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From Connected to Automated Buildings

REHVA EXPERT TALK IN LIGHT AND BUILDINGS
08.03.2024 Frankfurt

Dr. Ir.-Arch. Pieter Pauwels

Eindhoven University of Technology, The Netherlands

Outline

1. Buildings and Semantics
2. Building Data on the Web
3. From Smart Buildings to Connected Buildings
4. Every Building is a Data Hub

B4B: Brains for Building's Energy Systems

BRAINS 4 BUILDINGS

Content from tue-lighthouse.nl

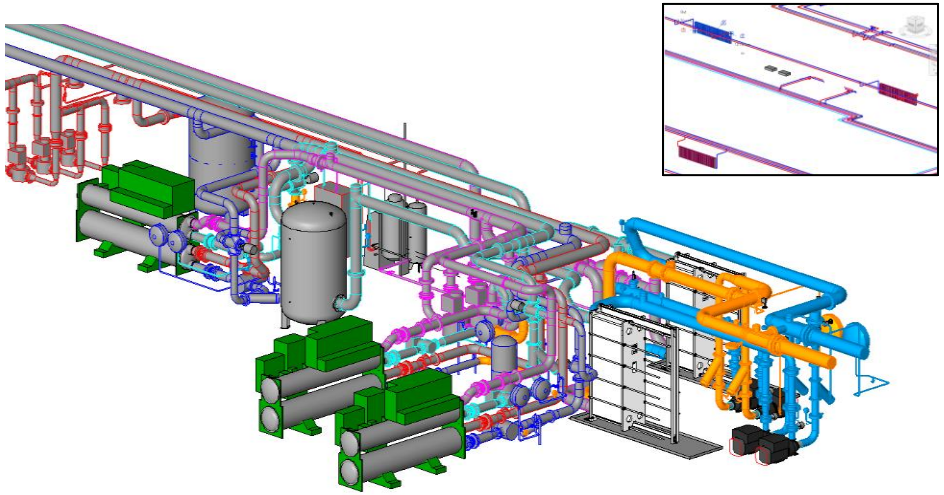
Modelling of Systems in the BIM model?

Often heard question: "why do we need 3D? We don't need 3D. What would we use it for!"

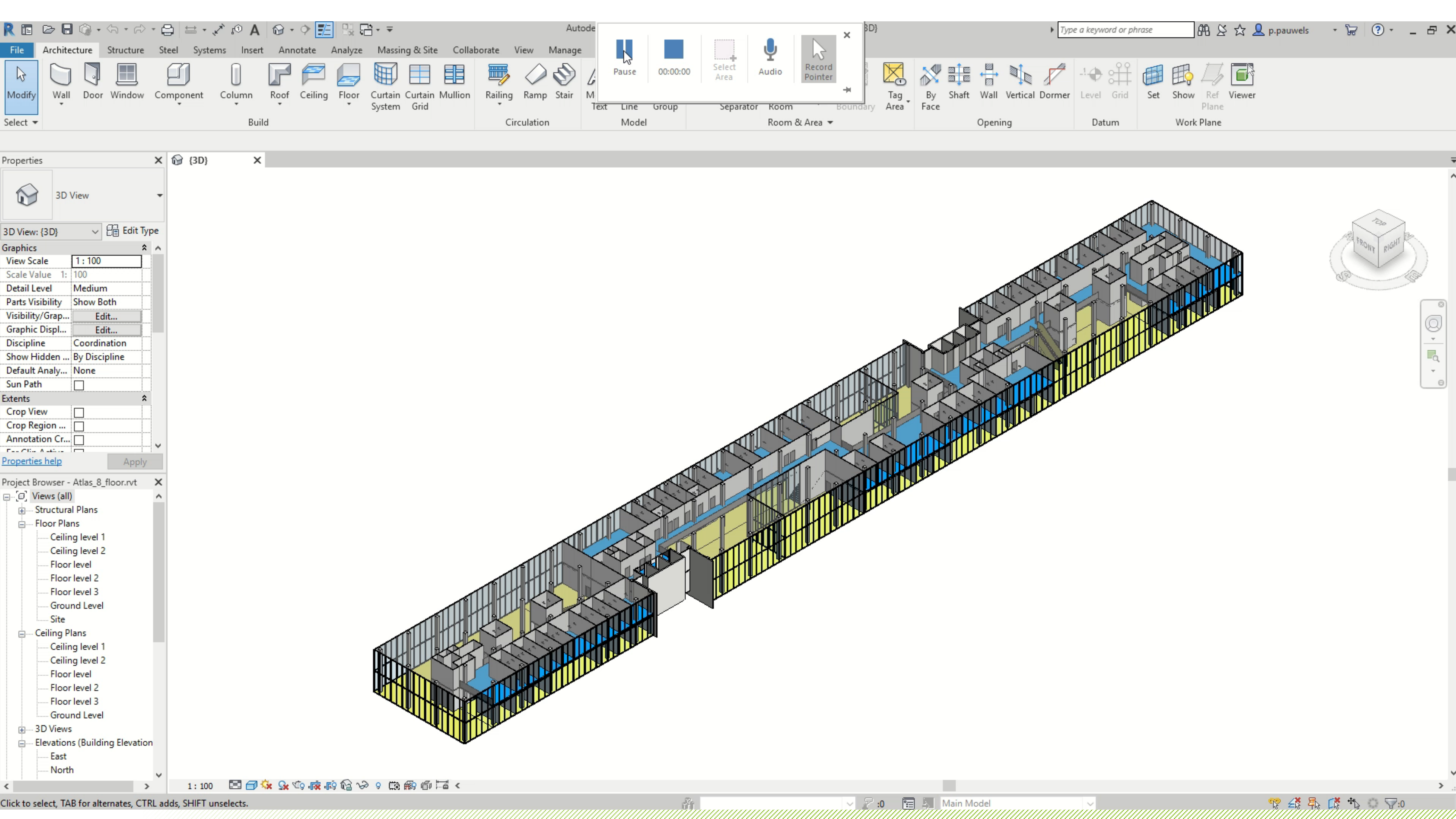
⇕ CONTRADICTION

Also often heard question: "We have all this IoT sensor data, but we have no idea which sensor they belong to. We also don't know which sensors we have and where they are."

Virtually modelled components

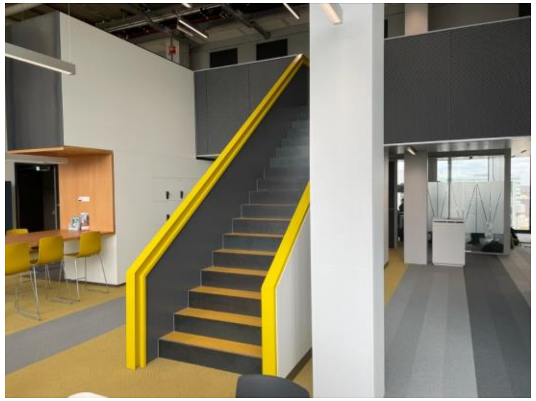


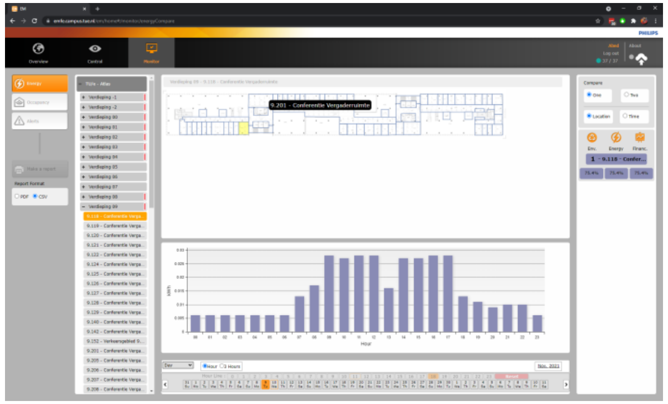
Tagged physical components


File
Architecture
Structure
Steel
Systems
Insert
Annotate
Analyze
Massing & Site
Collaborate
View
Manage
Modify
Select
Wall
Door
Window
Component
Column
Roof
Ceiling
Floor
Curtain System
Curtain Grid
Mullion
Build
Railing
Ramp
Stair
Circulation
Text
Line
Group
Model
Separator
Room
Boundary
Room & Area
Tag Area
By Face
Shaft
Wall
Vertical
Dormer
Opening
Level
Grid
Datum
Set
Show
Ref Plane
Viewer
Work Plane
Pause
00:00:00
Select Area
Audio
Record Pointer
Type a keyword or phrase
p.pauwels
Properties
3D View
3D View: {3D}
Edit Type
Graphics
View Scale
1 : 100
Scale Value 1:
100
Detail Level
Medium
Parts Visibility
Show Both
Visibility/Grap...
Edit...
Graphic Displ...
Edit...
Discipline
Coordination
Show Hidden ...
By Discipline
Default Analy...
None
Sun Path
Extents
Crop View
Crop Region ...
Annotation Cr...
Properties help
Apply
Project Browser - Atlas_8_floor.rvt
Views (all)
Structural Plans
Floor Plans
Ceiling level 1
Ceiling level 2
Floor level
Floor level 2
Floor level 3
Ground Level
Site
Ceiling Plans
Ceiling level 1
Ceiling level 2
Floor level
Floor level 2
Floor level 3
Ground Level
3D Views
Elevations (Building Elevation
East
North
{3D}
1 : 100
Click to select, TAB for alternates, CTRL adds, SHIFT unselects.
Main Model

