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Copula-based iterative approximate Bayesian calibration for urban building energy modelling (UBEM) and impact of time resolution

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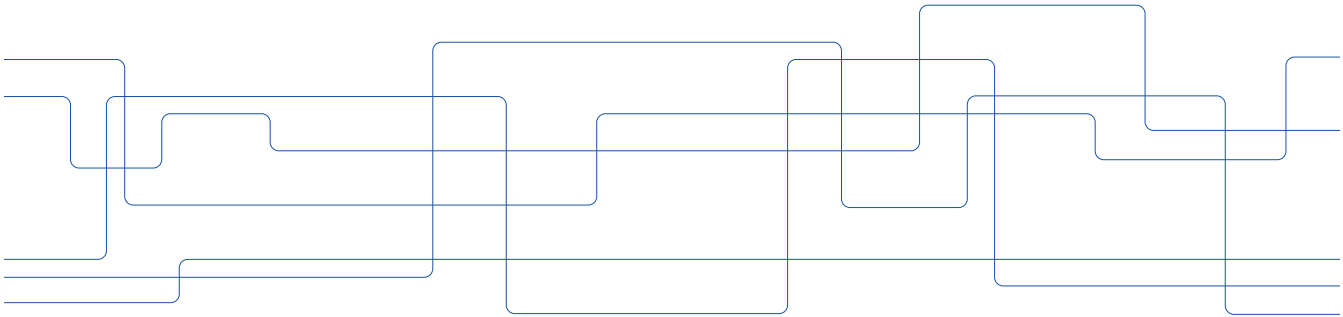
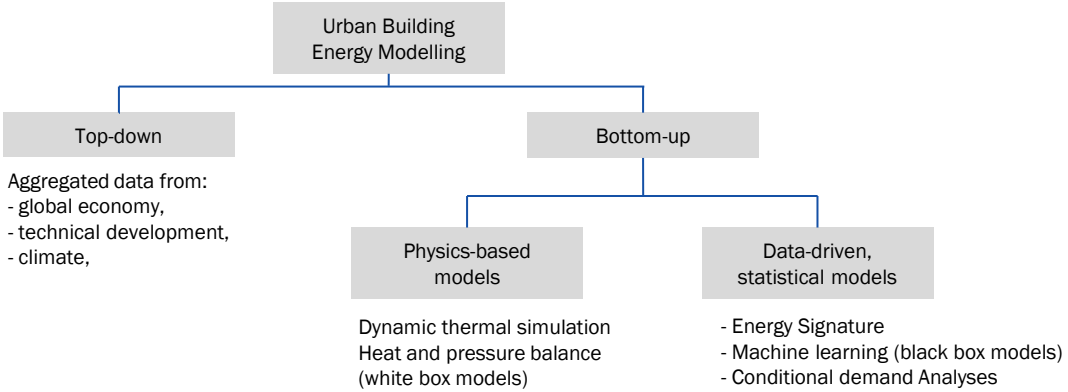
Airbus Research & Technology



What is Urban Building Energy Models ?

Different types of model for different usages :



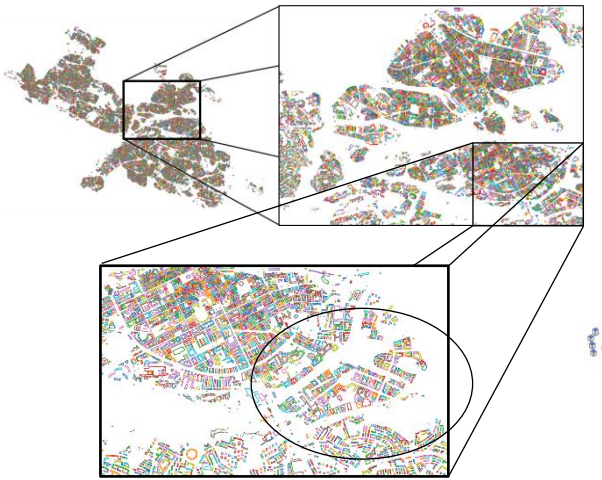
UBEM should have the ability to [Kavgic (2010)]:

- Estimate baseline energy demand of existing building stock
- Explore technical and economic effects of ECMs on global energy use and emission
- Consider impact of ECMs on indoor environment quality

→ Bottom-up, physics-based models

What is Urban Building Energy Models ?

What is urban scale ?



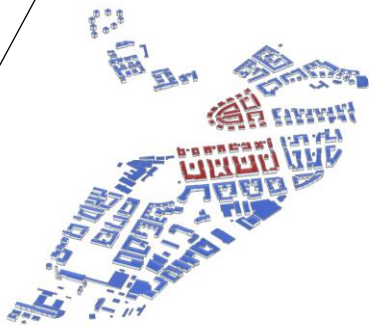
The county scale (~85 000 buildings) ?

The city scale (~10 000 buildings) ?

The small city scale (~5 000 buildings) ?

The large district scale (~300 buildings) ?

The small district scale (~40 buildings) ?



How to build Physics-based UBEM ?

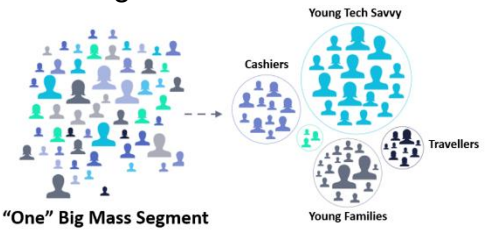
How to address the different scales ?

Ang et al., *From concept to application: A review of use cases in urban building energy modeling*, Applied Energy, Volume 279, 2020, 115738, ISSN 0306-2619,
https://doi.org/10.1016/j.apenergy.2020.115738

Scale	Nb of buildings	Geometry	Model Input
County	~ 85 000	Archetype	Archetype
City	~ 10 000	Archetype	Archetype
Small city	~ 5 000	Archetype / Polygons	Archetype
Large district	> 200	Archetype / Polygons	Archetype
Small district	> 20	Archetype / Polygons	Archetype / Specific
Neighborhood	< 20	Polygons	Specific

Split the urban areas into archetypes for either the geometry and/or model inputs.

Equivalent to market segmentation



https://www.smartera3s.com/products/customer-segmentation/

What criteria ?

Year of construction, Energy class, Floor area, Occupancy type, Energy carrier, Ventilation type, etc…

It generally depends on the use case !

(and computational capacities…)

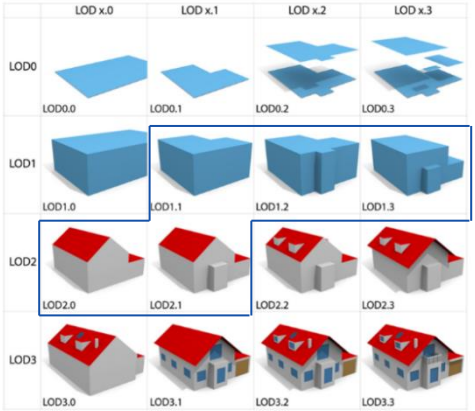
How to build Physics-based UBEM ?

What are the inputs ?

