Digital twins for positive energy districts

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DigiTwins4PEDs

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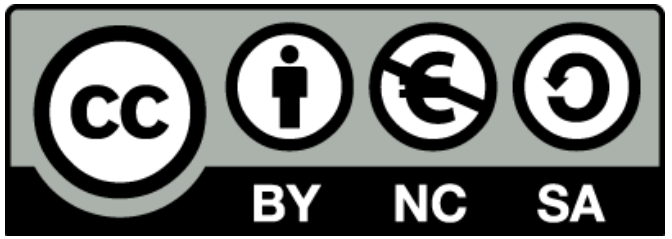
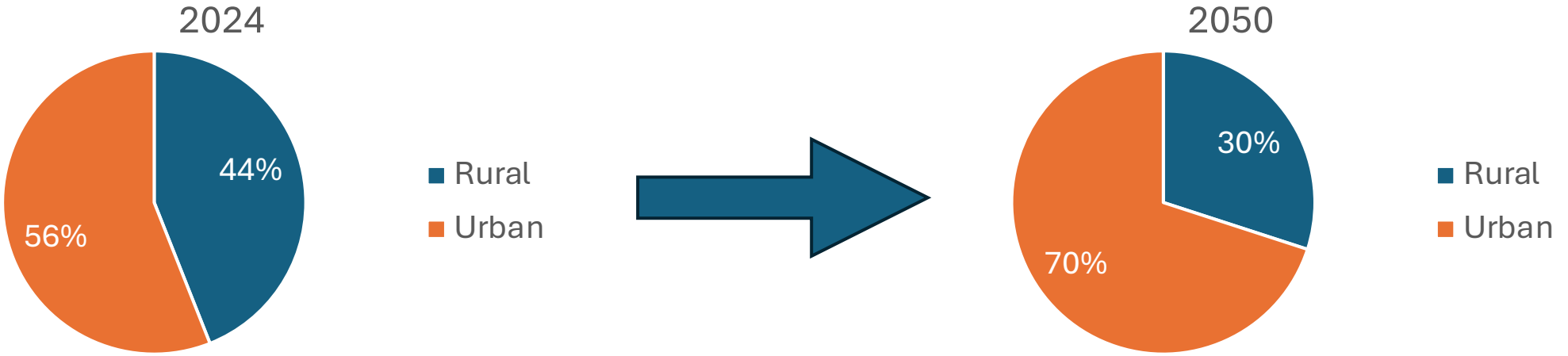


Context

- Planet's population is moving to urban areas



"Buildings are the **single largest energy consumer in Europe**"[1]

- Buildings require energy to ensure liveability and comfort
  - **Energy performance of a building** reflects its typical energy use
    - Envelope
    - Systems
    - Renewable

[1] https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/energy-performance-buildings-directive_en

Context

Urban Building Energy Modelling (UBEM)

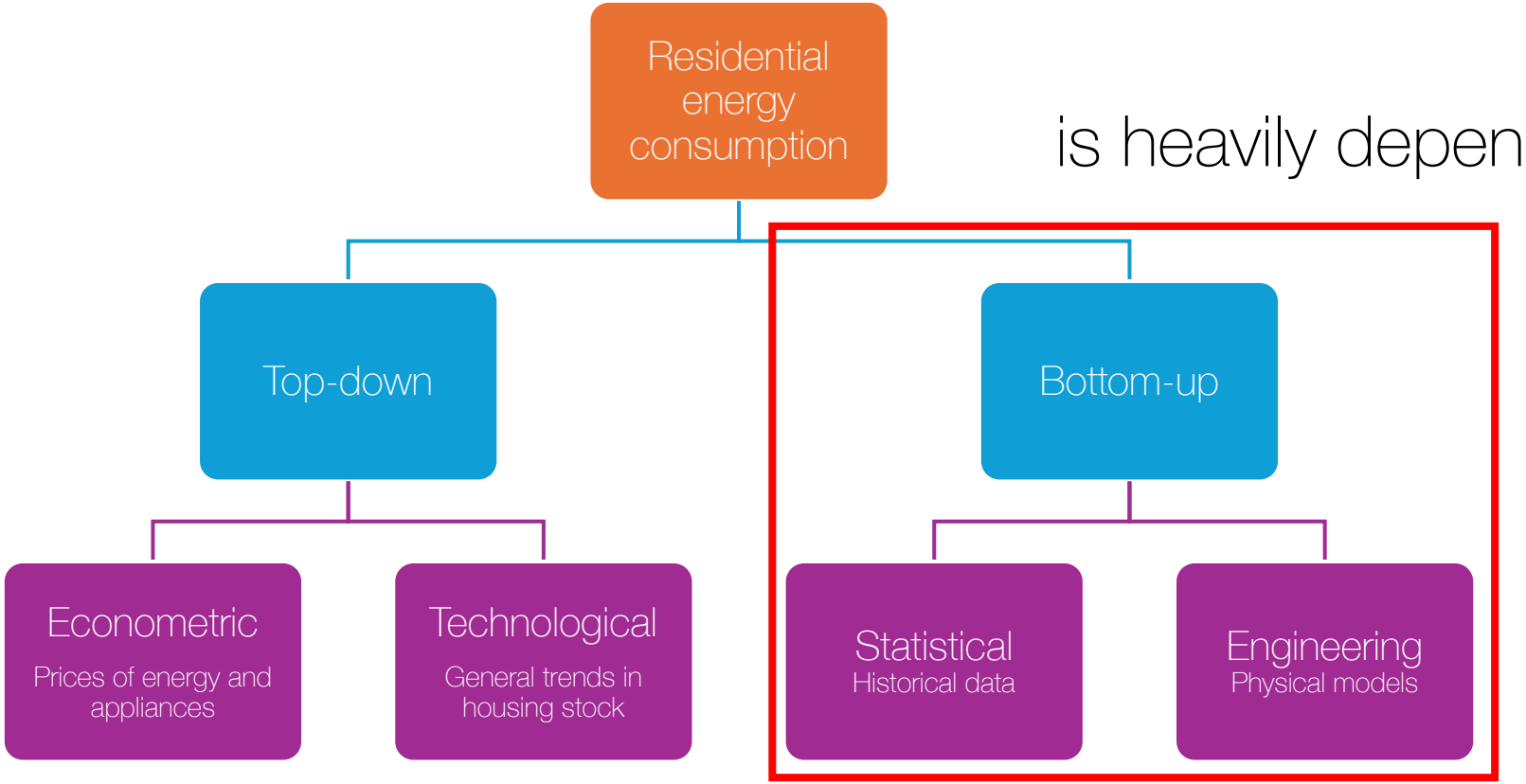
Involves:

- Techniques
- Methods
- Software tools

Enabling large-scale simulation and analysis of building energy performance

Context

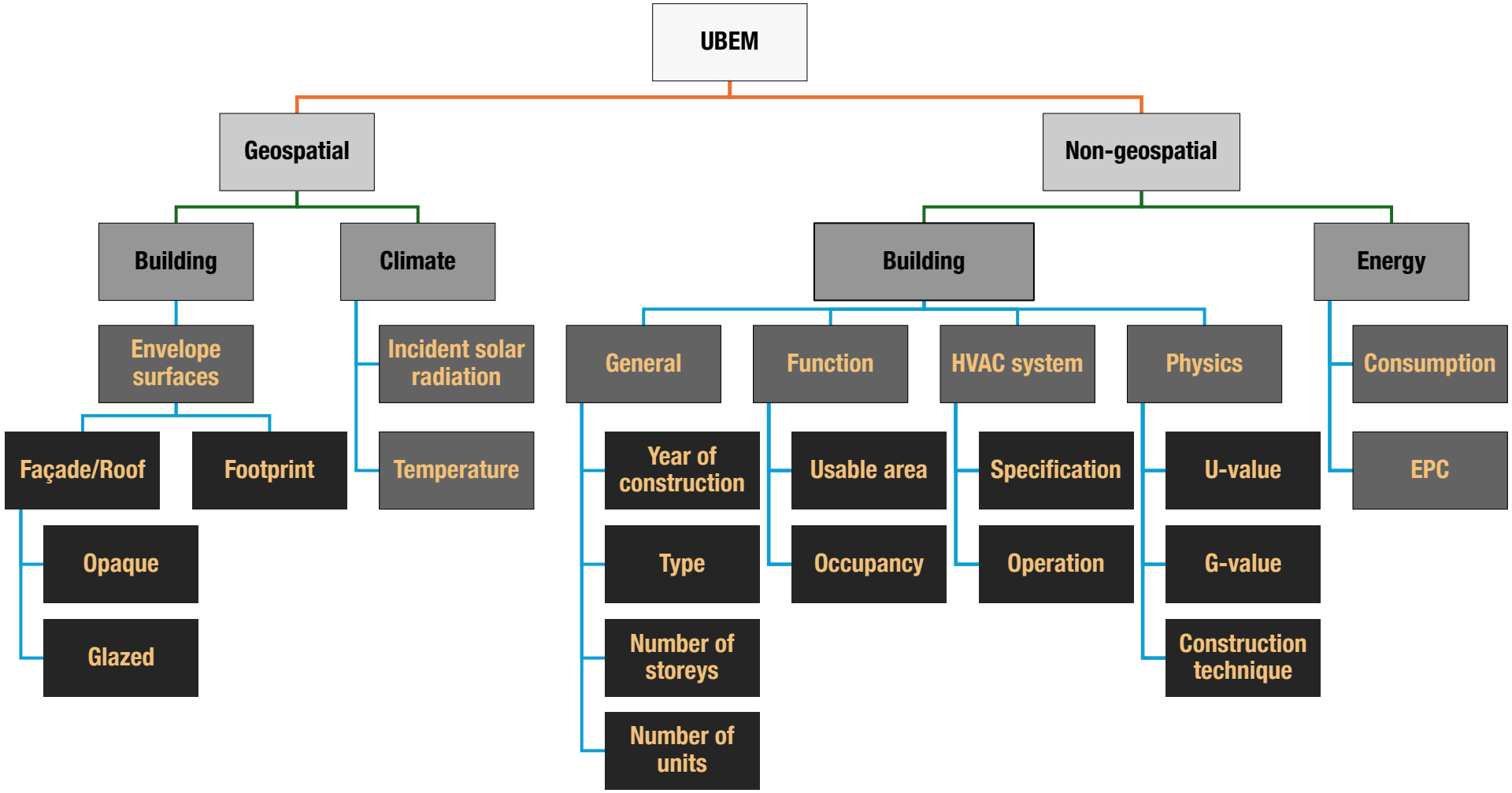
Urban Building Energy Modelling (UBEM)



is heavily dependent on data!

semantic 3D city models (s3DCMs) have emerged as a key asset in supporting bottom-up UBEM

Urban Building Energy Modelling (UBEM)



Urban Digital Twins?

DigiTwins4PEDs

- Digital representation of the real world
- Support modelling energy aspects of cities

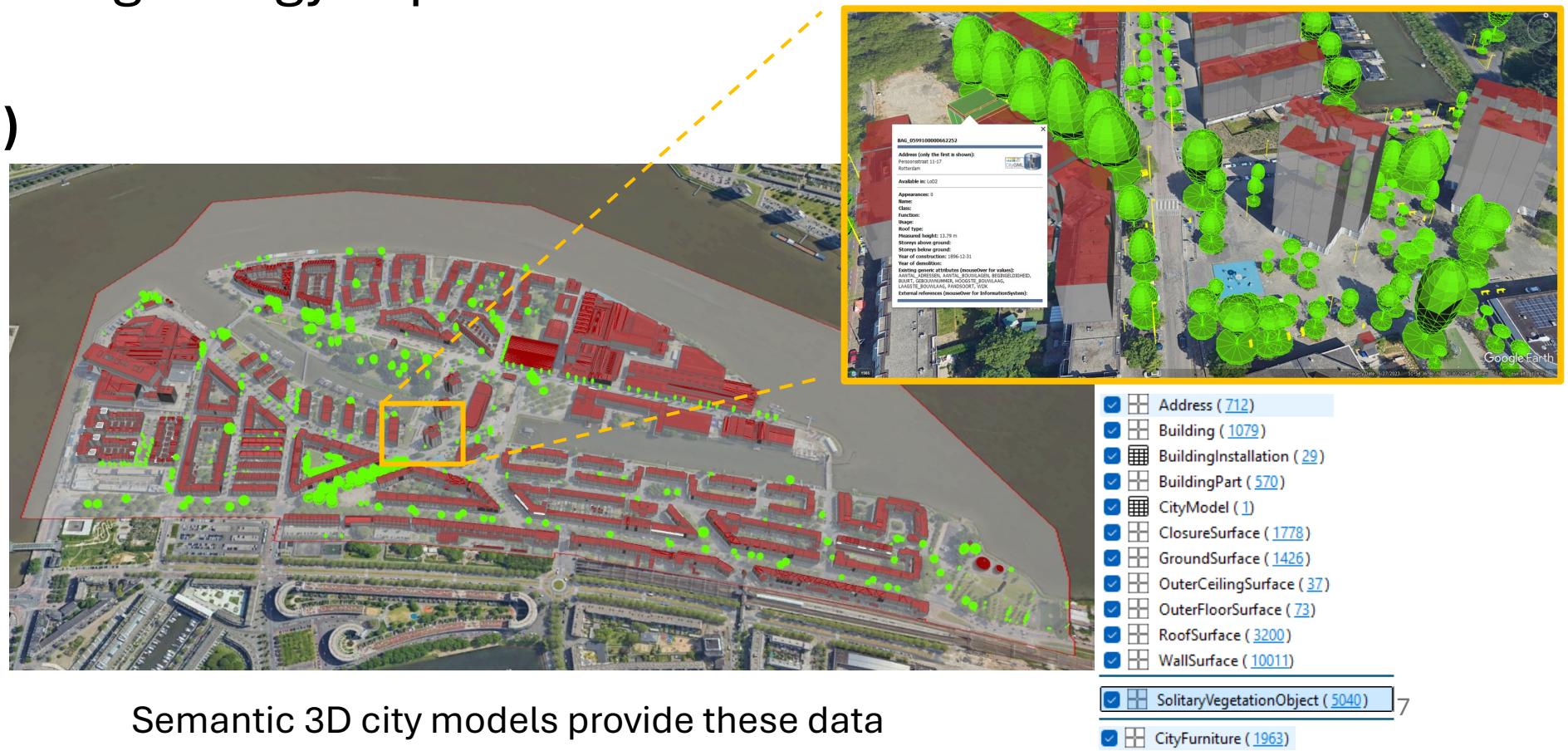
Feijenoord (Rotterdam)

CityGML:

Building

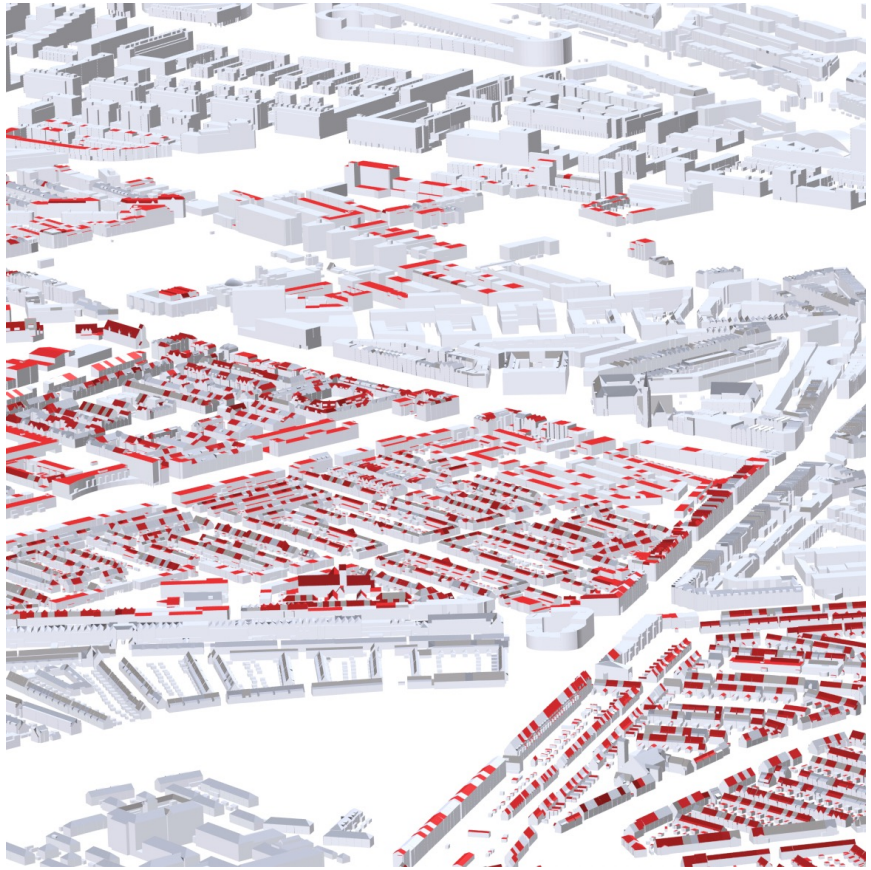
Vegetation

CityFurniture

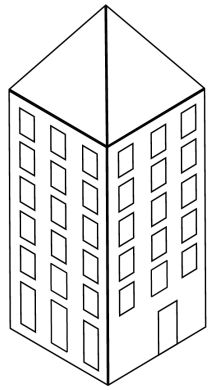


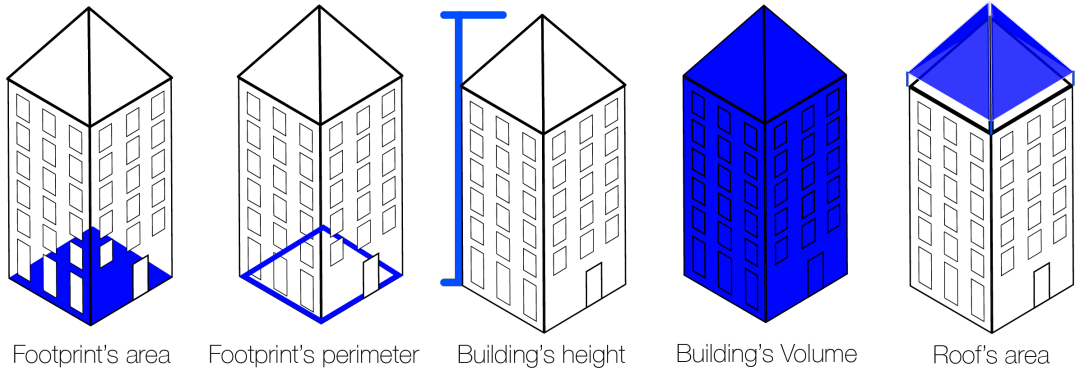
Semantic 3D city models provide these data