Making building data available for a machine: geometry and semantics

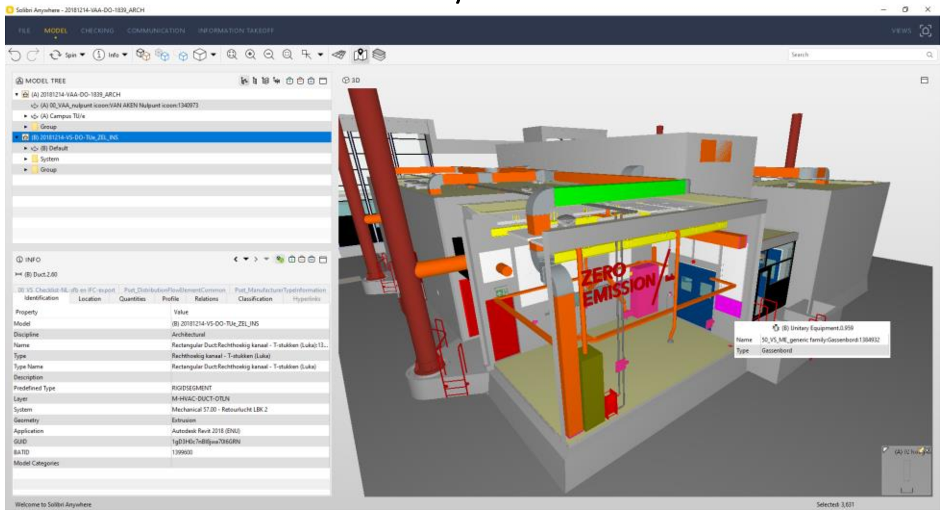
BIM for Digital Twinning





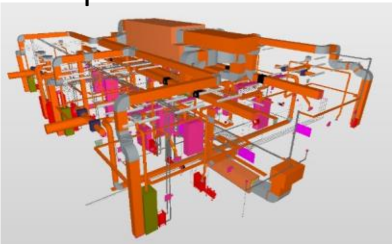
BMS System

Coordinated models / federated models

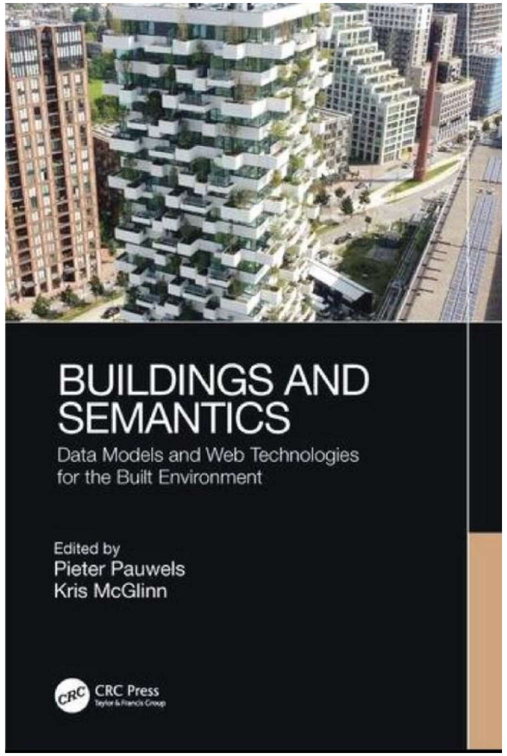


Aspect Model 1

Aspect Model 2



Buildings and Semantics: Data Models and Web Technologies for the Built Environment



Data Modelling

Applications and Systems

Pauwels, P., and McGlinn, K. (2022). Buildings and Semantics: Data Models and Web Technologies for the Built Environment. CRC Press. https://www.routledge.com/Buildings-and-Semantics-Data-Models-and-Web-Technologies-for-the-Built/Pauwels-McGlinn/p/book/9781032023120.

Data Integration needed: basic principles

- We want to integrate data. We also entirely *can* integrate data.
- This includes BIM data / building 'metadata' (so geometry and semantics; more static data) as well as more dynamic data (telemetry, sensor data).
- We have perfectly capable web technologies and communication protocols available.
- This needs to be shared via user-friendly and user-centric interfaces

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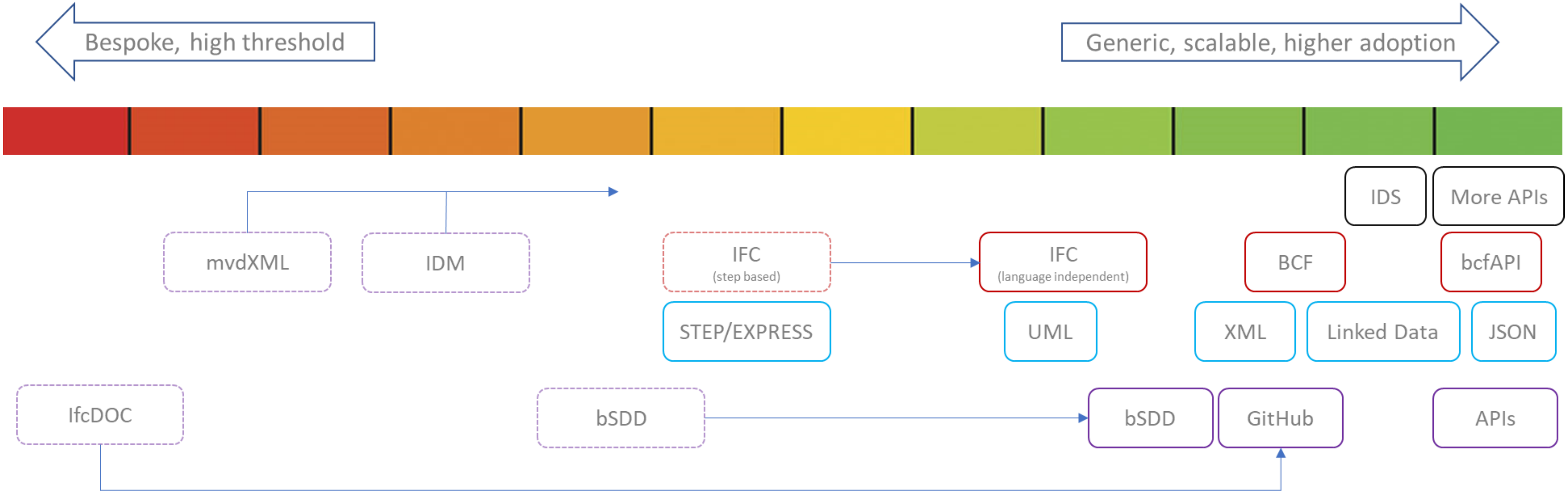
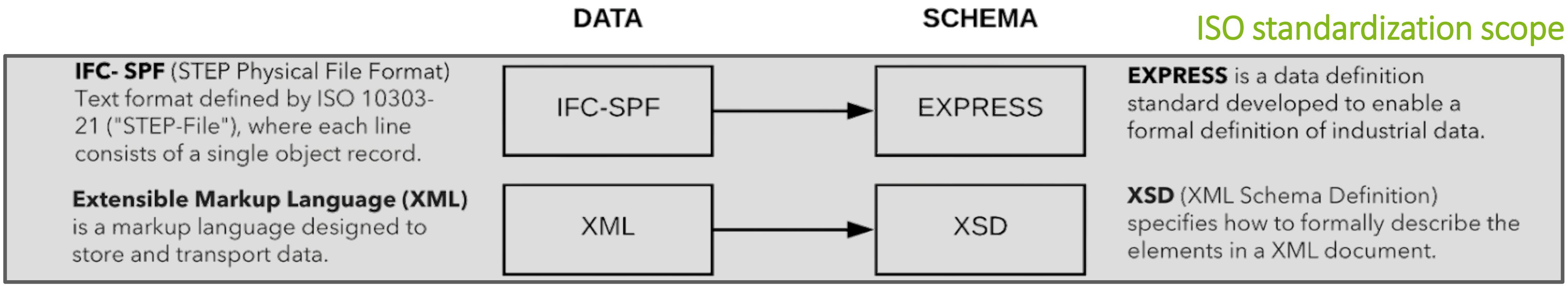
IFC Technical Roadmap
Move towards the web



https://www.buildingsmart.org/about/technical-roadmap/

An IFC schema that is web-ready? Web-based BIM?

