ONTOLOGY-BASED BUILDING ENERGY SYSTEM COMMISSIONING AND MONITORING

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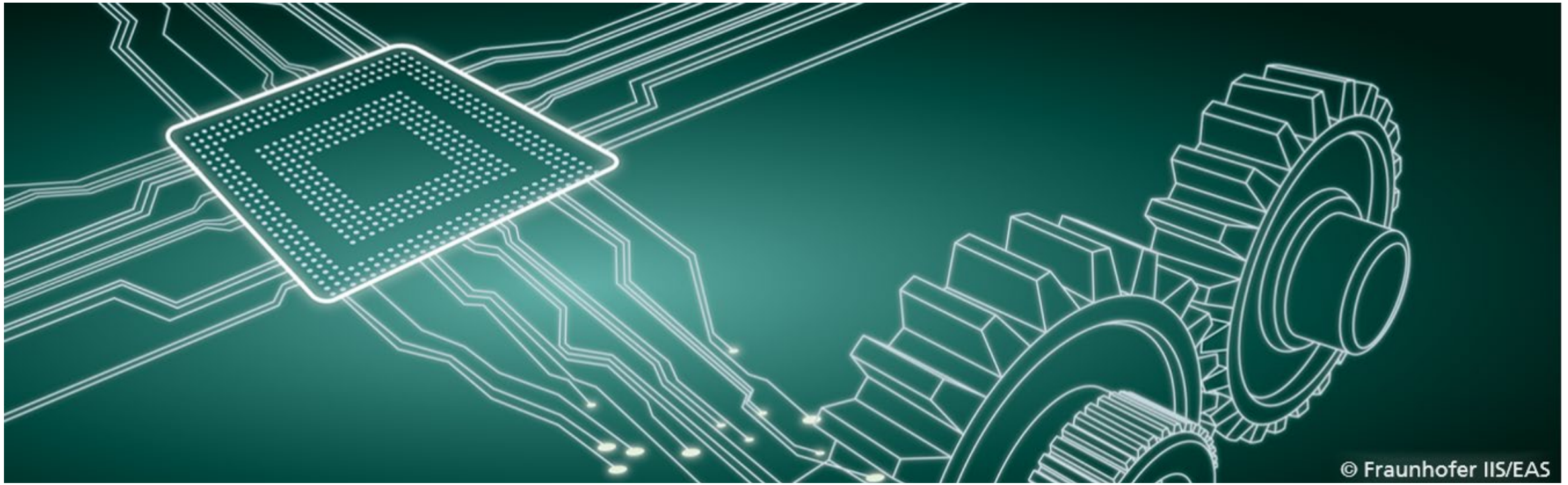

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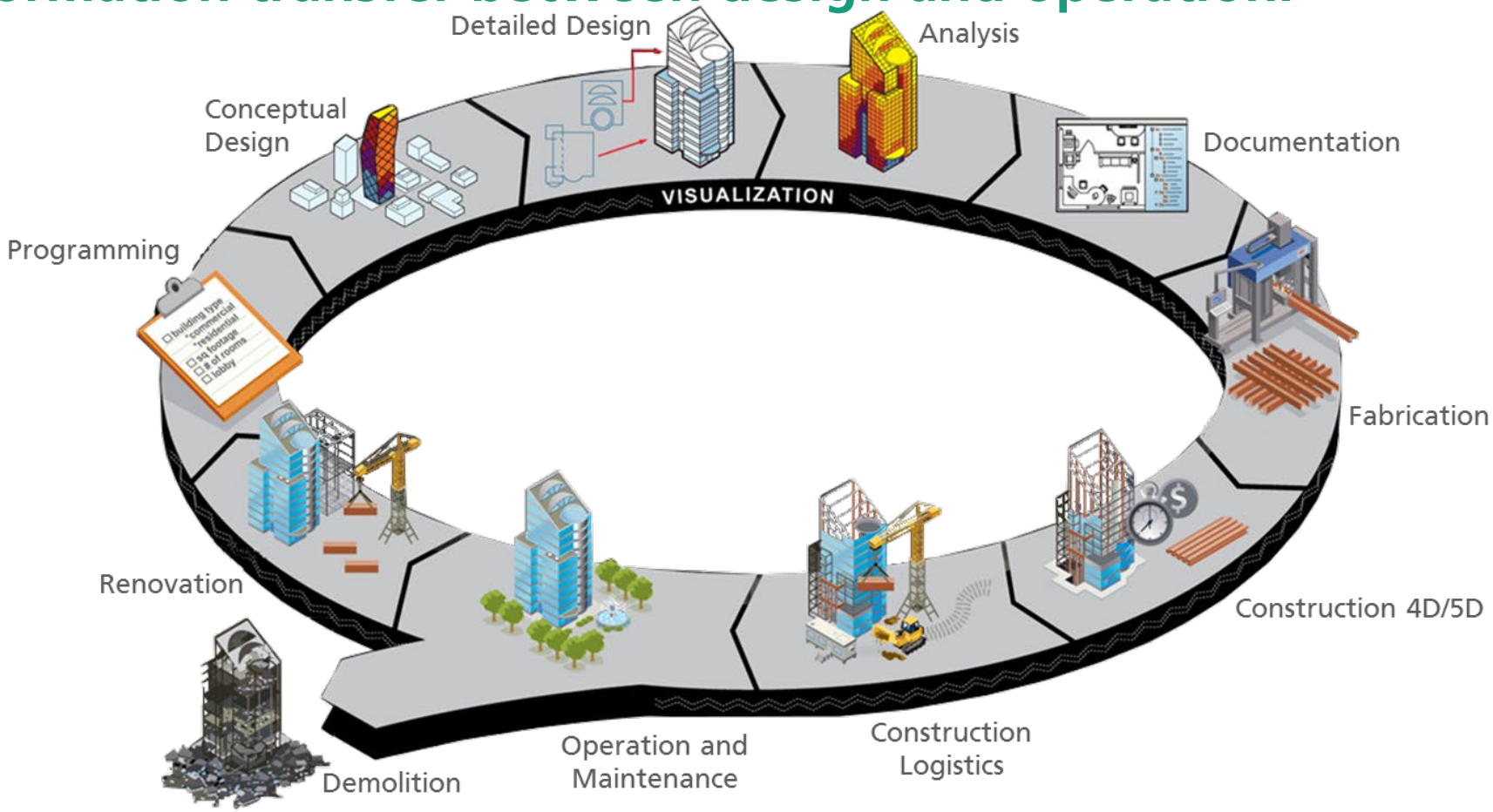
Building Life Cycle

Much information is generated during the whole building lifecycle. But still a gap in information transfer between design and operation.



Quelle: http://buildipedia.com/aec-pros/design-news/the-daily-life-of-building-information-modeling-bim

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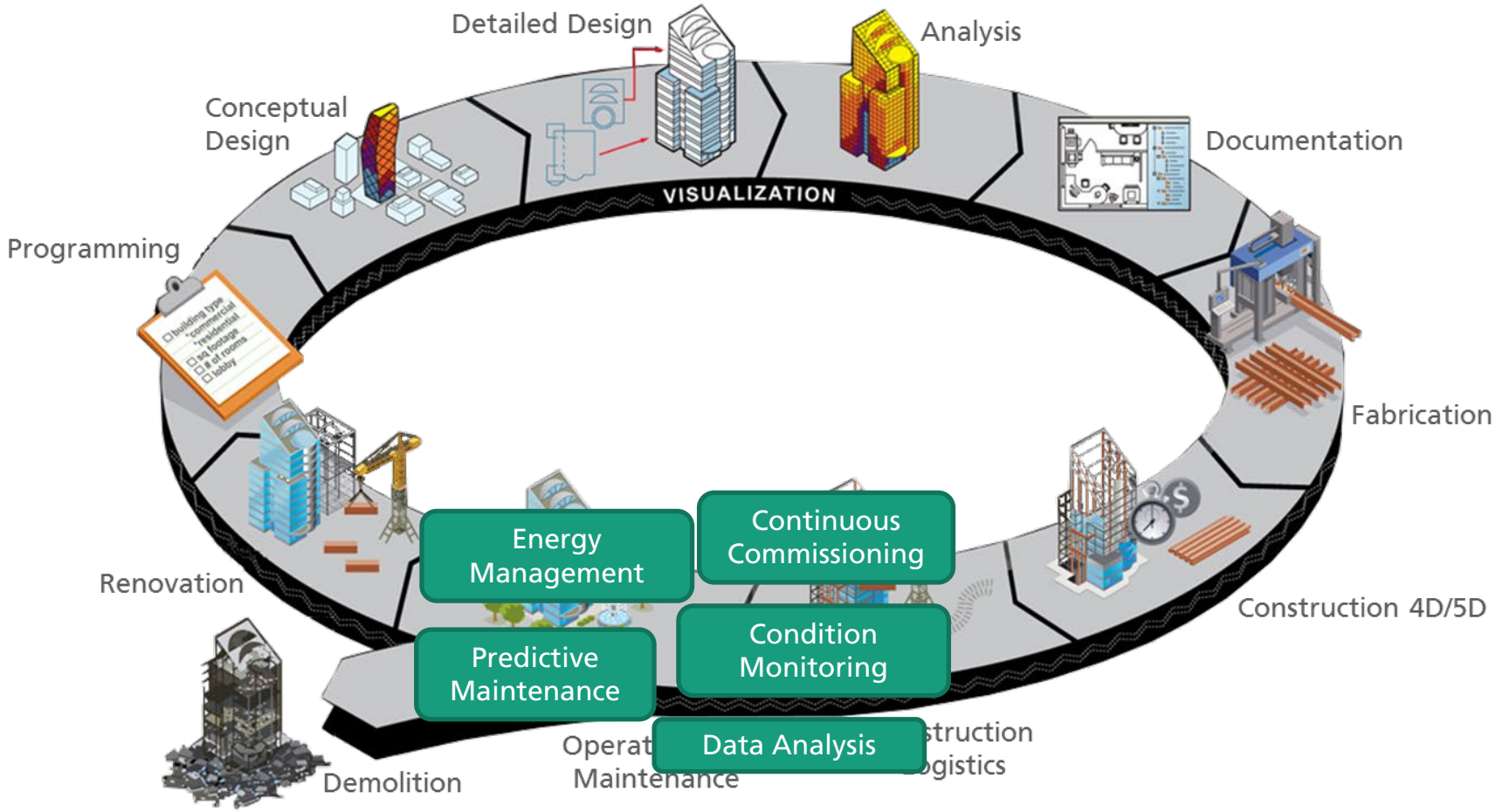
Building Life Cycle

How to reuse design information for automating building commissioning and operation?