For geometry

Building typology and Level of Details

Driven by data availability but also on cluster size
(no need to have LOD3.3 for large cluster)

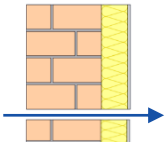


Biljecki et al., *An improved LOD specification for 3D building models,* Computers, Environment and Urban Systems, Volume 59, 2016, 25-37, ISSN 0198-9715, https://doi.org/10.1016/j.compenvurbsys.2016.04.005.

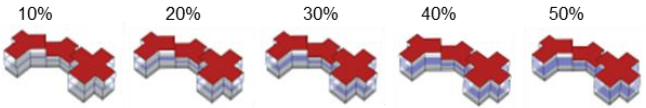
For model inputs

Static elements

Materials (insulation, inertia)
Envelope leakages

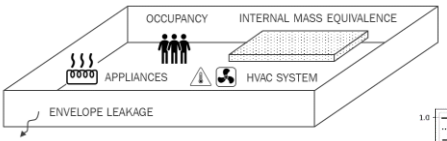


Window to wall ratio

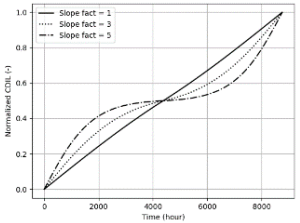


Dynamic elements

Temperature Setpoint adjustment (night/day, scheduled)
Large variation of occupancy rate
Demand controlled ventilation (based on activity and/or occupancy)
Internal gains (appliances, lightings, …)



$$CDIL = \frac{YearlyConsumption}{(1 + exp(-\gamma t))}$$

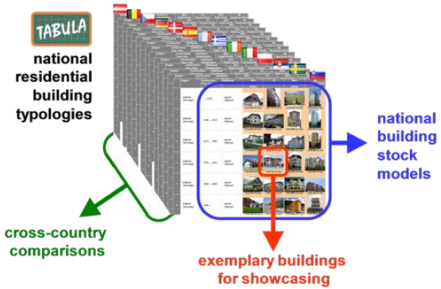


How to build Physics-based UBEM ?

What value(s) for each input ?

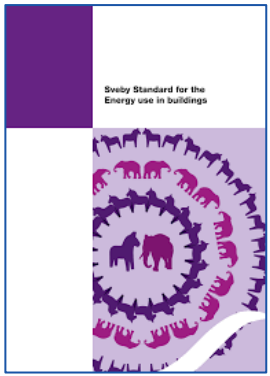
Building stock analyses :

IEE Project TABULA (2009 - 2012)
"Typology Approach for Building Stock Energy Assessment"



Swedish initiative from architecture view

SVEBY work on standards



Databases of Energy Performance Certificate (EPCs)

Boverket

Building regulation (threshold values on several specific points: U-values, envelope leakages, etc..)

How to build Physics-based UBEM ?

Probabilistic approaches ?

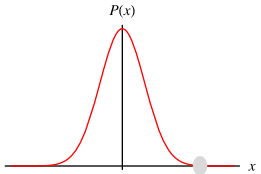
Each input gets a range of expectation and a distribution law

Unknown Inputs X_p

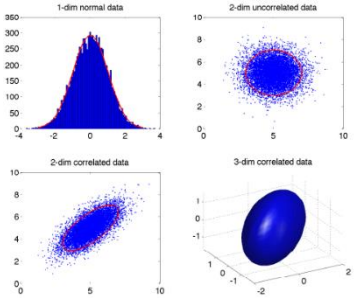
Parameters	Range of variation	Distribution law type
Parameter 1	$[x_{1m};\ x_{1M}]$	
Parameter 2	$[x_{2m};\ x_{2M}]$	
Parameter 3	$[x_{3m};\ x_{3M}]$	
...	...	
Parameter N	$[x_{Nm};\ x_{NM}]$	

Known Inputs
X_d

Model
$\hat{y} = f(X_d, X_p)$



Real value



Blom & Wargclou, *Does Copula beats linearity* Master's Thesis, 2016, Department of Mathematics and Mathematical Statistics Umeå University

How to consider correlations among all parameters ?

How to sample ?

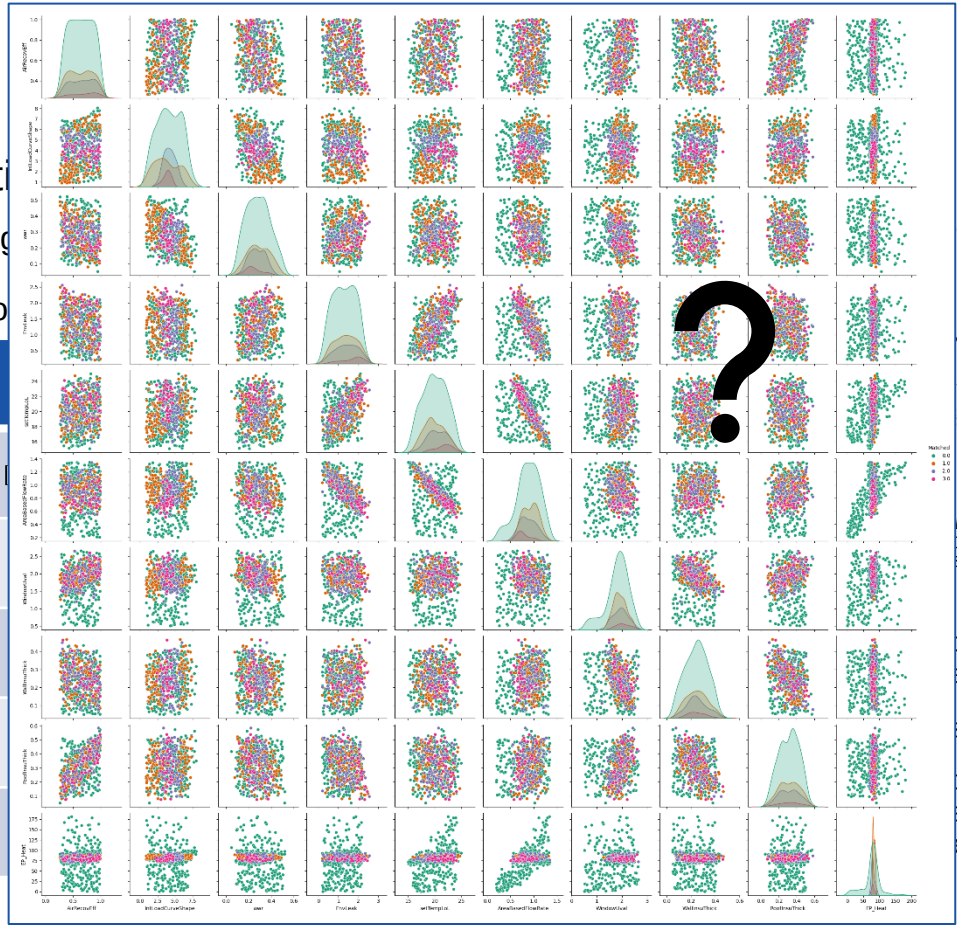
How accurate is the computed distribution ? Can it be thinner ?

