Digital twin in the Environment:
Urban microclimate

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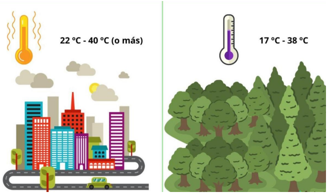
How do digital twins help us understand the effects of urban development on the microclimate?

Plan

Context

- Ecology and climate have become major issues, especially in cities where heat islands are developing
- Solutions: Greening, choice of suitable materials, and redesigned urban planning

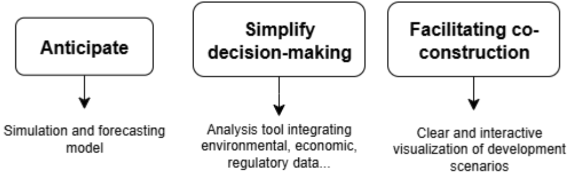


- Local authorities must therefore make decisions on the development strategies to be adopted and evaluate their environmental and health impact.

$\rightarrow$ Simulate and predict the effects of these choices on the urban microclimate and public health $\Rightarrow$ **Digital twin**

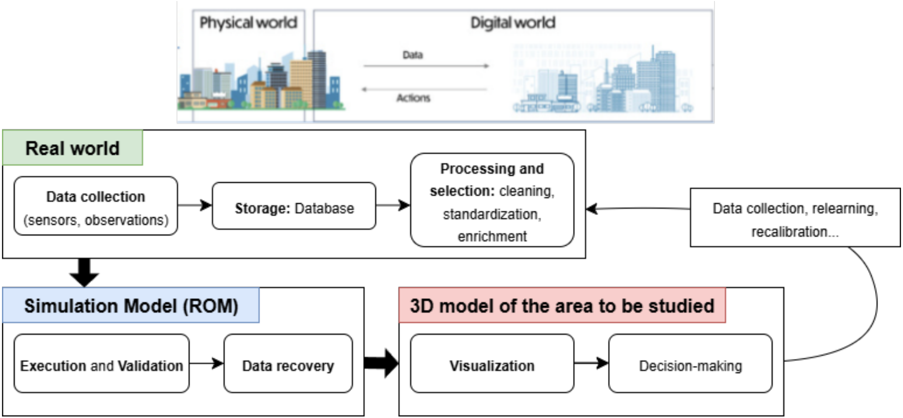
What is a digital twin?

- Virtual and dynamic replica of a real system, which, when coupled with simulation tools, allows its behavior to be analyzed and predicted under different conditions
- Based on real data (meteorological and urban) from sensors, observations, or physical models



Current challenge in France: JNFT project led by IGN, Cerema, and Inria, which aims to create a multi-thematic digital twin covering the French territory

How a digital twin works



Methods

Physical:

- Data (weather, material properties, air composition)
- Microclimate

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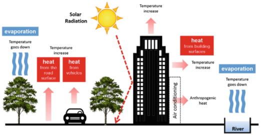
Digital:

- Parameters
- 3D mesh model



Physical models:

- Continuous physical phenomena: PDEs (Navier-Stokes, heat, transport, diffusion)
- Interaction between buildings, wind, vegetation: Fluid-Structure Interaction (NS + Elasticity)
- Airflow and heat exchange: Computational Fluid Dynamics (NS + Heat; Transport; radiative transfer)

ROM usage: Reducing the order of physical models to speed up simulations

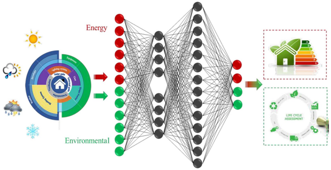
- **Offline:** Model preparation (hours / days)

  - Dimension reduction by capturing the essence of the system: Proper Orthogonal Decomposition (POD), Reduced Basis Method (RBM)
  - Hyper-reduction: Reduces computation time of nonlinear terms (DEIM: Discrete Empirical Interpolation Method, gappy POD: gappy Proper Orthogonal Decomposition)

- **Online:** Simulation of the reduced model to quickly test different scenarios (seconds / minutes)

Data-Driven Models: data-driven, fast prediction

- Regression: predicts phenomena (temperature, air quality, wind) from variables (materials, vegetation...)
- Gaussian Process: predicts and provides uncertainty for areas with little data
- Neural Networks: capture complex and non-linear relationships between variables



- Ensemble models: improving prediction accuracy and robustness by combining multiple models

Data assimilation: Combining physical models and data to correct simulations, achieve maximum accuracy, and make these simulations usable

- Vector Auto-Regression (VAR): adjusts the physical model so that simulations match observations (over one or more time steps)
- Kalman Filter: Updates predictions in real-time for dynamic tracking
- Parameterized-Background Data-Weak (PBDW), Generalized Empirical Interpolation Method (GEIM): reconstructs the system with little data, for an overview
- Virtual sensors: estimation of variables where there are no measurements, see the effect of new developments

Data & Instrumentation — Data Budget (Urban Microclimate)

Goal: quantify sensor data rates and daily volumes to size network & storage for real-time operation.