Quelle: http://buildipedia.com/aec-pros/design-news/the-daily-life-of-building-information-modeling-bim

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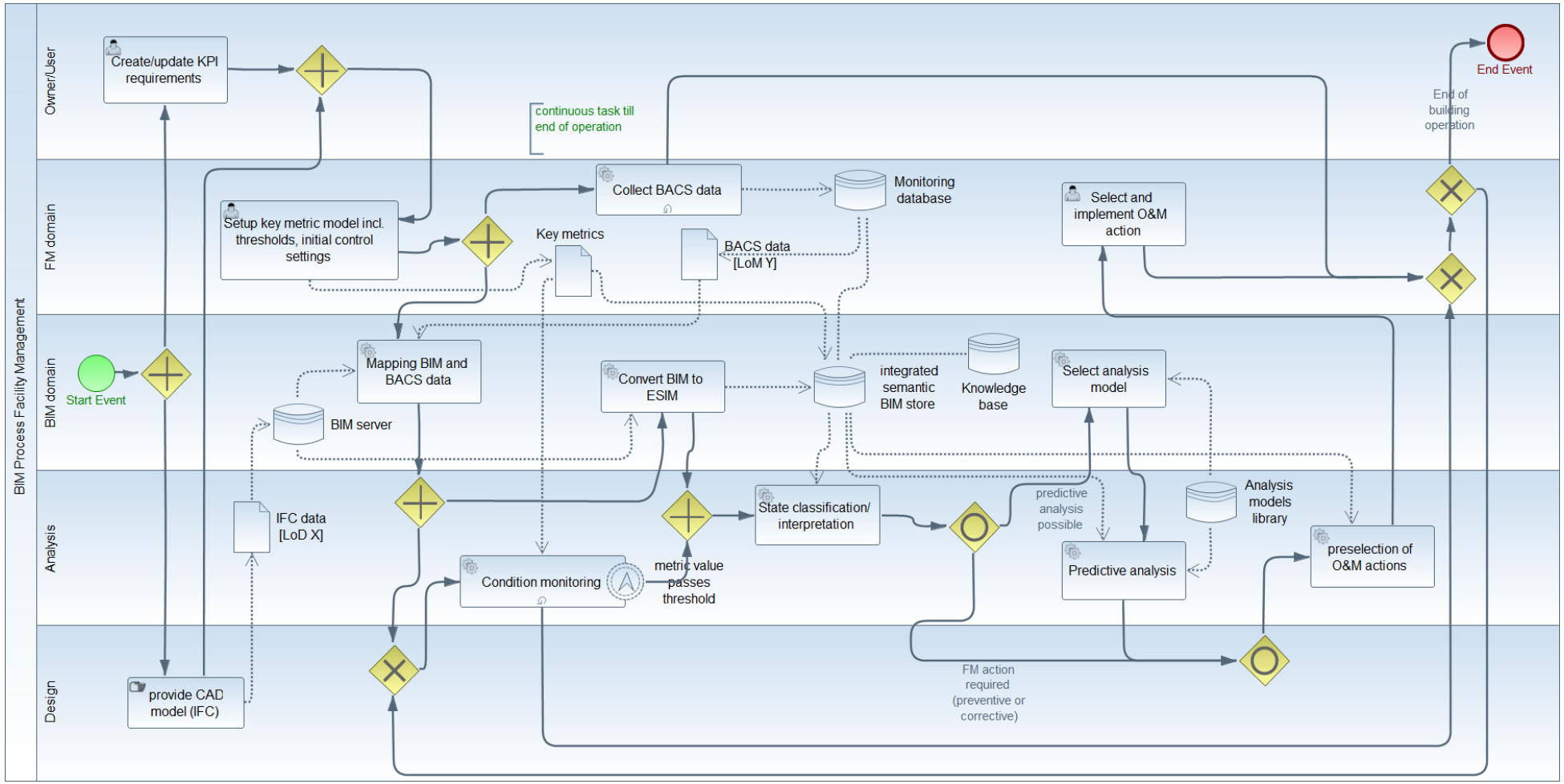
BIM Workflow for FM: BPMN Process (Business Process Modeling and Notations), ISO 19510

Main Elements:

- Link BIM and monitoring data
- Energy System Description
- Knowledge base
- Library of data analysis models / algorithms
- O&M actions catalogue (control actions, maintenance actions)



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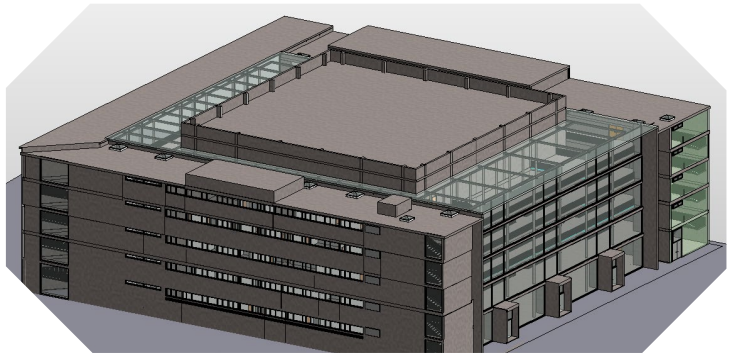
BIM4FM: BIM workflow for analysis automation

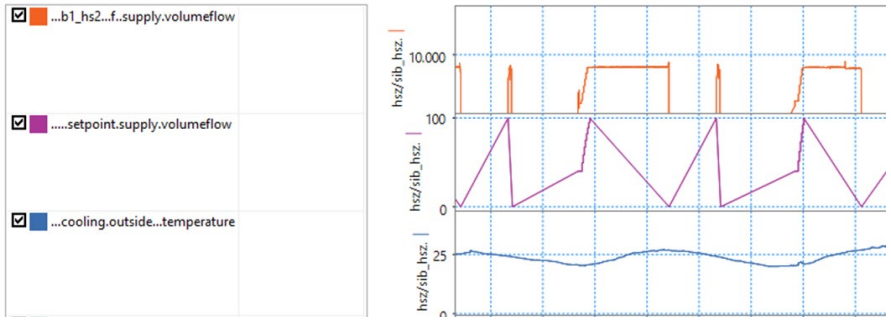
Digital model (example: Lecture Hall of the TU Dresden)



Building Design data

+

Building Monitoring data



IFC

Rule Set:
r1: A(?x) -> C(?x)
r2: B(?x) -> D(?x)
…

Knowledge Base

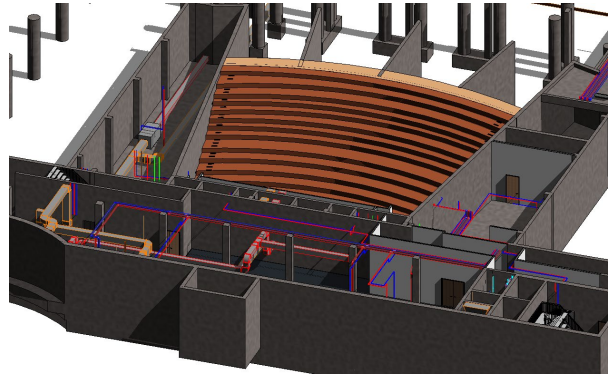
Semantic Analysis

Outputs:

Operational state of energy system and components:

- Inefficiency
- Energy wastes
- Malfunctions
- Failures

Integrated semantic building information model



Analysis Models Library

- Energy behaviour
- Aging / Wear
- System reliability
- …

Predictive Analysis

Outputs:

- Energy use
- efficiency rate
- Remaining service time
- Reliability state

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Analysis goal: check energy wastes and energy conservation measures

- Energy conservation measures are potential actions a building user or facility manager can perform on the overall energy system to save energy
- ECM formalized as rules in a knowledge base
- Defined at different Levels of Monitoring (LoM) and Levels of Control (LoC):
  - Building
  - Zone
  - Room
- For a specific building, applicable ECMs depend on building information and monitoring data

ECM1	**save cooling energy:**
ECM1-1	save energy by optimizing solar gain
ECM1-2	save energy when facility not occupied
ECM1-3	save energy by better matching energy and comfort needs
ECM1-4	save energy avoiding HVAC operating errors
ECM1-5	save energy avoiding wastes through openings
ECM2	**save heating energy:**
ECM2-1	save energy by optimizing solar gain
ECM2-2	save energy when facility not occupied
ECM2-3	save energy by better matching energy and comfort needs
ECM2-4	save energy avoiding HVAC operating errors
ECM2-5	save energy avoiding wastes through openings
ECM3	**save lighting energy:**
ECM3-6	save lighting energy turning off lights when space unoccupied
ECM3-7	save lighting energy optimizing natural light income
ECM4	**save electrical energy:**
ECM4-8	save electrical energy turning appliances down when room unoccupied