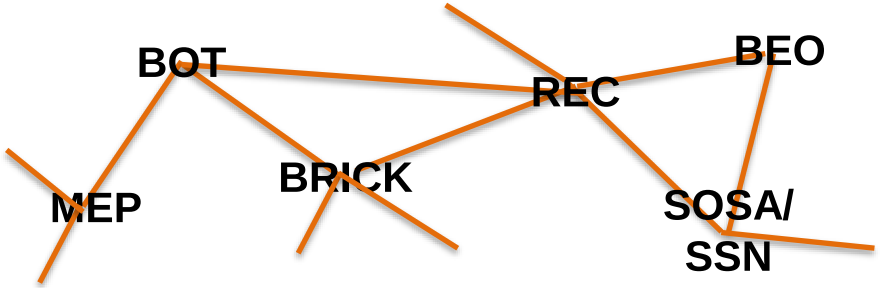
ISO standardization scope



File-based

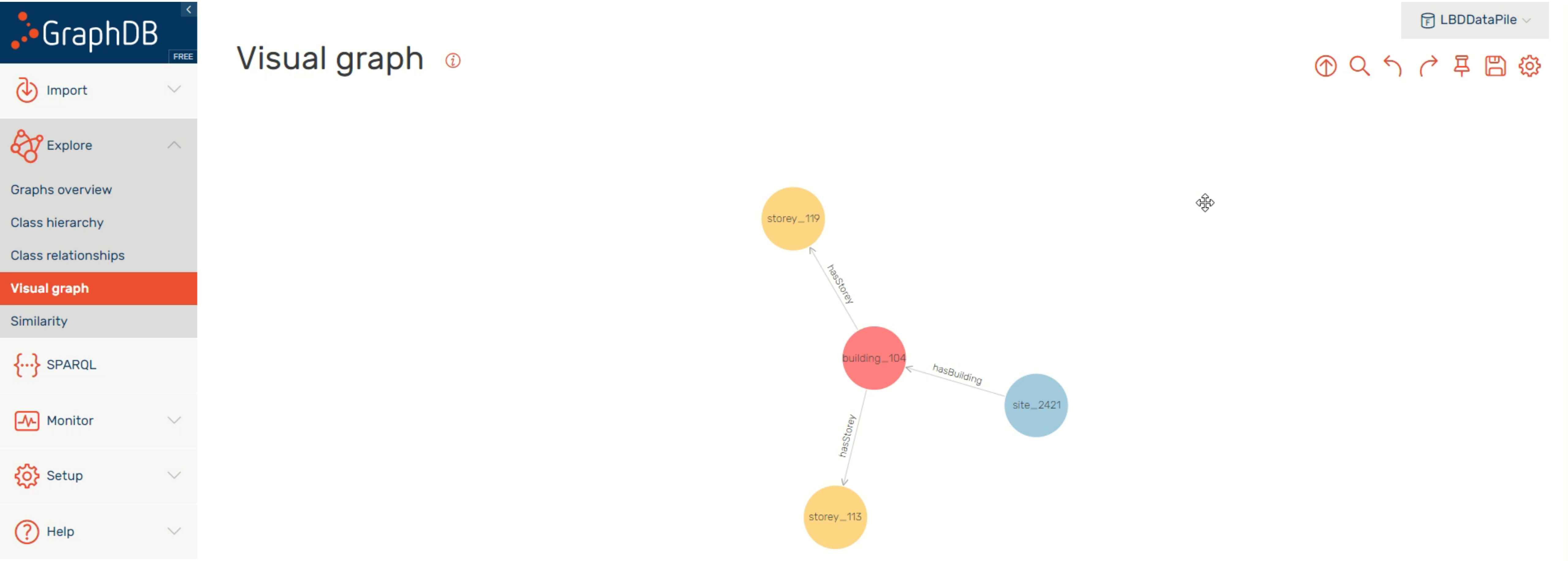
LBD

Linked Building Data (LBD) graphs



Data-oriented

Adapted from Pauwels, P., & Petrova, E. (2020). Information in construction. https://research.tue.nl/en/publications/information-in-construction.

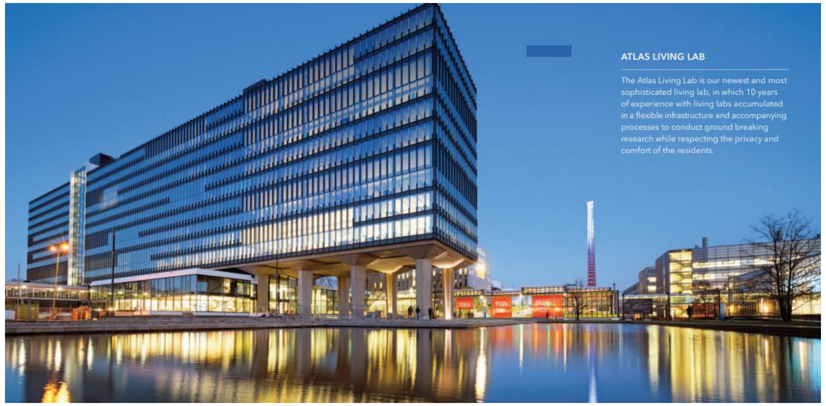

GraphDB
FREE
LBDDataPile
Visual graph
Import
Explore
Graphs overview
Class hierarchy
Class relationships
Visual graph
Similarity
SPARQL
Monitor
Setup
Help
storey_119
hasStorey
building_104
hasBuilding
site_2421
hasStorey
storey_113

Semantic Graphs with Building Data

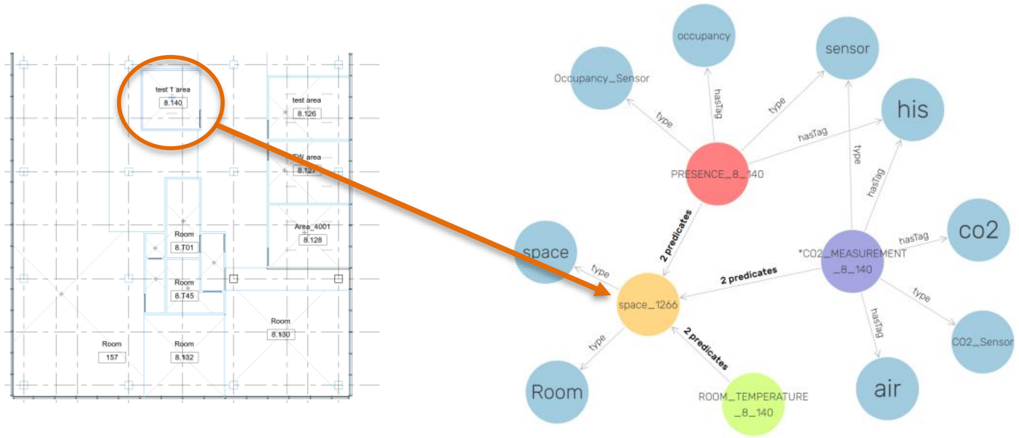
```
@prefix brick: <https://brickschema.org/schema/Brick#> .
@prefix inst: <http://linkedbuildingdata.net/ifc/resources20201208_005325/> .
@prefix ph: <https://project-haystack.org/def/ph/3.9.11#> .
@prefix phIoT: <https://project-haystack.org/def/phIoT/3.9.11#> .
@prefix phScience: <https://project-haystack.org/def/phScience/3.9.11#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .

inst:11NR008LT-001PIRTM a brick:Occupancy_Sensor,
        phIoT:sensor ;
    rdfs:label "PRESENCE_8_128"^^xsd:string ;
    brick:hasLocation inst:space_892 ;
    ph:dis "PRESENCE_8_128"^^xsd:string ;
    ph:hasTag phIoT:his,
        phIoT:occupancy ;
    phIoT:spaceRef inst:space_892 .

inst:11NR008LT-003PIRTM a brick:Occupancy_Sensor,
        phIoT:sensor ;
    rdfs:label "PRESENCE_8_127"^^xsd:string ;
    brick:hasLocation inst:space_1023 ;
    ph:dis "PRESENCE_8_127"^^xsd:string ;
    ph:hasTag phIoT:his,
        phIoT:occupancy ;
    phIoT:spaceRef inst:space_1023 .
```

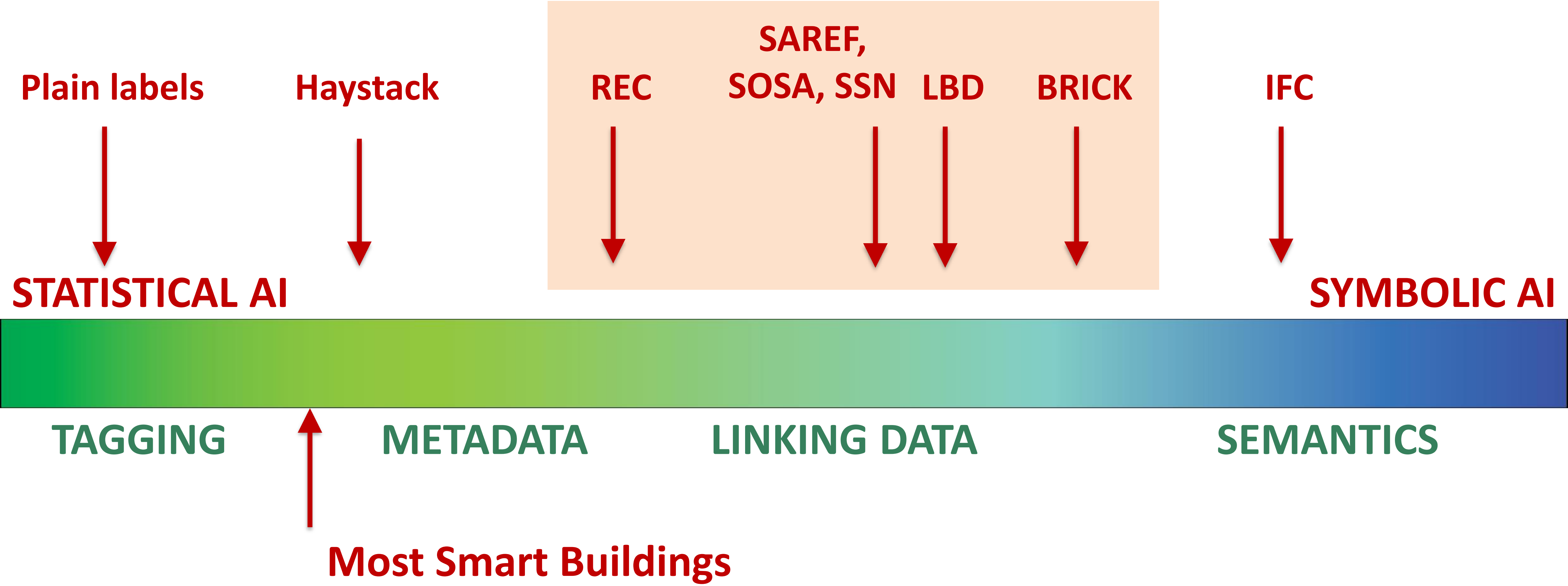


ATLAS Building TUe



Chamari, L., Petrova, E., & Pauwels, P. (2022). A web-based approach to BMS, BIM and IoT integration: a case study. In Proceedings of the REHVA 14th HVAC World Congress (CLIMA 2022) https://doi.org/10.34641/clima.2022.228