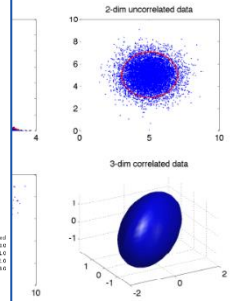
Probabilisti

Each input g

Unkno

Parameters	
Parameter 1	
Parameter 2	
Parameter 3	
...	
Parameter N	





Does Copula beats linearity
016, Department of Mathematics
Statistics Umeå University

consider correlations
ll parameters ?

sample ?

curate is the
ed distribution ?
e thinner ?

How to build Physics-based UBEM ?

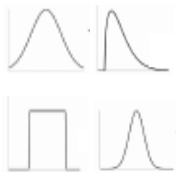
How to generate correlated sample with non (necessary) normal parameters that have non (necessary) linear relationships ?

By the use of *Copulas :*

A copula is a function which joins or "couples" a multivariate distribution function to its one-dimensional marginal distribution functions. [Nelsen, 2005]

Sklar's theorem (1959) : $F(x_1, \dots, x_n) = C\left(F_1(x_1), \dots, F_n(x_n)\right)$

Multivariate distribution — Copula — Marginals' CDF



Widely used in finance and risk assessment since the late 1990, in hydrology since ~2000 and ecology (~2010).

Used for UBEM application by Ina De Jaeger in her PhD :
On the impact of input data uncertainties on the reliability of building energy models, KU Leuven, 2021

4 papers found in Scopus with '*copula*' and '*building energy*' (oldest from 2019, and one from Ina De Jaeger)

How to use UBEM ?

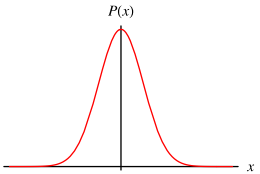
Workflow of UBEM :

Scale of Analyses

Archetypes definition
(Geometry, Inputs)

Produce Sample

Run Probabilistic
Simulation



How to use UBEM ?

Workflow of UBEM

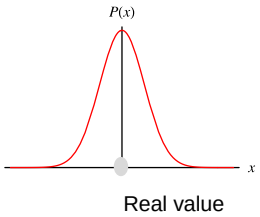
Scale of Analyses

Archetypes definition (Geometry, Inputs)

Model Calibration

Produce Sample

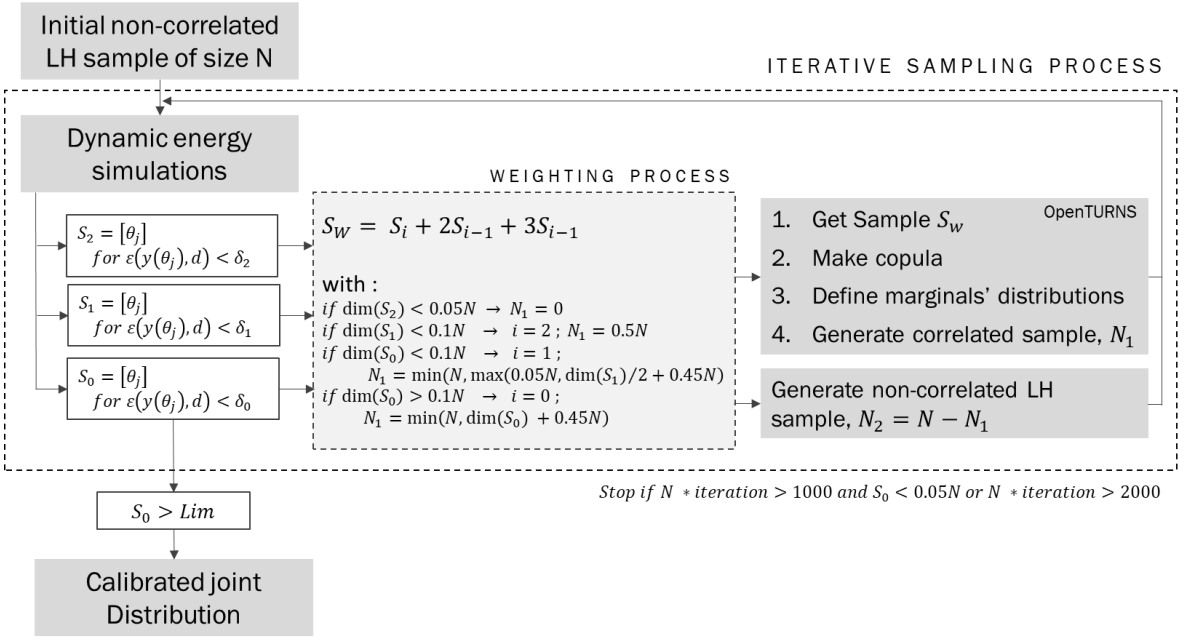
Run Probabilistic Simulation



Real value

Calibration of Physics-based UBEM

Enhancing the trust of UBEM by undertaking calibration.
→found the joint distribution of unknown inputs that makes UBEM tool reliable.



Calibration of Physics-based UBEM

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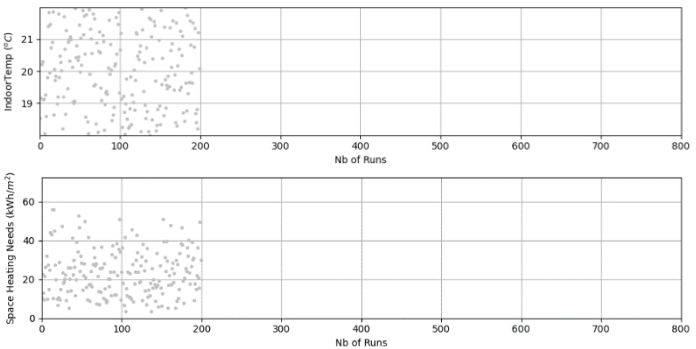
Initial non-correlated LH sample of size N

↓

Dynamic energy simulations



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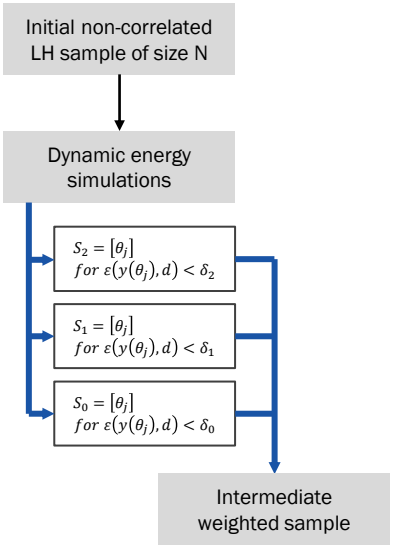