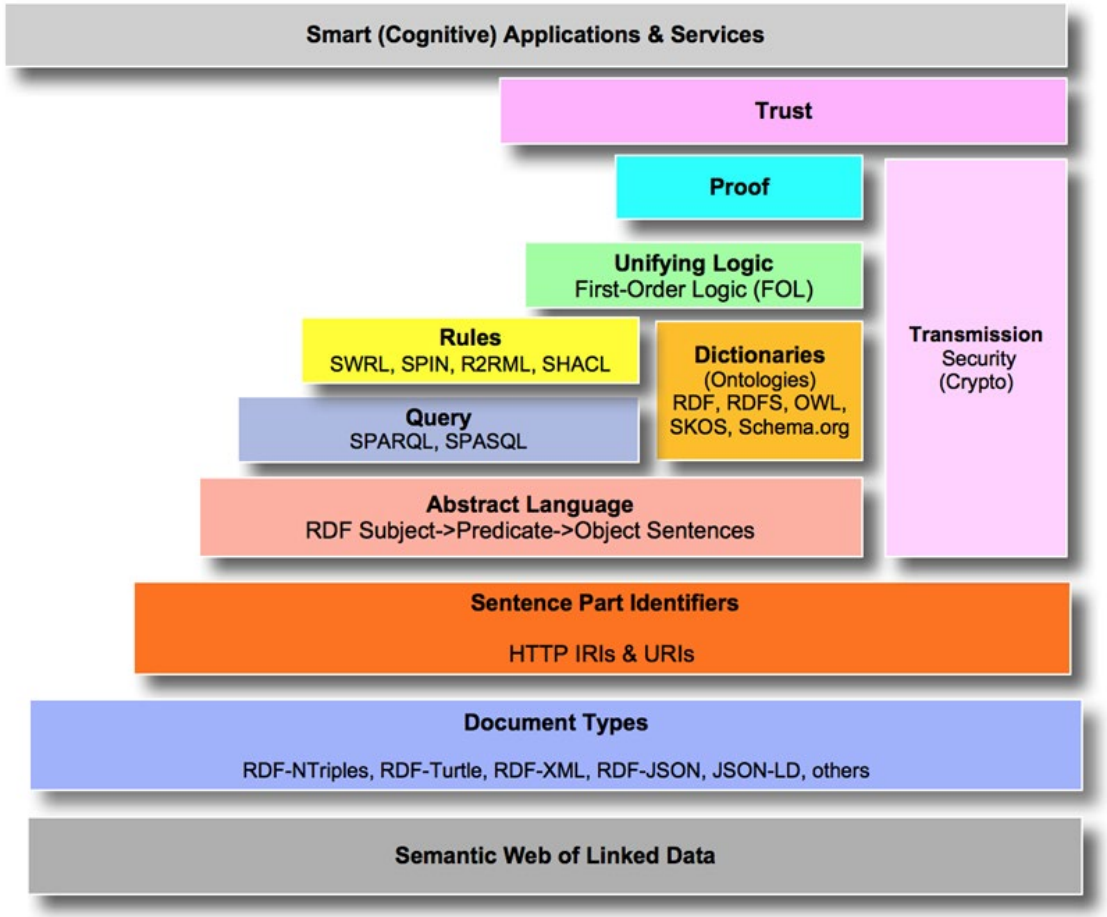
Use of Semantic Web technics for building energy system description

- Architecture of the Semantic Web:

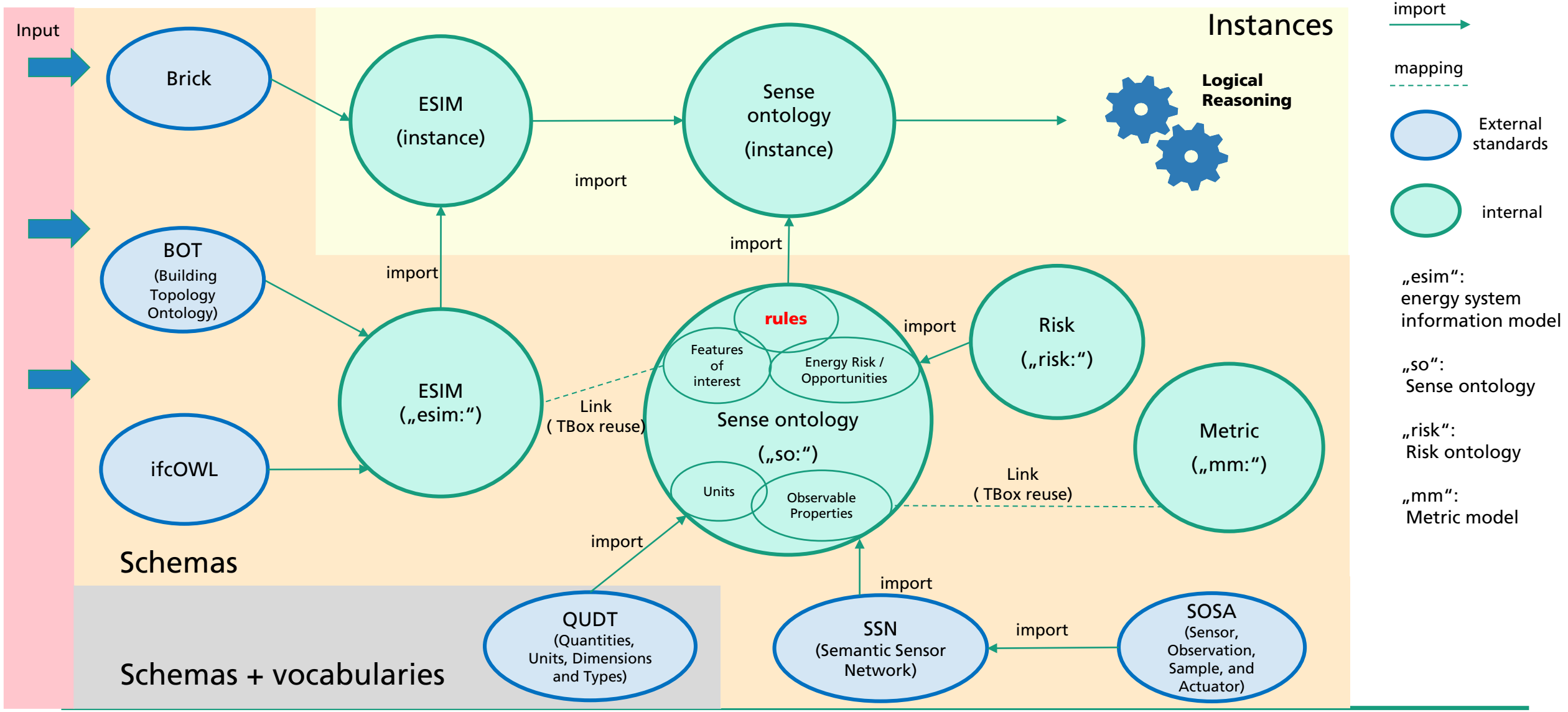
Logic Layer

Schema Layer

Metadata Layer



Linked Data implementation



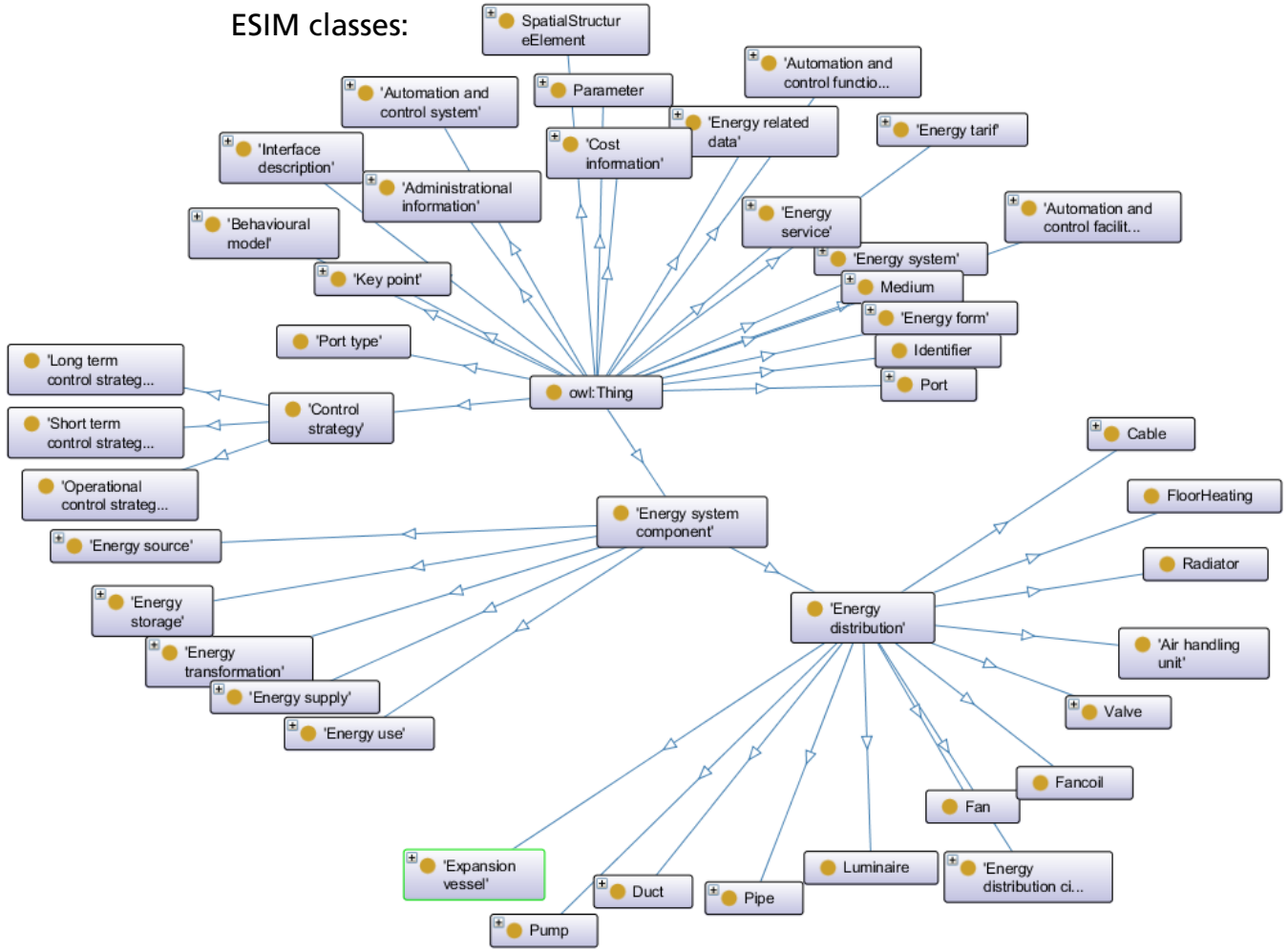
ESIM: Energy System Information Model

Energy System Information Model (ESIM) is a domain specific model that **provides information of the urban and building energy system including the automation and control systems**. It comprises **functional, structural and physical descriptions of the systems** as master data and additional **operational data**.

```
@prefix : <http://www.eas.iis.fraunhofer.de/dc/esim-instance#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix esim: <http://org.fhg.iis.eas.eee.esim/ESIMonto#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@base <http://www.eas.iis.fraunhofer.de/dc/esim-instance> .

<http://www.eas.iis.fraunhofer.de/dc/esim-instance> rdf:type owl:Ontology ;
                                                    owl:imports <http://org.fhg.iis.eas.eee.esim/ESIMonto> ;
                                                    owl:versionInfo "Created with TopBraid Composer" .


#################################################################
#    Individuals
#################################################################

###  http://www.eas.iis.fraunhofer.de/dc/esim-instance#BoilerPump
:BoilerPump rdf:type owl:NamedIndividual ,
                     esim:Pump .


###  http://www.eas.iis.fraunhofer.de/dc/esim-instance#CombiStorage
:CombiStorage rdf:type owl:NamedIndividual ,
                       esim:HotWaterTank ;
              rdfs:label "HotWaterTank_FASA" .
```

