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

Özge Tufan 2022

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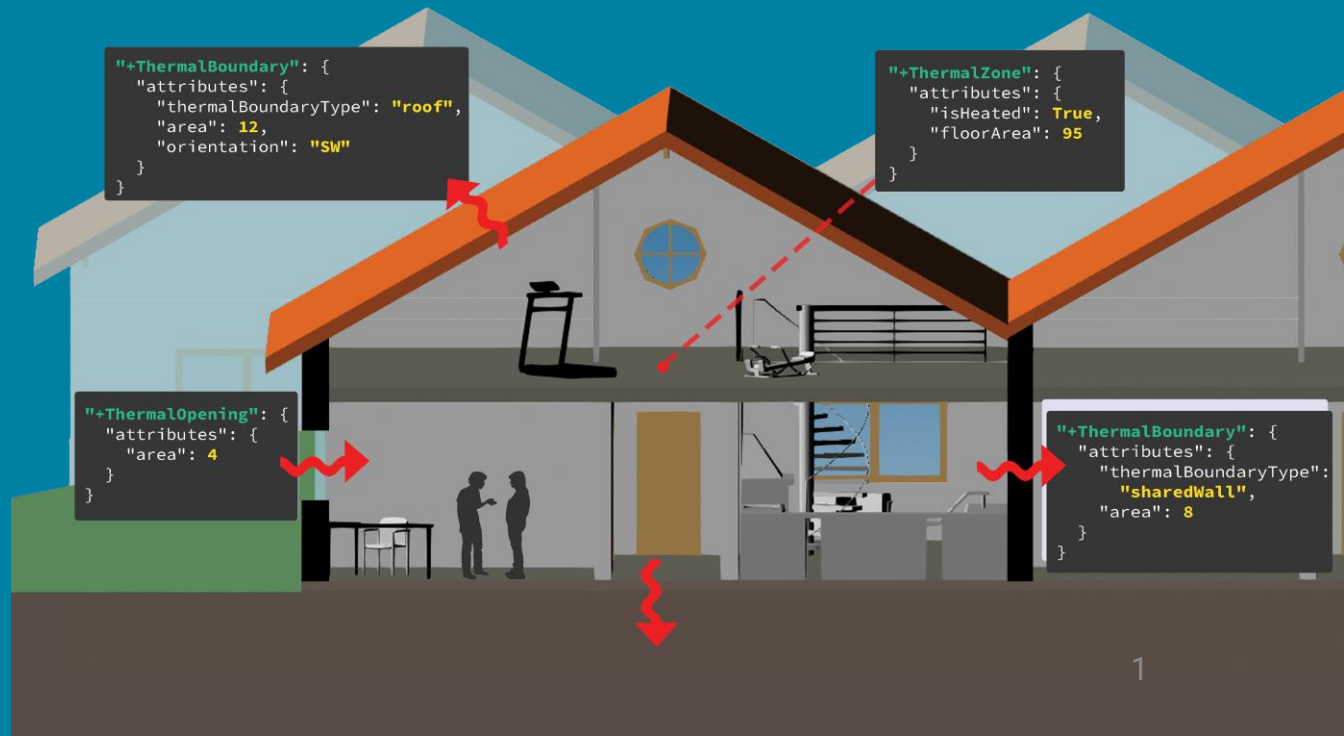

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Content

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1. Motivation & Research questions

1.1 Motivation

- Energy performance of buildings as a prevalent discussion
- *Urban Energy Modelling* with semantic 3D city models

Energy demand analysis

Agugiaro (2016)

Solar irradiance analysis

Leon-Sanchez et al. (2021)

Refurbishment measures

Nouvel et al. (2013)

1.1 Motivation

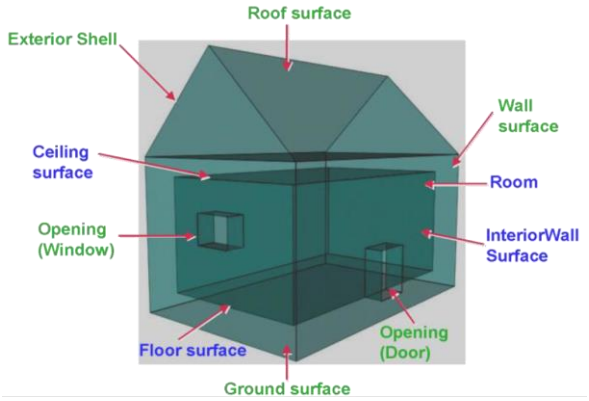
CityGML

- Modelling *City Objects*

Geometry in five Levels of Detail (LoD)

Biljecki et al. (2016)

Semantics



Gröger et al. (2012)

Three encodings:

- XML-based → CityGML
- JSON-based → CityJSON
- SQL-based → The CityGML Database 3D City DB

1.1 Motivation

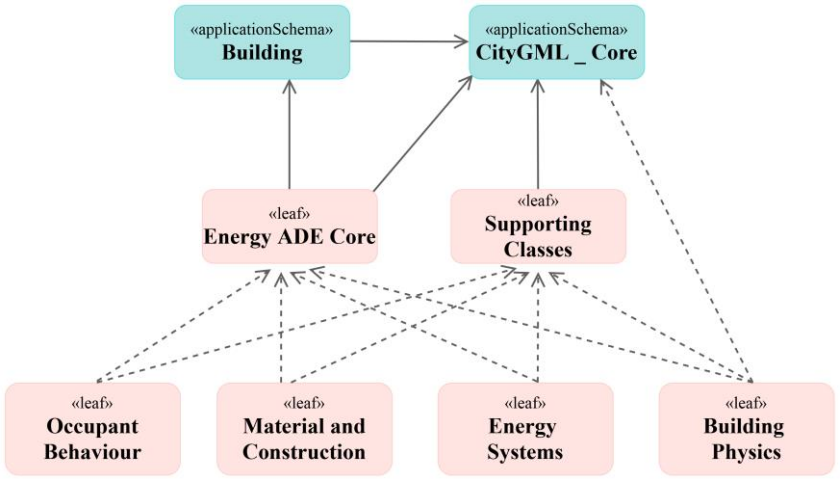
CityGML

Application Domain Extensions (ADE)

Energy ADE: stores energy-related data

- Highly complex structure

Energy ADE *KIT profile*



Benner (2018)

CityJSON

- Less hierarchical structure
- Also has Extension mechanism

+ Energy ?

1.2 Research question

How can a **CityJSON Energy Extension** be used to support the calculation of **space heating demand** of buildings?

1.2 Sub-questions

How can different types of objects, other than CityObjects, be defined in a CityJSON Extension?

How should the CityJSON Energy Extension differ from the Energy ADE?

How can space heating demand calculation be used during the design phase to test and improve the CityJSON Energy Extension?

To what extent is it possible to map CityGML ADEs to CityJSON Extensions? Should the CityJSON schema be extended to make this process more straightforward?