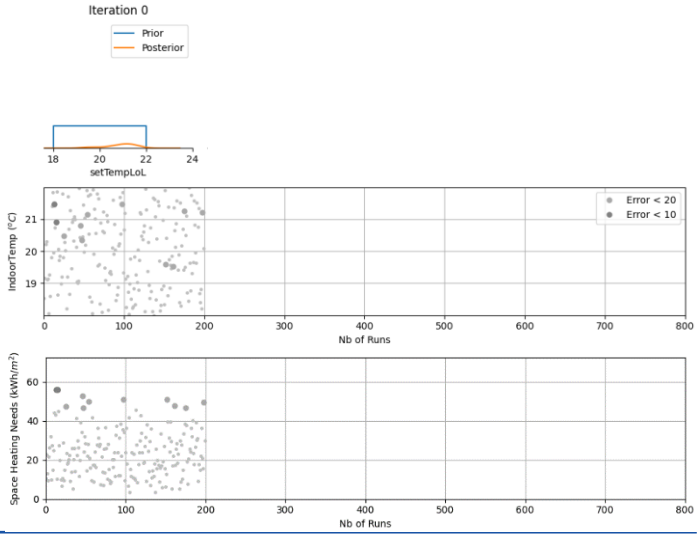

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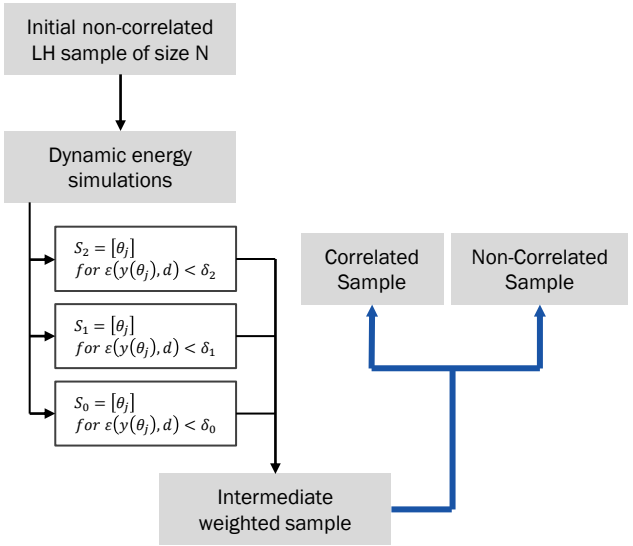

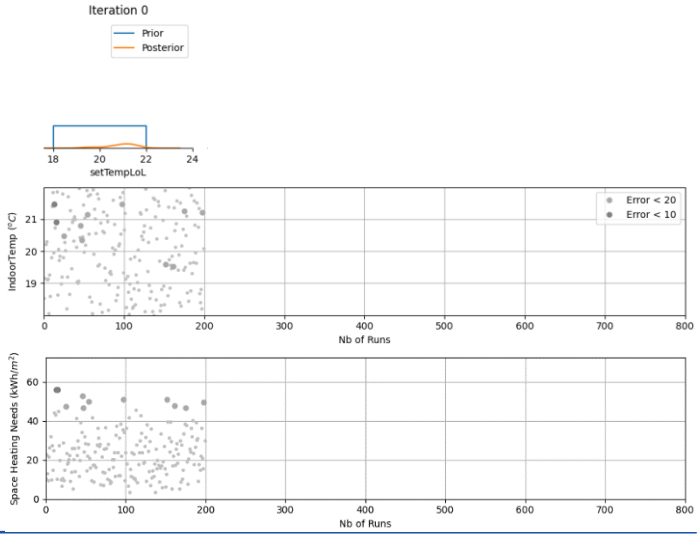

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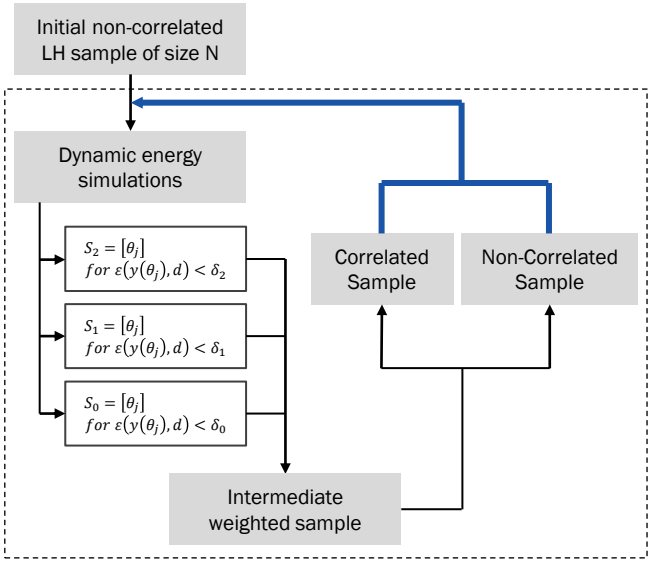

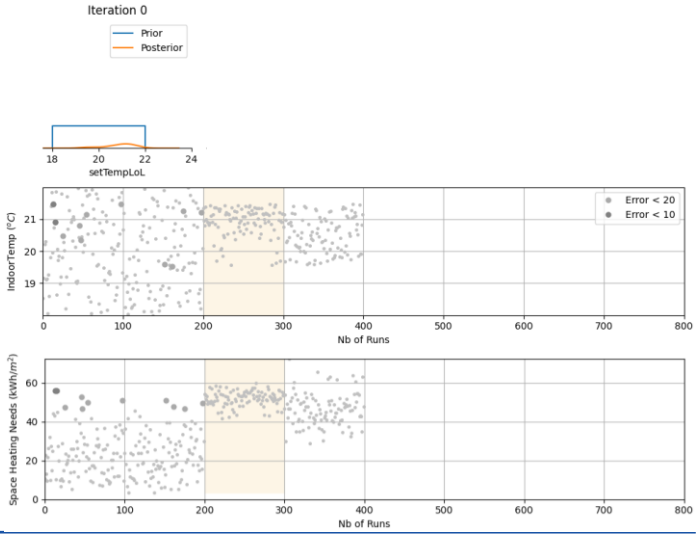

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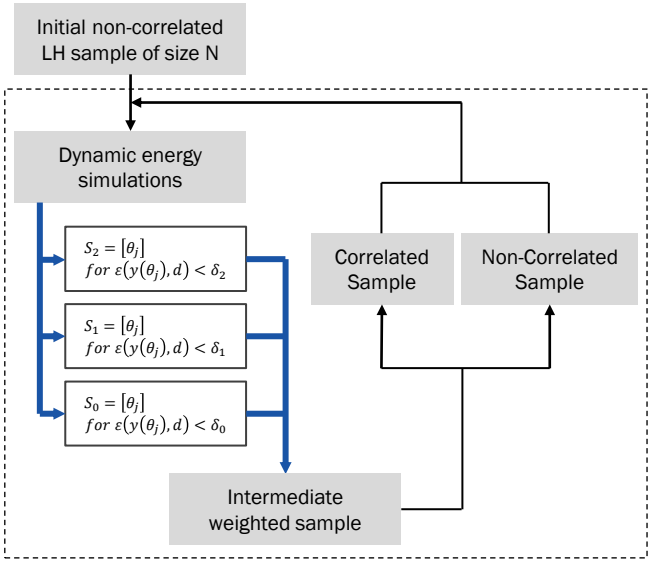