RDF serialization

ESIM classes:



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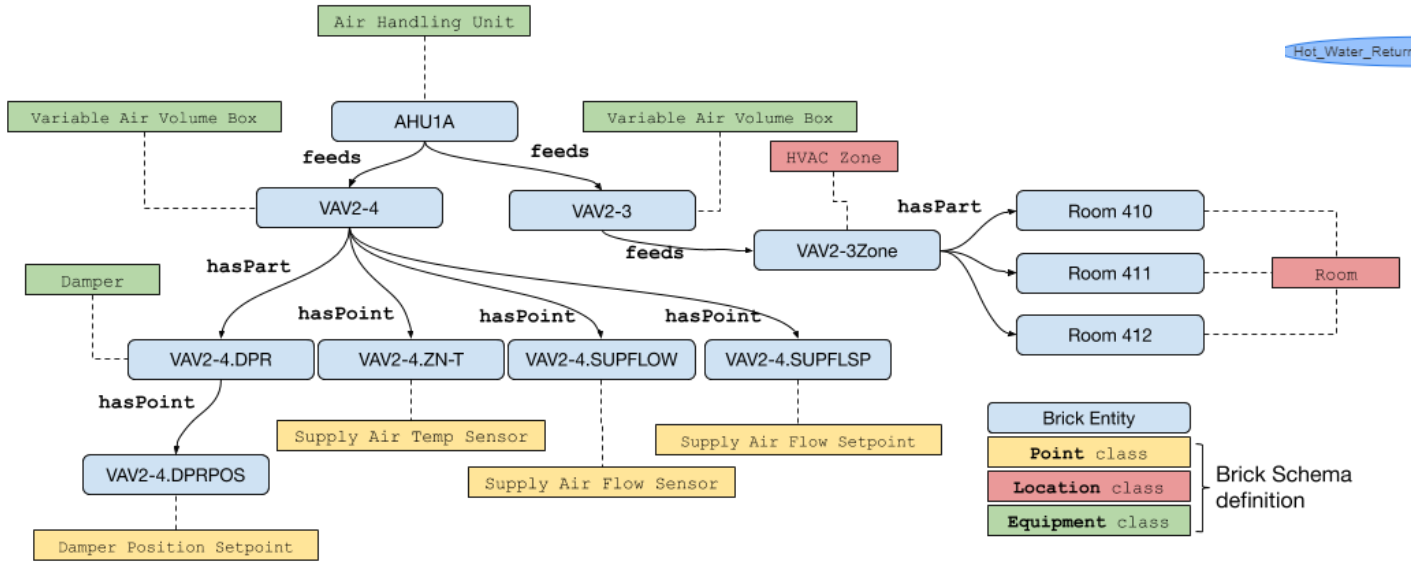
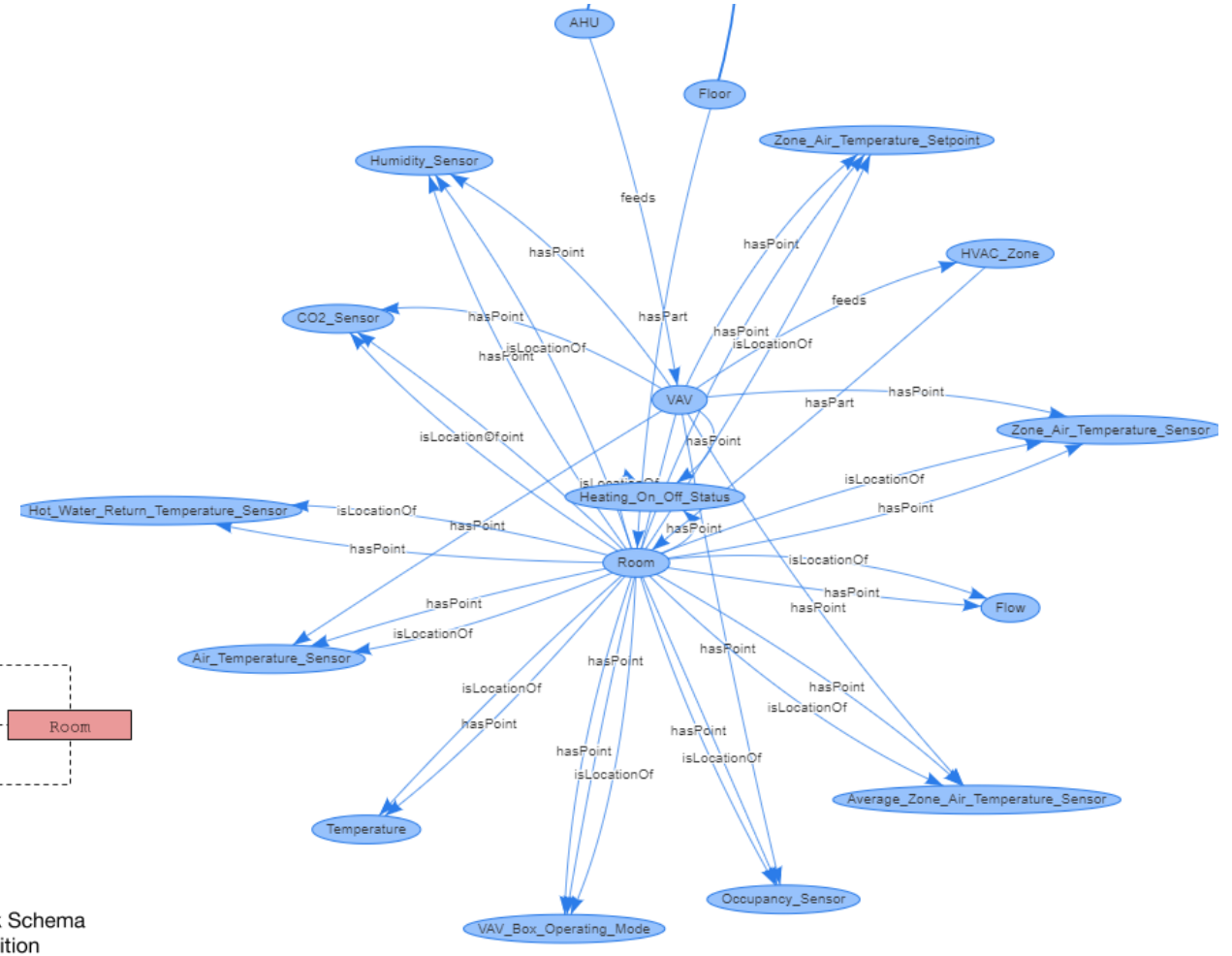
„Brick“ Schema

- open-source effort to standardize semantic descriptions of the physical, logical and virtual assets in buildings and the relationships between them.
- extensible dictionary of terms and concepts in and around buildings, a set of relationships for linking and composing concepts together.
- Source: https://brickschema.org/





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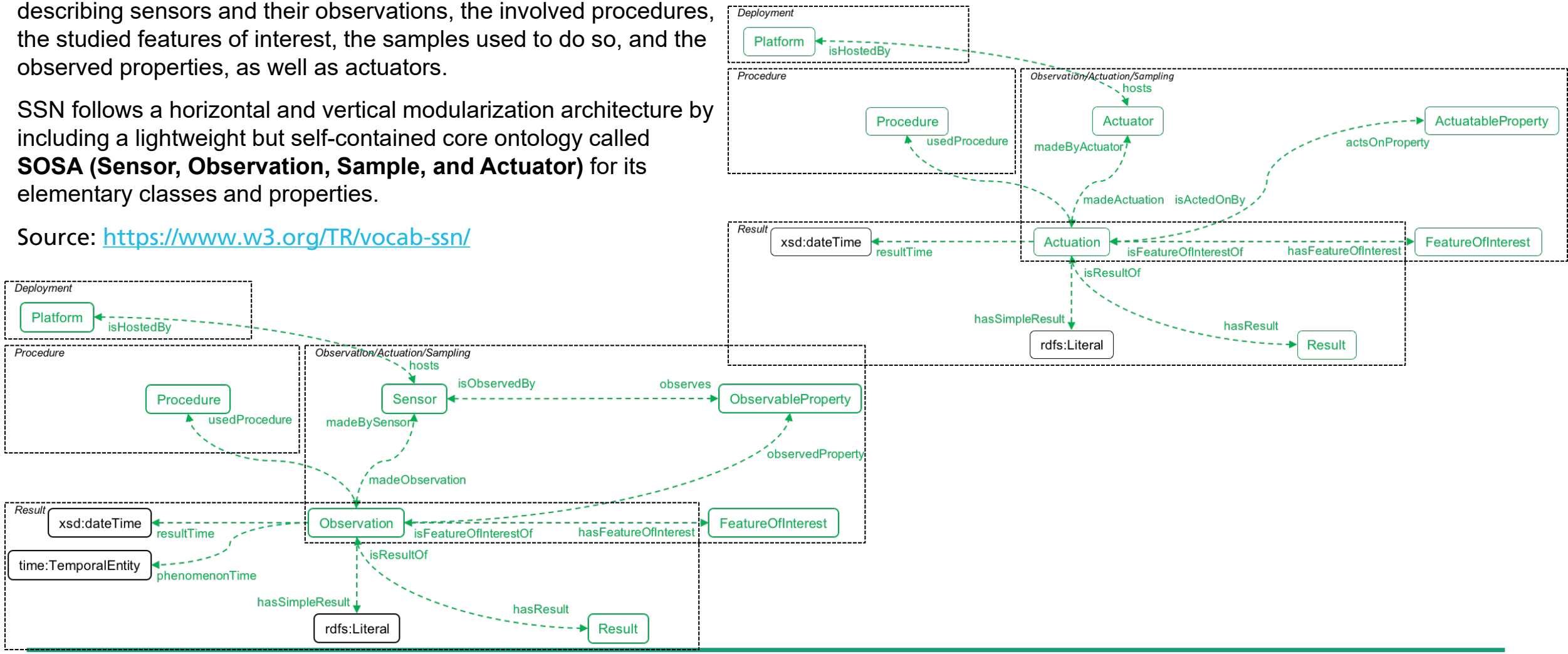
SSN: Semantic Sensor Network

