathematics and Computers in Simulation*, *53*(4–6), 367–370. DOI: 10.1016/S0378-4754(00)00228-7

Open Source Data: Aerodynamic Pressure Measurements from Wind Tunnel Experiments, Acquired with Aerosense

Aerosense [11]

- MEMS-based sensor system
- Surface pressure distribution
- Self-sustaining, wireless
- Low cost, easy to install and remove.
- Sampling rate: $100\ \mathrm{Hz}$.

Inferred quantities:

- Local angle of attack.
- Local wind velocity.

Measured quantities:

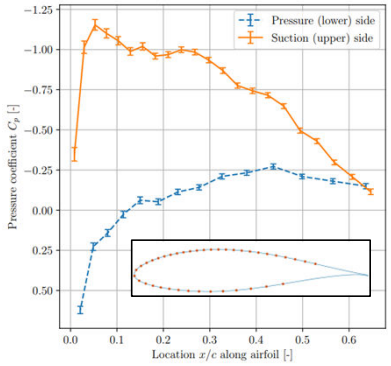
- Accelerations.
- Aerodynamic pressure distribution for:
  - Wind speeds and angles of attack
  - Excitation frequencies
  - Crack lengths

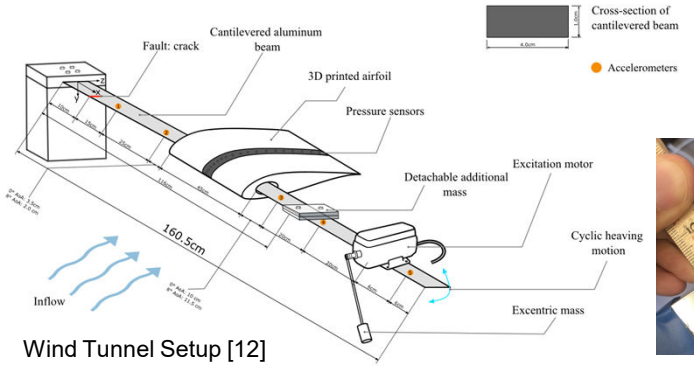
Design of experiments

- Eight inflow variants
- Six damage states
- Three measurements per inflow variant
- Test procedure:
  - $15\ s$ only wind
  - $135\ s$ wind and harmonic excitation



Aerosense system on Turbine Blade [11]





Wind Tunnel Setup [12]



[11] Barber et al., (2022): Development of a wireless, non-intrusive, MEMS-based pressure and acoustic measurement system for large-scale operating wind turbine blades
[12] Franz et al. (2025): On the potential of aerodynamic pressure measurements for structural damage detection.

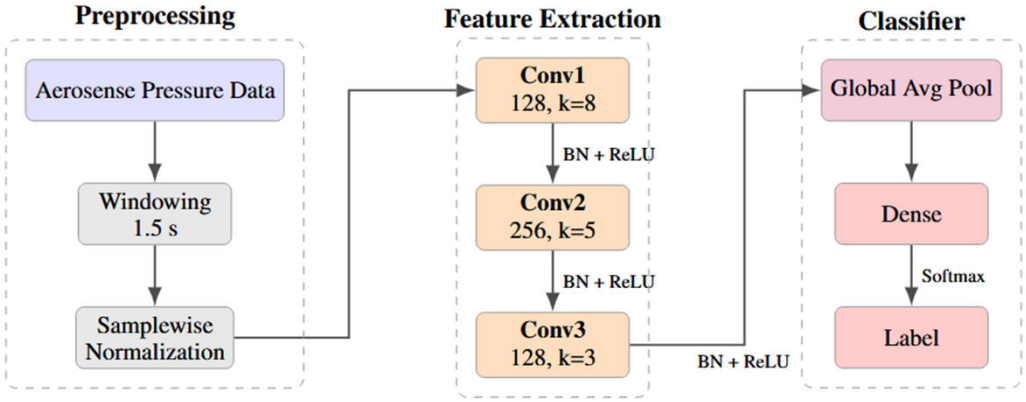
Open Source Code: Damage Detection and Severity Rating Algorithm

CNN-based Approach

- Segmentation and normalization;
- small dataset small Neural Network (CNN);
- implementation and trained models publicly available.