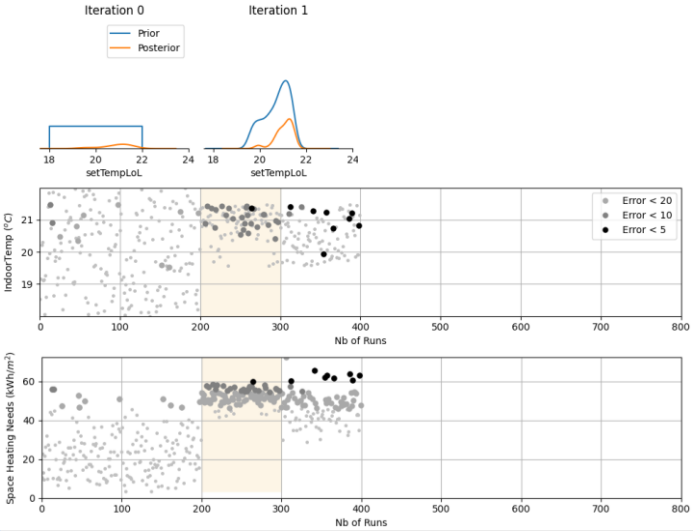

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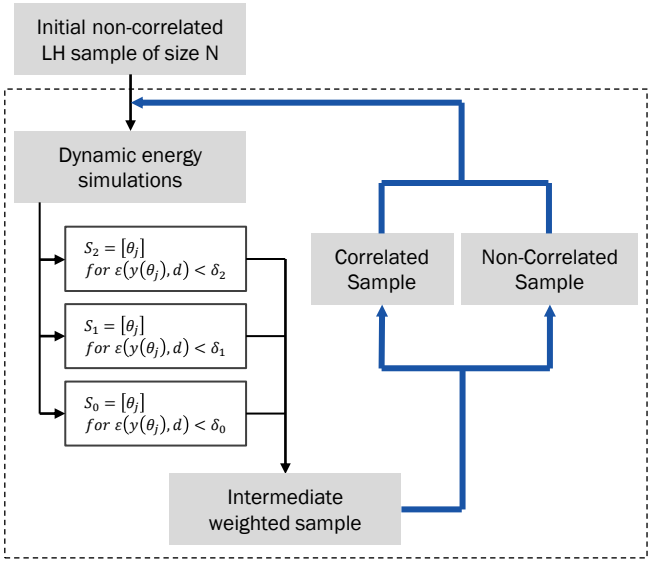

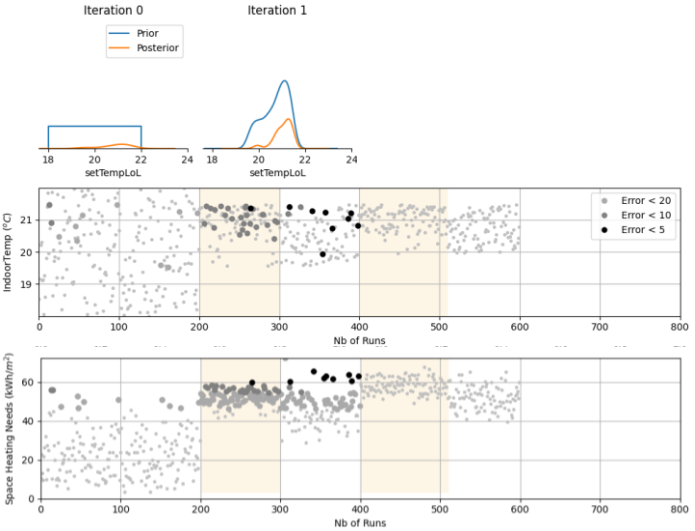

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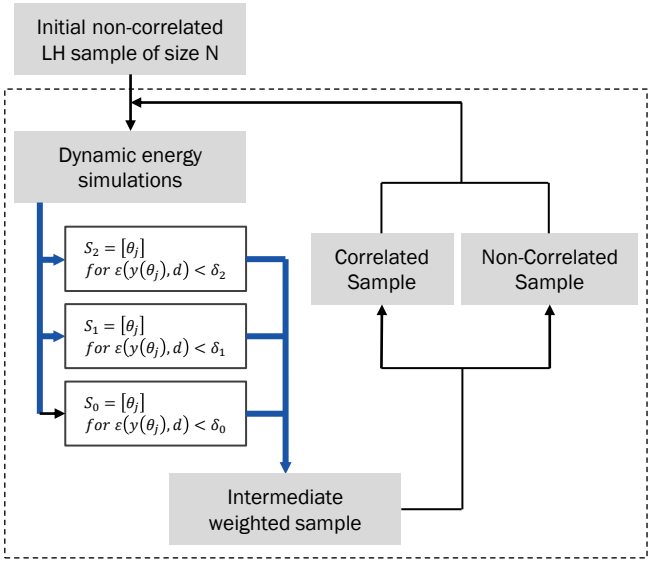

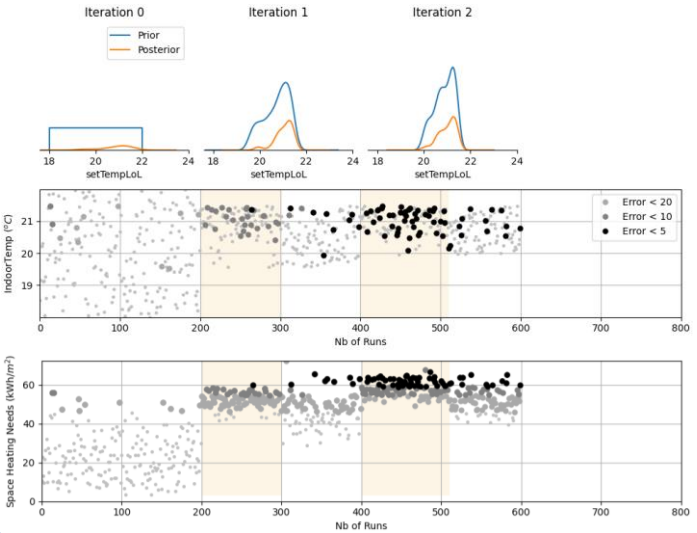

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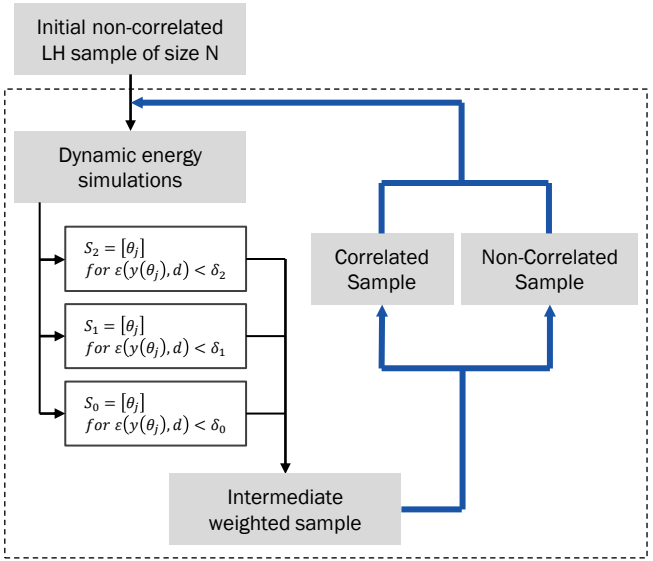