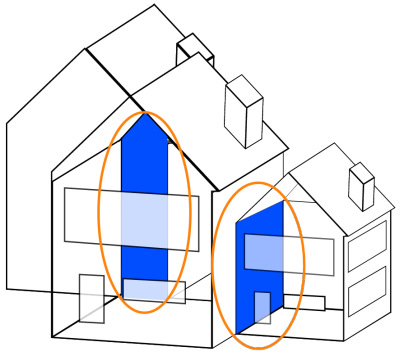
Building data requirements for energy performance analyses

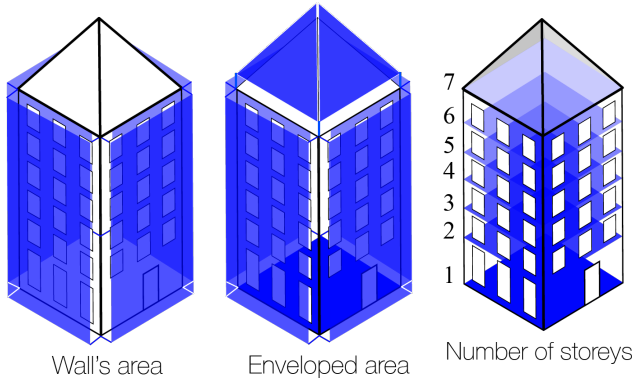


Kop van Zuid (Rotterdam), Netherlands

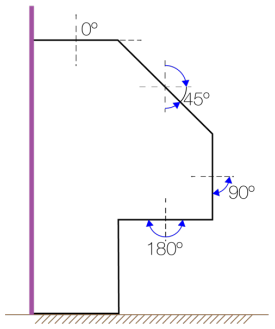


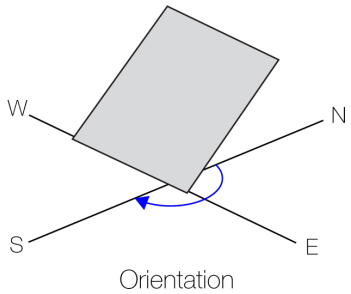






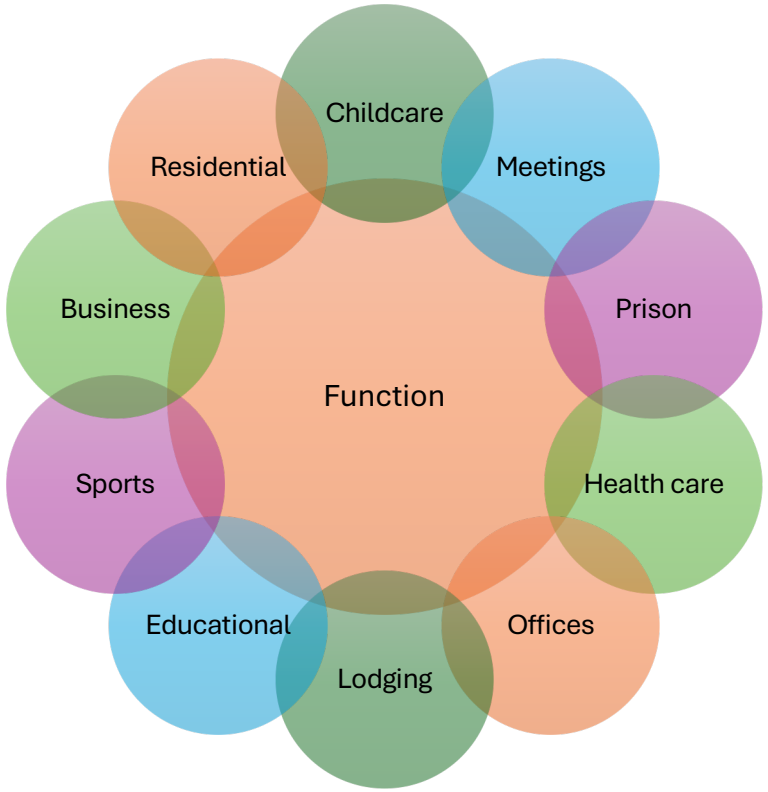
Geometry





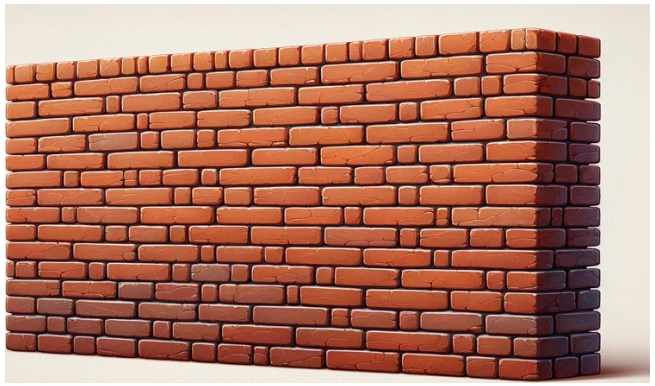
Building data requirements for energy performance analyses

Semantics

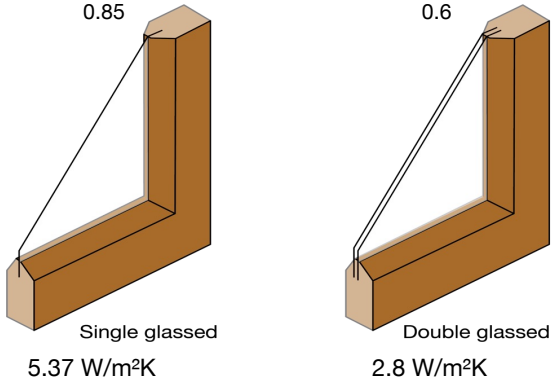


Usable area

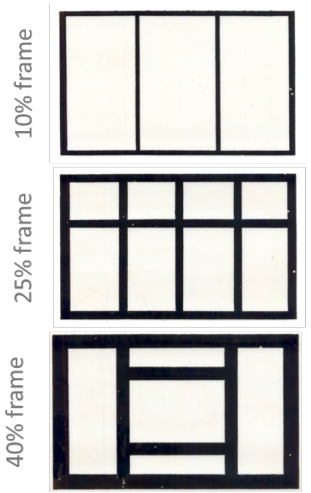
Units per property



Bricks 2.0
W/m²K

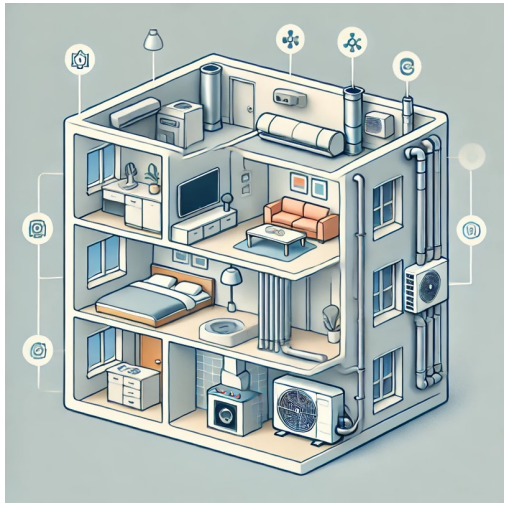


Year of construction



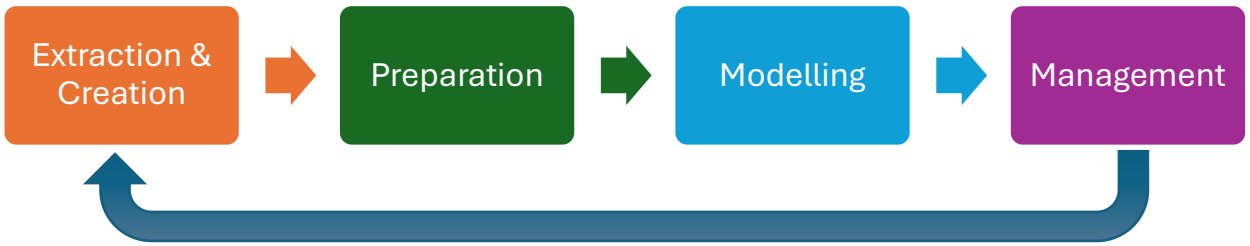
Windows to frame ratio

Insulated wall 0.3
W/m²K



HVAC systems

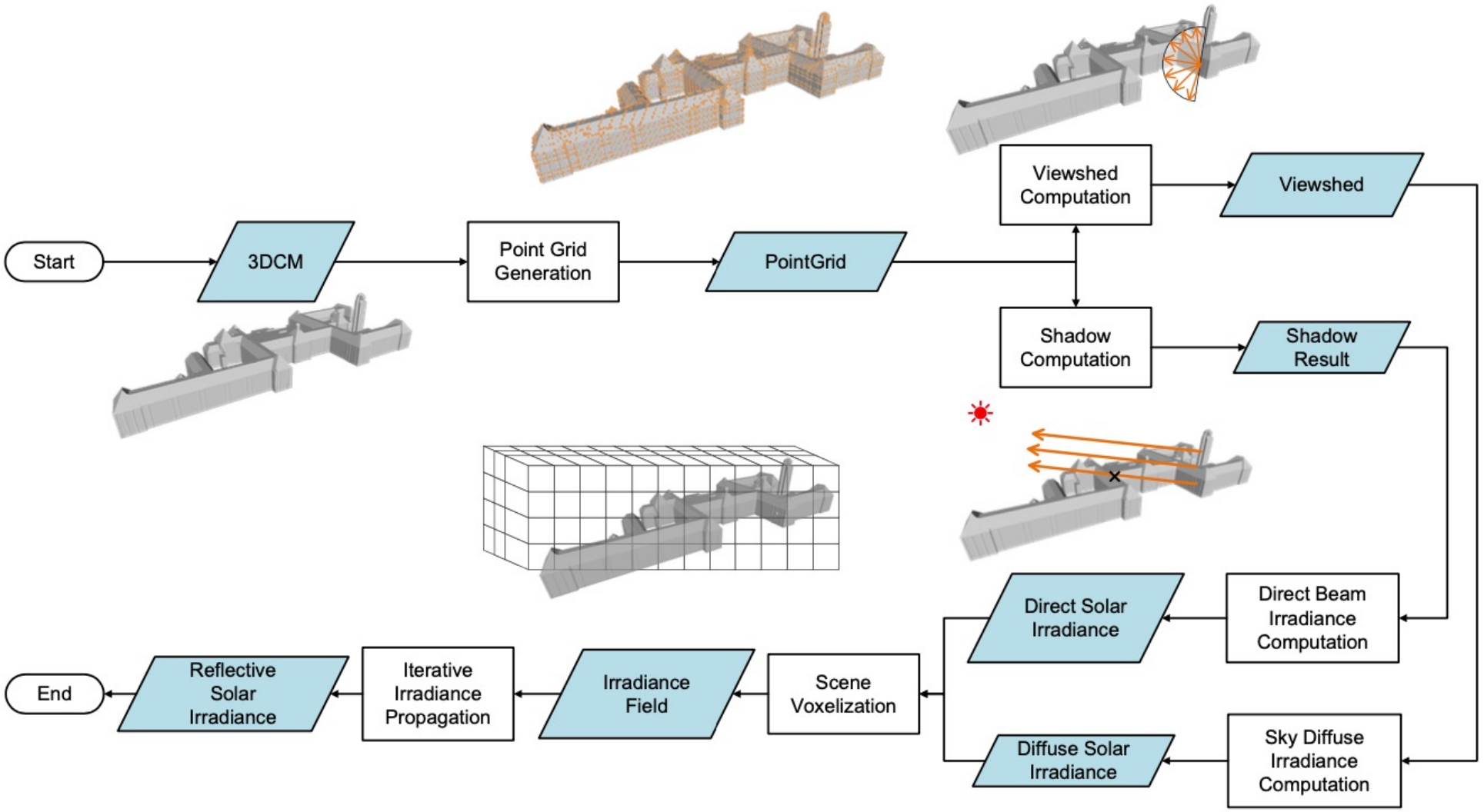
Data - The Interconnected Pipeline



Data extraction & data creation

Data Extraction & Creation

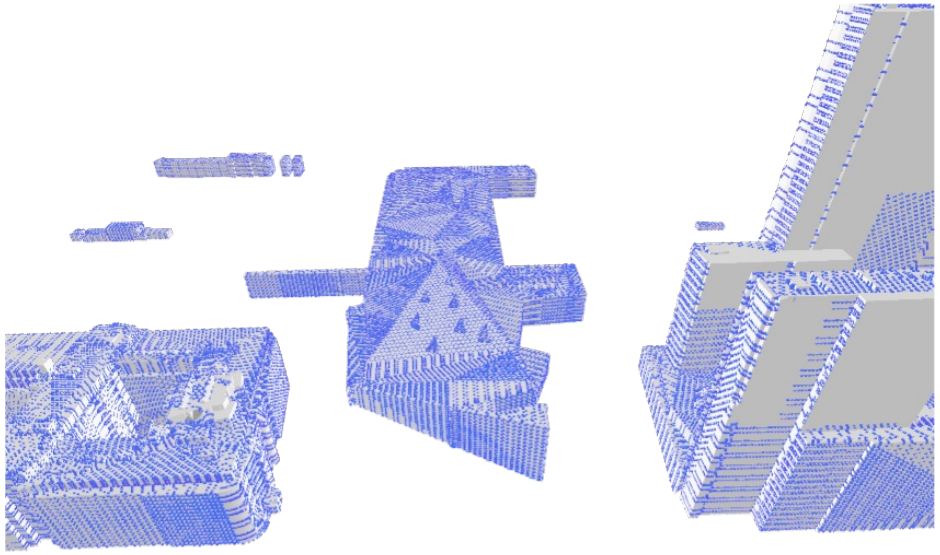
High-resolution, large-scale, and fast calculation of solar irradiance with 3D City Models

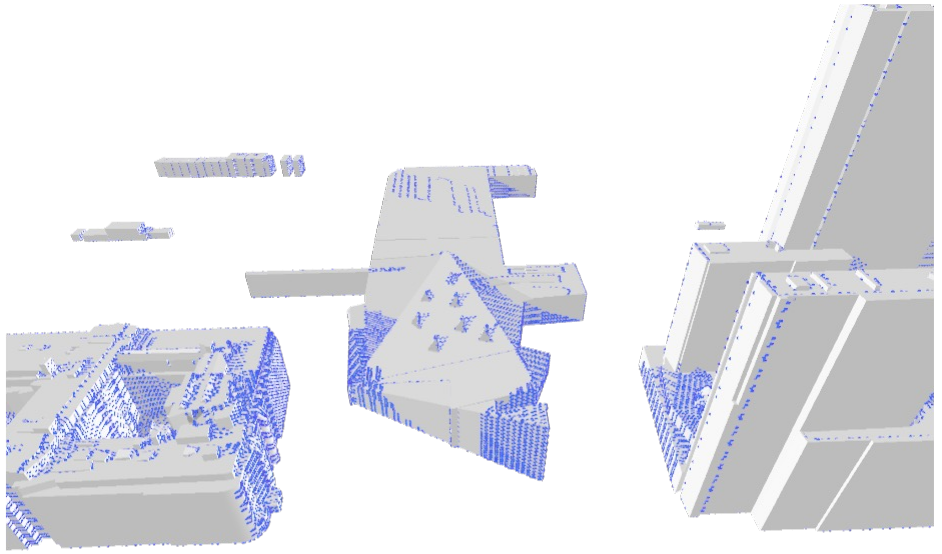


Data Extraction & Creation

High-resolution, large-scale, and fast calculation of solar irradiance with 3D City Models