2. Related work

2.3 CityJSON Extensions

Extension mechanism:

1. Creating new attributes
2. Creating new City Objects
3. Creating new root properties

```
{
  "type": "CityJSONExtension",
  "name": "Traffic",
  "description": "Extension to model the traffic",
  "uri": "https://someurl.org/traffic.ext.json",
  "version": "1.0",
  "versionCityJSON": "1.1",
  "extraAttributes": {},
  "extraCityObjects": {},
  "extraRootProperties": {}
}
```

Extension properties

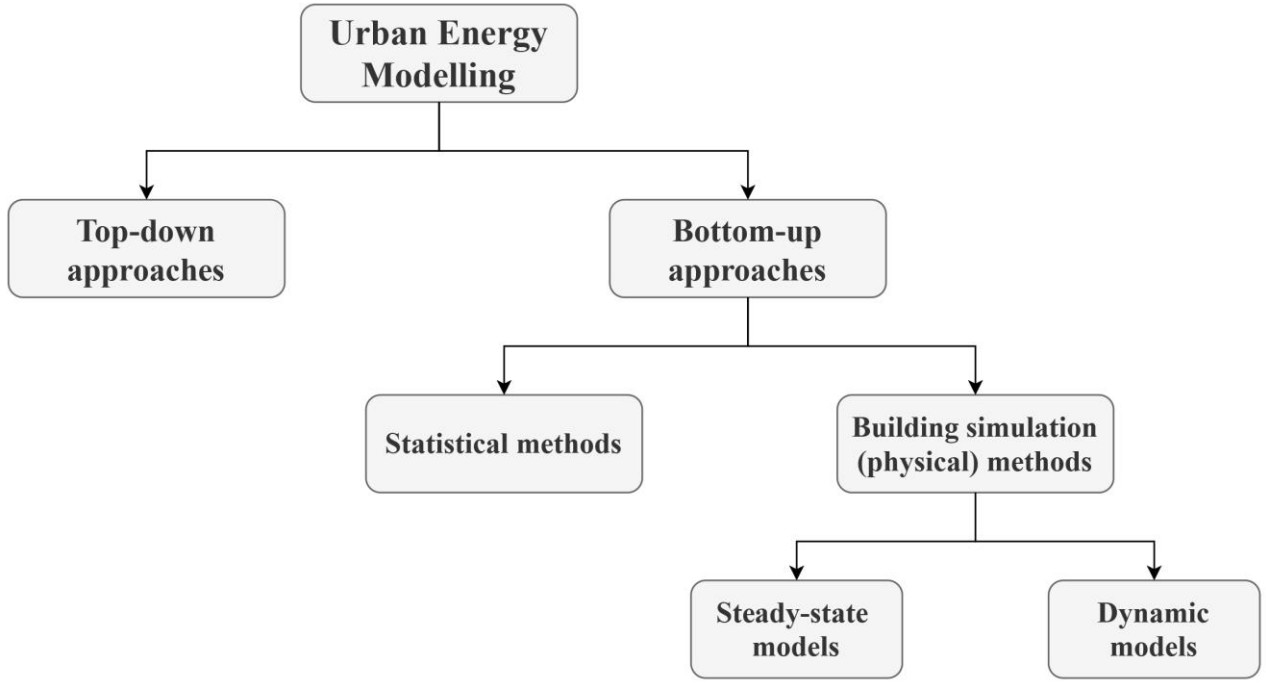
Current CityJSON extensions:

- Support for 3D point clouds
  Nys et al. (2021)
- Topology in 3D city models
  Vitalis et al. (2019)
- Building permits
  Wu (2021)
- Mapping the CityGML Noise ADE
  CityJSON team

2.4 Space heating demand calculation

Steady-state models:

- Highly used for space heating demand
- Less input parameters
- Simplifications and assumptions



City-scale energy simulation tools

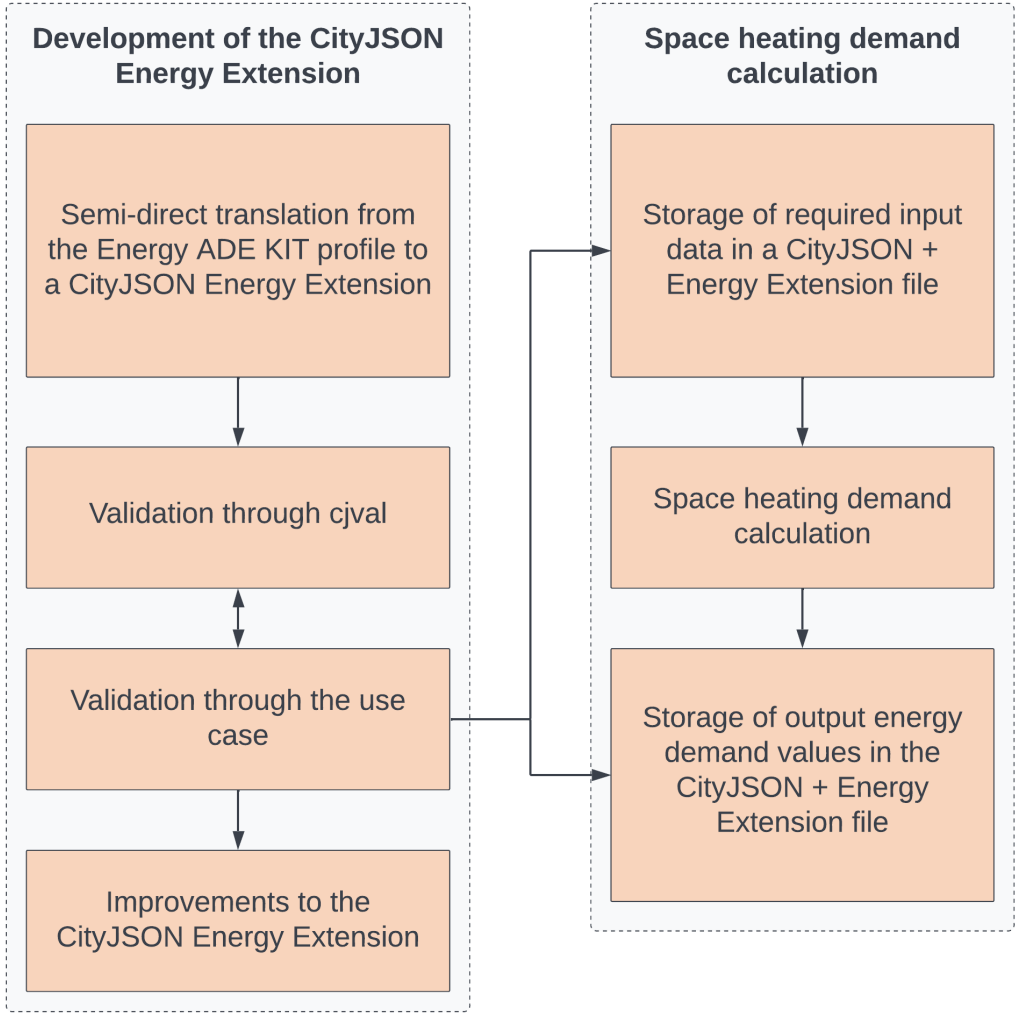
SimStadt

CitySim

Swan and Ugursal (2009);
Kaden and Kolbe (2014)