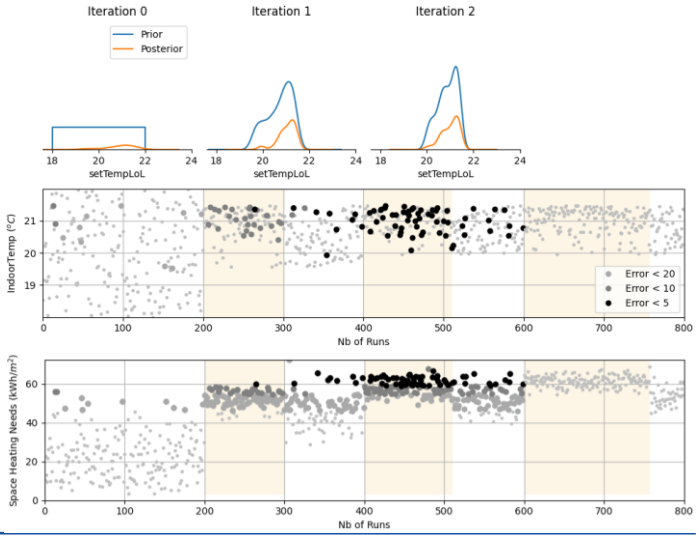

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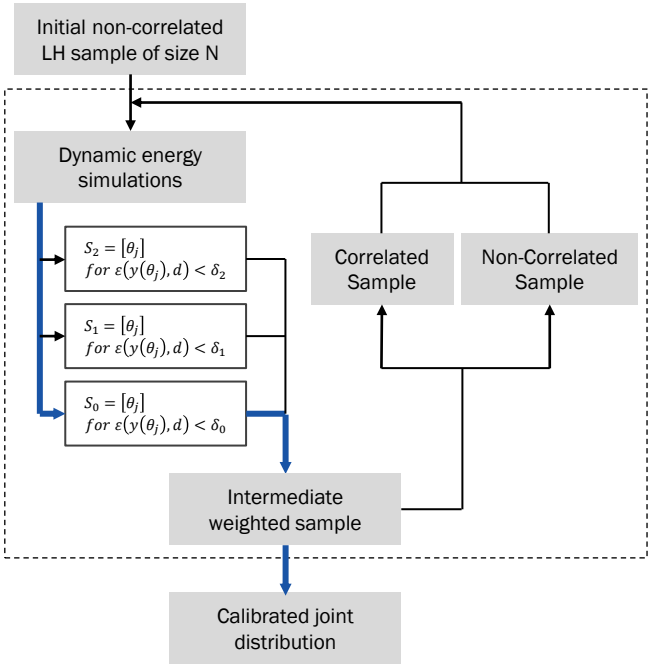
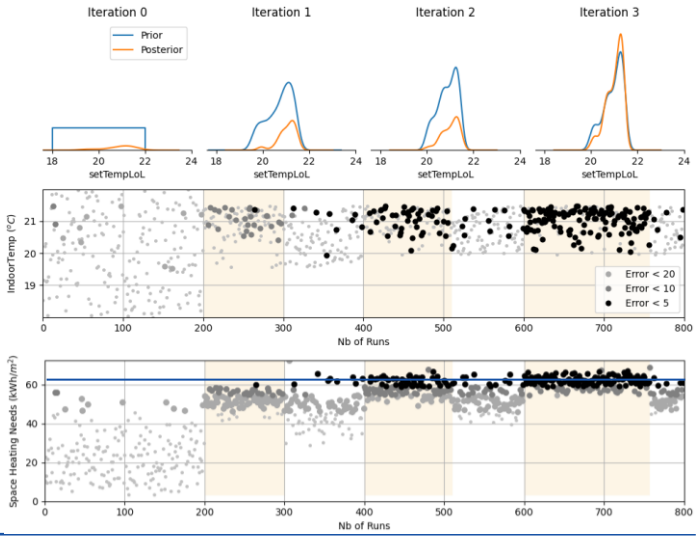
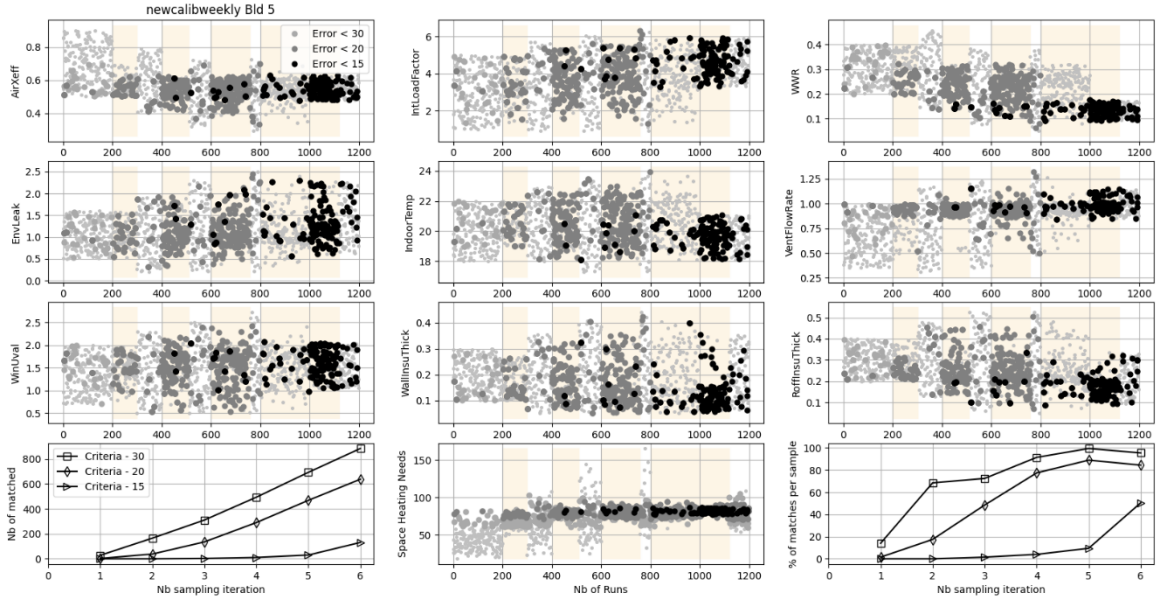




Calibration of Physics-based UBEM

Enhancing the trust of UBEM by undertaking calibration.
→found the joint distribution of unknown inputs that makes UBEM tool reliable.

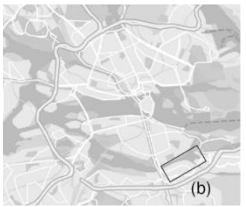
All the unknown parameters are tuned all together thanks to the iterative copula-based sampling process and to the newcomers (non correlated parameters)



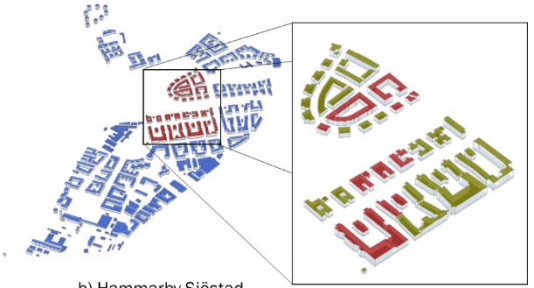
The use case with UBEM tool

The new calibration method has been tested with a 35 buildings district using hourly measured data for space heating and DHW with 9 unknown parameters.