- The **Semantic Sensor Network (SSN)** ontology is an ontology for describing sensors and their observations, the involved procedures, the studied features of interest, the samples used to do so, and the observed properties, as well as actuators.
- SSN follows a horizontal and vertical modularization architecture by including a lightweight but self-contained core ontology called **SOSA (Sensor, Observation, Sample, and Actuator)** for its elementary classes and properties.
- Source: https://www.w3.org/TR/vocab-ssn/



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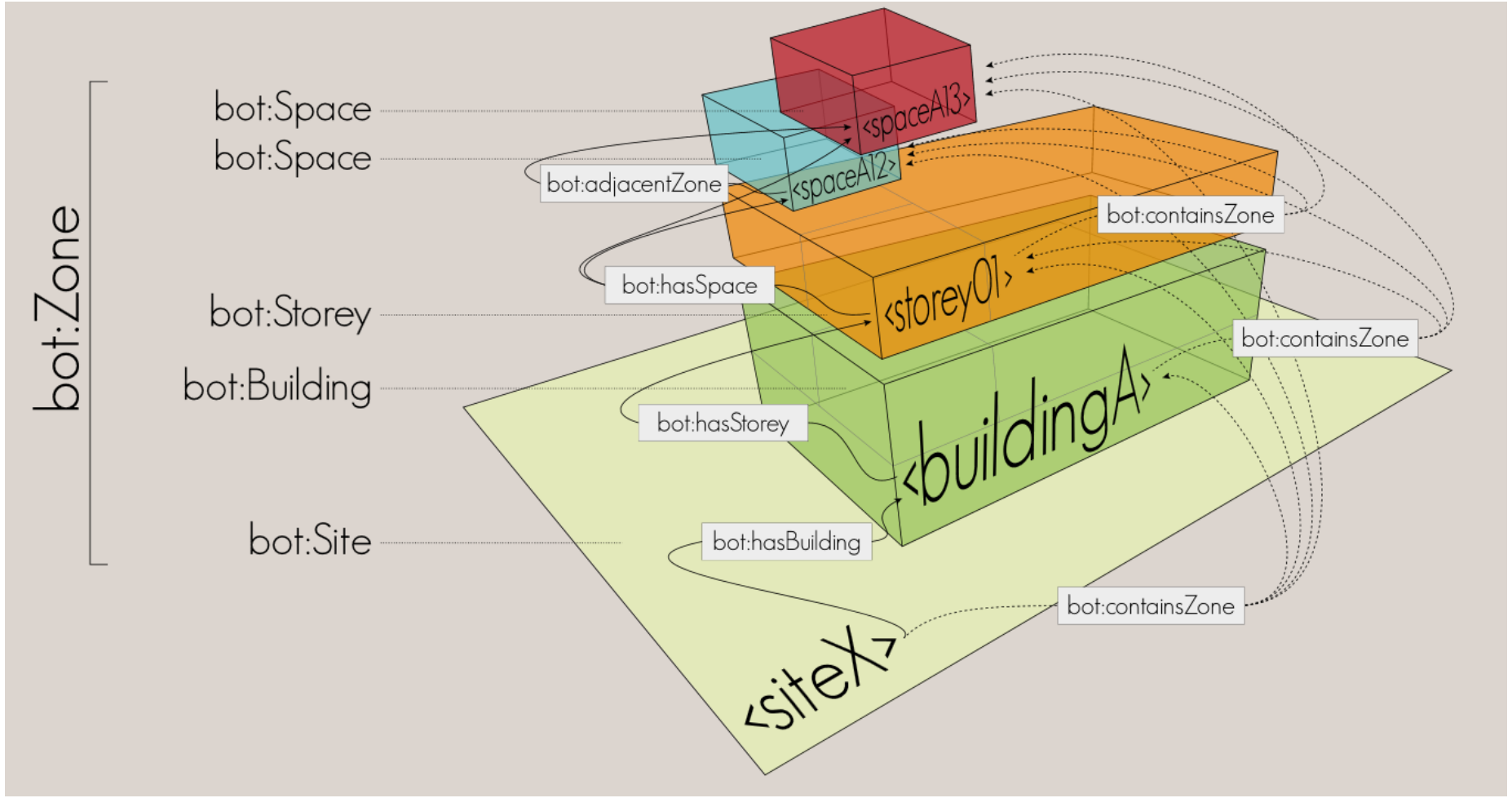
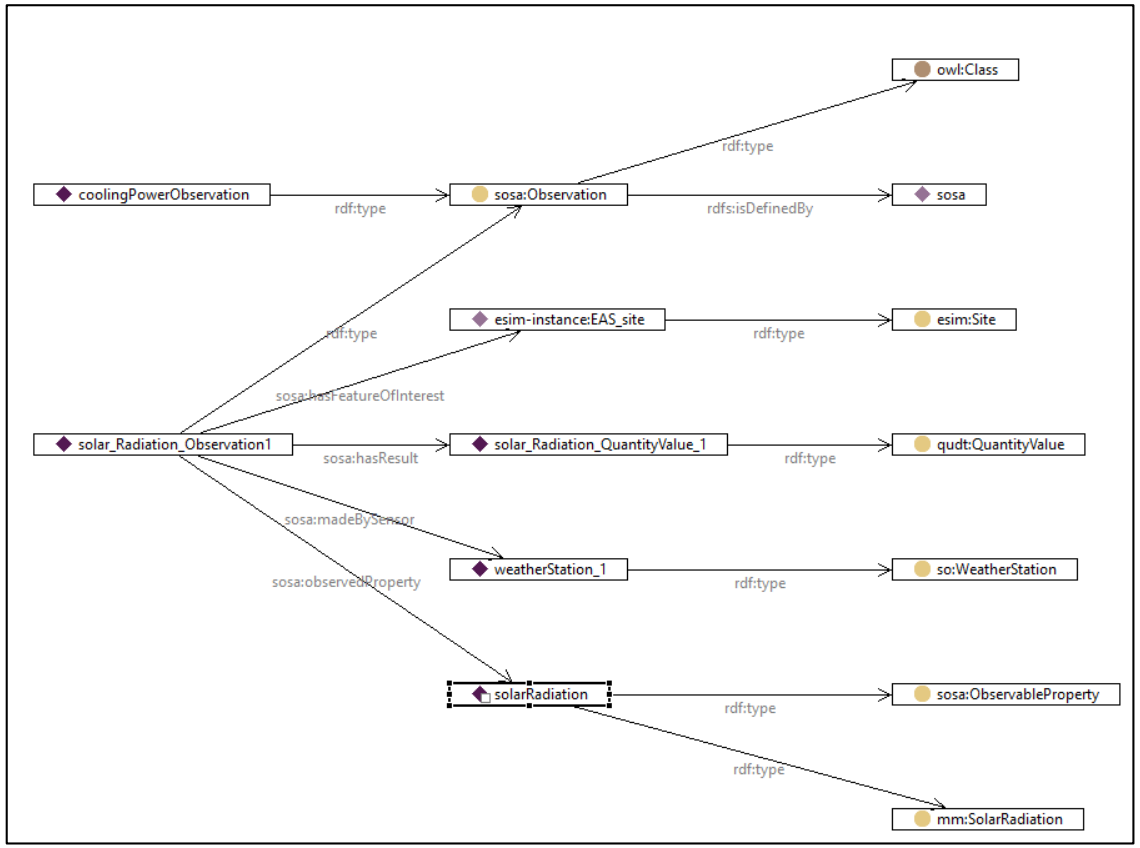
bot:Zone - “Matryoshka”- style nesting

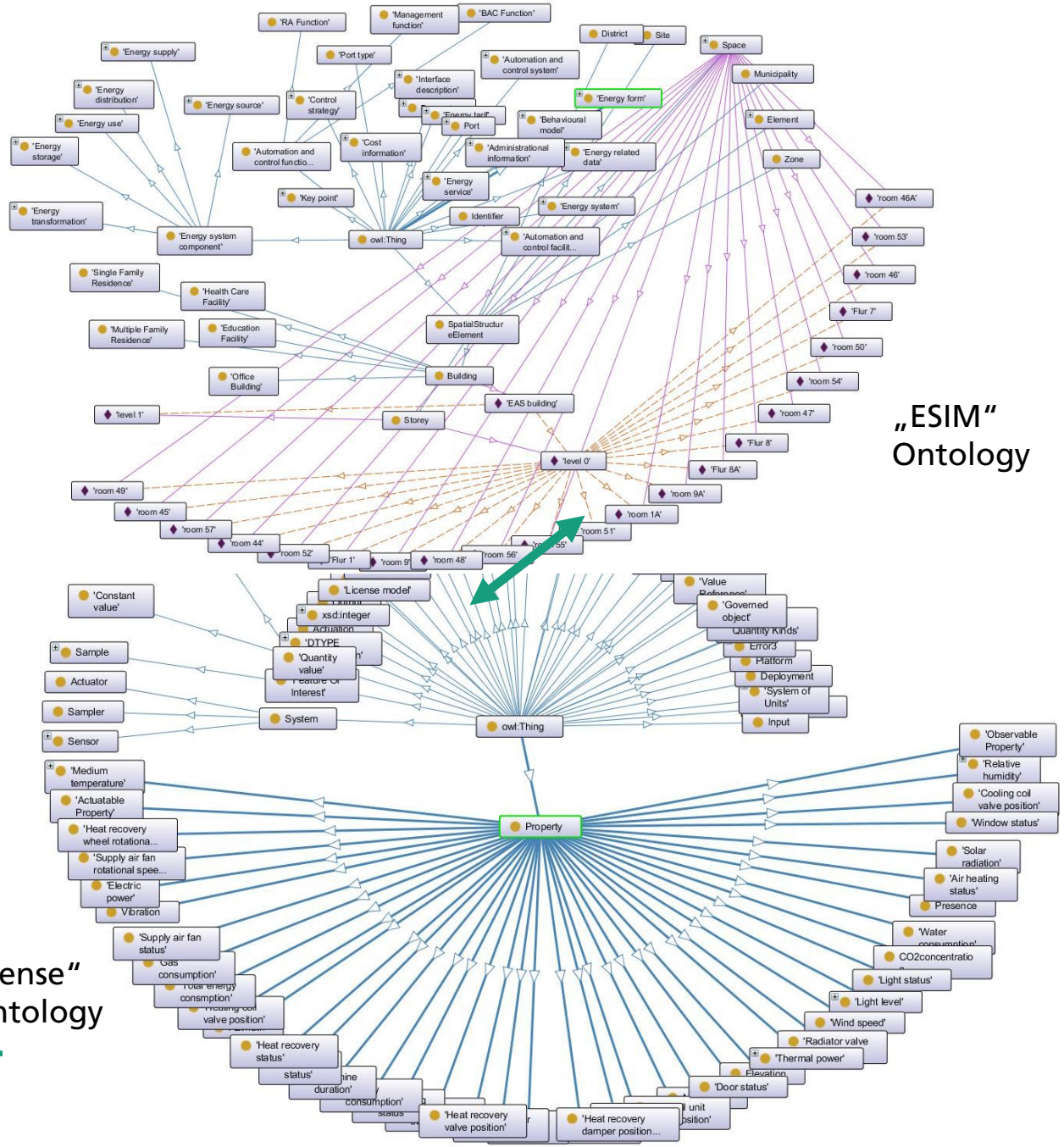


Mads Holten Rasmussen, Maxime Lefrançois, Georg Ferdinand Schneider, Pieter Pauwels (2020). BOT: the Building Topology Ontology of the W3C Linked Building Data Group, Semantic Web Journal, IOS Press