3. Methodology

3. Methodolody



3.1 Semi-direct translation

Energy ADE KIT profile → CityJSON Energy Extension

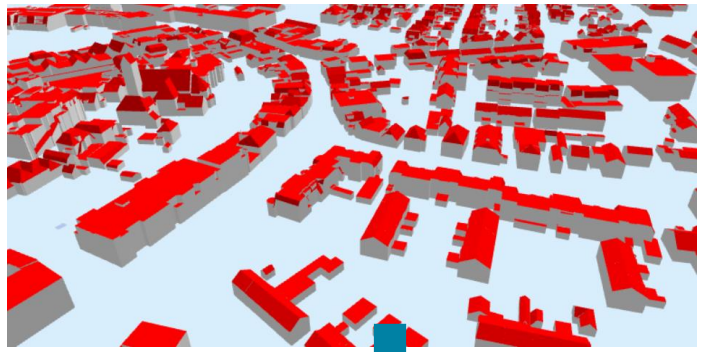
Considered elements	**CityJSON Extension mechanism**
• New CityObjects • New attributes to existing CityObjects	*extraCityObjects* *extraAttributes*
• New non-CityObjects • Additional data types, enumerations, code lists • Relations between CityObjects and non-CityObjects	

3.2 Validation and improvements

Through the use case

CityJSON + Energy Extension file

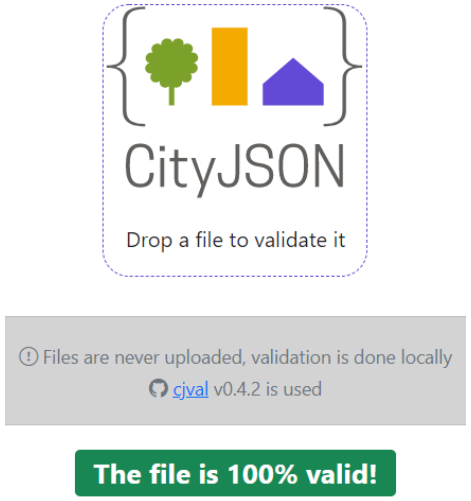
- Storage of input data
- Efficiency on data retrieval



Through cjval

Official validator of CityJSON, checks:

- JSON syntax
- CityJSON schemas
- Extension schemas



https://github.com/cityjson/cjval

3.3 Space heating demand calculation

- Dutch standard NTA 8800
- Steady-state energy balance method:

$$\underbrace{Q_{H;nd;zi;mi}}_{\text{Monthly space heating demand}} = \underbrace{(Q_{H;tr;zi;mi} + Q_{H;ve;zi;mi})}_{\text{Heat losses}} - n_{H;gn;zi;mi}\underbrace{(Q_{H;int;zi;mi} + Q_{H;sol;zi;mi})}_{\text{Heat gains}}$$

Heat losses through transmission : $Q_{H;tr;zi;mi}$

Heat losses through ventilation : $Q_{H;ve;zi;mi}$

Internal gains : $Q_{H;int;zi;mi}$

Solar gains : $Q_{H;sol;zi;mi}$

Utilization factor : $n_{H;gn;zi;mi}$

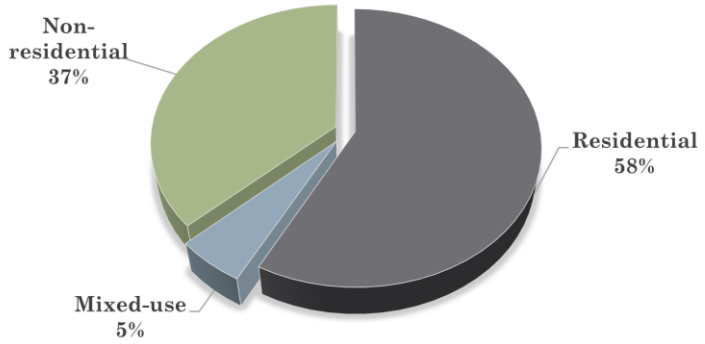
4. Study area and datasets

4.1 Study area

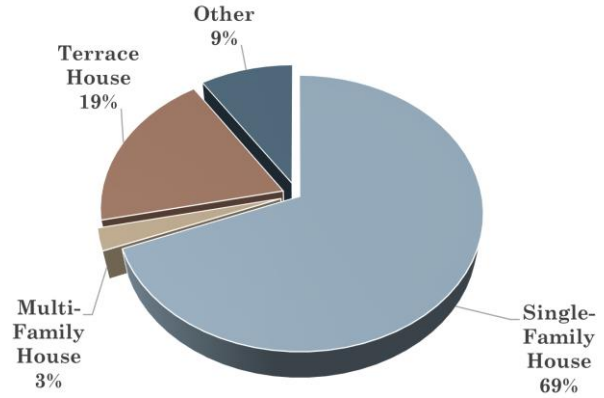
Rijssen-Holten, Netherlands

- 3318 buildings

Building usage



Building typologies



4.3 Datasets

3D city model of Rijssen-Holten

- In **CityGML** format
- Geometry in LoD0 & **LoD2**
- Semantics: WallSurface, RoofSurface, GroundSurface

Pre-processing:

 → Slope of surfaces
Perimeter of buildings

citygml-tools & cjio → CityGML to CityJSON

Python → Data cleaning

Used attributes:

- Building class & function
- Building type
- Year of construction
- Roof “footprint” area
- Building volume
- # of storeys
- Adjacent buildings
- Surface inclination, direction & area

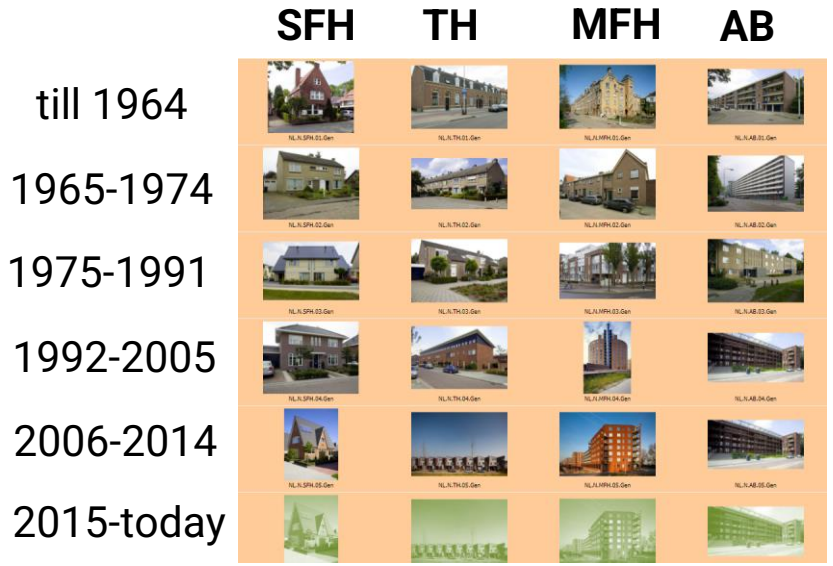
4.3 Datasets

Basisregistratie Adressen en Gebouwen (BAG)

- Usable area
- Number of residential units

TABULA building physics library

- U-value
- g-value
- Window ratio



https://webtool.building-typology.eu

Meteorological Data Portal & NTA8800

- Outdoor air temperature
- Monthly solar radiation
- Shading reduction factor

SFH = Single-family house
TH = Terrace house
MFH = Multi-family house
AB = Apartment block