- 1122 appartements.
- 129 340 m2 of residential type of occupancy (including modelling assumptions).
- 9 280 m2 of other type of occupancy (including modelling assumptions).



a) Stockholm



b) Hammarby Sjöstad

Data time resolution was considered by using yearly, monthly and weekly values as observations for the calibration process.

The calibrated UBEM tool was further used to compute energy savings from an ECM : Improving window's U-value.

ECM on formerly unknown parameter → modify the parameter's marginal
ECM on formerly known parameter → unique value, outside the joint distribution

The process was repeated 6 times :
~130 000 simulations – 9.5 days with 9 cores → 1 hour per building / Archetype in average

The use case with UBEM tool

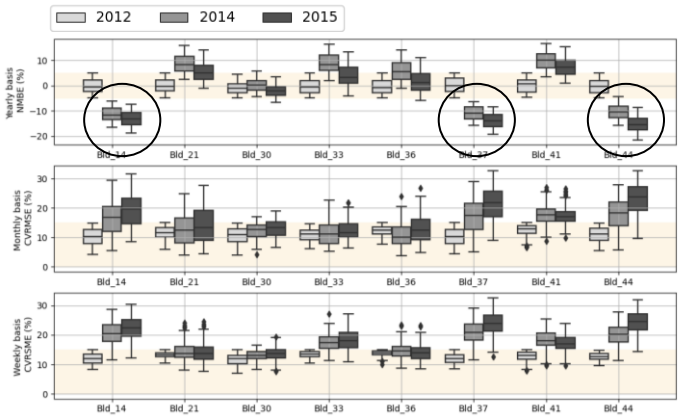
Results on the calibration process :

yearly basis → 32 buildings calibrated

monthly basis → 30 buildings calibrated

weekly basis → 27 buildings calibrated

- 973 appartements.
- 107 530 m2 of residential type of occupancy.
- 8 530 m2 of other type of occupancy.



Validation was performed using two other years on some buildings.

The worst cases correspond to changes in the energy signature.

Of course :

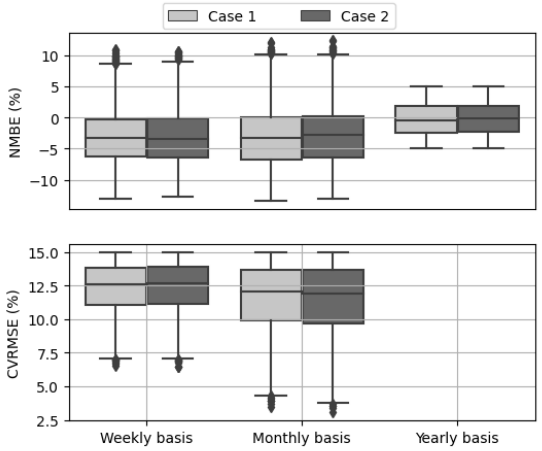
Other cases are needed, data, climate, etc….to confirm the strong potential of such approach.

The use case with UBEM tool

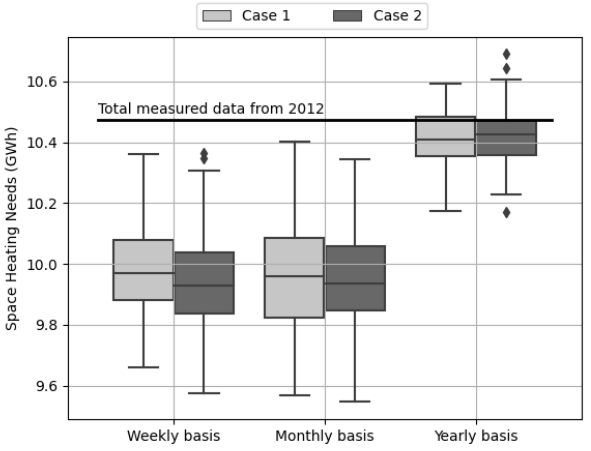
Results on the calibration process :

Building versus District scale, how good are the models ?

Error function distributions
(building scale of analyses)



Total energy needs for space heating
(district scale of analyses)



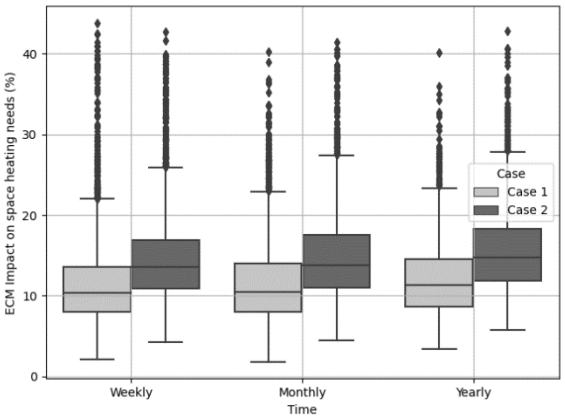
The global relative error remains around 5% in average, but the absolute is still around 500 MWh

The use case with UBEM tool

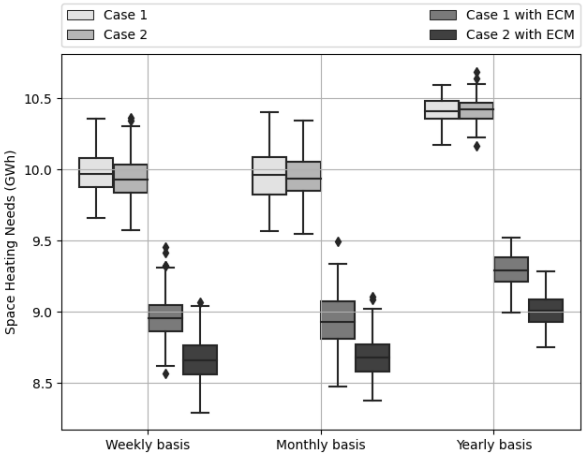
Results on the forecasted energy savings :

Building versus District scale, how close are the models ?

Energy Savings distributions
(building scale of analyses)



Total energy savings
(district scale of analyses)



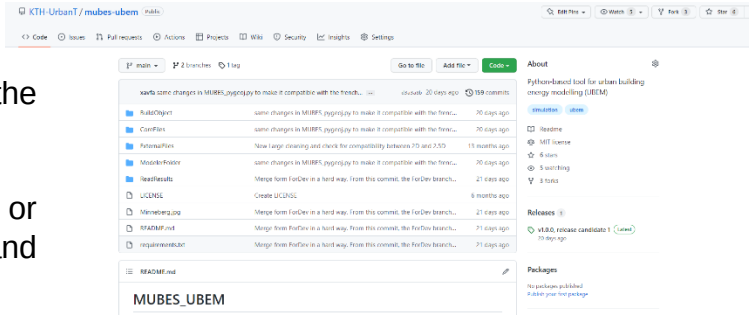
Case 1 and 2 differ by 3%. But this could still make the difference between different ECMs !!