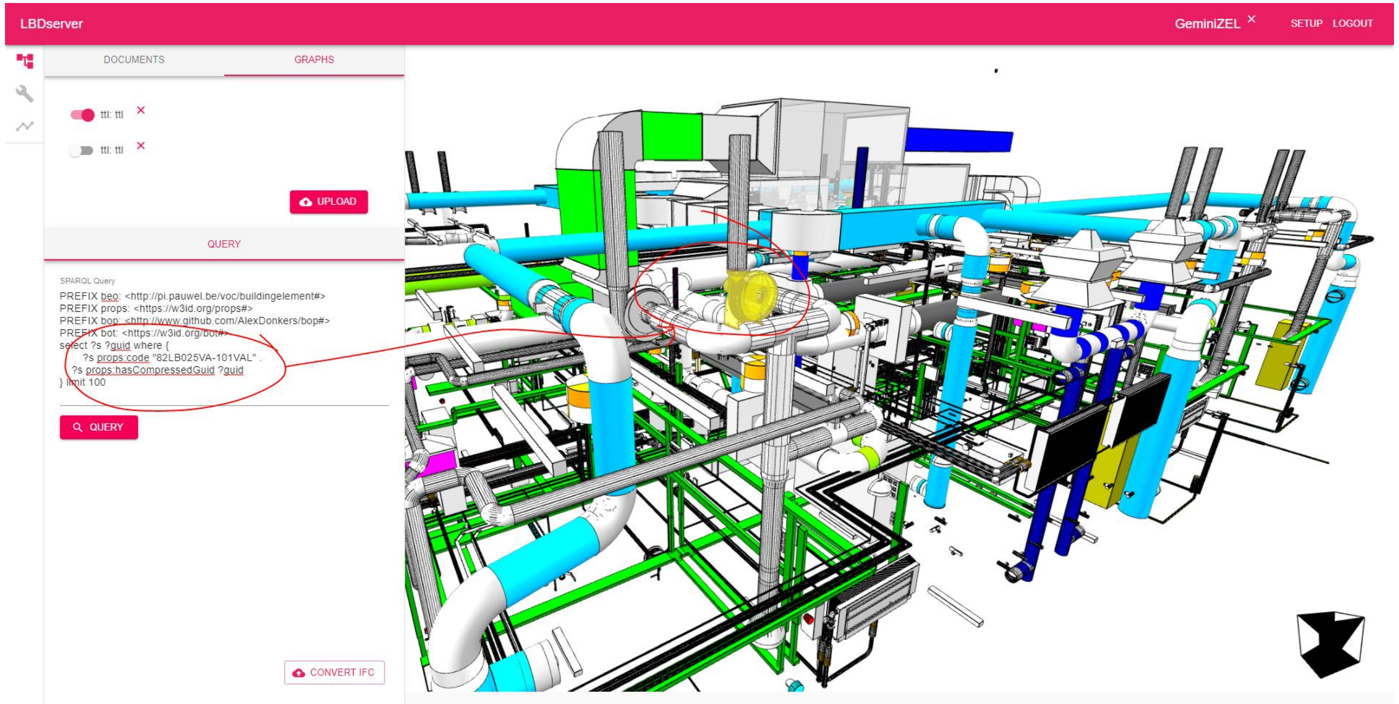
The Scale of AI Methods



REHVA
Federation of European Heating, Ventilation and Air Conditioning Associations

Pauwels Pieter, Data Integration for Smart Communication. Presentation for the FHI Bits, Bricks, Behaviour conference, Rotterdam, Netherlands. November 2021 https://research.tue.nl/en/activities/data-integration-for-smart-communication
Fierro, G., & Pauwels, P. (2022). Survey of metadata schemas for data-driven smart buildings (Annex 81). CSIRO. https://annex81.iea-ebc.org/publications

A Cloud of Linked Building Data



Reference ontologies used:

BOT	https://w3id.org/bot#
BE	https://pi.pauwel.be/voc/buildingelement/
MEP	https://pi.pauwel.be/voc/distributionelement/
OMG	https://w3id.org/omg#
FOG	https://w3id.org/fog#
BPO	https://www.w3id.org/bpo#
OPM	https://www.w3id.org/opm#

Revit to LBD exporter: on demand

IFC to LBD converter: on demand

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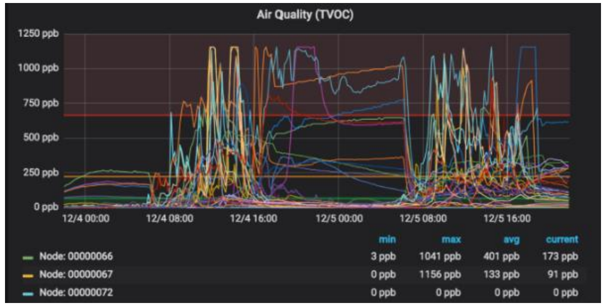
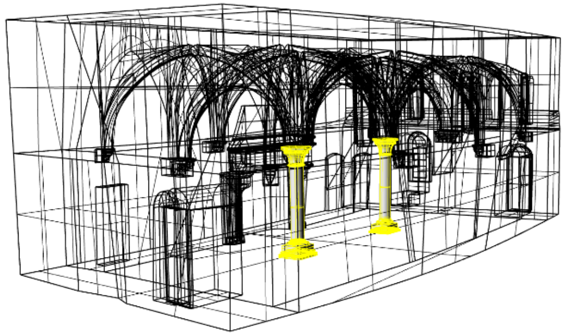
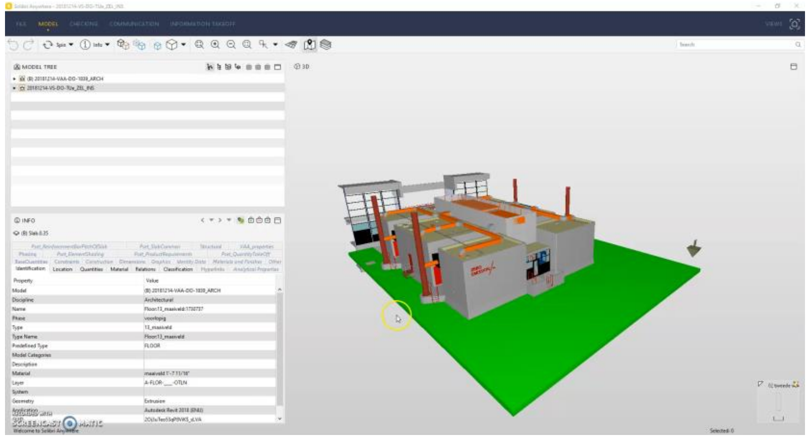
4. Every Building is a Data Hub

Different kind of data involved, not everything should be RDF graphs







Data sources to integrate

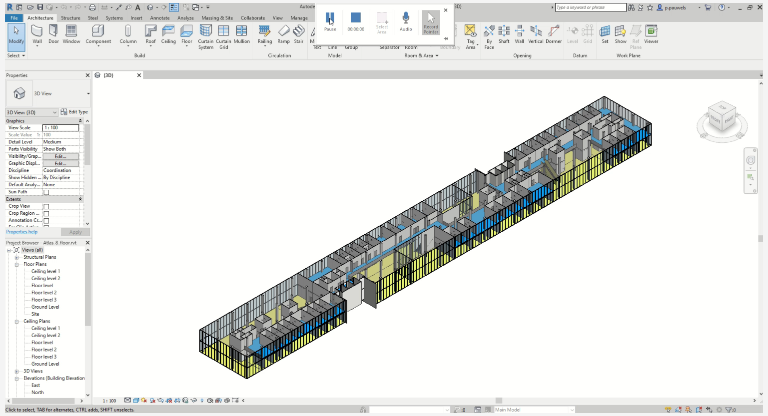
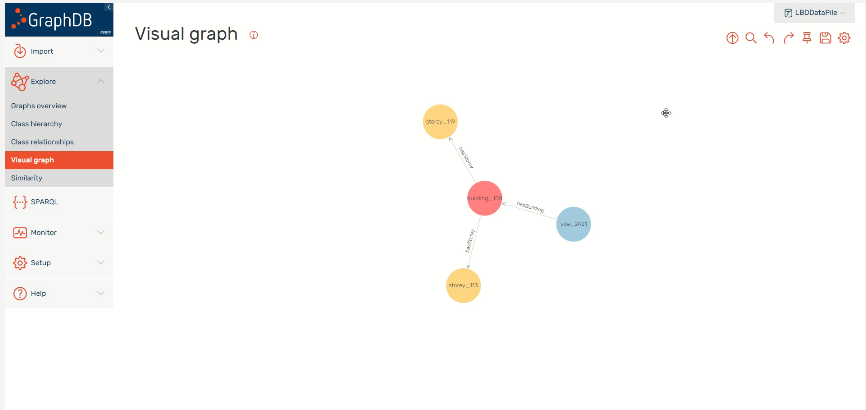
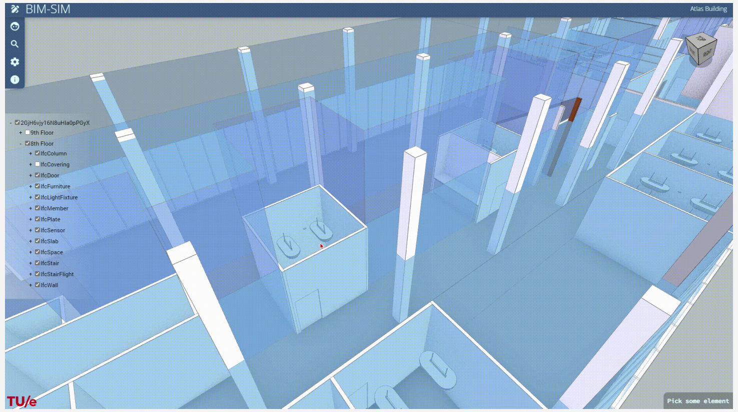
- Plenty of semantic data models (RDF/OWL) allowing semantic inference:
  - LBD: BOT, BEO, MEP, FOG, BPO, BRICK, HTO, IFC, SSN, SOSA, …
  - Modular approach of smaller scale specialized semantic models in graphDBs
  - Rules, queries, and inference readily available (declarative coding)
- Tabular and/or timeseries data allowing list-oriented and statistic machine learning (pattern recognition, fault detection, etc.)
  - Plenty of data wrangling => ML
- Specialised 2D and 3D data, images, point clouds and documents
  - Specialised algorithms (procedural coding): 3D computations and analysis, NLP, image recognition, visual data analysis, etc.