Sensor	#	Freq (Hz)	sample	Throughput (kB/s)	Vol/day (GB)	Comments
Air thermometer (T)	20	1.00	8	0.16	0.014	Ambient temperature
Hygrometer (RH)	10	1.00	8	0.08	0.007	Relative humidity
Anemometer (3-axis)	5	1.00	12	0.06	0.005	Wind speed & direction
Pyranometer (solar)	5	0.20	16	0.016	0.0014	Global irradiance
Thermal camera*	2	0.033	500,000	33.0	2.85	H.264, store temperature maps

Formulas:

Throughput (kB/s) & Volume/day (GB)

$$Throughput(kB/s): \quad = \frac{\# \times \text{sample} \times \text{Freq}}{1000}$$

$$Volume/day(GB): \quad = \frac{\text{Throughput (kB/s)} \times 86\,400}{10^6}$$

Protocols/latency: LoRaWAN for low-rate sensors (2–5 s latency); Wi-Fi/4G for cameras (< 0.5 s).
Privacy: camera streams anonymized on edge; only thermal maps stored.

V&V & UQ — Verification, Validation & Uncertainty Quantification

Goal

Goal: ensure accuracy, reliability, and safety of decisions in the urban microclimate digital twin.

Step	**Purpose**	**Methods / Indicators**
1 Verification	Check model implementation and numerical stability.	Compare the Reduced Order Model (ROM) with the full CFD model. Ensure no numerical or stability errors.
2 Validation	Evaluate how well the model matches real-world data.	Compare predictions with sensor measurements (T°, wind, humidity). Metrics: **MAE**, **RMSE**, **R^2**.
3 Uncertainty Quantification (UQ)	Estimate the confidence level of model predictions.	Methods: Monte Carlo, sensitivity analysis, Bayesian estimation. Example: $T = 32 \pm 1.5^\circ$C.
4 Veto / Alert Mechanism	Prevent wrong or unsafe decisions when uncertainty is too high.	If confidence interval $>$ threshold $\rightarrow$ trigger alert or model recalibration.

Outcome: a validated, uncertainty-aware model ensuring trustworthy real-time decisions.

Transfer & Deployment — CI/CD, Edge vs Cloud, Observability, Risks

Goal

ensure a smooth transition from R&D to real-time operation of the urban microclimate digital twin.

Aspect	Description	Tools / Key Points
CI/CD (Continuous Integration & Deployment)	Automate the update cycle for models and data.	GitHub Actions, Docker, unit tests for ROM/data, dashboard updates.
Containers & Orchestration	Ensure portability and scalability of digital twin services.	Docker / Kubernetes: deployment of ROM model, APIs, dashboards.
Edge vs Cloud Computing	Balance local computing (edge) and centralized storage (cloud).	Edge: low latency (cameras, sensors). Cloud: heavy computations (assimilation, ROM training).
Observability & Monitoring	Track performance, errors, and model drifts.	Logs, metrics, and alerts through Grafana / Prometheus.
Costs & Risks (CAPEX/OPEX)	Optimize hardware resources and minimize downtime.	CAPEX: servers / sensors. OPEX: maintenance, energy, network. Risk: failure, model drift.

Outcome: a reliable, automated, and maintainable digital twin for long-term operation.

Perspectives — Toward a Sustainable Digital Twin

- **Scalability:** extend the model to larger urban areas using cloud computing and ROM optimization.
- **Continuous improvement:** integrate new sensors (CO, fine particles) and additional data sources (satellite, weather).
- **Optimization:** further automate calibration and data assimilation for faster model updates.

Goal: make the digital twin more complete, faster, and more useful for urban decision-making.

Limitations and Current Challenges

- **Robustness:** sensors may fail or produce noisy data so adaptive models are needed.
- **Bias:** the model can overfit to one district which means multi-scenario validation is required.
- **Costs:** find the right balance between accuracy, speed, and budget (cloud, maintenance).

These challenges highlight what must be improved to make the digital twin reliable and sustainable in the long term.

Thank you for your attention!

Any questions?

University of Strasbourg – 2025

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