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Urban Digital Twins

– Current State and Scientific Challenges

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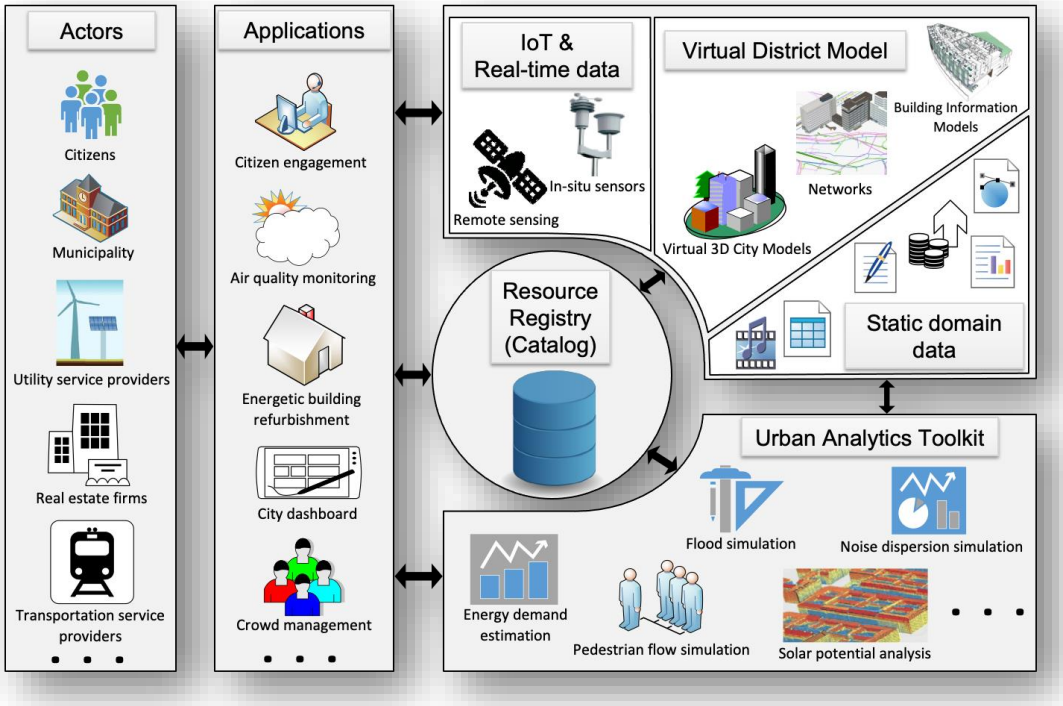
https://www.asg.ed.tum.de/gis/

BUILD-IT 2023 Workshop, Rome,
19th of October 2023



The Urban Challenge

- More than 50% of all humans live in cities
  - likely to increase to 70% until 2050
- Climate change – energy and environment
  - most energy is consumed in/by cities
  - cities & the urban work and life are responsible for the majority of the emissions of green house gases
  - reduction of emissions urgently required