Pauwels, P., & Fierro, G. (2022). A Reference Architecture for Data-Driven Smart Buildings Using Brick and LBD Ontologies. In Proceedings of the REHVA 14th HVAC World Congress (CLIMA 2022) https://doi.org/10.34641/clima.2022.425

Server-based Digital Twinning

1. Three types of information: geometry, semantics, dynamic data streams
2. Dedicated storage desired
3. Well-organized server-based storage

SERVER-BASED DT

GEOMETRY	SEMANTICS	IoT DATA STREAMS
		

Reference System Architecture for Data-Driven Smart Buildings


IEEE Access

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Digital Object Identifier 10.1109/ACCESS.2023.3325767

RESEARCH ARTICLE

An End-to-End Implementation of a Service-Oriented Architecture for Data-Driven Smart Buildings

LASITHA CHAMARI, EKATERINA PETROVA, AND PIETER PAUWELS

Department of the Built Environment, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands

Corresponding author: Lasitha Chamari (l.c.rathnayaka.mudiyanselage@tue.nl)

This work was supported by the Dutch Ministry of Economic Affairs and Climate Policy and the Ministry of the Interior and Kingdom Relations under the MOOI Program through the Brains for Buildings Project.

ABSTRACT Buildings connect with multiple information systems like Building Management Systems (BMS), Energy Management Systems (EMS), IoT devices, Building Information Models (BIM), the electricity grid, weather services, etc. Data-driven smart building software demands seamless integration of the above systems and their data. The lack of a system architecture with well-defined Application Programming Interfaces (APIs) poses a significant challenge for developing reusable, modular and scalable applications. This article presents a service-oriented system architecture designed with data-driven smart buildings in mind. The architecture relies on the Zachman framework and consists of seven service categories: 1) existing business applications, 2) new microservice-based applications, 3) databases, 4) integration software, 5) infrastructure services, 6) shared services, and 7) user interfaces. It closely resembles the MACH architectural principles: Microservices, API-first, Cloud-based components, and Headless principles. This architecture is implemented as a proof-of-concept, including three smart building applications. These include a Digital Twin application integrating sensor data with a BIM model, a web application merging real-time sensor data with semantic building graphs, and a data exploration tool using sensor data, the Brick ontology, and Grafana dashboards. Future implementations include real-time control applications such as Model Predictive Control (MPC). The proposed architecture and its implementations provide a blueprint for a reusable, modular, and scalable architecture in the smart building domain.

INDEX TERMS Building Information Modeling, data-driven buildings, data integration, IoT, linked building data, microservices, reference architecture, REST API, real-time data acquisition, solution architecture.

I. INTRODUCTION

Smart buildings must fulfil various operational objectives related to energy efficiency, energy flexibility, Indoor Environmental Quality (IEQ), occupant comfort and well-being, etc. Current approaches aiding the fulfilment of these objectives often rely on software programs designed for the purpose. The latter are commonly referred to as smart building applications [1], [2], [3] and tend to be data-driven. Examples of such applications include Demand Side Management (DSM) using flexible energy sources [4], [5], automated Fault Detection and Diagnosis (FDD) [6], [7], optimising Heating, Ventilation and Air Conditioning (HVAC) loads to achieve cost and comfort objectives [5], [8], [9], Digital Twins [10], [11], [12], etc. Data-driven applications rely on various components related to training machine learning models, forecasting energy demand, solving optimisation problems, and running predictive controllers such as Model Predictive Control (MPC). These applications also require supporting services such as data cleaning, aggregation, extract-transform-load (ETL) tools to gather and process data from different sources, etc. Since the above data are heterogeneous, integration is required and essential. Furthermore, system integration is also needed because the

The associate editor coordinating the review of this manuscript and approving it for publication was Fabrizio Messina.

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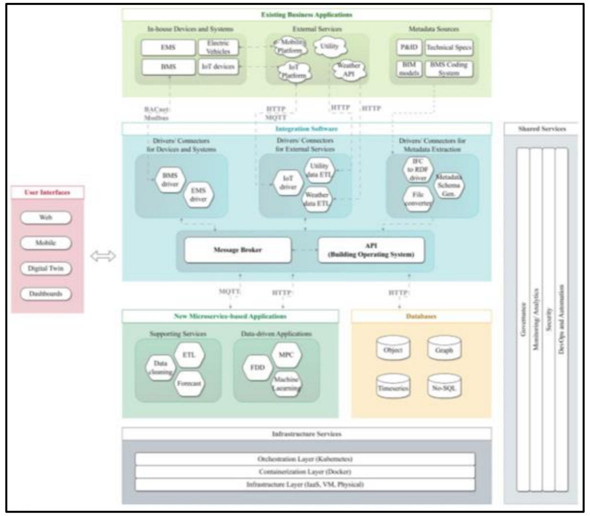
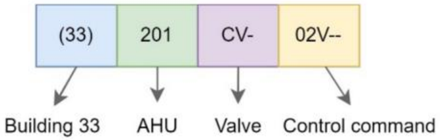


PhD candidate Lasitha Chamari winning the Charles M. Eastman Best PhD Paper Award for the paper ***"Extensible real-time data acquisition and management for IoT enabled smart buildings"*** as part of the 40th anniversary of the CIB W78 conference

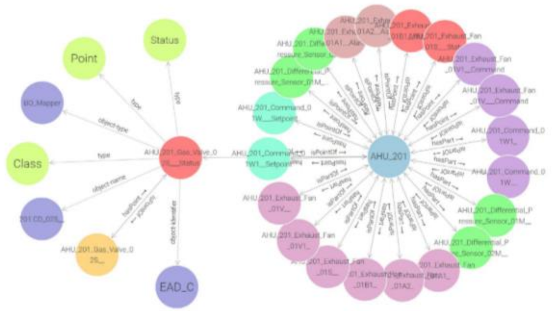
Chamari, L., Petrova, E., & Pauwels, P. (2023). An End-to-End Implementation of a Service-Oriented Architecture for Data-Driven Smart Buildings. IEEE Access, Vol. 11, Article 10287934. Advance online publication. https://doi.org/10.1109/ACCESS.2023.3325767