Test-Case for PE-ML

- Several confounders:
  - slightly varying rotational excitation;
  - downwards drift in measurements;
- test case for PE-ML based monitoring approaches.



Building blocks of CNN-based approach, taken from [2]

Accuracy	Split 1	Split 2	Split 3	Average
AoA 0°	82,6 %	98.5 %	93.7 %	91,6 %
AoA 8°	81.8 %	96.0 %	89.8 %	89.2 %

Classification Results, taken from [3]

Data

Abdallah, I., Deparday, J., Marykovskiy, Y., & Barber, S. (2023). *AeroSense Measurements: Wind Tunnel EPFL* [Data set]. doi: 10.34808/gq12-wx33

Code

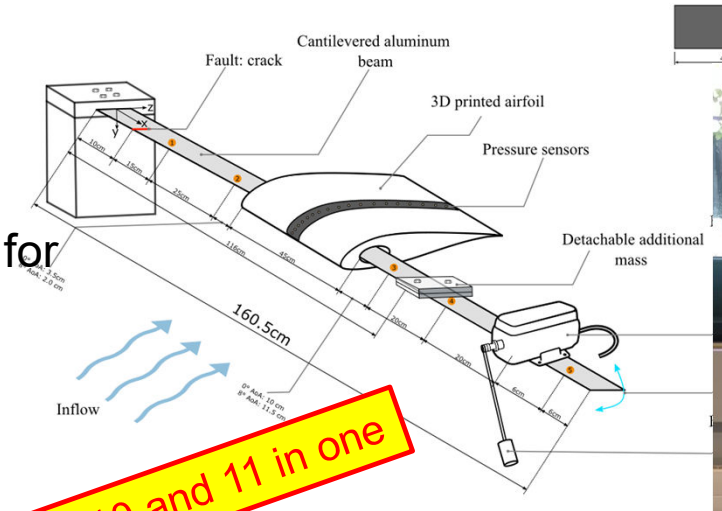
Repository doi: 10.5281/zenodo.17911886

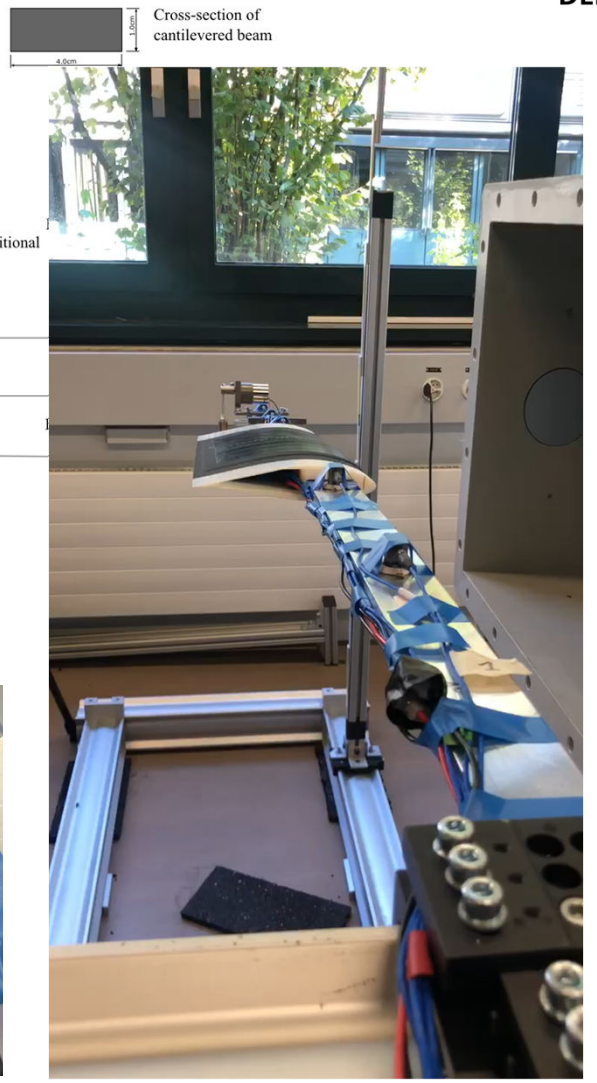
[13] Franz et al. (2026): *Towards Interpretable Damage Detection based on Aerodynamic Pressure Measurements*