5. Implementation

5.1 Mapping rules of the semi-direct translation

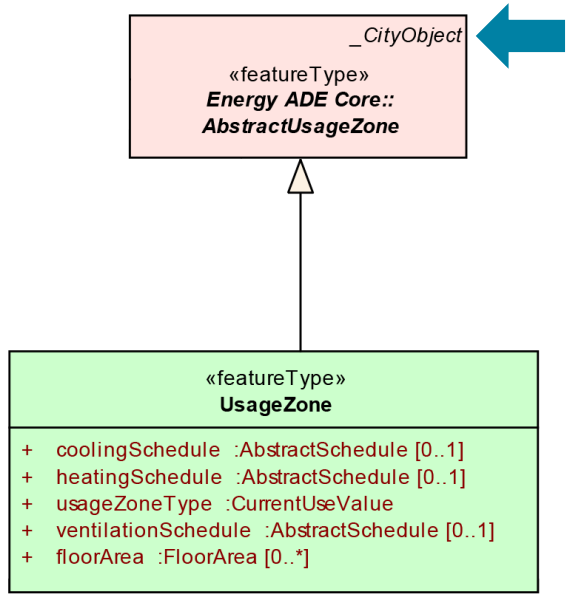
Creating new CityObjects

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"
      }
    }
  }
}
```



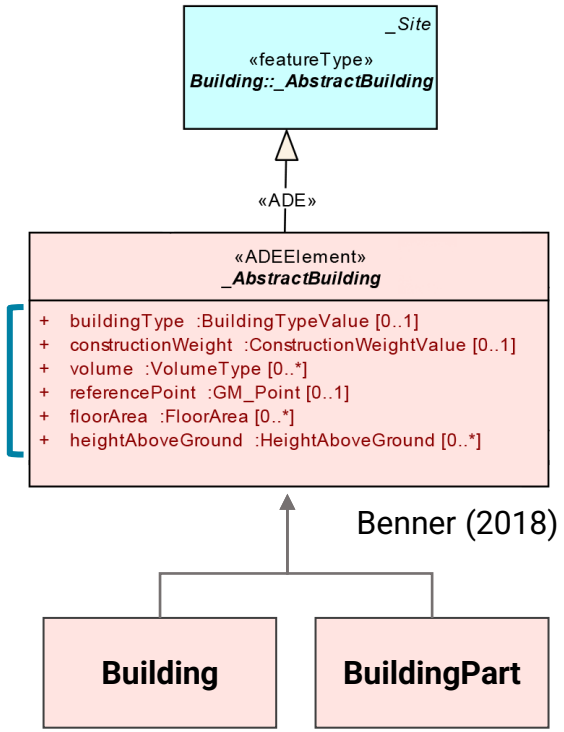
Benner (2018)

5.1 Mapping rules of the semi-direct translation

Creating new attributes

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

Extension schema



Benner (2018)

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

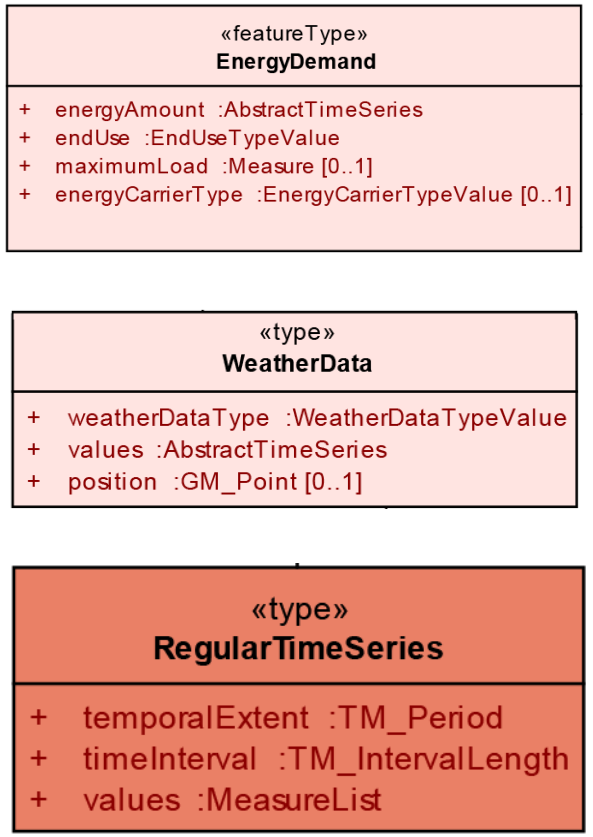
Example object

5.1 Mapping rules of the semi-direct translation

Creating new non-CityObjects

- Not in the Extension mechanism

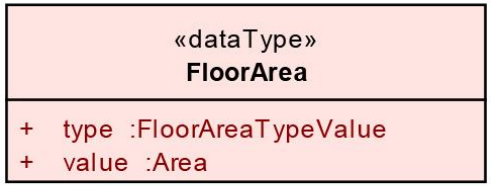
```
"extraCityObjects": {
  "+EnergyDemand": {
    "type": "object",
    "properties": {
      "type": {...},
      "attributes": {
        "type": "object",
        "properties": {
          "energyAmount": {...},
          "endUse": {...},
          "maximumLoad": {...},
          "energyCarrierType": {...}
        }
      ...
}
```

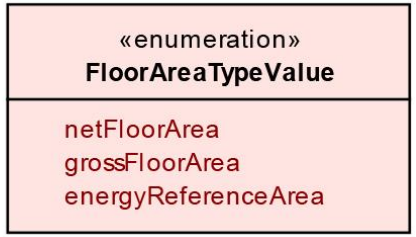


Benner (2018)

5.1 Mapping rules of the semi-direct translation

Creating new data types and enumerations





Benner (2018)

Extension schema

```
"definitions": {
  "floorArea": {
    "type": "object",
    "properties": {
      "type": {
        "enum": ["netFloorArea",
            "grossFloorArea",
            "energyReferenceArea"]
      },
      "value": {...}
    }
  }
}
```

```
"extraAttributes": {
  "Building": {
    "+floorArea": {
      "type": "array",
      "items": {
        "$ref": "#/definitions/floorArea"
      }
    },
    ...
  }
}
```

5.1 Mapping rules of the semi-direct translation

Relations: CityObjects

- Parent - children relationship

ThermalZone – UsageZone