Rotterdam Centraal
2023-10-01





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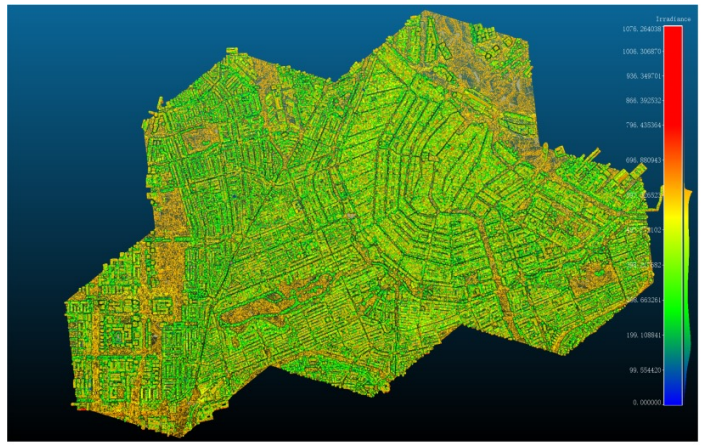
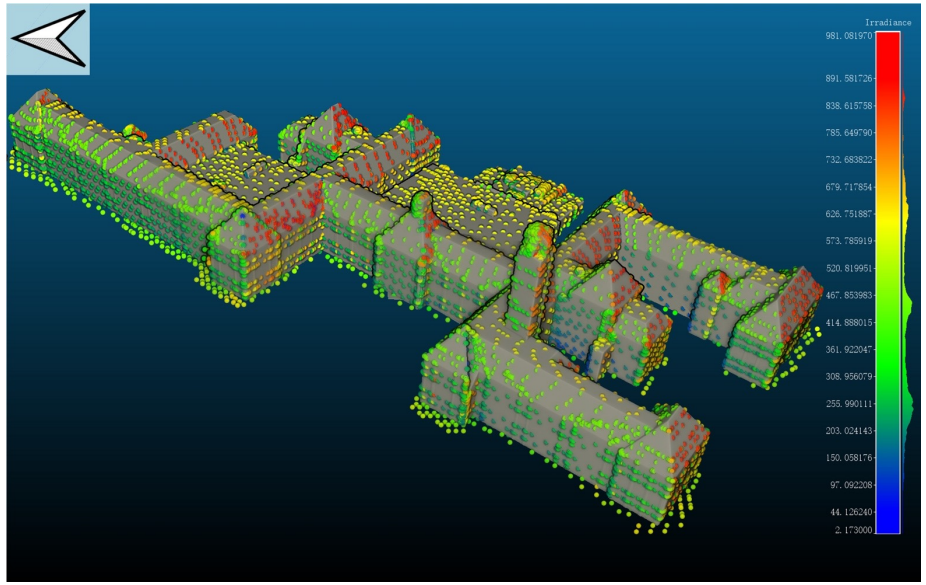
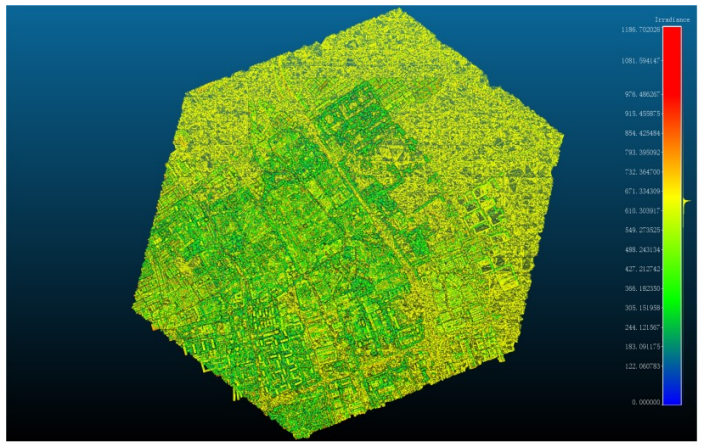


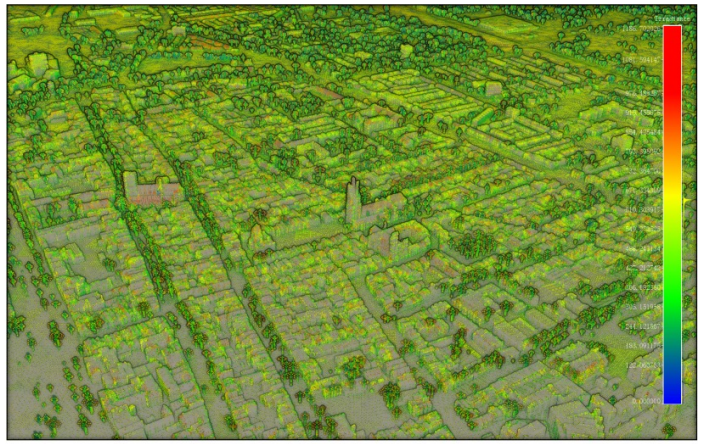
(a) Amsterdam - overview

(b) Amsterdam - zoomed in





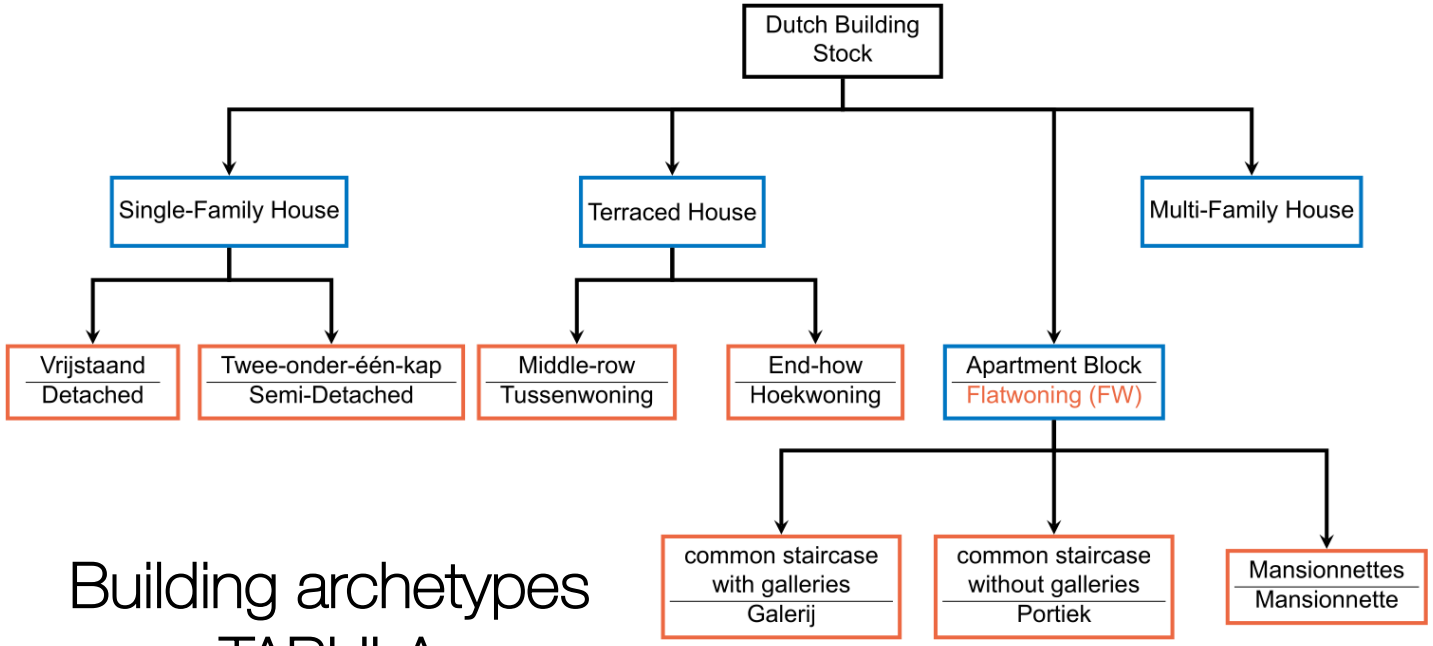
(c) Delft - overview



(d) Delft - zoomed in

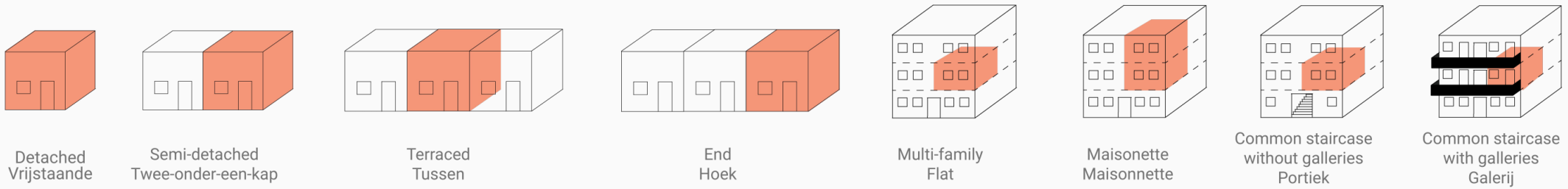
Data Extraction & Creation

Inferring the residential building type from 3DBAG



Building archetypes TABULA

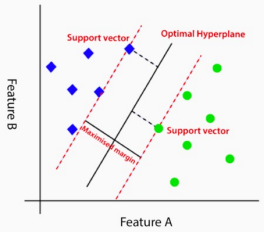
- Dutch residential buildings



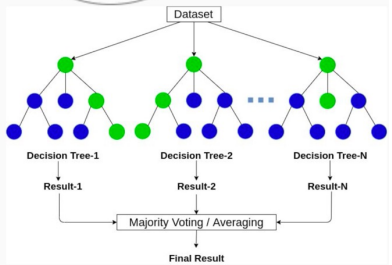
Data Extraction & Creation

Inferring the residential building type from 3DBAG

Support Vector Machine

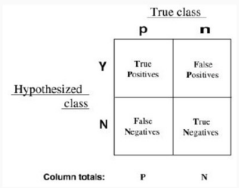


Random Forest



Confusion Matrix

- Precision
- Recall
- F1-score



$$\text{Precision} = \frac{TP}{(TP+FP)}$$

$$\text{Recall} = \frac{TP}{(TP+FN)}$$

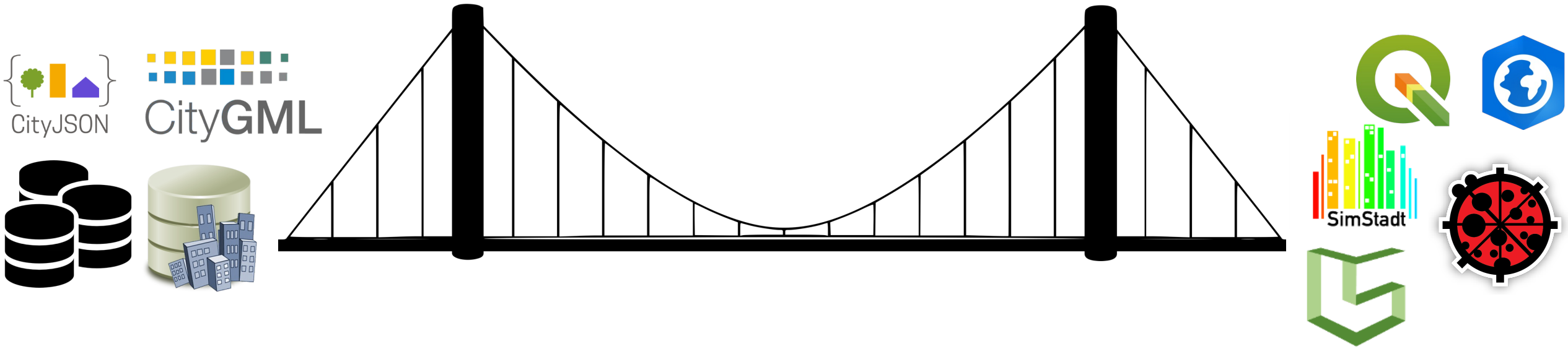
$$\text{F1-score} = \frac{2(Precision \cdot Recall)}{(Precision + Recall)}$$

	F1-score	Model
Case study 3 flat	0.95	c2 SVM ANOVA-F
Case study 4 galerij	0.69	c2 RF impurity, c2 RF permutation
Case study 5 maisonnette	0.30	c2 RF permutation
Case study 6 portiek	-	-
Case study 7 rij_2o1k	0.94*	c1 RF impurity, c1 RF permutation, c2 RF permutation
Case study 8 vrijstaande	1.00	c1 SVM MI, c1 RF permutation

		Case Study 1				Case Study 2			
		SVM ANOVA-F	SVM MI	RF impurity	RF permu.	SVM ANOVA-F	SVM MI	RF impurity	RF permu.
Case Study 3 flat	Accuracy	75.8%	79.5%	87.9%	82.1%	85.4%	43.7%	80.2%	90.4%
	Balanced accuracy	49.2%	50.6%	53.9%	51.6%	36.7%	24.9%	74.9%	66.7%
Case Study 4 galerij	Accuracy	85.5%	86.0%	87.7%	87.3%	80.3%	30.0%	90.3%	89.4%
	Balanced accuracy	59.6%	60.4%	64.5%	60.5%	32.3%	11.3%	78.2%	81.5%
Case Study 5 maisonnette	Accuracy	60.1%	59.9%	63.5%	61.1%	75.0%	53.4%	67.5%	69.8%
	Balanced accuracy	54.7%	49.6%	62.3%	65.5%	39.6%	26.0%	60.5%	60.6%
Case Study 6 portiek	Accuracy	17.0%	18.1%	26.7%	63.1%	82.1%	34.0%	68.5%	71.2%
	Balanced accuracy	42.8%	43.0%	44.8%	51.6%	40.2%	33.0%	68.6%	62.6%
Case Study 7 rij_2o1k	Accuracy	89.4%	83.2%	89.2%	89.0%	60.8%	27.9%	80.2%	86.0%
	Balanced accuracy	71.8%	62.8%	67.7%	67.4%	35.4%	23.9%	74.9%	78.9%
Case Study 8 vrijstaande	Accuracy	98.0%	98.5%	81.9%	98.5%	86.9%	83.4%	93.0%	93.0%
	Balanced accuracy	90.6%	94.2%	66.6%	91.4%	43.4%	28.6%	72.0%	64.2%