Figure source: PhD Defense of Mads Holten Rasmussen: http://www.student.dtu.dk/~mhoras/presentations/defense.html#/

Overall Linked Data Model





„ESIM“ Ontology

„Sense“ Ontology

Sense ontology: system characterization using logical axioms and rules

- Equivalent class axiom for classifying heating zones

```
esim:HeatingZone
  a owl:Class ;
  rdfs:comment "A space or group of spaces with heating requirements maintained by a heating system" ;
  rdfs:label "Heating zone" ;
  rdfs:subClassOf esim:ConditionedZone ;
  owl:equivalentClass [
      a owl:Class ;
      owl:intersectionOf (
          esim:SpatialStructureElement
          [
            a owl:Restriction ;
            owl:onProperty esim:hosts ;
            owl:someValuesFrom [
                a owl:Class ;
                owl:intersectionOf (
                    esim:EnergyDistribution
                    [
                      a owl:Restriction ;
                      owl:onProperty esim:composes ;
                      owl:someValuesFrom esim:HeatingSystem ;
                    ]
                  ) ;
              ] ;
          ]
        ) ;
    ] ;
.
```

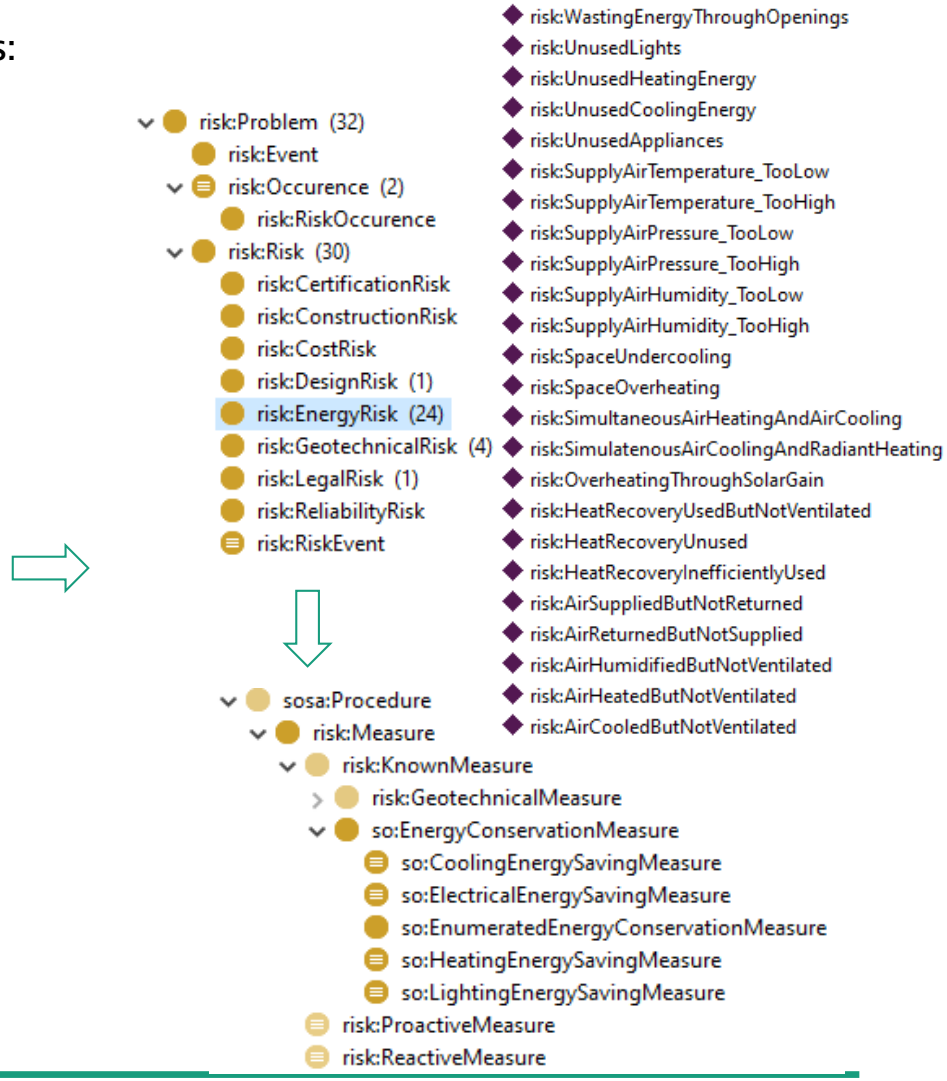
⇔

```
Class: HeatingZone

    EquivalentTo:
        SpatialStructureElement
         and (hosts some
            (EnergyDistributionComponent
             and (composes some HeatingSystem)))

    SubClassOf:
        ConditionedZone
```

Sense ontology: system characterization using logical axioms and rules

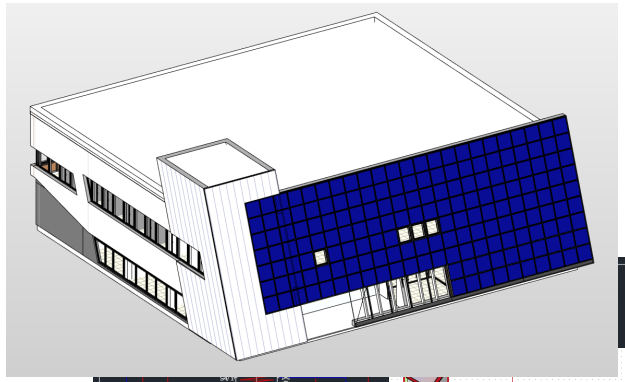
- Examples of SWRL rules used for identification of energy risks in air handling units:

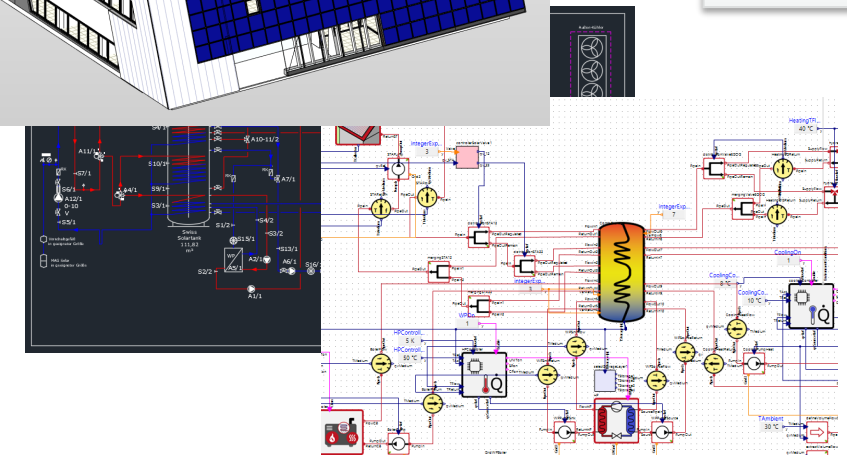
Nr	*Rule definition in human-readable syntax*
(1)	brick:AHU(?ahu) ∧ brick:Heating_Coil(?hc) ∧ brick:Cooling_Coil(?cc) ∧ brick:hasPart(?ahu, ?hc) ∧ brick:hasPart(?ahu, ?cc) → risk:hasRisk(?ahu, risk:SimultaneousAirHeatingAndAirCooling)
(2)	brick:AHU(?ahu) ∧ brick:Heating_Coil(?hc) ∧ brick:Cooling_Coil(?cc) ∧ brick:hasPart(?ahu, ?hc) ∧ brick:feeds(?hc, ?cc) → risk:hasRisk(?ahu, risk:SimultaneousAirHeatingAndAirCooling)
(3)	brick:AHU(?ahu) ∧ brick:Heating_Coil(?hc) ∧ brick:Supply_Fan(?sf) ∧ brick:hasPart(?ahu, ?hc) ∧ brick:hasPart(?ahu, ?sf) → risk:hasRisk(?ahu, risk:AirHeatedButNotVentilated)
(4)	brick:AHU(?ahu) ∧ brick:Cooling_Coil(?cc) ∧ brick:Supply_Fan(?sf) ∧ brick:hasPart(?ahu, ?cc) ∧ brick:hasPart(?ahu, ?sf) → risk:hasRisk(?ahu, risk:AirCooledButNotVentilated)
(5)	brick:AHU(?ahu) ∧ brick:Humidifier(?h) ∧ brick:Supply_Fan(?sf) ∧ brick:hasPart(?ahu, ?h) ∧ brick:hasPart(?ahu, ?sf) → risk:hasRisk(?ahu, risk:AirHumidifiedButNotVentilated)
(6)	brick:AHU(?ahu) ∧ brick:Exhaust_Fan(?hf) ∧ brick:Supply_Fan(?sf) ∧ brick:hasPart(?ahu, ?hf) ∧ brick:hasPart(?ahu, ?sf) → risk:hasRisk(?ahu, risk:AirReturnedButNotSupplied) ∧ risk:hasRisk(?ahu, risk:AirSuppliedButNotReturned)
(7)	risk:hasRisk(?e, ?ri) ∧ risk:assessedBy(?ri, ?ru) ∧ so:Rule(?ru) → so:hasRule(?e, ?ru)



so:Rule = state interpretation rule (based on dynamic data) ⇄ System characterization rule (based on design information)