MUBES is available and OpenSource

https://github.com/KTH-UrbanT/mubes-ubem

MUBES : Massive Urban Building Energy Simulation

E2B2 research program, project No. 46896-1



Compatible with 2D and 3D polygons for the building geometry.

Inputs can be given deterministically or probabilistically by distribution types and numbers of runs to launch.

Shadowing script from GeoJson is also available to consider specific surrounding effect.

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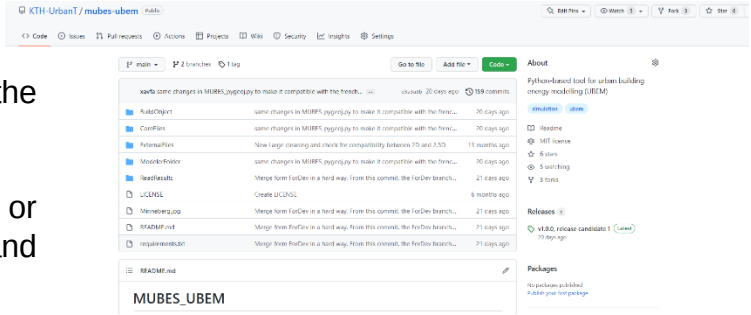

Compatible with 2D and 3D polygons for the building geometry.

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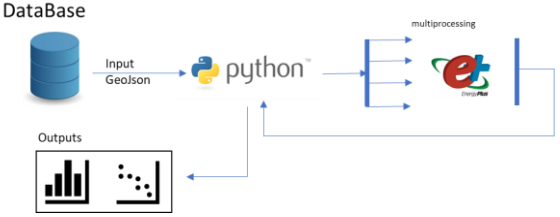
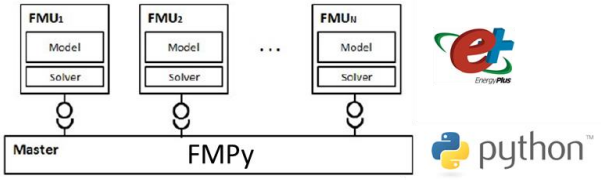
Made for

1) Automatic modelling and simulations



2) FMUs construction for co-Simulation



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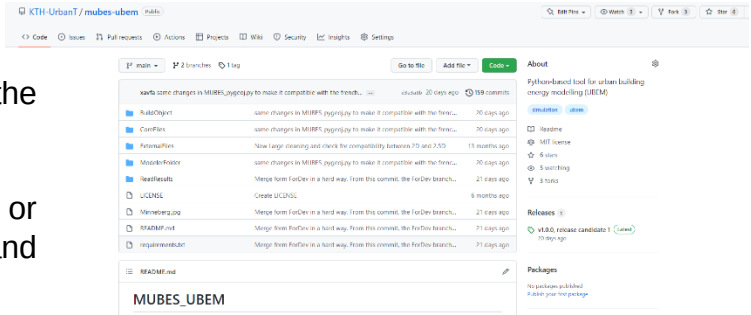


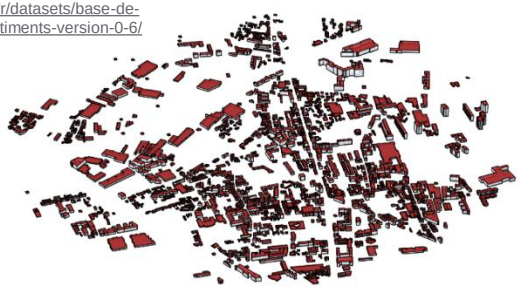
Compatible with 2D and 3D polygons for the building geometry.

Inputs can be given deterministically or probabilistically by distribution types and numbers of runs to launch.

Shadowing script from GeoJson is also available to consider specific surrounding effect.

Compatible with several input / Databases

French national building database :
https://www.data.gouv.fr/fr/datasets/base-de-donnee-nationale-des-batiments-version-0-6/



City database :
https://data.boston.gov/dataset/boston-buildings2

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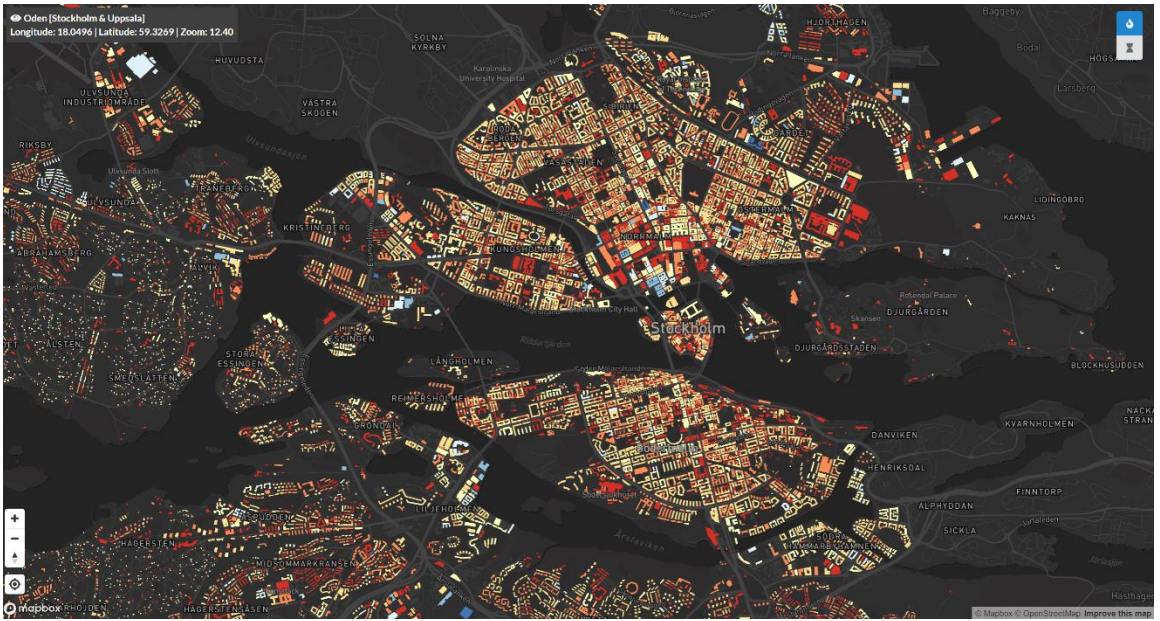
MUBES : Massive Urban Building Energy Simulation

E2B2 research program, project No. 46896-1

Of course, compatible with *ODEN* and available (soon) directly from the web page ☺ !



Massive Urban Building Energy Simulation / Modeling (MUBES-UBEM)

Thank You

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Xavier Faure

UrbanT, Research Group for Urban Analytics and Transitions
REI, Division of Resources, Energy and Infrastructure
SEED, Department of Sustainable Development, Environmental Science and Engineering
ABE, School of Architecture and the Built Environment