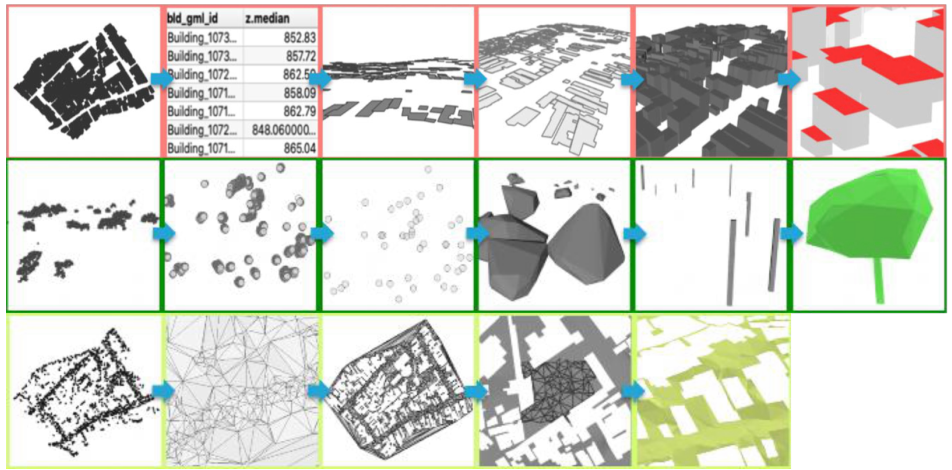
Data Preparation

Data Preparation

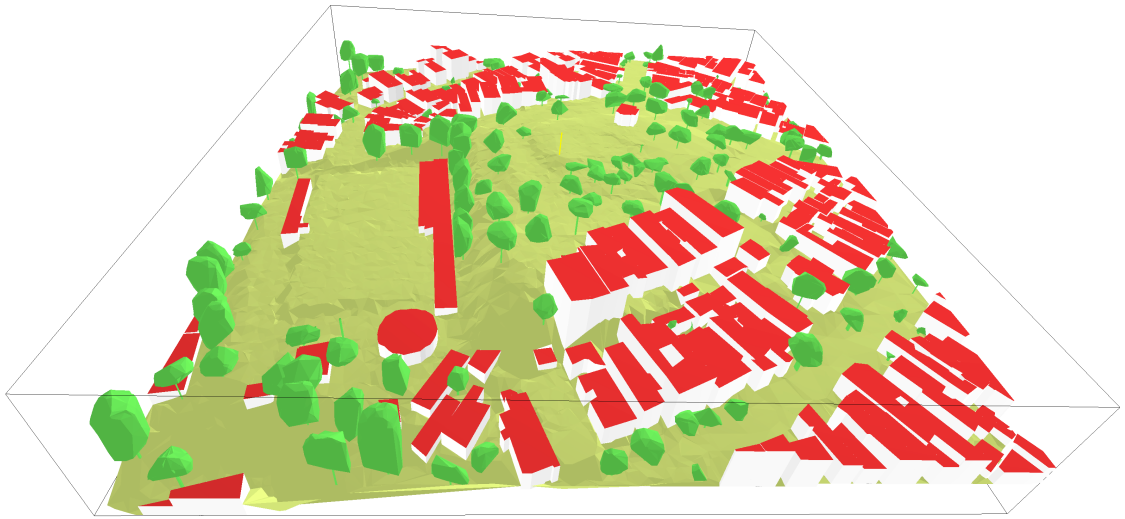


Data Preparation

Solar analysis on buildings of favelas in São Paulo to estimate pv potential



FME



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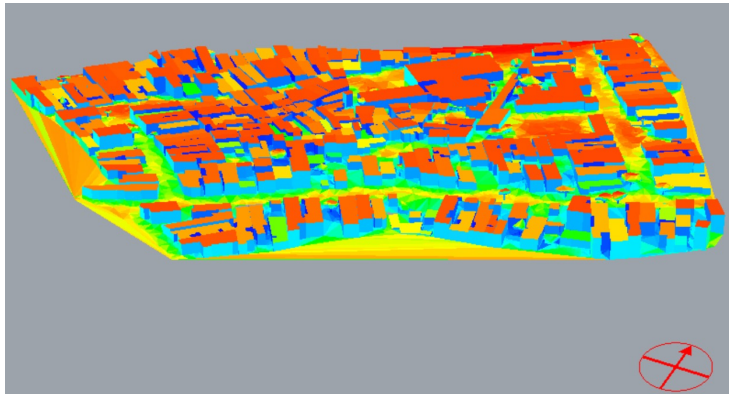
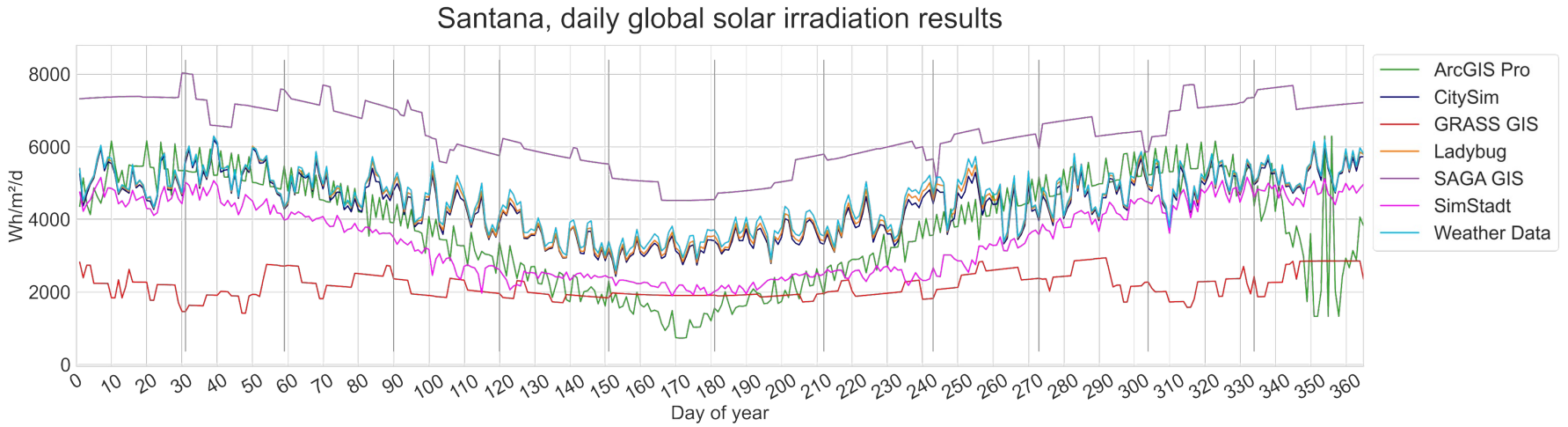
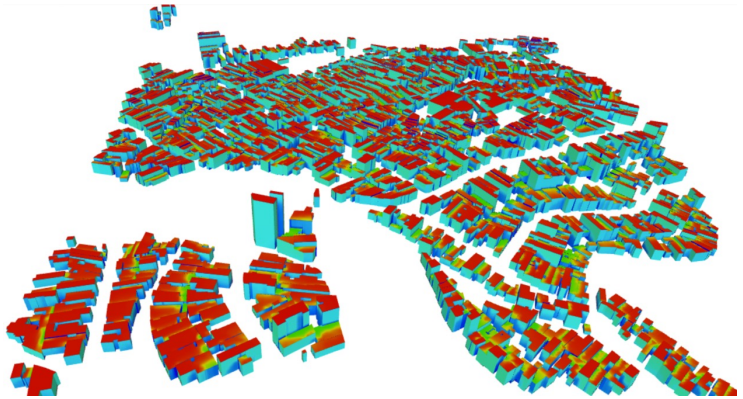
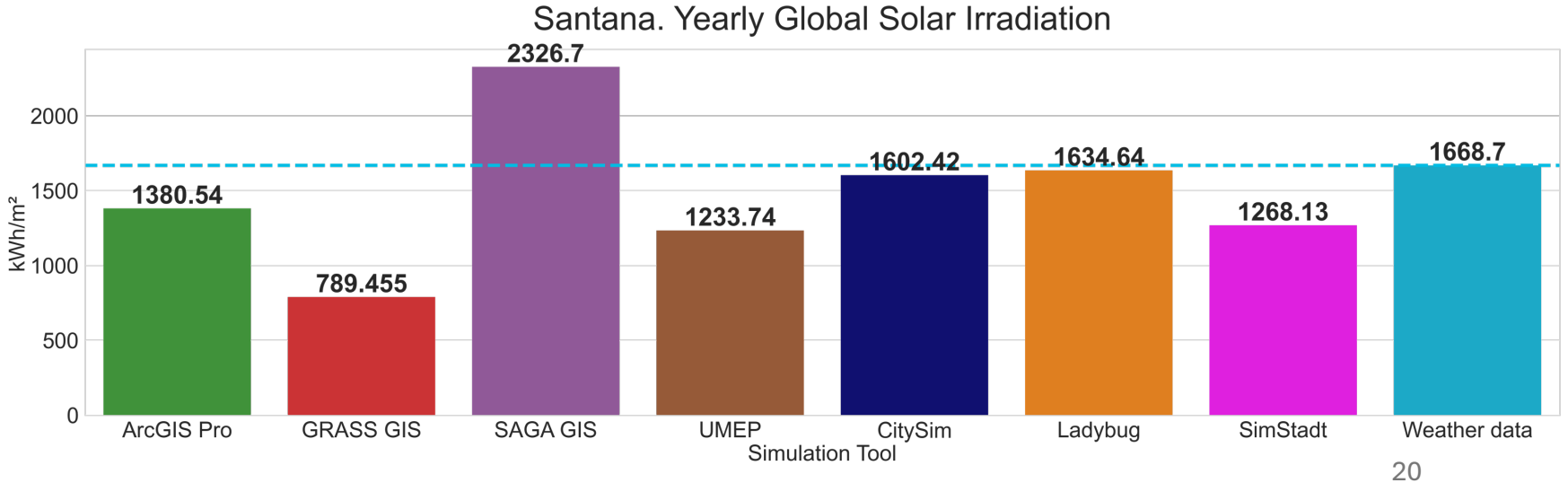


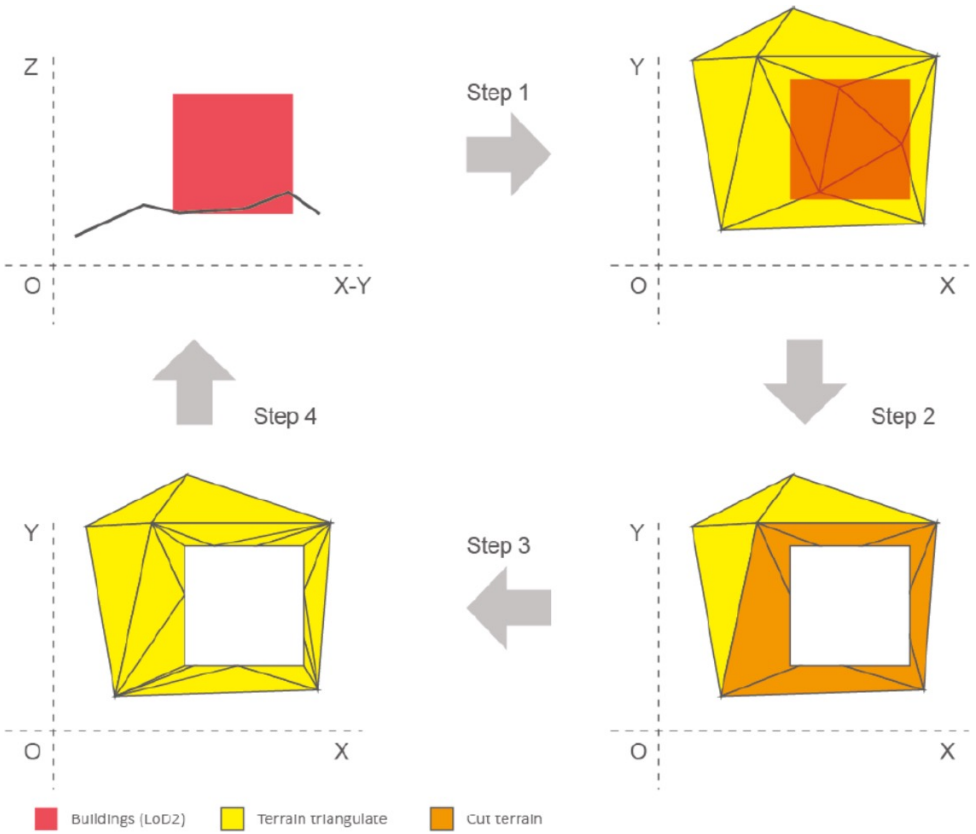


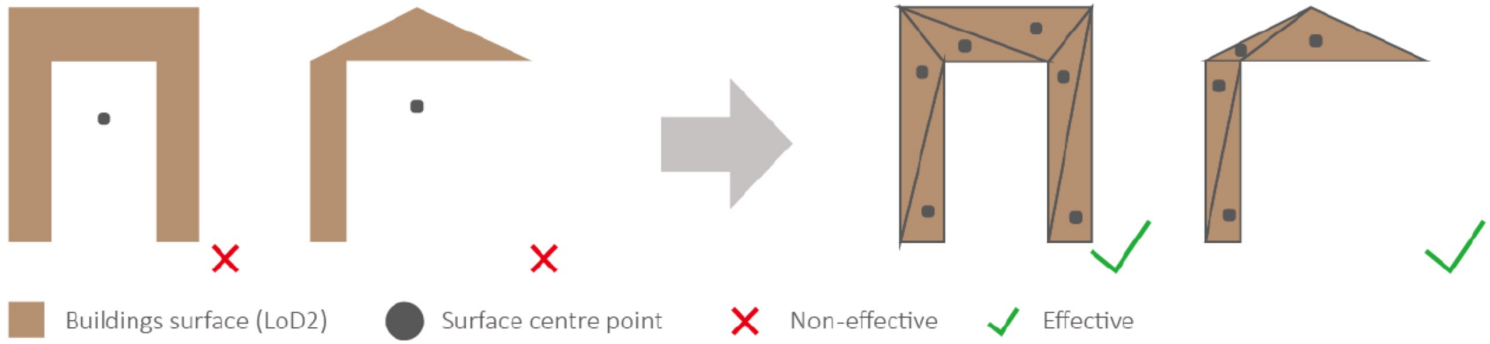


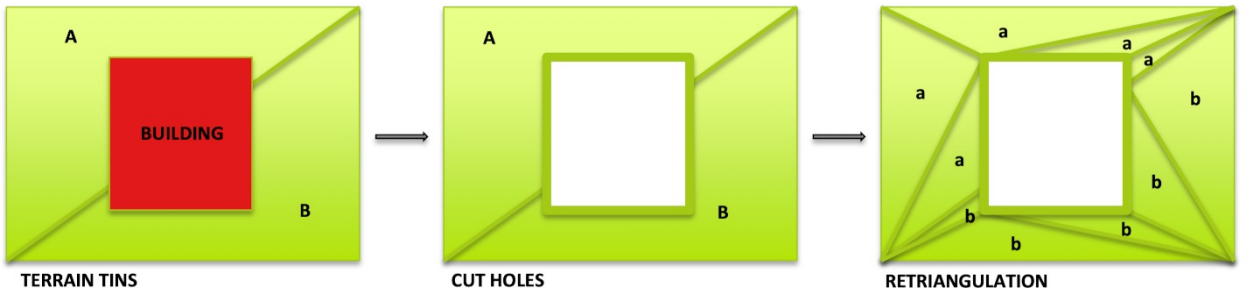


Data Preparation

Dynamic energy simulations based on the 3D BAG 2.0



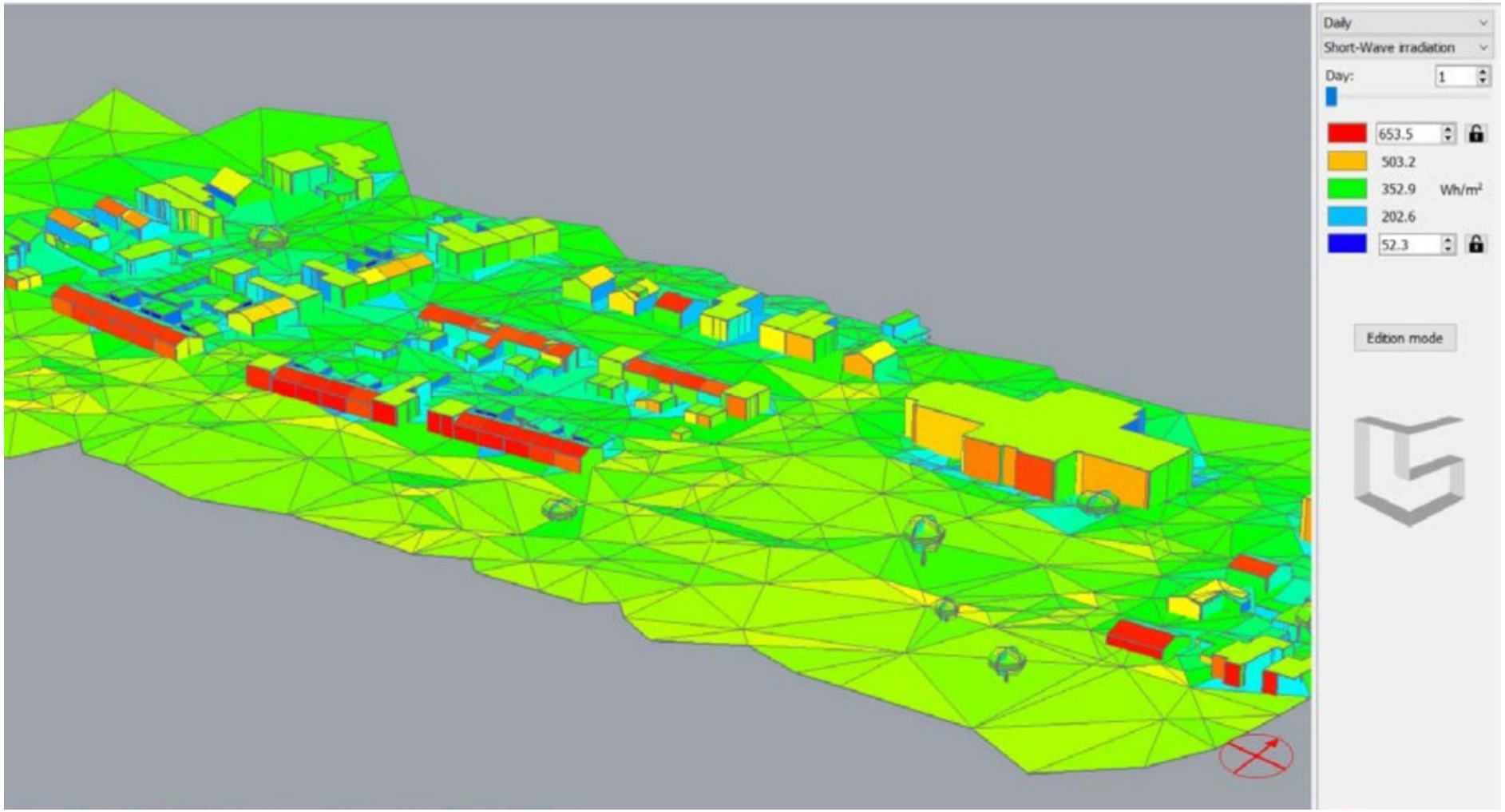




Data Preparation

Dynamic energy simulations based on the 3D BAG 2.0

Building physics data from Building archetypes



Data Preparation

Modelling tree-planting strategy to reduce heating and cooling demand under 2050 climate conditions

You would like the view of the tree in general

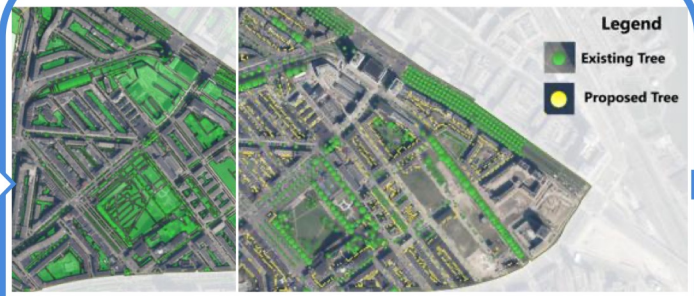
In summer, you'd appreciate the coolness it brings

But in winter, that same tree blocks the warmth you long for

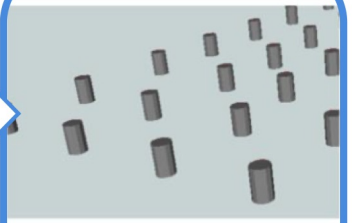
More heater use = higher electricity bill

Can we support the **3-30-300 rule** to help reduce the effects of **climate change, without unintentionally increasing electricity bills** across neighbourhoods?