Open Source Data: Aerodynamic Pressure Measurements from Wind Tunnel

Setup & Measured quantities

- Aerodynamic pressure distribution for
  - Different wind speeds
  - Angles of attack
  - Excitation frequencies
  - Crack lengths
- Accelerations

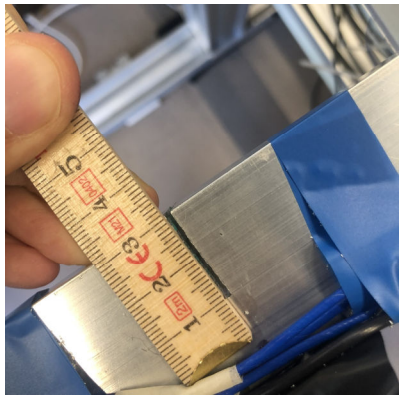




Collapse 10 and 11 in one

Design of experiments

- Eight inflow variants
- Six damage states
- Three measurements per inflow variant
- Test procedure:
  - 15 s only wind
  - 135 s wind & harmonic excitation



Probabilitstic Forecasting of Waste Water Treatment Plant Inflow

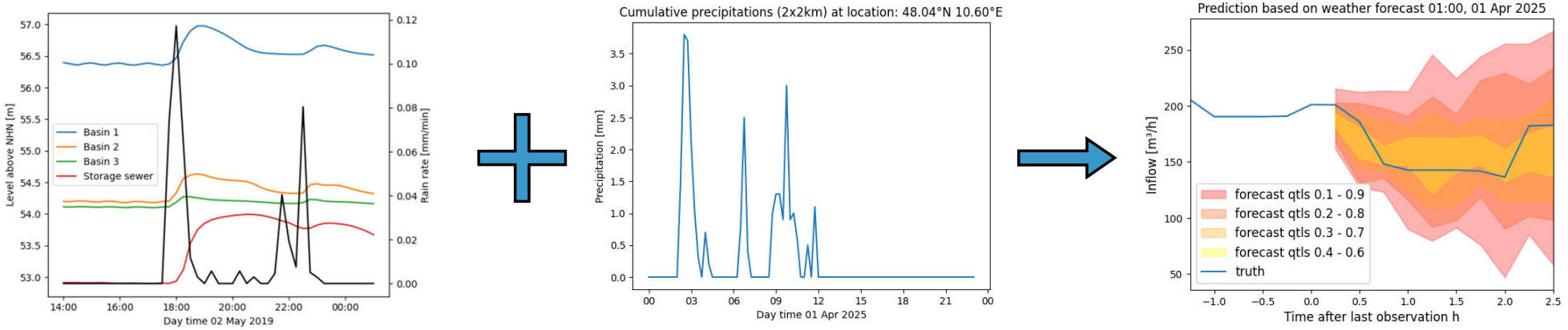
- Goal: forecasting Waste Water Treatment Plant (WTTP) inflow using measurements from sewage system and weather forecasts
- Open data from WWTP in Weiden, Germany [14]:
  - Time series in fifteen minutes interval for three years
  - Inflow at WWTP.
  - Water level measured at four stations along the sewage network.
  - Rain rate and forecast from radar raster data from open data of the German weather service [15] aggregated in [14].