```
"Zone1": {
  "type": "+ThermalZone",
  ...,
  "children": ["Usage1"]
},
"Usage1": {
  "type": "+UsageZone",
  "attributes": {
    "usageZoneType":"residential"
  },
  "parents": ["Zone1"],
  ...
}
```

Relations: CityObjects and non-CityObjects

- Additional attributes

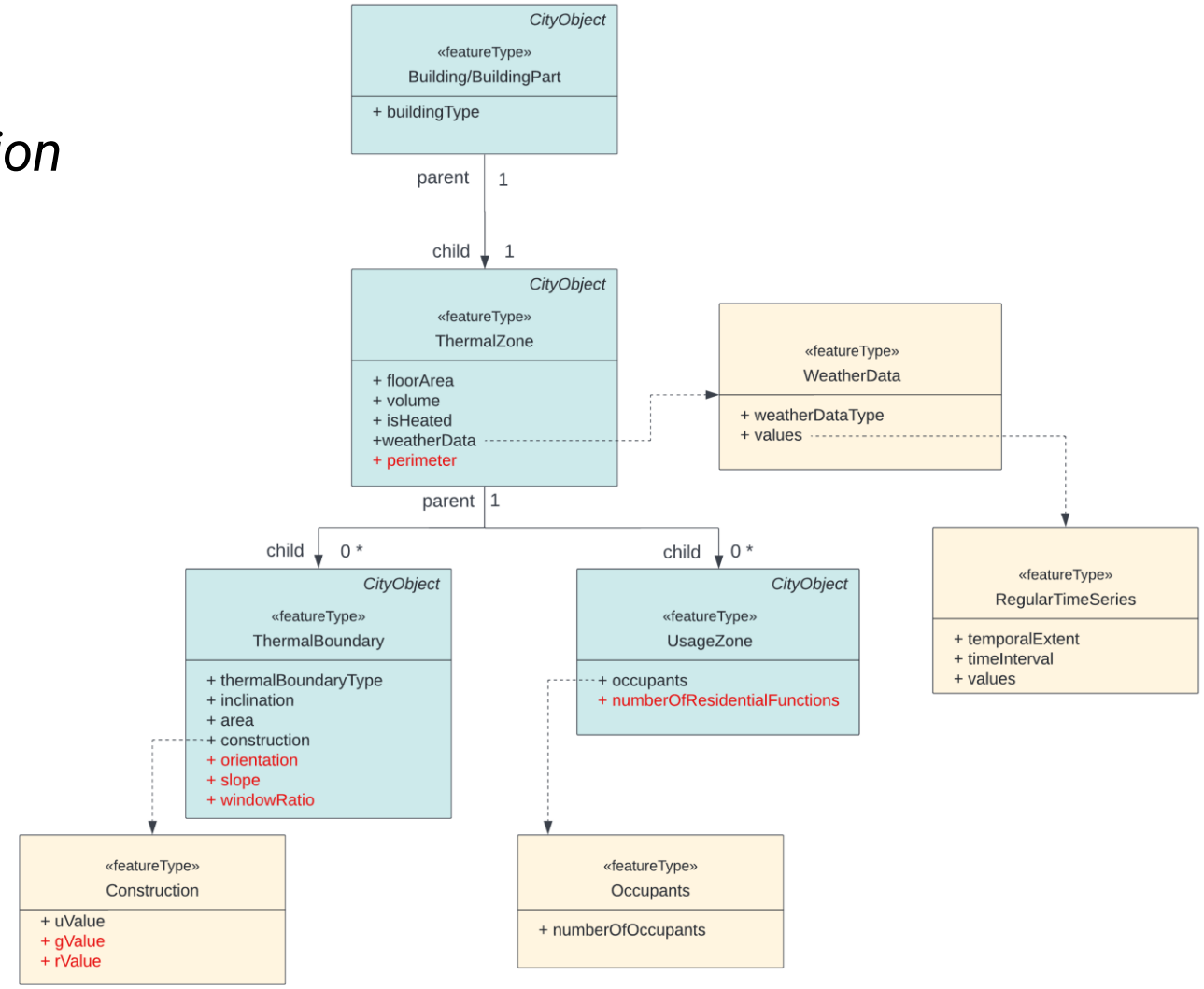
Building (CO) – EnergyDemand (non-CO)

```
"Build1": {
  "type": "Building",
  "geometry": [...],
  "attributes": {
    "+buildingType": "singleFamily",
    ...
    "+energyDemand":["Demand1"
    ]
  }
}
```

ID of EnergyDemand object

5.2 Validation through the use case

Storage of input data in a *CityJSON + Energy Extension* file



5.2 Validation through the use case

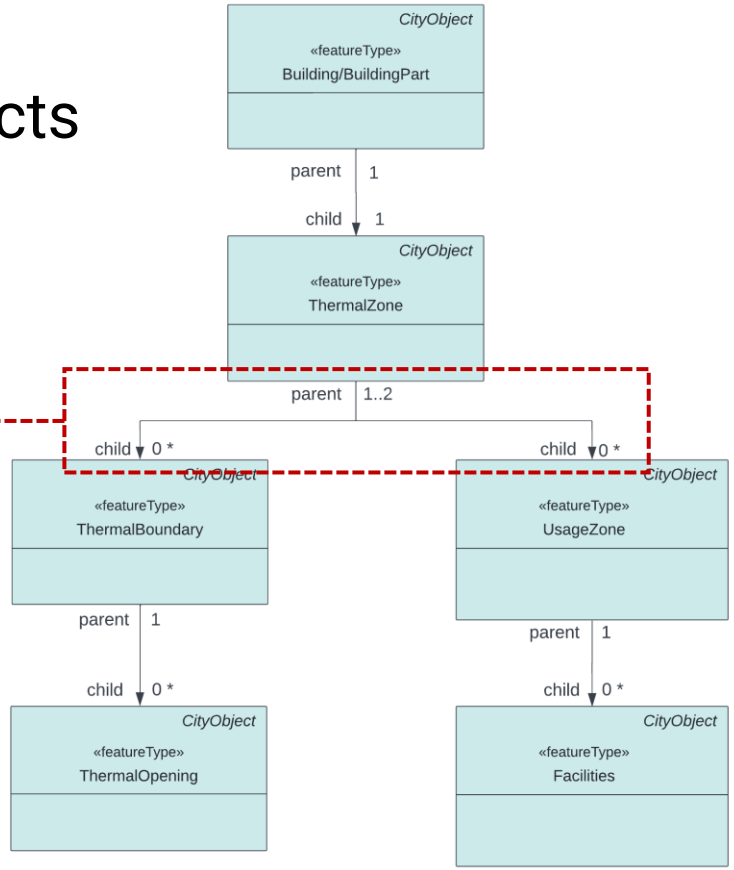
Space heating demand calculation

- Implemented in Python
- Assumptions and simplifications:
  - → Only residential & mixed-use buildings
  - → Heating period: [October, March]
  - → Constant value for indoor air temperature
  - → Each building as single thermal zone
  - → Window ratio instead of individual windows

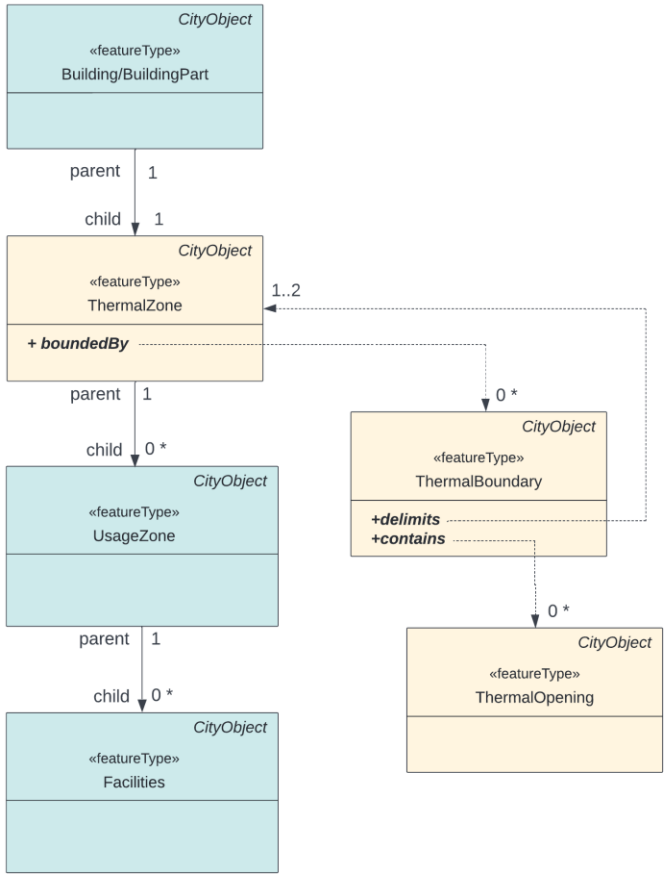
5.3 Limitations & improvements

Relations among objects

Ambiguity in parent/children relationship



Semi-direct translation

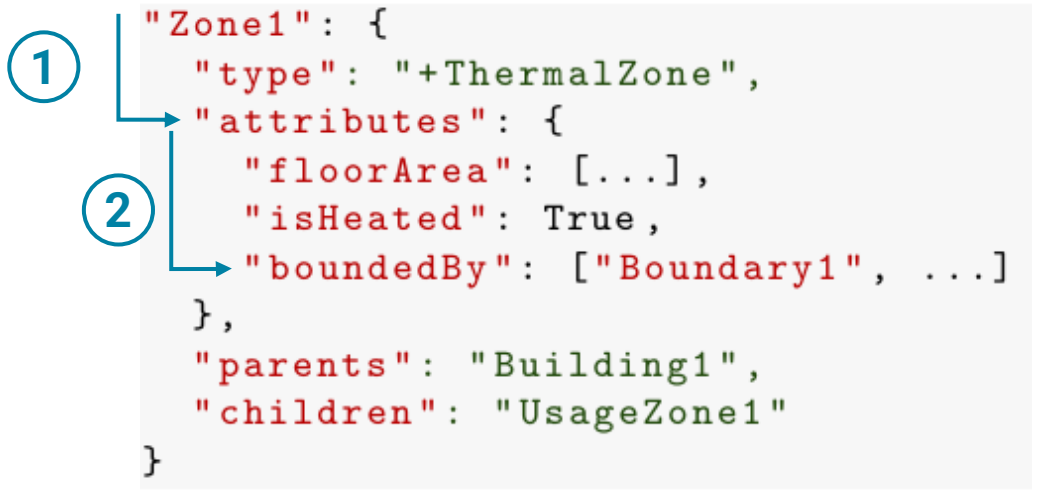


Final CityJSON Energy Extension

5.3 Limitations & improvements

Storage of relations among objects

With attributes



Semi-direct translation

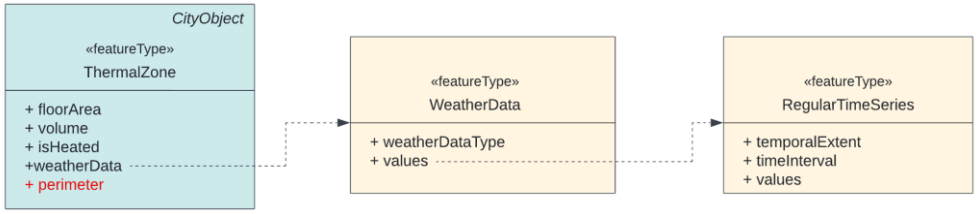
With properties

Final CityJSON Energy Extension

5.3 Limitations & improvements

Deep hierarchical structures – *WeatherData object*

Stored as extra object

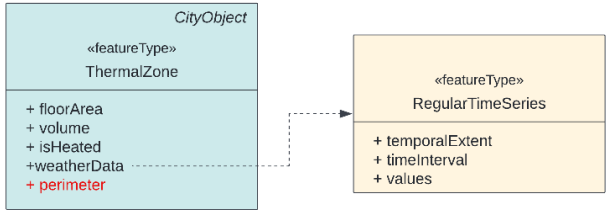