Process land use data



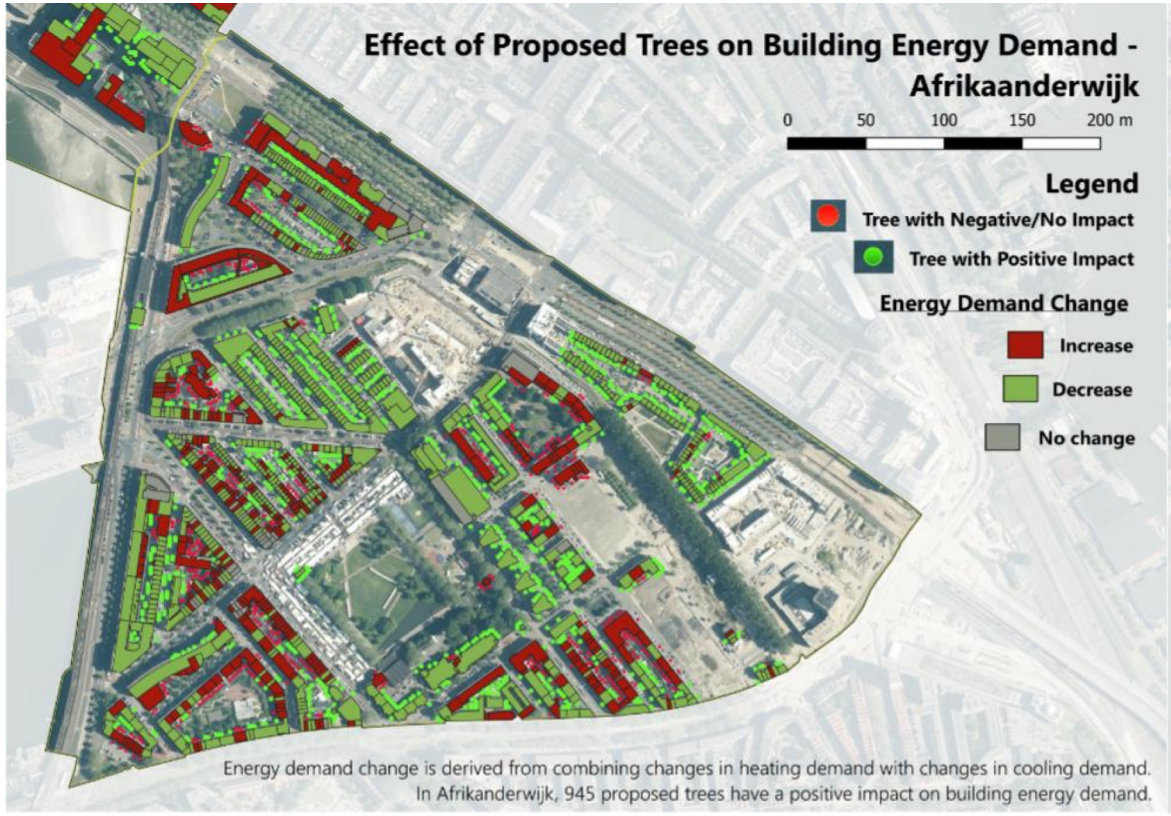
To generate potential planting areas and then generate the proposed tree points on it

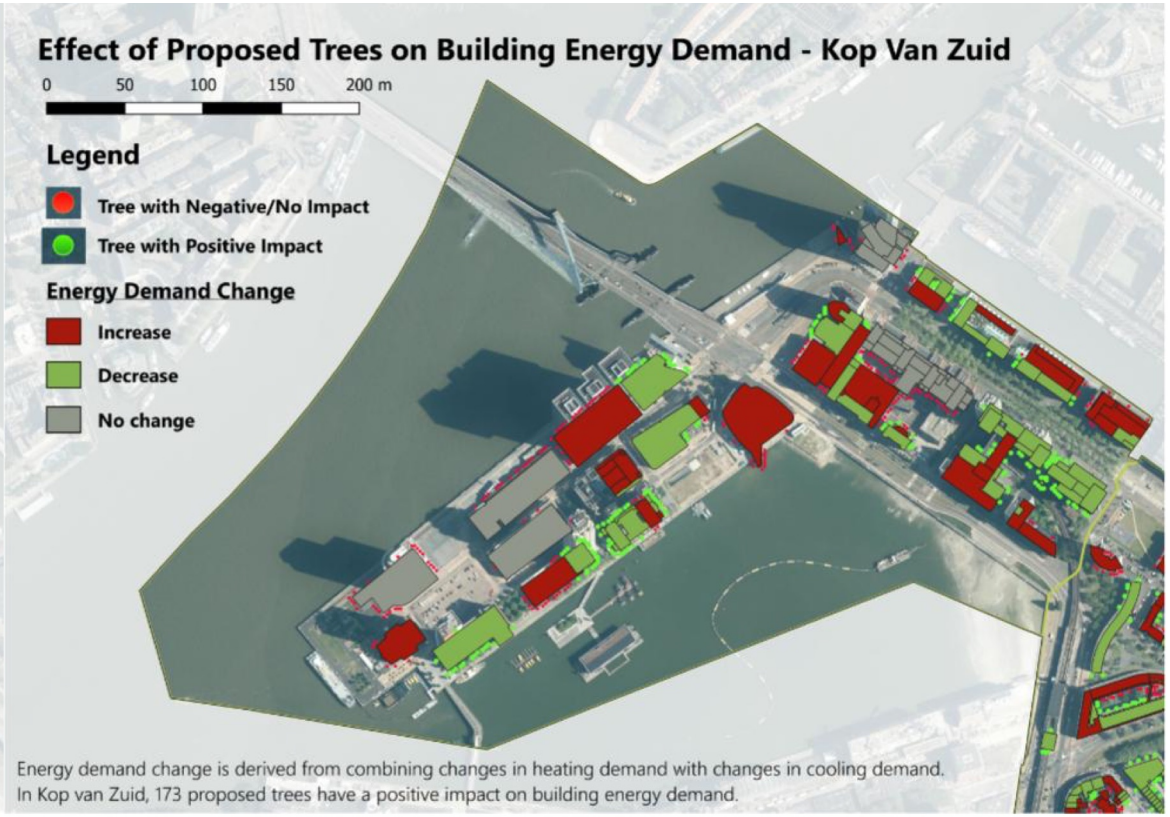


Cyllindrical proposed trees

Data Preparation

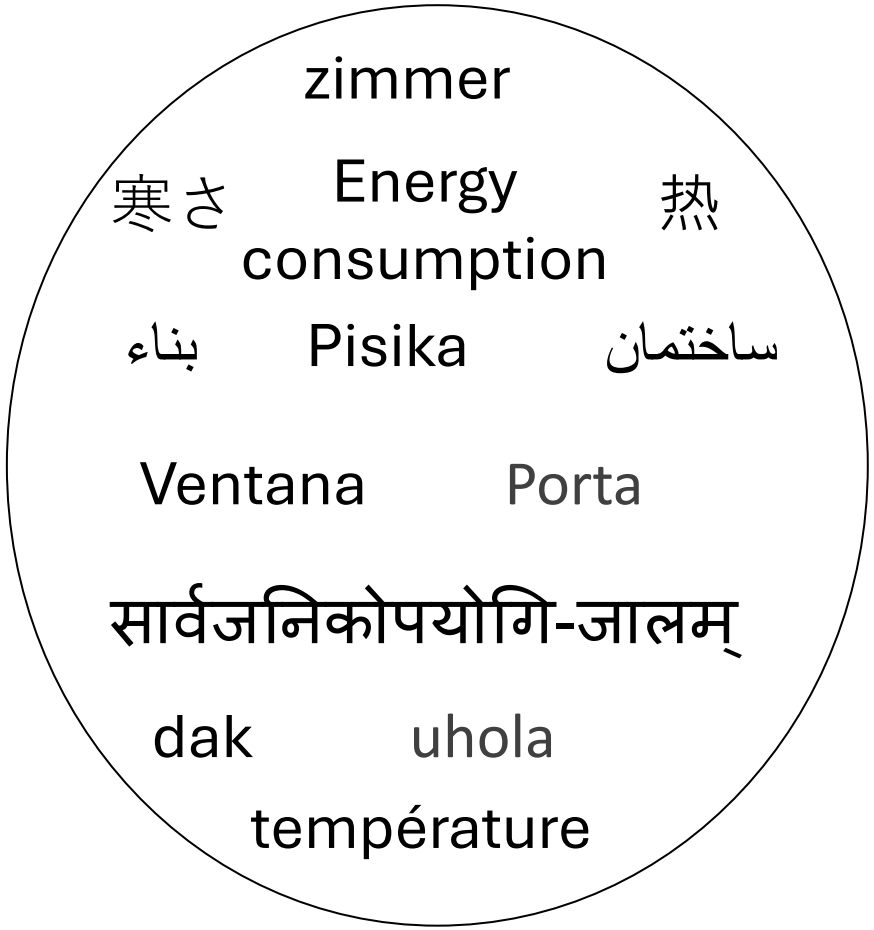
Modelling tree-planting strategy to reduce heating and cooling demand under 2050 climate conditions





Data Modelling

Data Modelling



harmonisation

using a common language with a unique definition (semantics)

Energy application

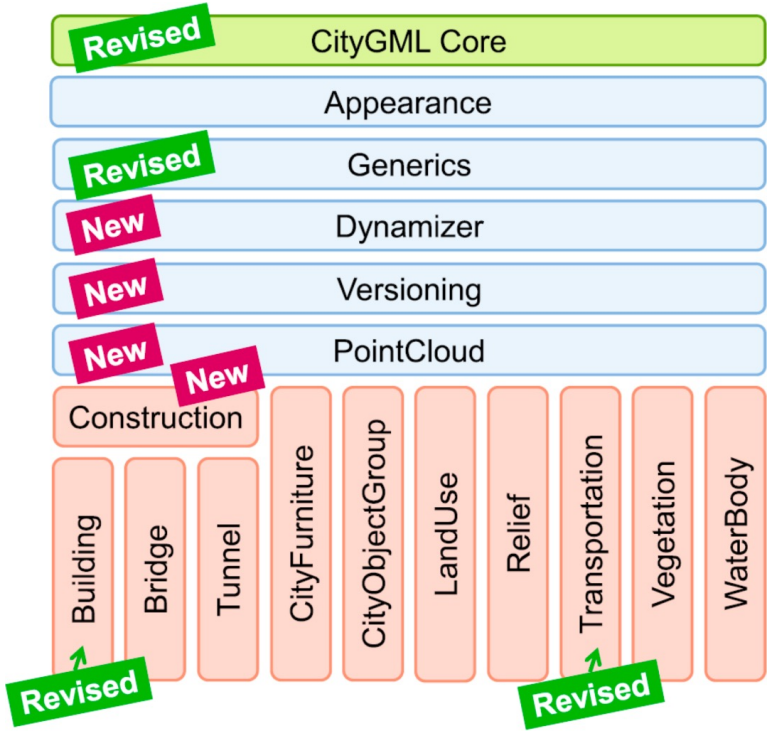
Data Modelling

Data Modelling

Mapping the Energy ADE to CityGML 3.0

Energy ADE v1.0 was developed as an extension for CityGML 2.0

- Stores energy related information on the individual building level
- Provides the necessary input data for UBEM simulations

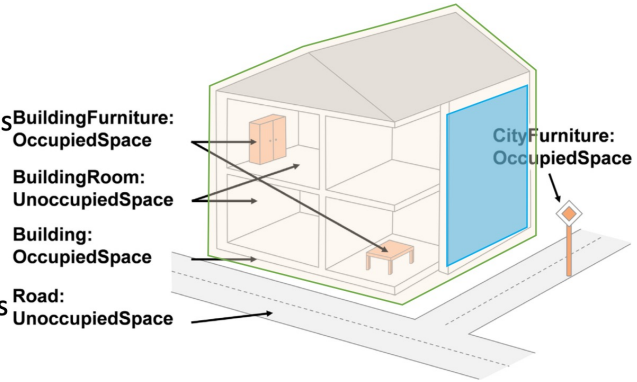


AbstractSpace:

- Volumetric extent
- Buildings, trees, traffic spaces

AbstractSpaceBoundary:

- Areal extent
- Delimits and connects spaces
- Roof surfaces

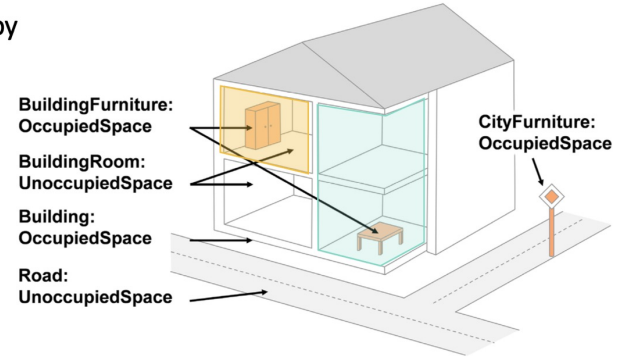


AbstractPhysicalSpace:

- Fully or partially bound by physical objects
- Room, furniture

AbstractLogicalSpace:

- Defined according to thematic considerations
- Aggregation of rooms

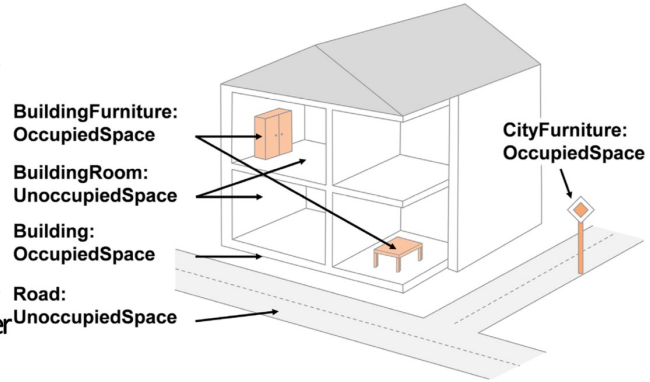


AbstractOccupiedSpace:

- Volumetric physical objects
- Occupy space in its surroundings

AbstractUnoccupiedSpace:

- Volumetric physical objects
- Do not block space for other things



Data Modelling

Mapping the Energy ADE to CityGML 3.0

Model-Driven Approach leaned on van den Brink et al., 2013

Define Data Model at Conceptual Level

- Select a formal modelling language
- Relate new classes to CityGML base classes
- Choose subclasses to be extended
- Define Code lists
- Define geometry re-presentation
- Decide on LOD