System description and ontology integration into the workflow





Converter

ifcOWL

Brick

ESIM

import

Sense

Rules
r1: A(?x) -> C(?x)
r2: C(?x) -> A(?x)

Inference Machine

import

SSN

import

metric

import

QUDT

Monitoring Database

Importer

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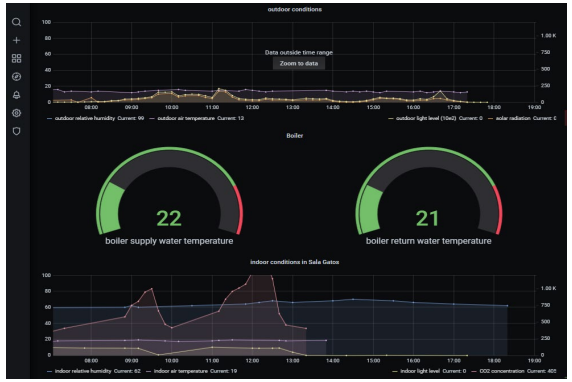
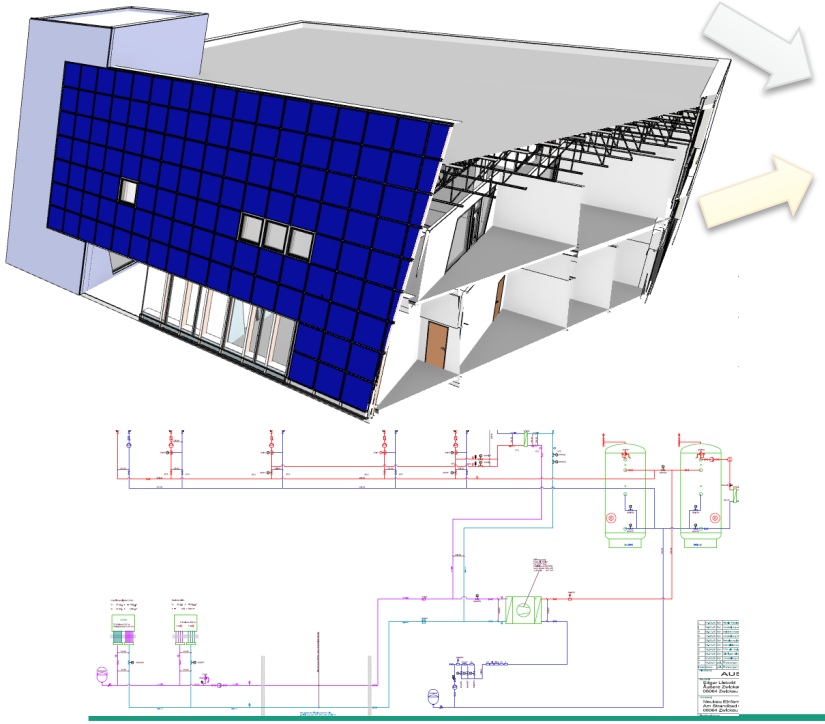
Prototype implementation of the Expert System





Monitoring System Back-End Storage

Import

Fact Base

cached data

monitoring metadata

building metadata

Rule Set
r1: A(?x) -> C(?x)
r2: C(?x) -> A(?x)
...

Knowledge Base (Energy Conservation Measures)

Inference Module

Building elements topology:

site
building
zone
storey
room
component
system

relations to building topological elements

- *recommendation* x_0
- *recommendation* x_1
- *recommendation* x_n
- ...

export

Front-End App

3 levels of inference rules:

- ***1st level*: system characterization**
  - Rules used for system characterization
- ***2nd level*: state interpretation**
  - Rules for interpretation of operational conditions
- ***3rd level*: procedural rules:**
  - Generate warnings / recommendations on basis of system characterization and state interpretation

- Selection of energy-optimized control strategies, energy conservation measures
- Operational state of HVAC system and components: energy wastes, malfunctions, failures…
- Configuration of BACS system

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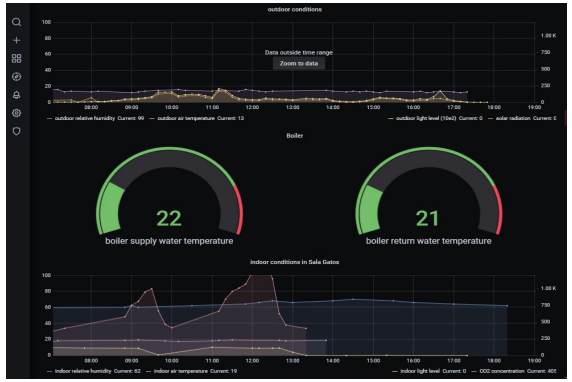
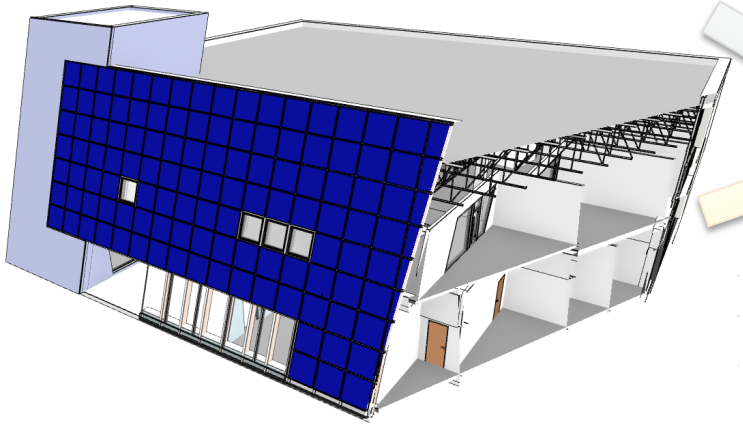
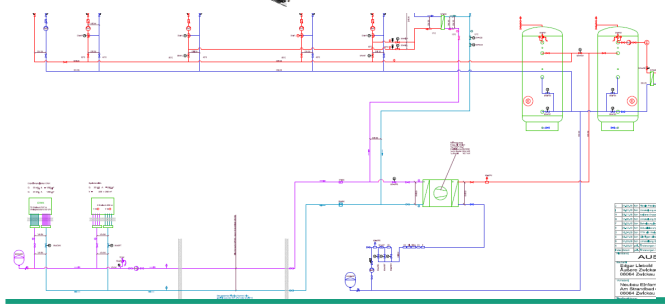
Prototype implementation of the Expert System







Monitoring System Back-End Storage

SQL

Import

Fact Base

cached data

monitoring metadata

building metadata

R D F

Building elements topology:

site

building

zone

storey

room

component

system

relations to building topological elements

Rule Set

r1: A(?x) -> C(?x)

r2: C(?x) -> A(?x)

...

Knowledge Base (Energy Conservation Measures)

Inference Module

- *recommendation* x_0
- *recommendation* x_1
- *recommendation* x_n
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Front-End App

3 levels of inference rules:

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W3C OWL

REST API

{JSON}

- Selection of energy-optimized control strategies, energy conservation measures
- Operational state of HVAC system and components: energy wastes, malfunctions, failures…
- Configuration of BACS system

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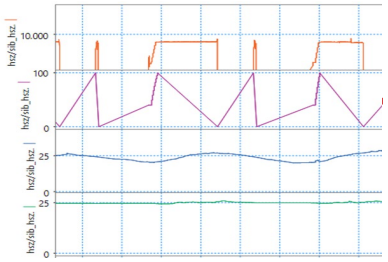
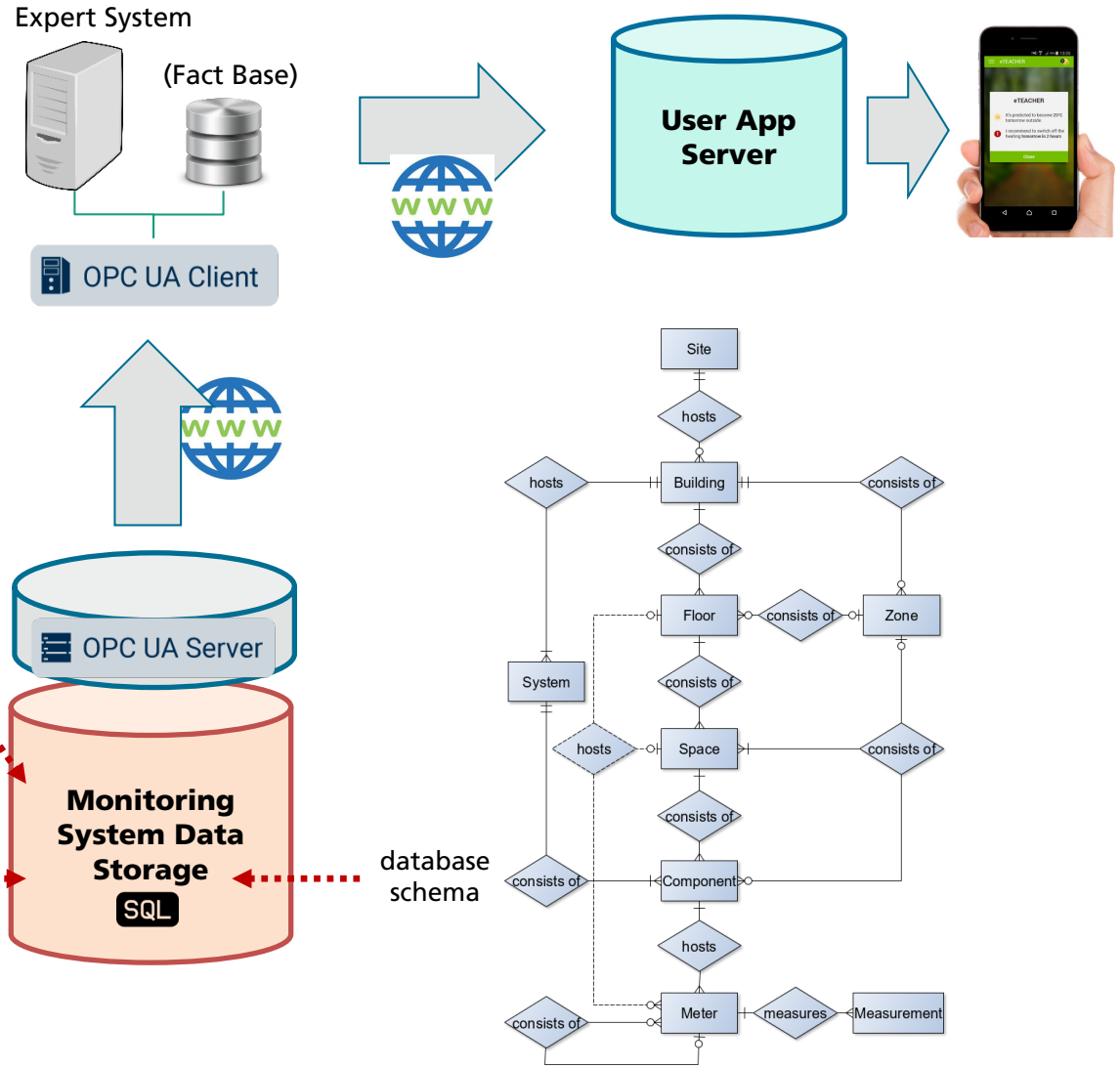
First system deployment