[14] Sonnenschein, B., & Ziel, F. (2023). *Probabilistic intraday wastewater treatment plant inflow forecast utilizing rain forecast data and sewer network sensor data*. *Water Resources Research*, 59, e2022WR033826. https://doi.org/10.1029/2022WR033826
[15] Index of /climate_environment/CDC/grids_germany/5_minutes/radolan/reproc/2017_002/bin/
Data vailable at Wastewater Treatment Plant Inflow Rate, Network Water Levels and Rain Rate for Koeln Weiden, Germany | Zenodo

Implementation of Probabilistic Forecasting

Model implementation by authors of [14], open source and available at [16]:



- Measurements for inflow, water levels and precipitation over the last 1.5 hrs
- Rain forecast for the next 2.5 hrs

- Generalized Additive Model for Location Scale and Shape
- Trained with historical data for 2 years and tested with remaining 1 year
- Daily and seasonal patterns in data are learned by the model

- Probabilistic forecast of the inflow for the next 2.5 hrs
- Confidence intervals for prediction obtained as the quantiles of the probability distribution estimated by the model

[16] wilecoyote2015/wtp_inflow_distributional_forecast: Initial Release | Zenodo

Use of OS Data and Code in New Project

- The open source data and code presented here was used as a robust starting point for application to other WWTP forecasting problem.
- Open source data:
  - validation of new developed methods, to compare with original model of [1];
  - comparison with new data (from other WWTP), especially for daily and seasonal patterns.
- Open source code:
  - starting point for model development;
  - extended to:
    - longer forecasts (24 hrs);
    - more measurement variables (more stations along the sewage network);
    - forecasting of waste water composition (inflow + chemical oxygen demand).

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Thank you!



Selected references:

[1] Bonari, J., Kühn, L., von Danwitz, M., & Popp, A. Towards Real-Time Urban Physics Simulations with Digital Twins. In: Proceedings of the 28th IEEE/ACM International Symposium on Distributed Simulation and Real-Time Applications (DS-RT 2024), pp. 18–25, 2024

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[12] Franz et al. (2025): On the potential of aerodynamic pressure measurements for structural damage detection.

[13] Franz et al. (2026): Towards Interpretable Damage Detection based on Aerodynamic Pressure Measurements

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- [2] N. Demo, M. Tezzele and G. Rozza, “EZyRB: Easy Reduced Basis method (Version 1.1.1)”, 2018. doi: https://doi.org/0.21105/joss.00661
- [3] F. Ballarin, A. Sartori, and G. Rozza, “Rbnics – reduced order modelling in fenics,” 2015. url: https://www.rbnicsproject.org/
- [4] G. Rozza, F. Ballarin, L. Scandurra, and F. Pichi, Real Time Reduced Order Computational Mechanics, ser. SISSA Springer Series. Springer Cham, 2024
- [5] J. Biehler, J. Nitzler, S. Brandstaeter, M. Dinkel, V. Gravemeier, L. J. Haeusel, G. Robalo Rei, H. Willmann, B. Wirthl & W. A. Wall, “QUEENS: An Open-Source Python Framework for Solver-Independent Analyses of Large-Scale Computational Models“, 2025. doi: https://arxiv.org/abs/2508.16316
- [6] L. Kühn, J. Bonari, M. von Danwitz, A. Popp, "Intrusive and Non-Intrusive Model Order Reduction for Airborne Contaminant Transport: Comparative Analysis and Uncertainty Quantification“, preprint, 2026. doi: https://arxiv.org/abs/2602.21996.

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- [1] Barber, Sarah; Deparday, Julien; Marykovskiy, Yuriy; Chatzi, Eleni; Abdallah, Imad; Duthé, Gregory et al. (2022): *Development of a wireless, non-intrusive, MEMS-based pressure and acoustic measurement system for large-scale operating wind turbine blades*. In: *Wind Energy Science* 7 (4), S. 1383–1398. DOI: 10.5194/wes-7-1383-2022.
- [2] Franz, Philip; Danwitz, Max von; Duthé, Gregory; Popp, Alexander; Chatzi, Eleni (2026): *Towards Interpretable Damage Detection based on Aerodynamic Pressure Measurements*. [preprint accepted for publication] DOI: arxiv.org/pdf/2605.08187.
- [3] Franz, Philip; Abdallah, Imad; Duthé, Gregory; Deparday, Julien; Jafarabadi, Ali; Jian, Xudong et al. (2025): *On the potential of aerodynamic pressure measurements for structural damage detection*. In: *Wind Energy Sci.* 10 (12), S. 3001–3026. DOI: 10.5194/wes-10-3001-2025.