Transfer Format

- Derive Schema File

Conversion

- Create Test Data
- Build Conversion Tool

Model-Driven Approach leaned on van den Brink et al., 2013

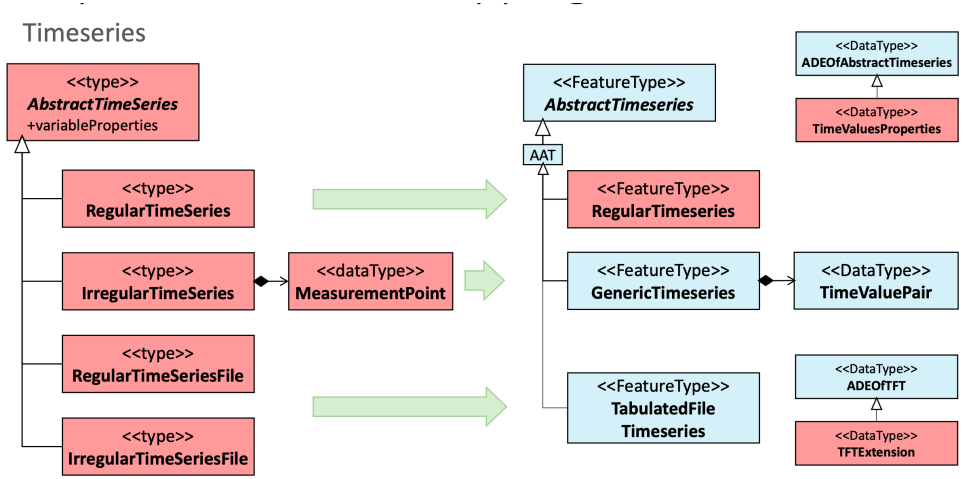
Define Data Model

ENTERPRISE ARCHITECT

Transfer Format

ShapeChange

Conversion

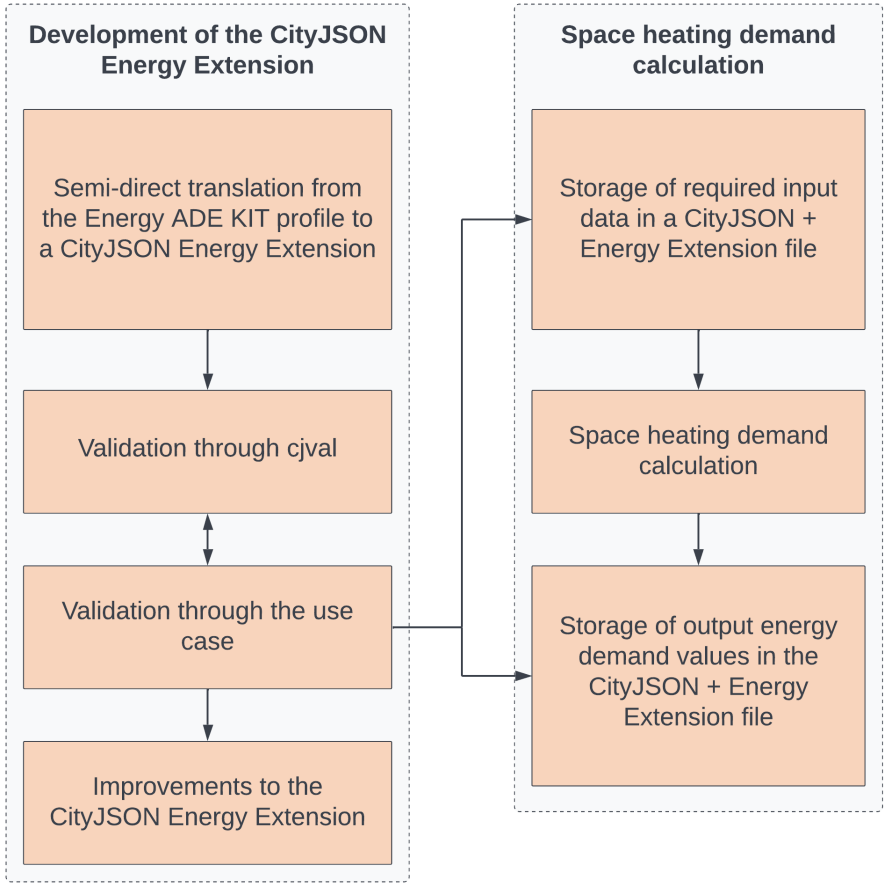


Data Modelling

Development and Testing of the CityJSON Energy Extension for Space Heating Demand Calculation

CityJSON

- Extension mechanism:
  - Creating new attributes
  - Creating new City Objects
  - Creating new root properties



Data Modelling

[Development and Testing of the CityJSON Energy Extension for Space Heating Demand Calculation]

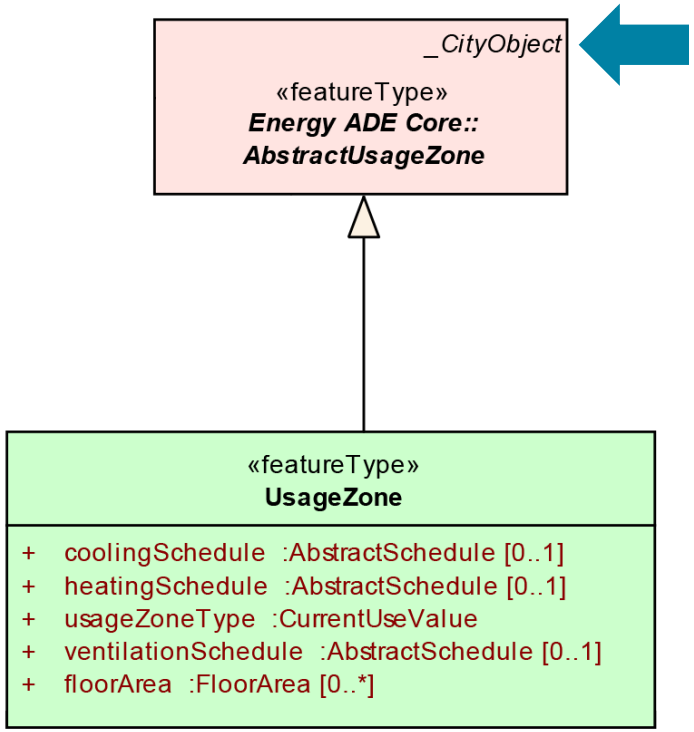
Creating new CityObjects

Extension schema

```
"extraCityObjects": {
  "+UsageZone": {
    "allOf": [
      {"$ref":"cityobjects.schema.json#/
          _AbstractCityObject"},
      {
        "properties": {
          "attributes": {
            "type": "object",
            "properties": {
              "usageZoneType": {
                "type": "string"
              },
              "floorArea": {...}
            }
    ...
}
```

Example object

```
"Usage1": {
  "type": "+UsageZone",
  "attributes": {
    "usageZoneType": "residential",
    "floorArea": {
      "type": "netFloorArea",
      "value": {
        "value": 100,
        "uom": "m2"
      }
    }
  }
}
```



Data Modelling

[Development and Testing of the CityJSON Energy Extension for Space Heating Demand Calculation]

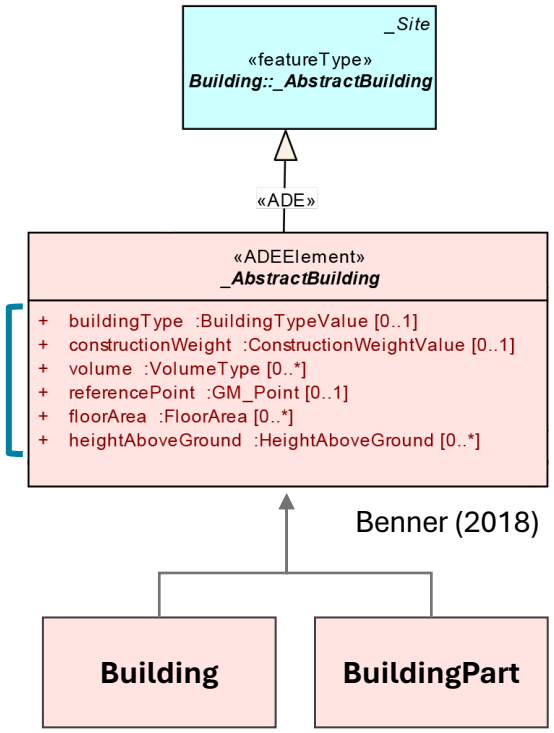
Creating new attributes

Extension schema

```
"extraAttributes": {
  "Building": {
    "+buildingType": {...},
    "+constructionWeight": {...},
    "+volume": {...},
    "+floorArea": {...},
    "+heightAboveGround": {...}
  }
}
```

Example object

```
"Build1": {
  "type": "Building",
  "geometry": [...],
  "attributes": {
    "+buildingType": "singleFamily",
    "+constructionWeight": "heavy",
  }
}
```



Data Modelling

Development and Testing of the CityJSON Energy Extension for Space Heating Demand Calculation

Extra root property “+UnitOfMeasurement”

Enable the storage of the uom only once per file

```
{
  "type": "CityJSON",
  "version": "1.1",
  "extensions": {"Energy": {...}},
  "transform": {...},
  "CityObjects": {...},
  "vertices": [...],
  "+unitOfMeasurement": {
    "volume": "m^3",
    "floorArea": "m^2",
    "energyDemand": "kWh",
    ...
  }
}
```

Data Management

Data Management

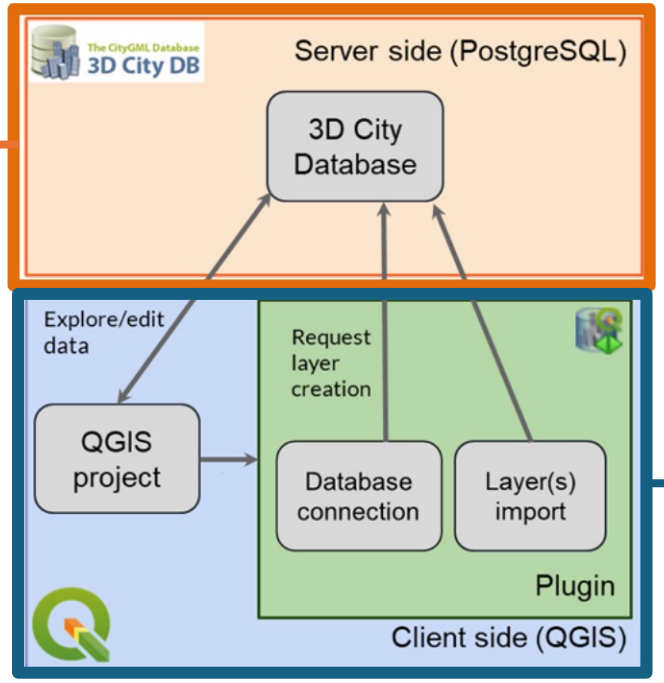
3DCityDB Tools for QGIS

Adds support to QGIS for CityGML data

- CityGML data is managed as Simple Feature for SQL (SFS) layers

PostgreSQL "QGIS Package"

- Creates and manages layers as views (attributes) linked to materialized views (geometry) following the SFS model
- Manages
  - users and privileges
  - multiple citydb schemas
- Adds default users with ro & rw privileges



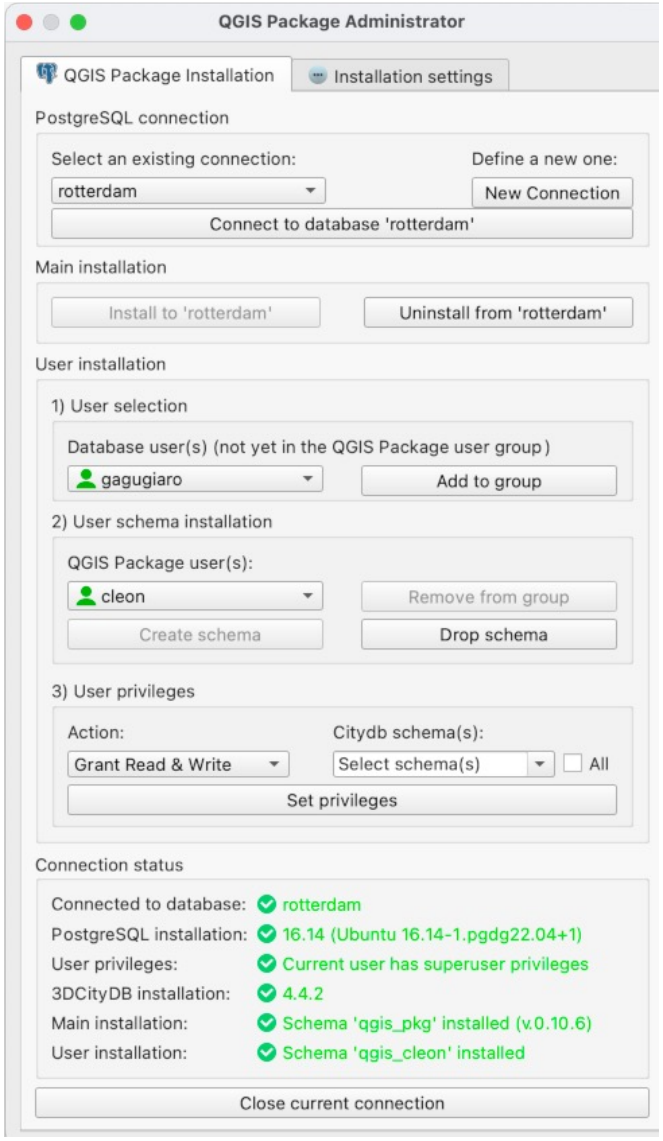
Client-side
QGIS plugin "3DCityDB-Tools"

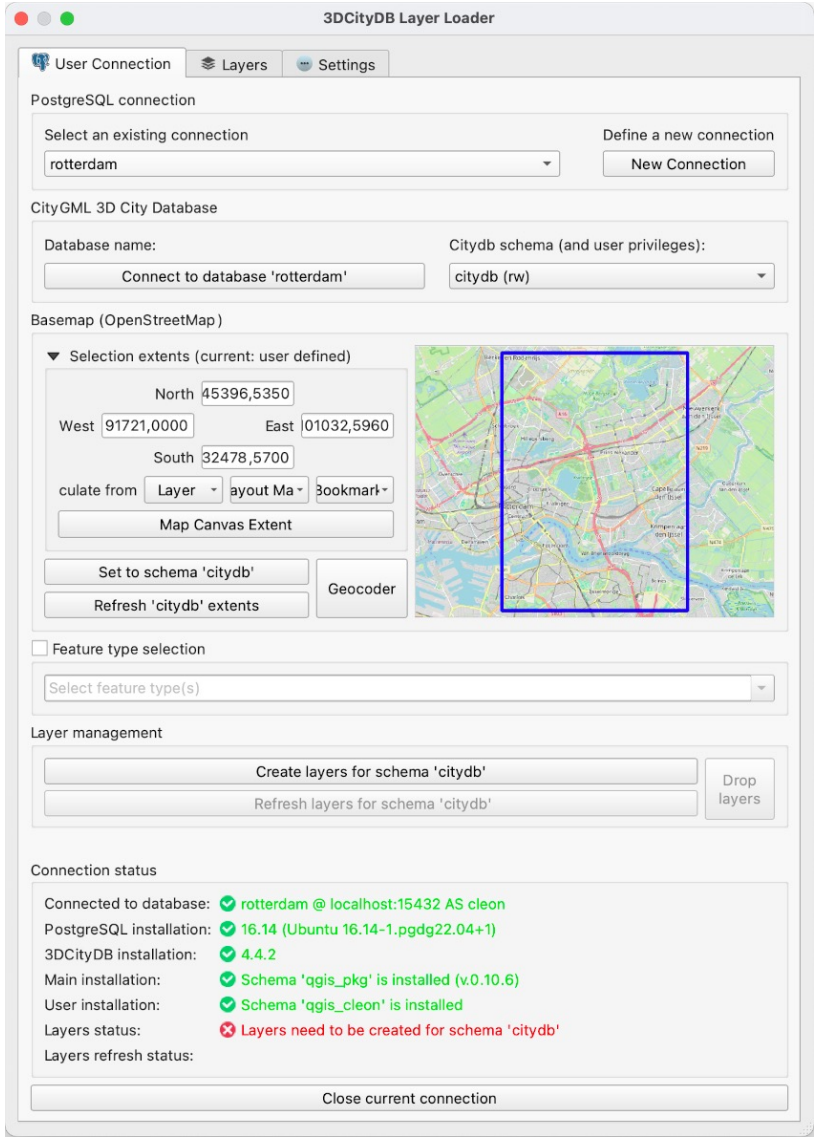
- Manages database connections + installation of the QGIS Package
- GUI-based
  - layer management
  - editing of feature attributes
- GUI includes
  - support for children tables
  - CityGML enumerations
  - Codelists
- Creates a hierarchical Table of Contents