- OPC-UA communication standard as interface between Expert System and Building Monitoring Data Storage (Back-End)
- REST API for Interface with the Server of the end-user App (Front-End)

building information

sensor / meter data





System outcomes

3. Inference Engine


```
{
  "location": {
    "site": {
      "id": "5",
      "name": "OAR",
      "ifcGuid": null
    },
    "building": {
      "id": "9",
      "name": "Office Building 2",
      "ifcGuid": null
    },
    "zone": null,
    "storey": {
      "id": "14",
      "name": "Second",
      "ifcGuid": null
    },
    "space": {
      "id": "22",
      "name": "Segunda planta (Openspace-2)",
      "ifcGuid": null
    },
    "component": null
  },
  "timestamp": "2021-09-22T09:57:37.580465",
  "recommendations": [
    {
      "id": "ECMYawmetswsctwwcio",
      "label": "You are wasting much energy through some windows, so close the windows while cooling is on.",
      "effect": {
        "id": "ECM1-5",
        "label": "save cooling energy"
      },
      "validityPeriod": "PT14M",
      "estimation": {
        "saving": {
          "savedResource": "cooling energy",
          "resourceUnit": "kWh/(m2.a)",
          "savingPotentialUnit": "%",
          "savingPotential": 8
        }
      },
```


payloads

Locations Different buildings and their structural elements

POST	/locations	add a location
GET	/locations	get locations
GET	/locations/{locationId}	get a location
PUT	/locations/{locationId}	update a location
DELETE	/locations/{locationId}	delete a location

Metrics Available metrics from digital twin (real or computed data)

Recommendations Advices provided by the Artifical Intelligence for specific locations

POST	/recommendations	add a recommendation
GET	/recommendations	get recommendations
POST	/recommendations/template	add a recommendation template
GET	/recommendations/template	Get recommendation templates
GET	/recommendations/{recommendationId}	get a recommendation
PUT	/recommendations/{recommendationId}	update a recommendation
DELETE	/recommendations/{recommendationId}	delete a recommendation

Notifications Messages that are relevant to specific locations

POST	/notifications	add a notification
GET	/notifications	get notifications
GET	/notifications/{notificationId}	get a notification
PUT	/notifications/{notificationId}	update a notification
DELETE	/notifications/{notificationId}	delete a notification

REST API

„Recommendations / warnings“

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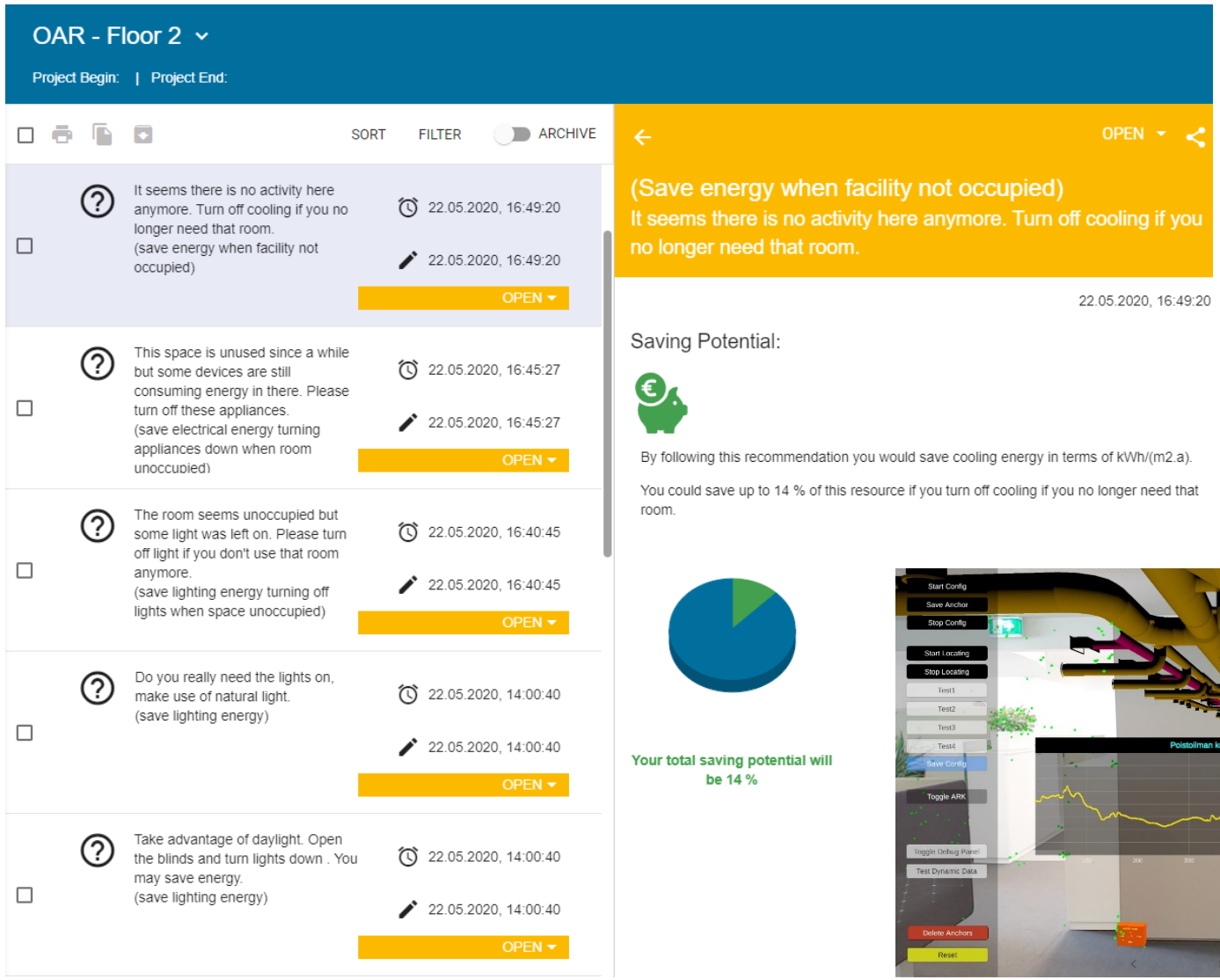
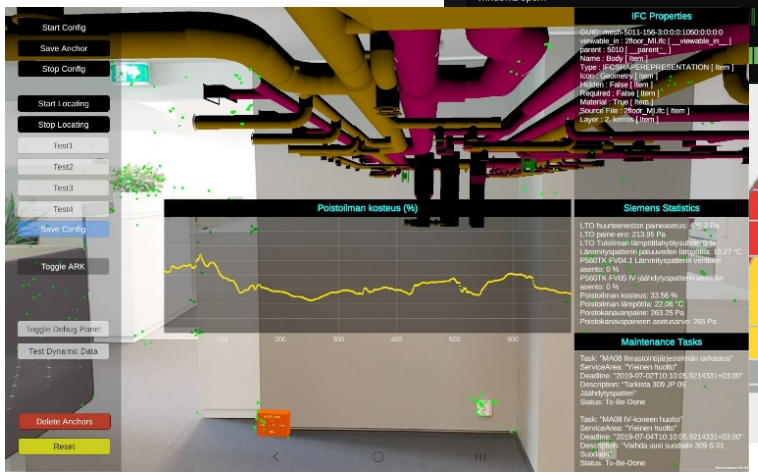
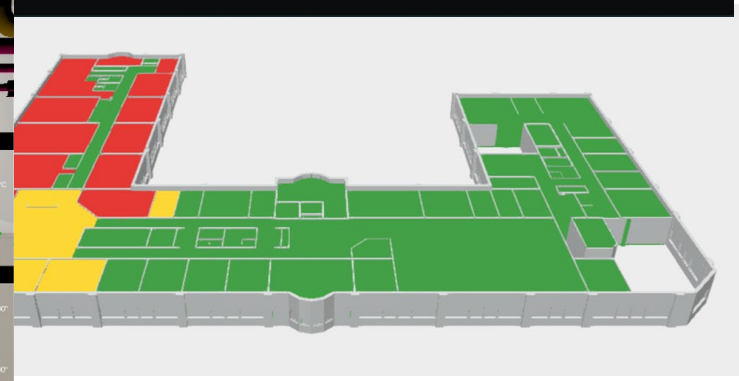
Integration with third party applications







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Conclusions and future works

- Reuse of building design information in commissioning and operation
- Expert system relying on semantic web and data analytics
- Model-based approach for bringing flexibility -> analysis automation
  - new building -> new model
  - avoids reprogramming of the tool
- Next steps:
  - Finish BIM / LBD import and realize full BIM4FM worklow
  - Fault Detection and *Diagnosis* (FDD)
  - Automatic BACS and BMS configuration
  - Further integrations: Machine Learning
  - Further potential integration with other UI tools: Augmented Reality

THANK YOU FOR YOUR ATTENTION

For more information do not hesitate to contact us!

References:

- project eTEACHER: http://www.eteacher-project.eu/
- project BIMLIFE

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