Generate My Metadata experiment

Custom naming schemes

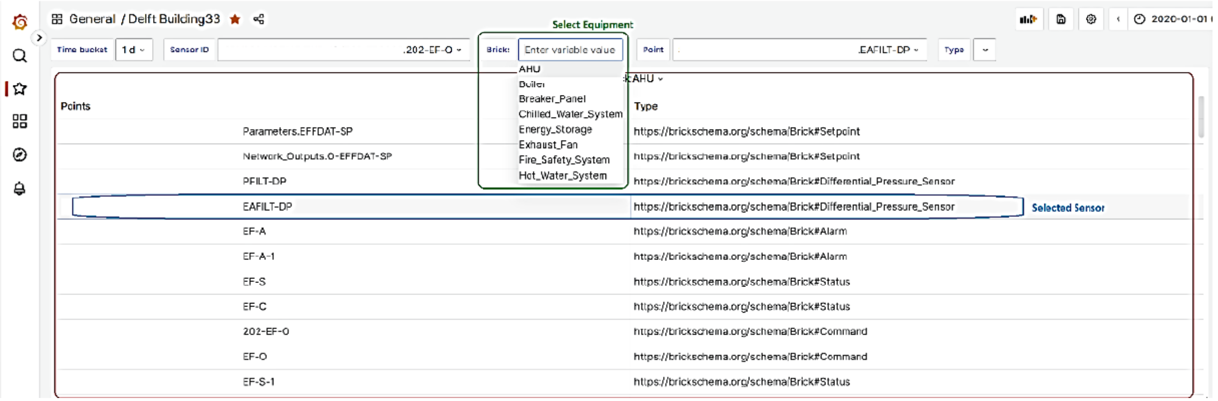


.py transformer



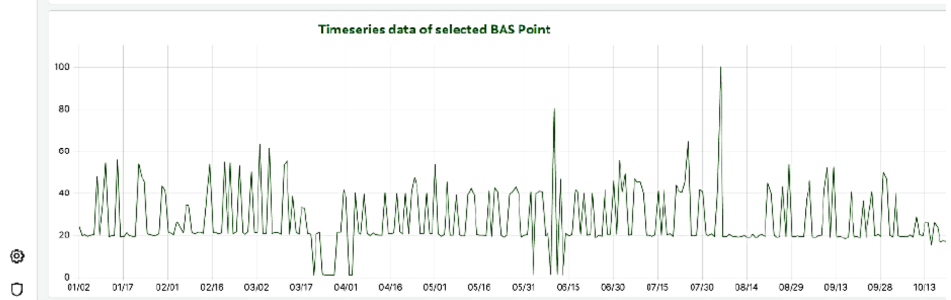
HTTPS

Grafana Dashboard



IoT Data Streams

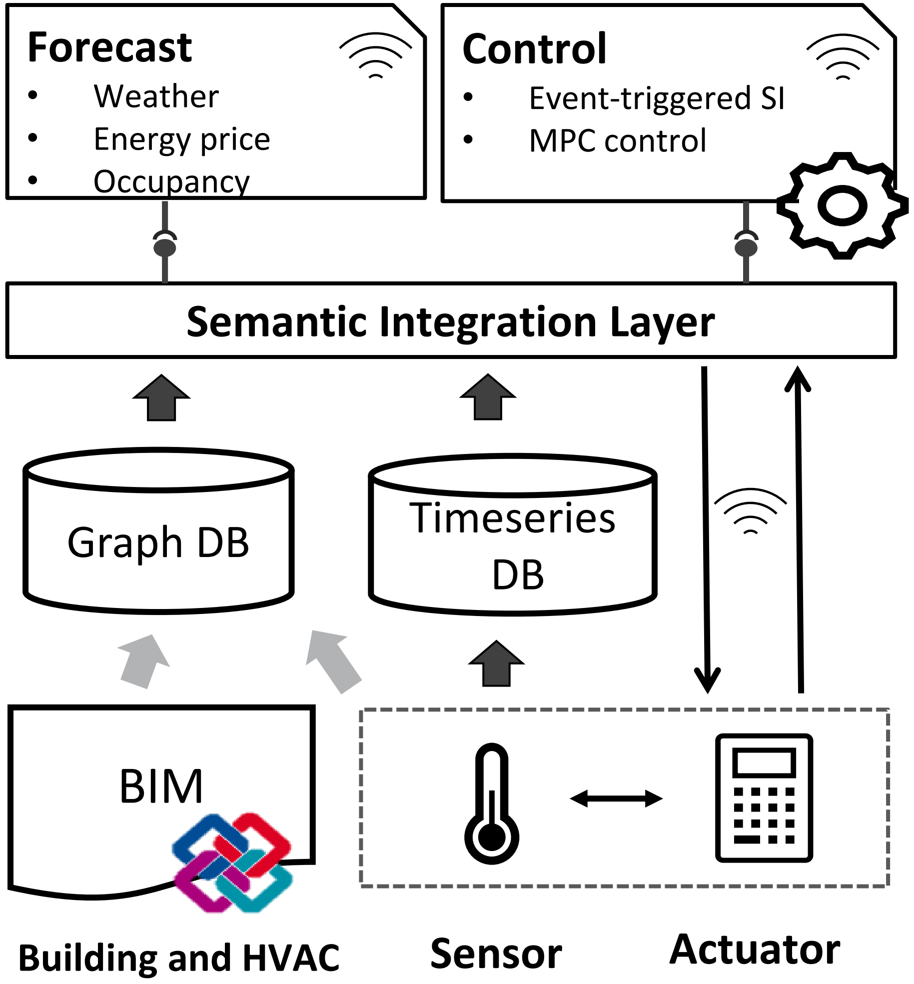
MQTT



Chamari, L., Petrova, E., Pauwels, P., van der Weijden, J., Boonstra, L., & Hoekstra, S. (2023). Generating metadata schema for data-driven smart buildings. In Proceedings of the 2nd Research Day on Digitalization of the Built Environment.

Example: Semantic-assisted architecture for MPC

Overview

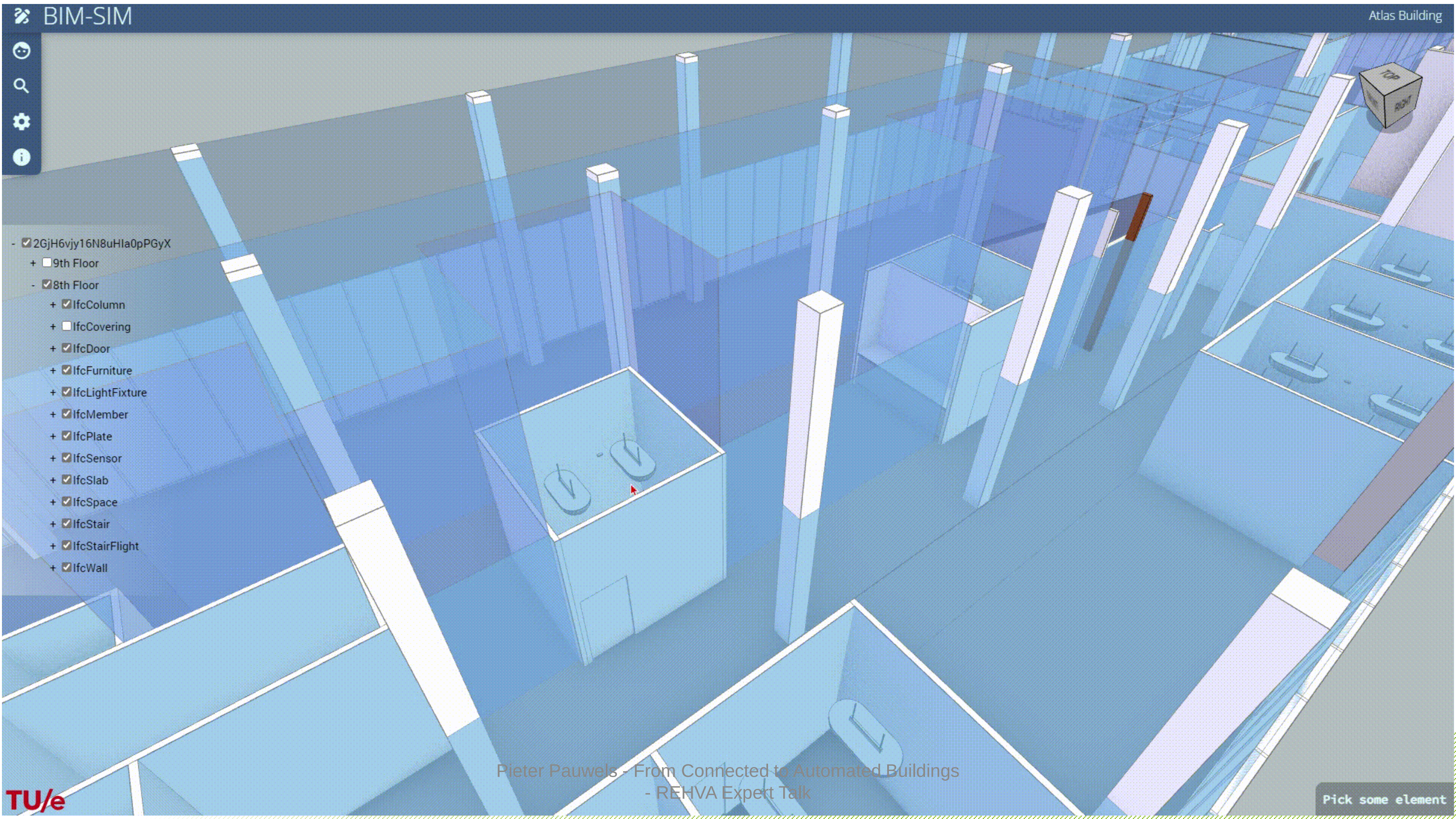


Requirement for the integrated framework

- Diverse data required for setting up the MPC algorithms
- Reusability

A service-oriented-architecture

- Data sources (BIM model, BMS sensor measurements)
- Database management system (Graph database and timeseries database)
- Semantic integration layer (Data integration and interpretation)
- Services: forecasts and control


BIM-SIM
Atlas Building
2GjH6vjy16N8uHla0pPGyX
9th Floor
8th Floor
IfcColumn
IfcCovering
IfcDoor
IfcFurniture
IfcLightFixture
IfcMember
IfcPlate
IfcSensor
IfcSlab
IfcSpace
IfcStair
IfcStairFlight
IfcWall
Pick some element
Pieter Pauwels - From Connected to Automated Buildings
- REHVA Expert Talk
TU/e

Digital Twinning of TUe Campus Buildings

EAISI EINDHOVEN AI SYSTEMS INSTITUTE

TU/e

TU/E CAMPUS DIGITAL TWIN FOR SMART BUILDING MANAGEMENT AND CONTROL

Pieter Pauwels (BE), Elena Torta (ME), Gamze Dane (BE), Sonja Rijlaarsdam (RE), Thijs Meulen (RE), and Annemieke Pelt (ME)

- Build a Digital Twin system for the Atlas and Gemini buildings (Zero Emission Lab, Gemini building)
- Smart management of facilities through on-site anomaly detection and device monitoring
- Unsupervised robot navigation through semantic (model-driven) path detection and real-time data analysis (data-driven)
- Developing a 3D campus information system for digital accessibility of campus facilities and services in buildings and open spaces

Under Development

https://www.tue.nl/en/research/institutes/eindhoven-artificial-intelligence-systems-institute/digital-twin-lab