Data Management

3DCityDB Tools for QGIS

Users management

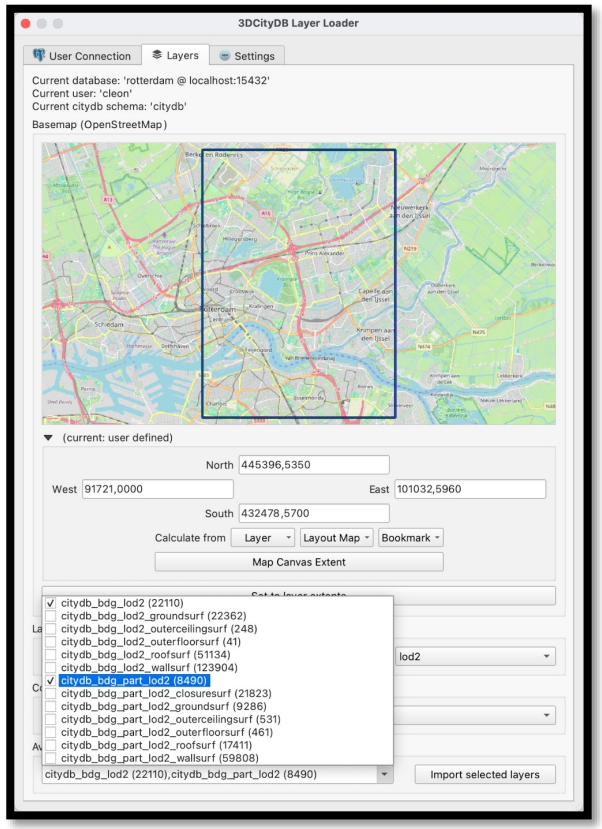


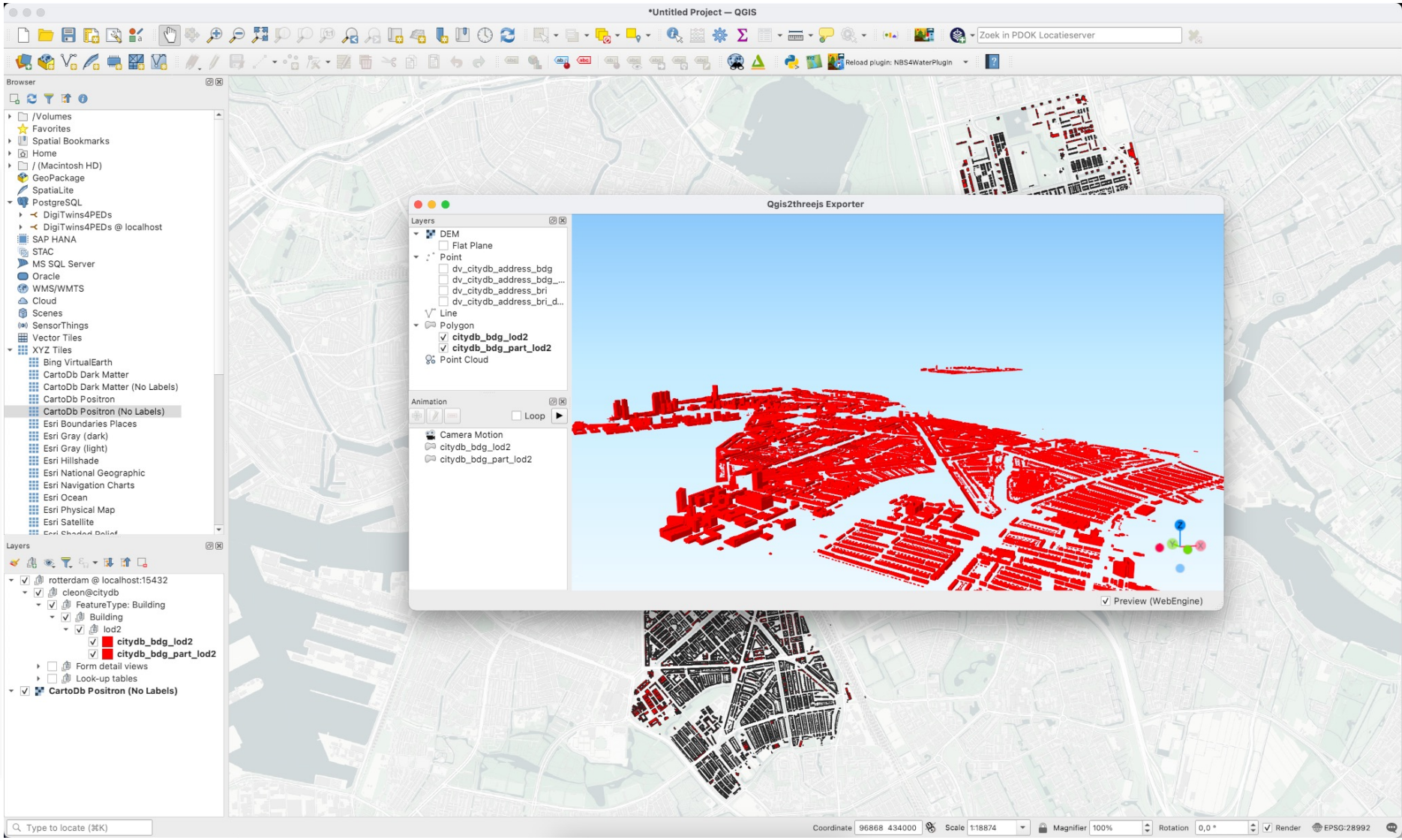


Layers management

Data Management

3DCityDB Tools for QGIS





DigiTwins4PEDs

Utilisation of urban digital twins to co-create flexible positive energy systems for districts

Hochschule für Technik Stuttgart

Gemeente Rotterdam

Stadt Wien

Uniwersytet Przyrodniczy we Wrocławiu

INFO SOLUTIONS

BOKU

TU Delft
Delft University of Technology

AIT Austrian Institute of Technology

DUT Driving Urban Transitions

Co-funded by the European Union

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

NCBR National Centre for Research and Development

NWO

FFG Promoting Innovation

Federal Ministry Republic of Austria Climate Action, Environment, Energy, Mobility, Innovation and Technology

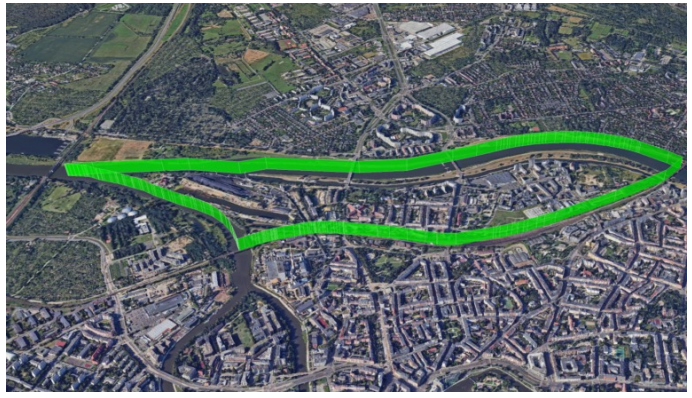
Positive Energy Districts?

urban neighbourhood with annual **net zero energy import** and **net zero CO_2 emissions** working towards a surplus production of renewable energy, integrated in an urban and regional energy system

4 Participant cities

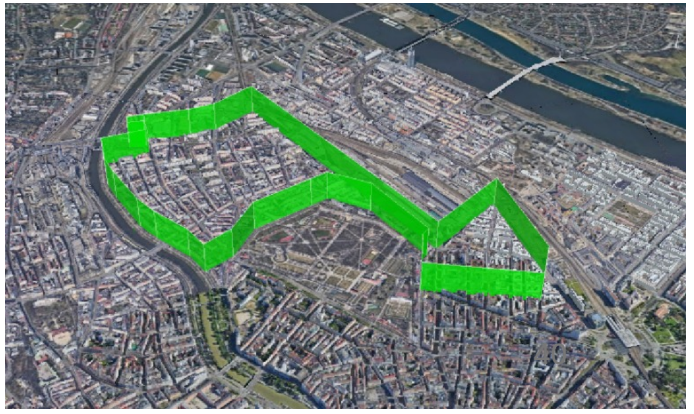
Stuttgart – Nordbanhnhofviertel

Wrocław District – Kleczków



Rotterdam – Prinsenland and Feijenoord

Vienna “Grätzl 20 + 2”



DigiTwins4PEDs

Specifications

- All participant cities implement the same simulations
  - Heating demand
  - Electricity demand
  - Electric vehicles impact
  - Solar energy adoption (Photovoltaic potential analysis)
  - Refurbishment of the Building stock

- Gemeente Rotterdam priority is **cooling** demand
  - We implemented several simulation-based scenarios
    - Detailed Window to wall ratios
    - Shading
    - Tree planting
    - Refurbishment scenarios

DigiTwins4PEDs - Rotterdam

Architecture

Gemeente Rotterdam

CityGML

Geometry repair

Data Enrichment

kadaster

BAG data

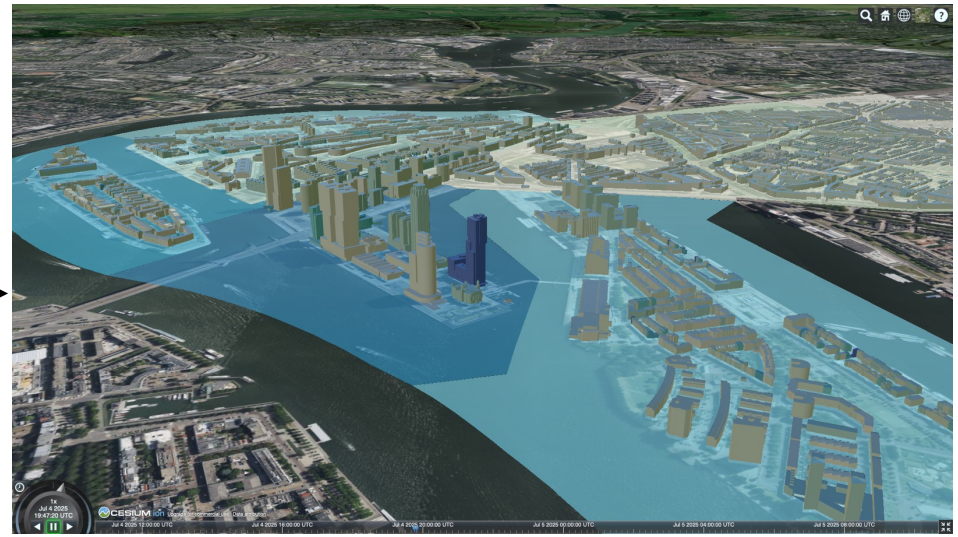
QGIS

TABULA WebTool

Building typology

SimStadt

3D CityDB



CESIUM 3DTiles

Visualization / Interaction

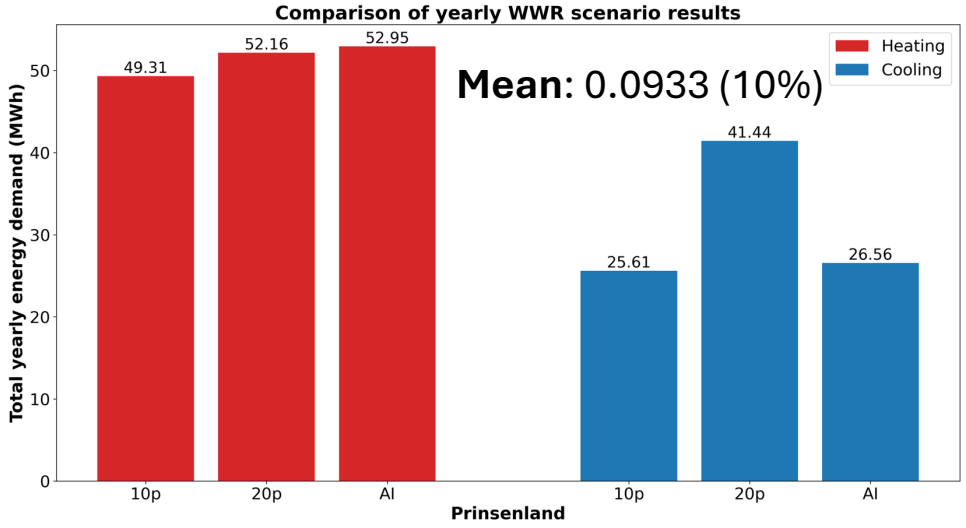
Koninklijk Nederlands Meteorologisch Instituut

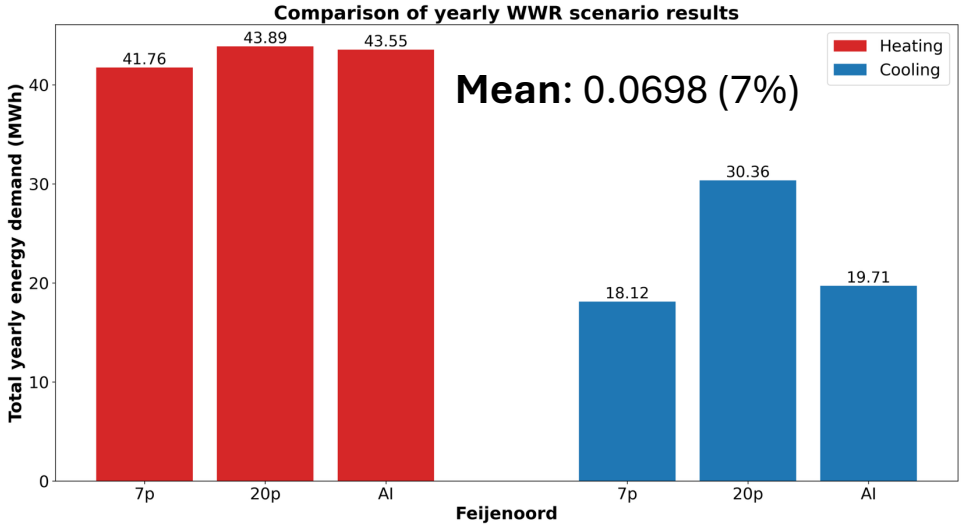
Ministerie van Infrastructuur en Waterstaat

Weather data

Scenario-based simulation: Window to wall ratios

- *Data extracted from aerial images* of the measured window to wall ratios for **two neighbourhoods**
- **Enriched** our 3D models with the new received values
- **Conducted** simulations and analysis of Heating and Cooling



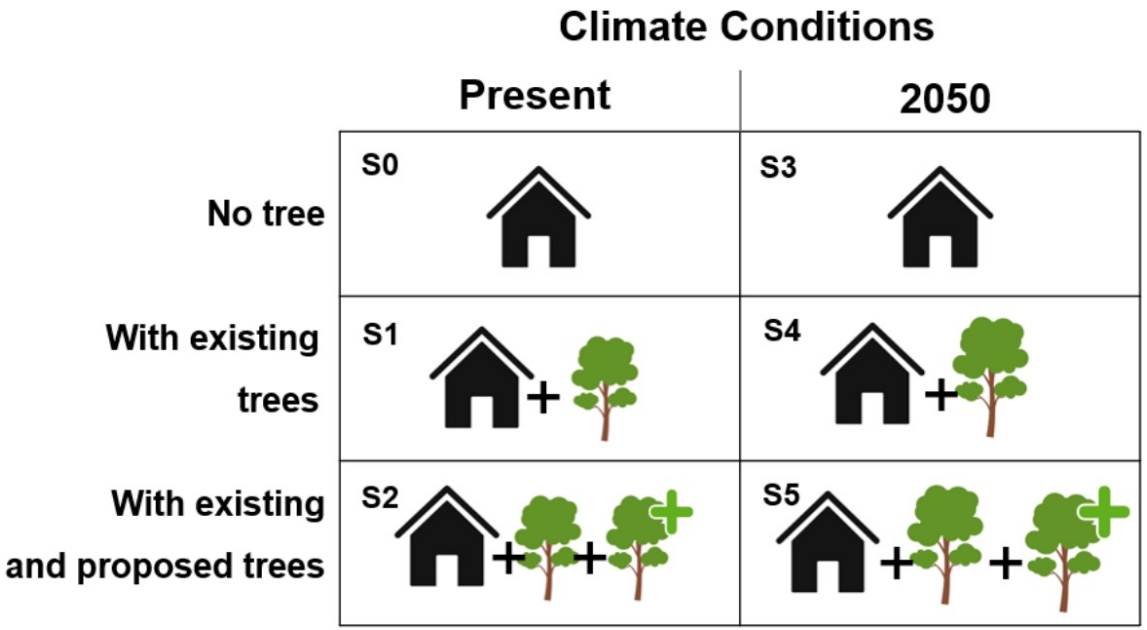


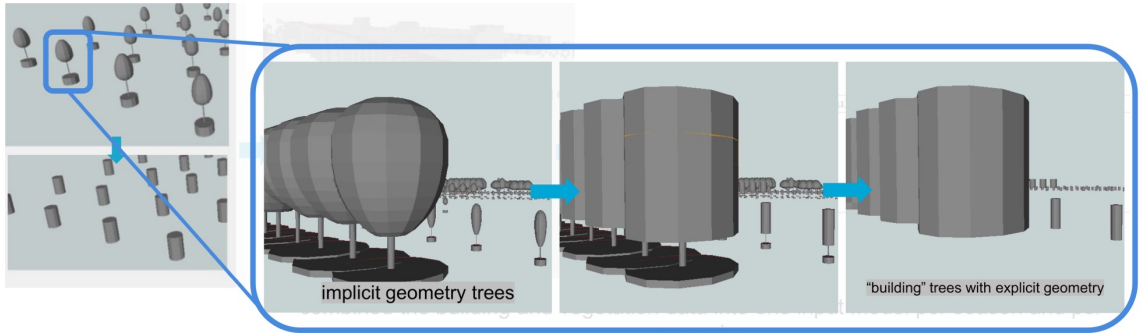
Cooling Outlier **+1505.3%**

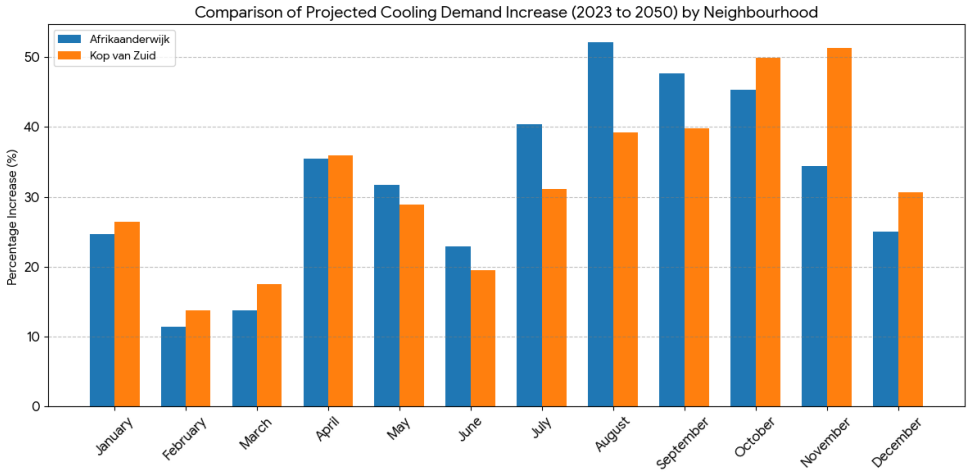
Cooling Outlier: **+685.5%**

Heating Outlier **+103.5%**

Scenario-based simulation: Modelling tree-planting strategy to reduce heating and cooling demand under 2050 climate conditions