```
"Build1": {
  "type": "Building",
  "geometry": [...],
  "attributes": {
    "+buildingType": "singleFamily",
    ...
    "+weatherData":["OutdoorTemperature"]
  }
}
```

ID of WeatherData object

Semi-direct translation

Stored as subschema




```
"Build1": {
  "type": "Building",
  "geometry": [...],
  "attributes": {
    "weatherData": [
    {"weatherElement": "airTemperature",
        "weatherDataLocation": "indoor",
          "values": "RegularTimeSeries1"}
    ]
  ...
}
```

Final CityJSON Energy Extension

6. Results & Analysis

6.1 Energy ADE KIT profile vs. CityJSON Energy Extension

Energy ADE KIT profile	CityJSON Energy Extension	Impact
• **Limited** support for the use case	• **Full** support for the use case	
• **Deep hierarchical** structure	• Deep **hierarchies** are **removed**	
• **Clear distinction** between the storage of CityObjects and non-CityObjects	• **No distinction** between the storage of CityObjects and non-CityObjects	
• **Uses** inheritance	• **No** inheritance	No significant impact

6.2 Comparison on file size

- Only **25.2 MB** increase in CityJSON file size
- No comparison between Energy ADE and CityJSON Energy Extension
- Higher efficiency of CityJSON over CityGML

	3DCM in CityGML	3DCM in CityJSON	CityJSON + Energy Extension (only input data)	CityJSON + Energy Extension (output file)
# of objects	3318	3318	106848	108732
File size	165 MB	40.6 MB	63.7 MB	65.8 MB

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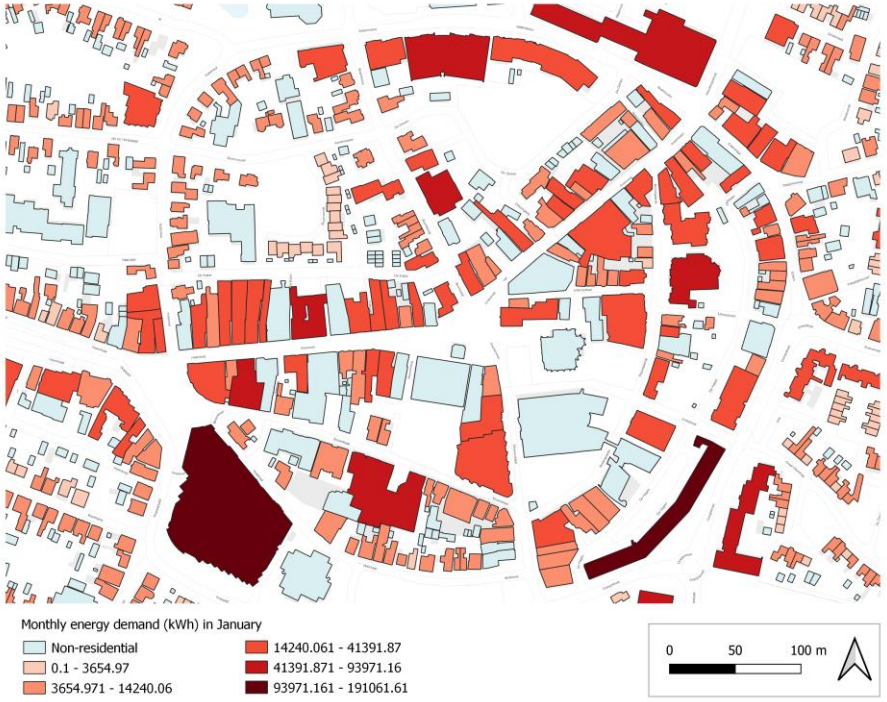
# of objects	3318	3318	106848	108732
File size	165 MB	40.6 MB	63.7 MB	65.8 MB

6.3 Results of the space heating demand calculation

- Calculated for *1884 buildings* out of the total of 3318
- Space heating demand in January:



Center of Rijssen

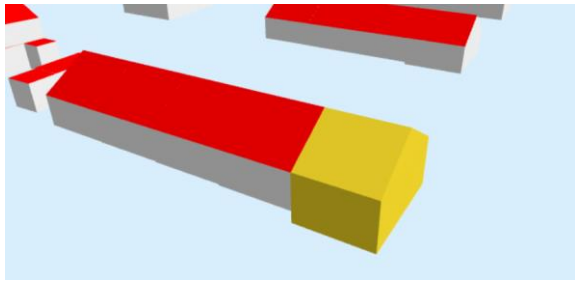
Residential area in Rijssen

6.3 Results of the space heating demand calculation

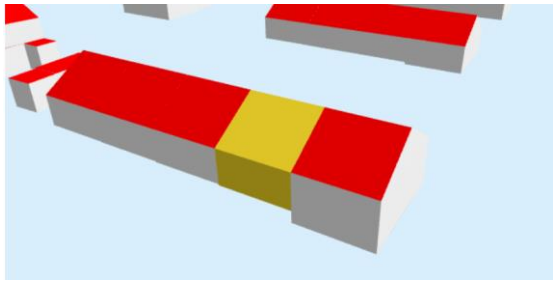
Impact of building position

Building position	Year	Building type	Building class	Usable area (m^2)	Building volume (m^3)	Energy demand - January (kWh/m^3)
Corner	1974	TH	Residential	94	377.67	10.45
Middle	1974	TH	Residential	92	308.52	8.48
Stand-alone	1985	SFH	Residential	183	703.13	6.22
Corner	1981	SFH	Residential	127	495.885	5.84

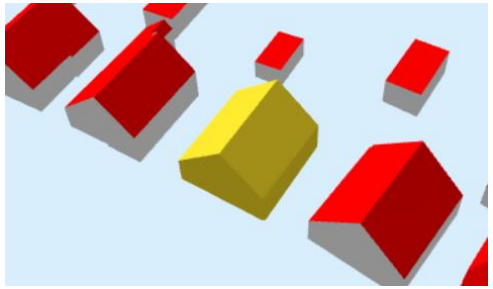
Corner building



Middle building



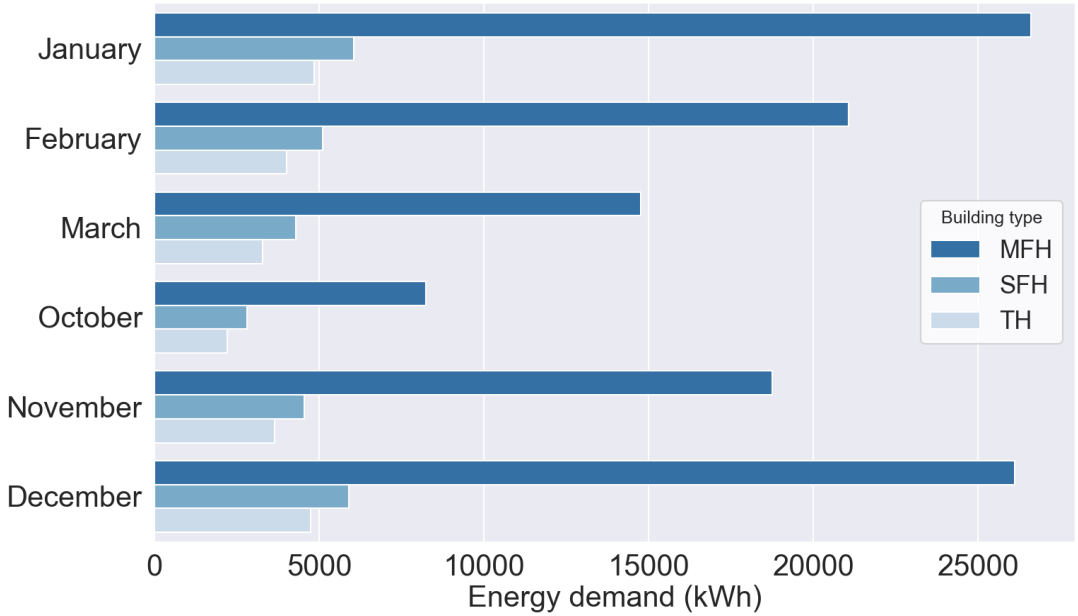
Stand-alone building



6.3 Results of the space heating demand calculation

Energy demand based on building typology

Monthly average values



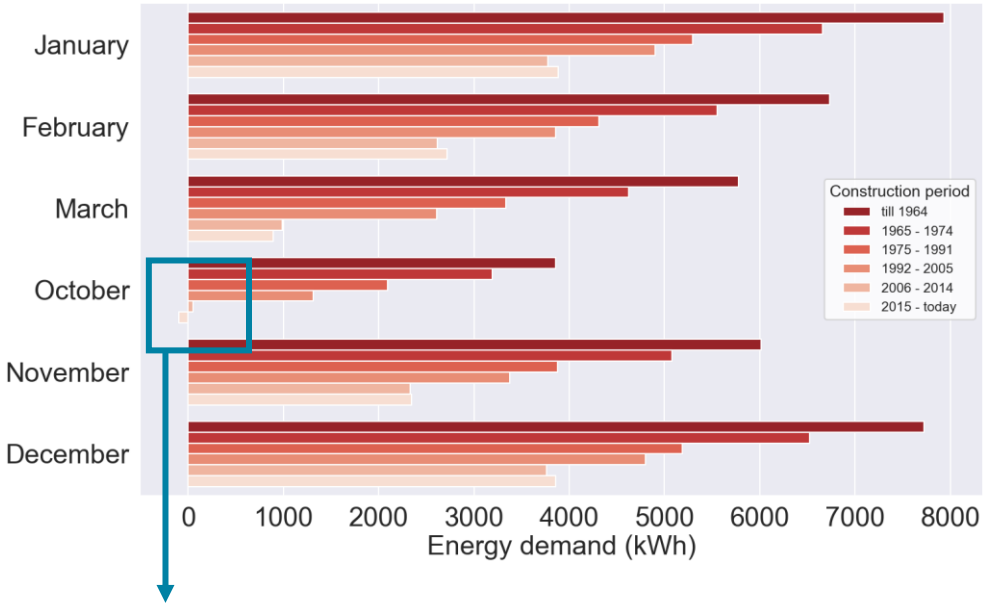
Building type	Average building volume (m^3)
Multi Family House	7694.98
Single Family House	592.35
Terrace House	537.21

MFH = Multi-family house
SFH = Single-family house
TH = Terrace house

6.3 Results of the space heating demand calculation

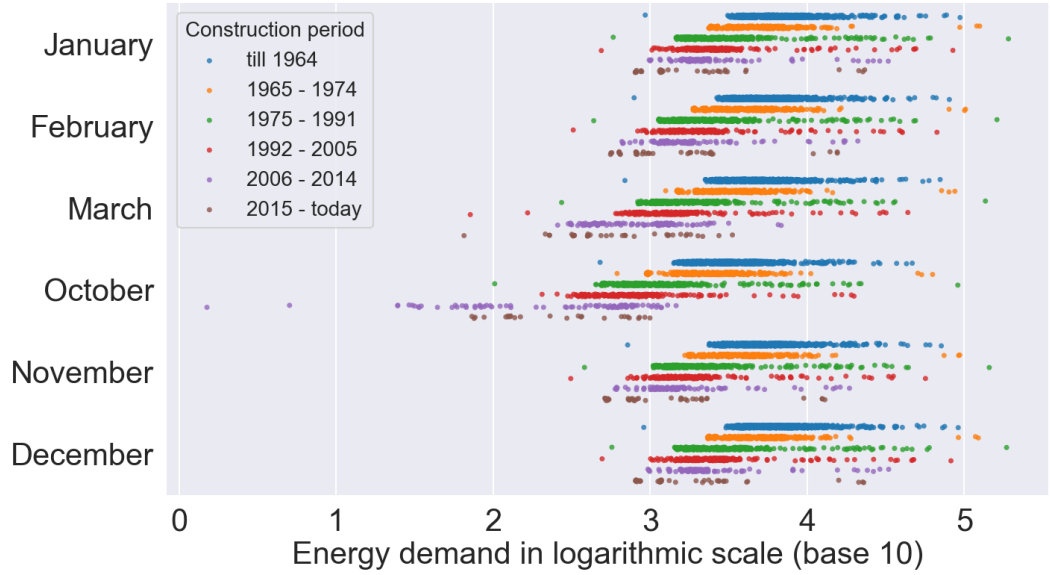
Energy demand based on construction periods

Monthly average values



Negative
average value!

Overall distribution

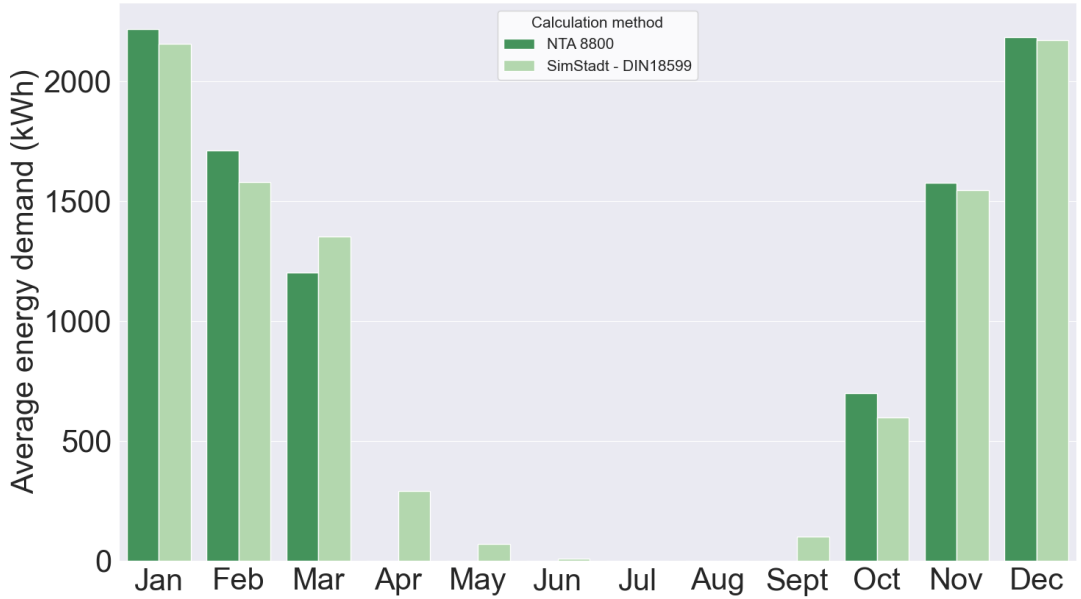


6.3 Results of the space heating demand calculation

Comparison with SimStadt values

- Dutch standard vs. German regulations
- Both use steady-state energy balance method