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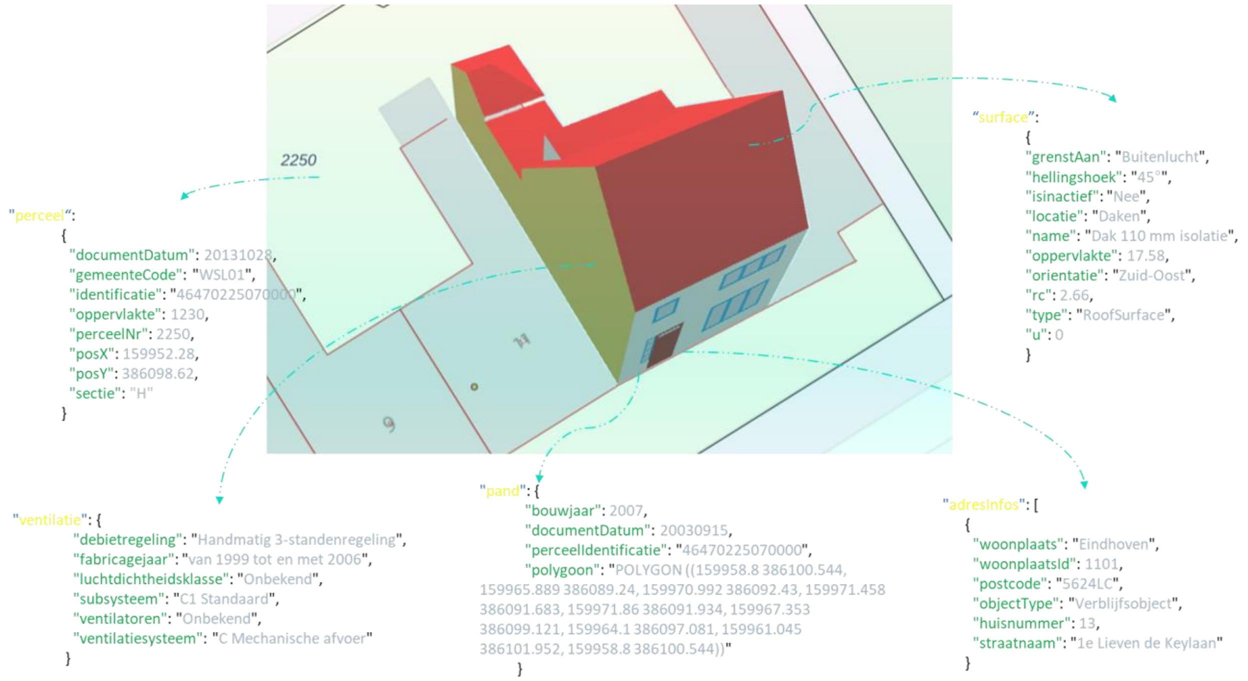
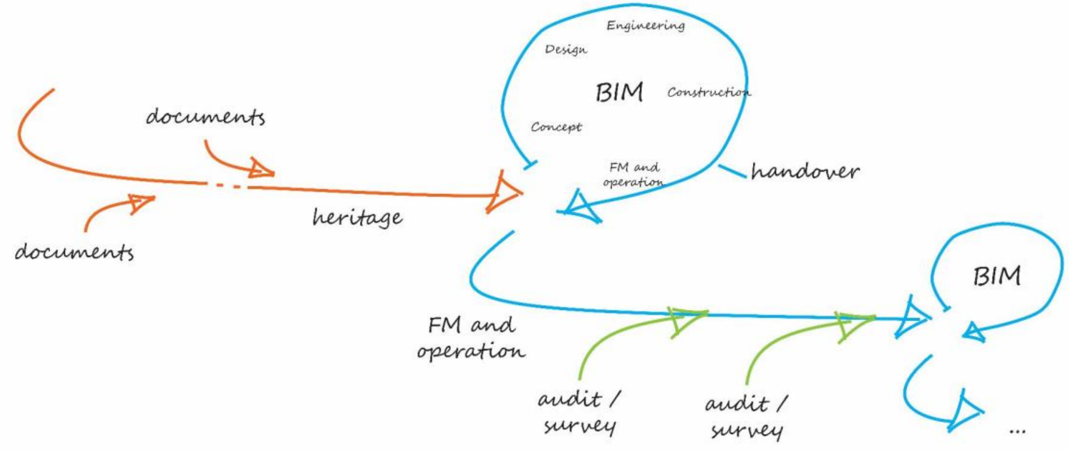
4. Every Building is a Data Hub

Every building is a data hub with many interconnections that change over time





Kafaei, M. (2022). Design and development of a data platform for managing the residential buildings' physical and geospatial information required for large-scale renovations. Technische Universiteit Eindhoven. https://research.tue.nl/en/publications/design-and-development-of-a-data-platform-for-managing-the-reside

Pieter Pauwels. Supporting decision-making in the building life-cycle using linked building data. Buildings 4 (3): 549–579. 2014.

Challenges in Digital Twinning for large areas

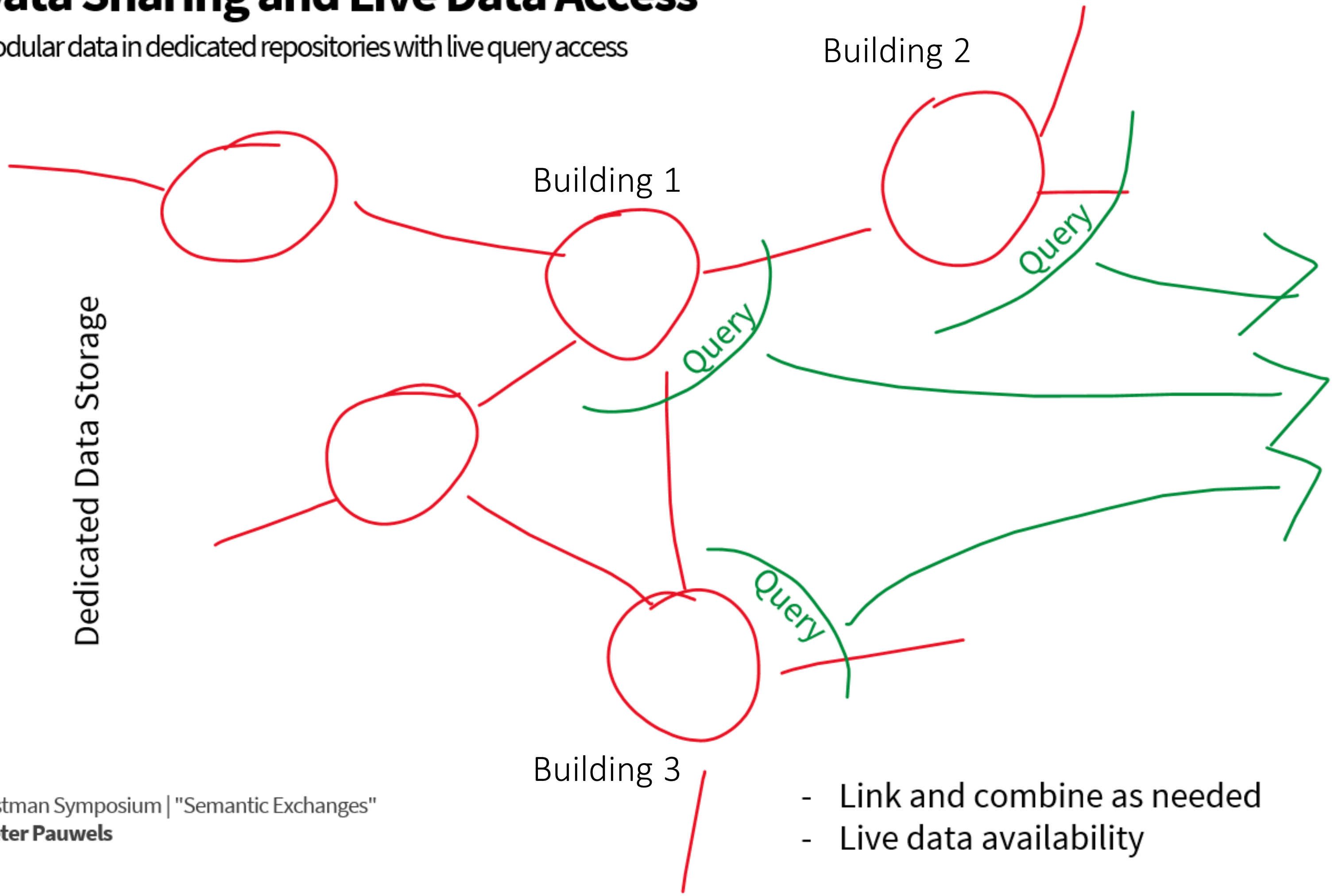
- Several databases are in use in different locations
  - national level, regional, local, private.
- Difficulty of connecting multiple databases
  - different schemas and protocols
  - overlapping content
- External databases are owned by external parties
  - data ownership challenge
  - outdated data

→ So, how to take part??

Data Sharing and Live Data Access

Modular data in dedicated repositories with live query access

Can we decentralize further?