S0 vs S3

Scenario-based simulation: Modelling tree-planting strategy to reduce heating and cooling demand under 2050 climate conditions

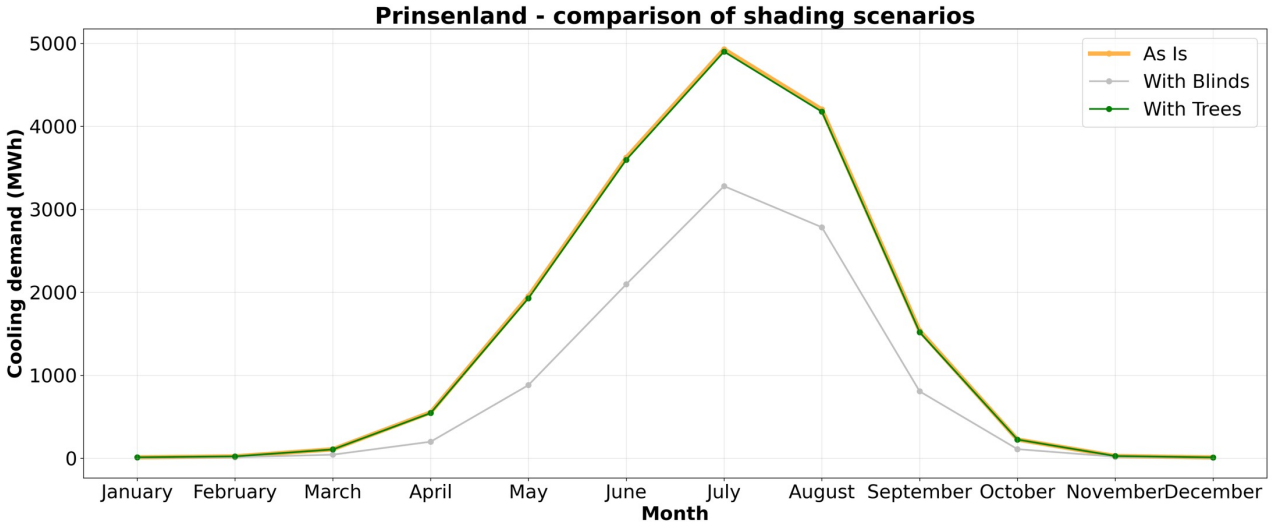
- Current climate

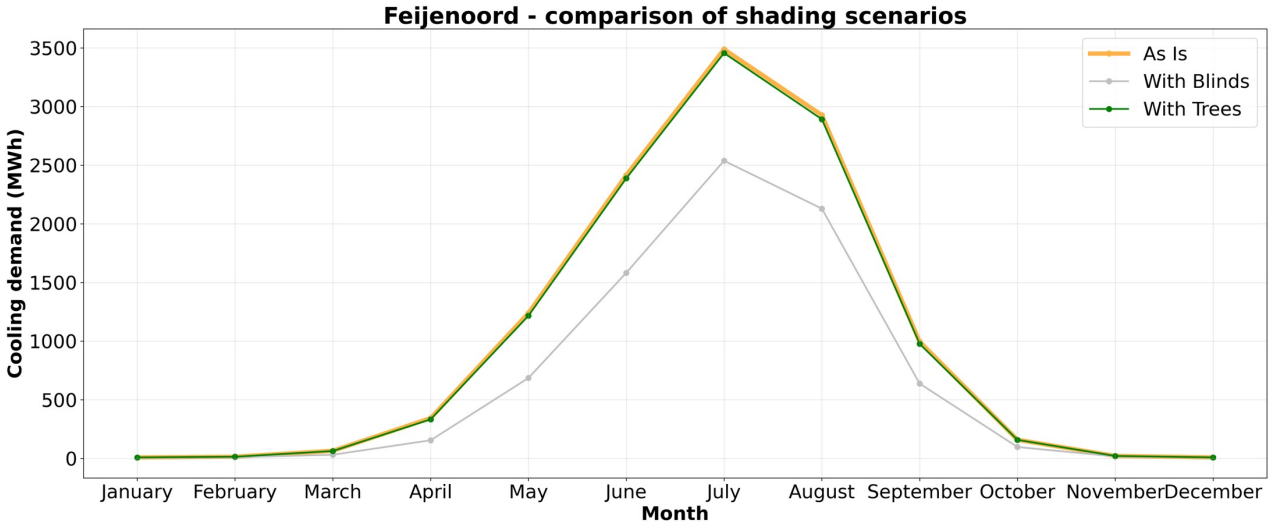
Scenario	Cooling (MWh/a)	Heating (MWh/a)	Total (MWh/a)
Afrikaanderwijk			
Existing trees	6,207	29,857	36,064
Existing + proposed trees	6,019	30,053	36,072
Change	-187	195	7
% Change	-3.03%	0.66%	0.02%
Kop van Zuid			
Existing trees	10,561	20,613	31,174
Existing + proposed trees	10,429	20,728	31,157
Change	-132	115	-16
% Change	-1.25%	0.56%	-0.05%

- 2050 climate

Scenario	Cooling (MWh/a)	Heating (MWh/a)	Total (MWh/a)
Afrikaanderwijk			
Existing trees	8,574	26,339	34,913
Existing + proposed trees	7,717	26,869	34,587
Change	-856	530	-325
% Change	-9.99%	2.01%	-0.93%
Kop van Zuid			
Existing trees	13,943	17,942	31,885
Existing + proposed trees	13,711	18,060	31,771
Change	-231	117	-113
% Change	-1.66%	0.66%	-0.36%

Scenario-based simulations: shading





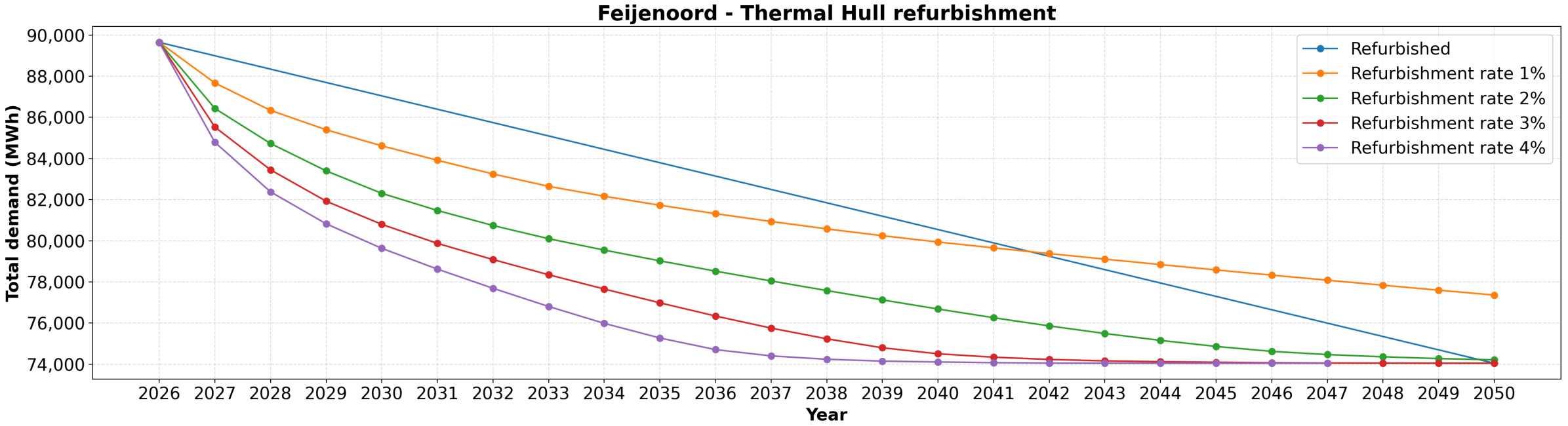
Three scenarios:

- As is (Archetypes)
- With Blinds (curtains)
- With Trees (as shadowing elements)

location	Cooling		
	Energy demand (MWh)	Blinds	Trees
Afrikaanderwijk	11,226	-34.43%	-0.93%
Bloemhof	14,378	-34.31%	-1.44%
Feijenoord	11,684	-32.40%	-1.27%
Hillesluis	15,265	-33.09%	-1.23%
Katendrecht	13,688	-35.14%	-0.38%
Kop van Zuid - Entrepot	16,513	-31.37%	-0.33%
Kop van Zuid	23,115	-19.17%	-0.02%
Noordereiland	5,183	-33.77%	-1.09%
Prinsenland	17,197	-40.43%	-0.77%
Vreewijk	23,275	-32.97%	-1.53%

Scenario-based simulations: Refurbishment of the building stock

- Refurbishment type: Whole Thermal Hull as built in 2025
- Weather data: 2050 forecasting from KNMI
- Analyses: Renovation rate of the building stock (1 – 4% per annum)



DigiTwins4PEDs results

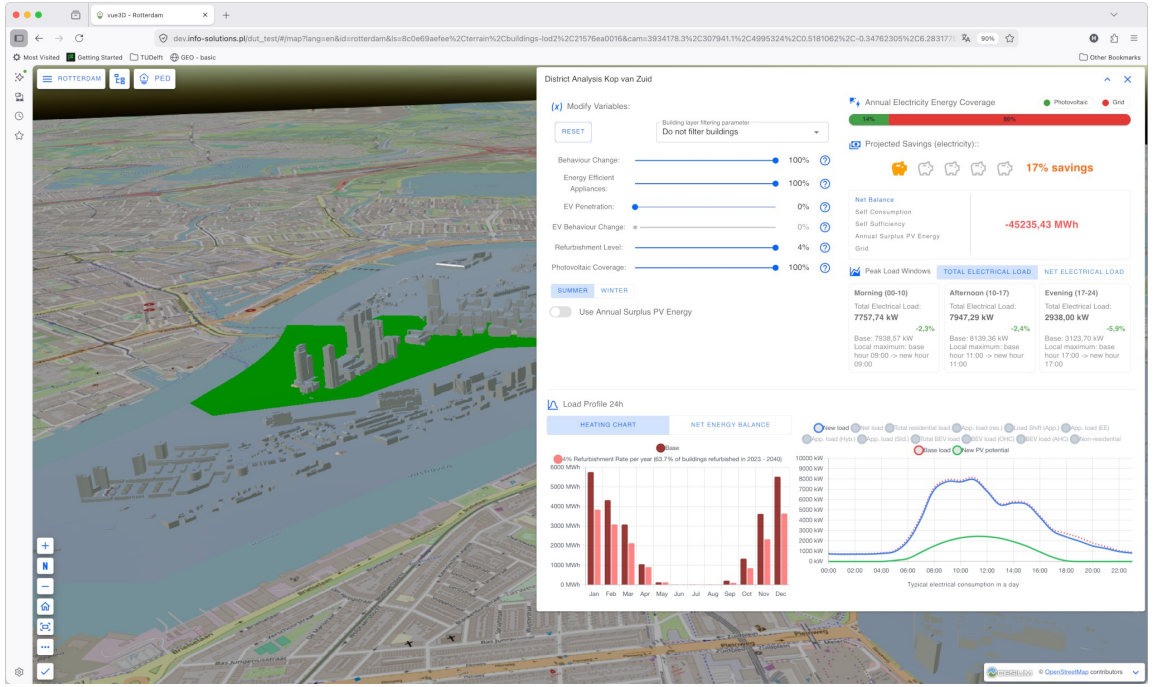
Cooling demand

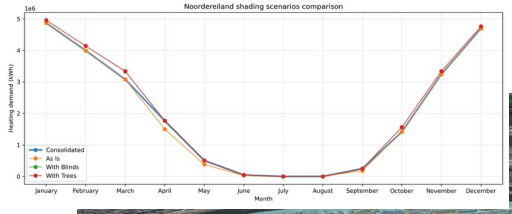
DigiTwins4PEDs results

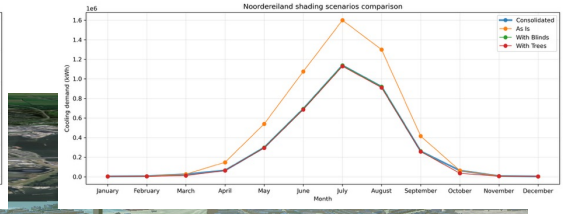
Heating demand

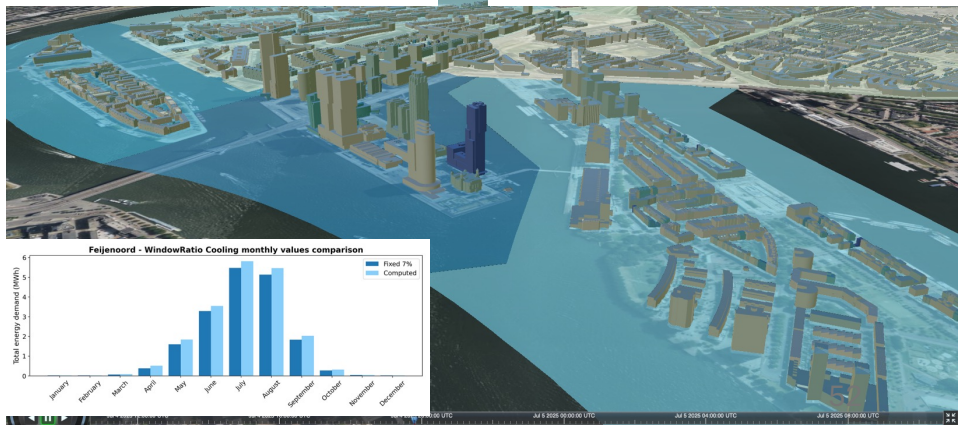
Final remarks

- This is only the technical aspects
- A realistic PED involves Co-creation activities
  - Citizen participation!
  - Only with their implication PEDs are feasible









Testing and enhancing the Scenario ADE in the context of building performance simulations in Rotterdam

- Frederick Auer Graduation ceremony (A4)
  - 19 Jun 2026
  - 15:00
  - BK - Hall Q

scenario-verse

UrbäNRG

https://3d.bk.tudelft.nl/events/energy2026/

References

- Data Extraction & Creation
  - Inferring the residential building type from 3DBAG
  - High-resolution, large-scale, and fast calculation of solar irradiance with 3D City Models
- Data Preparation
  - Solar analysis on buildings of favelas in São Paulo to estimate pv potential
  - Inferring the residential building type from 3DBAG
  - Dynamic energy simulations based on the 3D BAG 2.0
  - Modelling tree-planting strategy to reduce heating and cooling demand under 2050 climate conditions
- Data Modelling
  - Mapping the Energy ADE to CityGML 3.0
  - Development and Testing of the CityJSON Energy Extension for Space Heating Demand Calculation
- Data Management
  - Development of a QGIS plugin for the CityGML 3D City Database
  - Further Development of a QGIS Plugin for the CityGML 3D City Database
  - 3DCityDB-Tools plug-in for QGIS: Adding server-side support to 3DCityDB v.5.0
  -