- Negative values → not found in SimStadt

Difference in monthly averages for a 10-building subset



6.3 Results of the space heating demand calculation

Negative values

- 32 buildings with negative energy demand values
- 1401 buildings with negative solar gains values

Possible reasons:

→ Used window ratio data

→ Solar gains calculation

10-building subset with negative energy demand

ID	Year	Class	Type	Monthly space heating demand (kWh)						
				Jan	Feb	Mar	Apr - Sep	Oct	Nov	Dec
11	2006	Mix.	MFH	4926.104	3164.618	493.2403	0	-480.732	2951.648	4907.25
12	2008	Mix.	MFH	9307.493	6201.38	1204.335	0	-1136.18	5344.322	9260.464
13	2011	Res.	TH	1756.013	1158.104	386.3949	0	-29.8774	1066.519	1750.983
14	2010	Res.	TH	1786.082	1181.133	257.1867	0	-98.3848	1081.698	1797.701
15	2009	Res.	TH	1161.864	742.2068	300.3615	0	-18.9162	694.6194	1144.829
16	2010	Mix.	MFH	26330.35	17157.38	3156.998	0	-4463.61	14623.96	26365.8
17	2012	Res.	MFH	7946.015	4610.537	-851.415	0	-2420.32	4212.729	8107.341
18	2012	Mix.	MFH	28914.34	17449.27	1529.095	0	-5327.15	16200.62	28993.83
19	2014	Mix.	MFH	19637.98	10367.67	-5014.41	0	-11479.8	8306.489	19928.46
20	2013	Mix.	MFH	32795.87	20979.23	2316.002	0	-5191.17	18565.13	32985.15

Solar gains calculation

$$Q_{H;sol;wi,k,mi} = g_{gl;wi,k;H;mi} \cdot A_{wi,k} \cdot \left(1 - F_{fr;wi,k}\right) \cdot F_{sh;obst;wi,k;mi} \cdot I_{sol;wi,k;mi} \cdot 0.001 \cdot t_{mi} - Q_{sky;wi,k;mi}$$

Extra heat flow due to the radiation to the sky

7. Conclusions & Future work

7.1 Conclusions

Main research question

How can a **CityJSON Energy Extension** be used to support the calculation of **space heating demand** of buildings?

7.1 Conclusions

Defining different types of objects (other than CityObjects):

- Possible with the **extraCityObjects** property
- Negative impact on the **simplicity** and **understandability** of the Extension
- Limits the possibilities of creating **complex Extensions**

Differences with the Energy ADE:

- **Less hierarchical** structure & more **efficient** storage
- Providing **full support** for the use case

7.1 Conclusions

Use of space heating demand calculation:

- **Validating** the Extension in terms of **storage of data**
- Achieving **less hierarchy** and more **efficiency**

Mapping CityGML ADEs to CityJSON Extensions:

- **Direct mapping** depends on used objects
- Support is needed to define **non-CityObjects**

7.2 Contributions & Limitations

Contributions

- Popularity of CityJSON over CityGML
- Development of new CityJSON Extensions
- Development/improvement of CityJSON tools

Limitations

- Definition of new objects in the Extension schema
- Input data for the space heating demand calculation
- Results of the space heating demand calculation

7.3 Future work

- Further development of the CityJSON Energy Extension
  - → Testing with other use cases
  - → Incorporating the full Energy ADE

- Additional methods for validation and comparison
  - → Conversion between the Energy ADE and CityJSON Energy Extension
  - → Further analysis on file size: Energy ADE vs. CityJSON Energy Extension

Thank you for your attention!

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