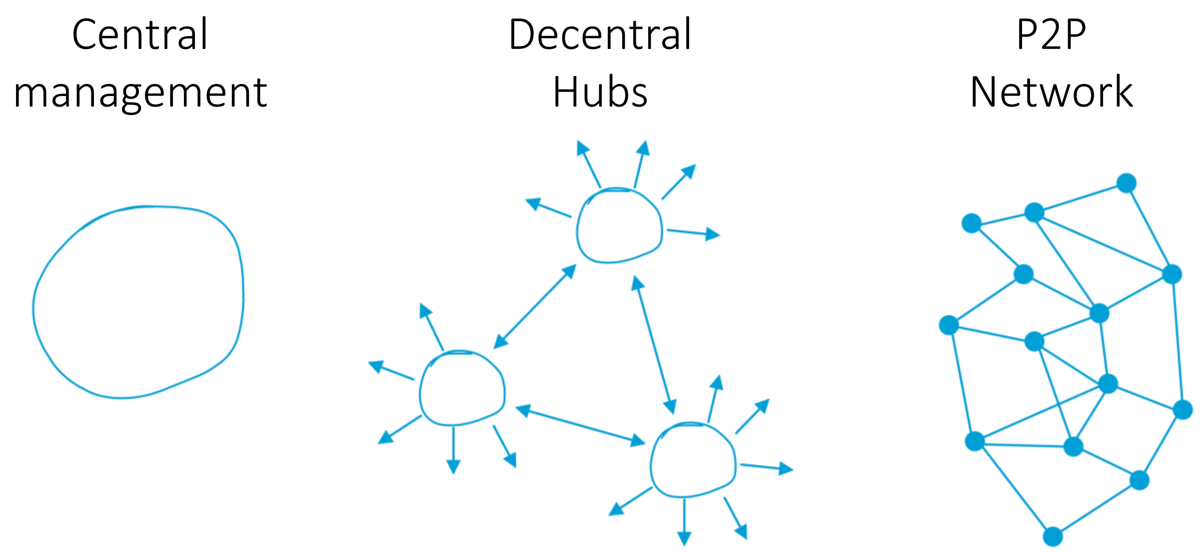


- Link and combine as needed
- Live data availability

Pauwels, P. (2021). Information Exchange over the Web for the AEC Industry. Paper presented at Eastman Symposium, Atlanta, Georgia, United States. https://research.tue.nl/en/publications/information-exchange-over-the-web-for-the-aec-industry

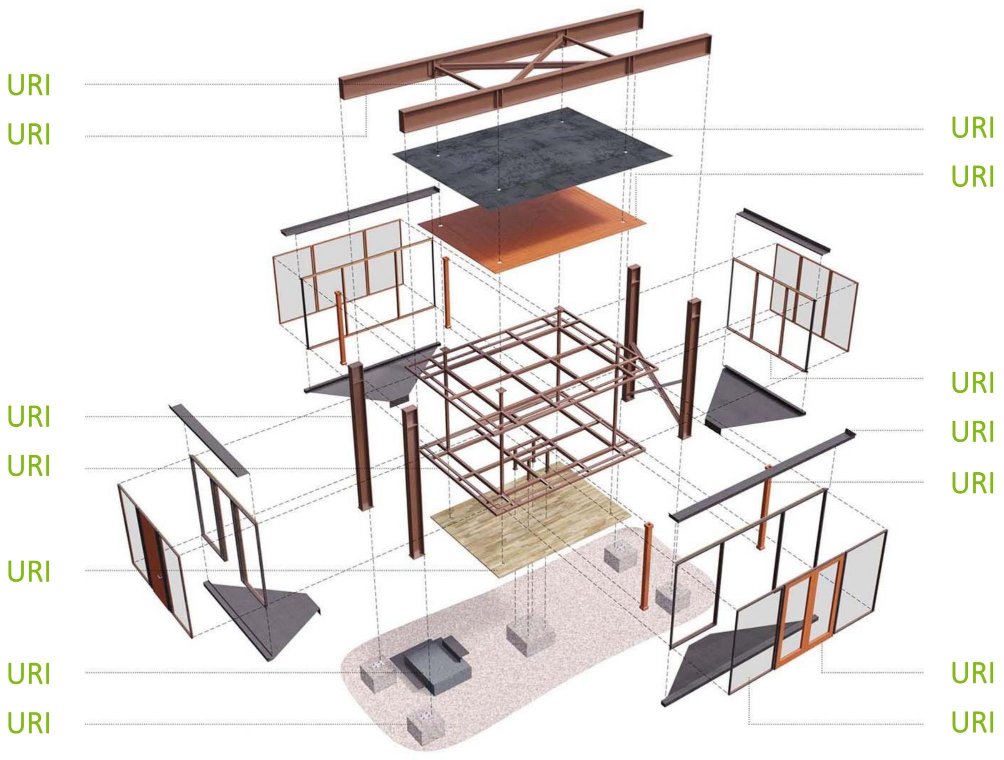
From Decentral Hubs to P2P Networks

1. Central Management
   - Who has data ownership?
   - Who pays the price?
   - Hard to scale in diverse communities
2. Decentral hubs
   - Achievable
   - Current trend and realisation
   - Dependency on shared use of infrastructure
   - Who has data ownership?
   - Who pays the price?
3. Peer-to-Peer (P2P) network
   - Not existing for the building sector
   - Scalable if done properly
   - Price and data ownership stays with the source
   - Infrastructure needed
   - How to manage this data mesh over time?



The future?

Element-based P2P Network of Data



1. Every building element has its authoritative URI identifier.
2. Data-follows-object principle for ownership and liability.
3. Layered and versioned information sharing.
4. Standardised information exchange mechanisms (e.g. structure of ISO 19650).
5. Object-centric exchange instead of geometry-centric exchange.

UPSCALE research project

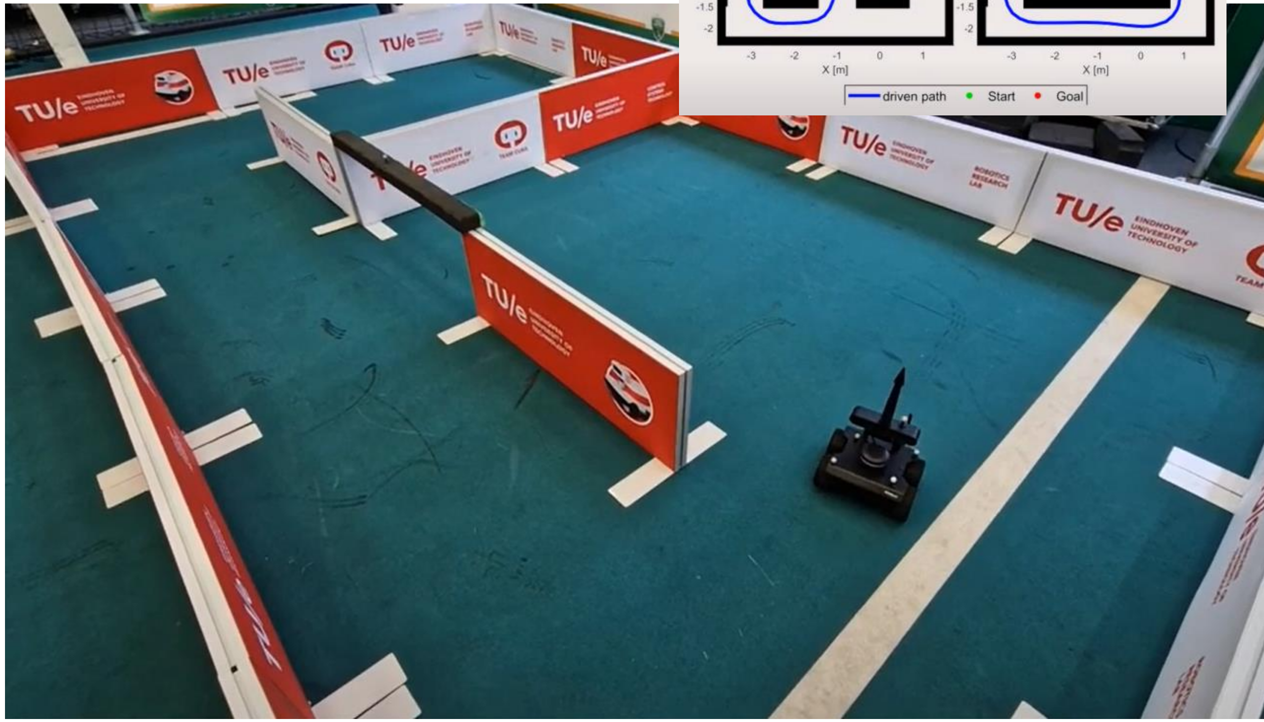
Circl demonstrator in Amsterdam

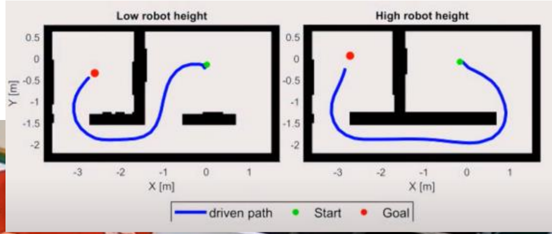
Circulaire Flexbouw De Meeuw

Circl. Toekomst van Circl: De volgende stap. https://circl.nl/verdieping/toekomst-van-circl-de-volgendestap

afbeelding van De Meeuw, De Alliatie - Karmijn, https://www.demeeuw.com/projecten/de-alliatie-karmijn/

Context-aware robotics based on up-to-date Digital Twin data (BIM, geometry, telemetry)





Hendrikx, B., Pauwels, P., Torta, E., van de Molengraft, M. J. G. R. & Bruyninckx, H. P. J. (2021). Connecting Semantic Building Information Models and Robotics: An application to 2D LiDAR-based localization. In: IEEE International Conference on Robotics and Automation (ICRA).

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https://www.youtube.com/watch?v=b7LKU3C6gCQ

Outline

1. Buildings and Semantics
2. Building Data on the Web
3. From Smart Buildings to Connected Buildings
4. Every Building is a Data Hub

Conclusions

1. Easy and very useful to represent and store building information into graphs (preferably, RDF, not LPG)
2. Do not transform everything into graphs, and instead rely on appropriate data storage solutions: geometry, semantics, sensor data
3. Transition to more granular data storage and systems: data-follows-object proposition.