Image: The Japan Times | KYODO

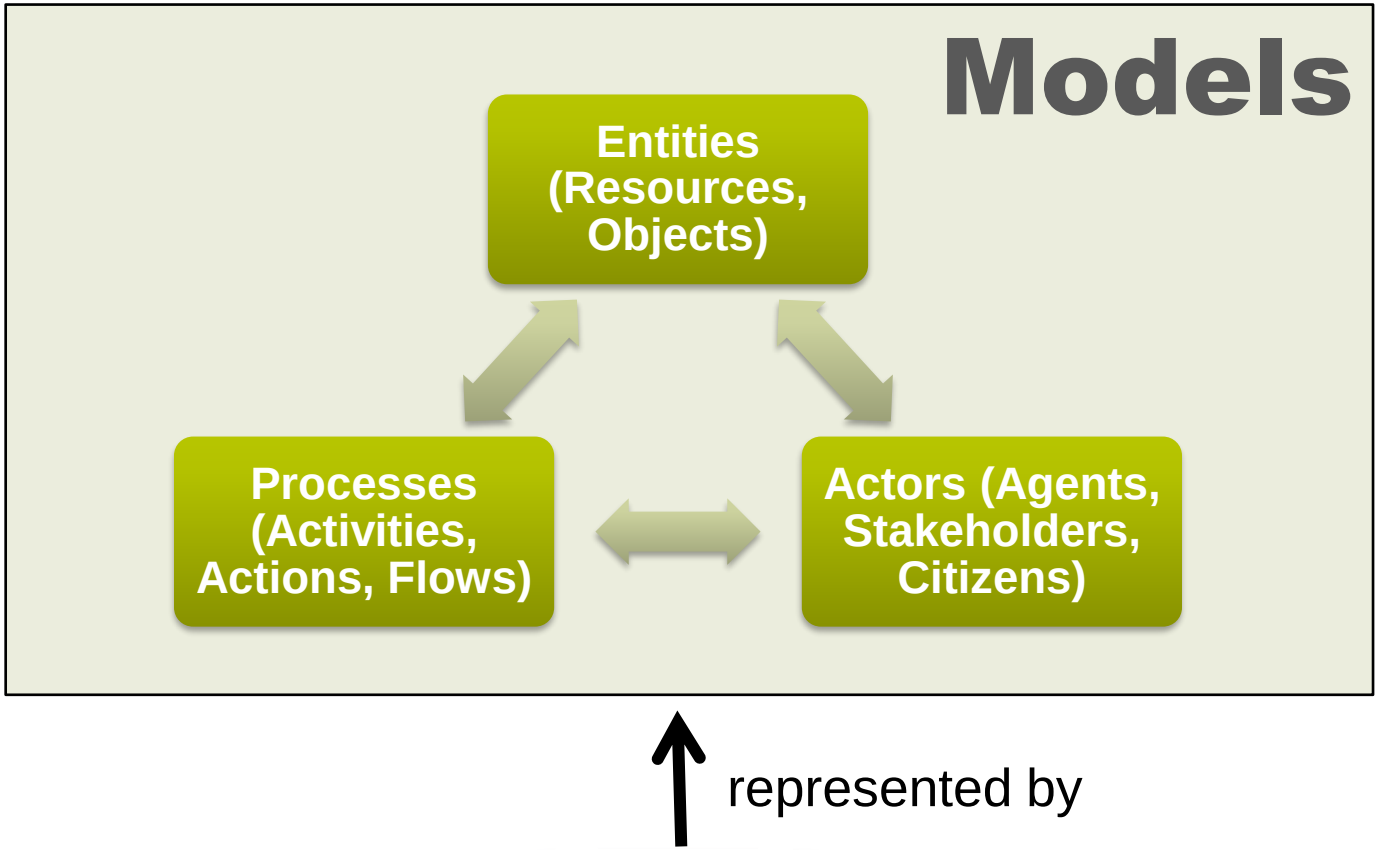
- Concentration of production and traffic
  - stress of the local environmental (air and water pollution, noise)
  - mobility / traffic flows
- Urban development must consider all these aspects simultaneously – and at the same time getting more efficient

Motivation: Urban planning of the future

- Urban development has always had to take into account **many different aspects**, including
  - economic
  - ecologic
  - energetic
  - mobility
  - urban planning
  - architectural
  - legal
  - sociological
  - security & safety
- **Integrated planning is very difficult** due to the many disciplines involved and the different approaches and information requirements
- **„Urban Digital Twins“** initiatives: Improvement through digital modeling of the relevant real world entities with an explicit bi-directional coupling
  - Promise / hypothesis: basis for the **integrated and well-informed planning and operation of cities**

City as a System

Urban Twinning requires City System Modeling



Today: Separate Modeling by Sectors

Energy

- Commu-nity
- Models
- Indicators
- Evalua-tion
- Planning

Mobility

- Commu-nity
- Models
- Indicators
- Evalua-tion
- Planning

Ecology

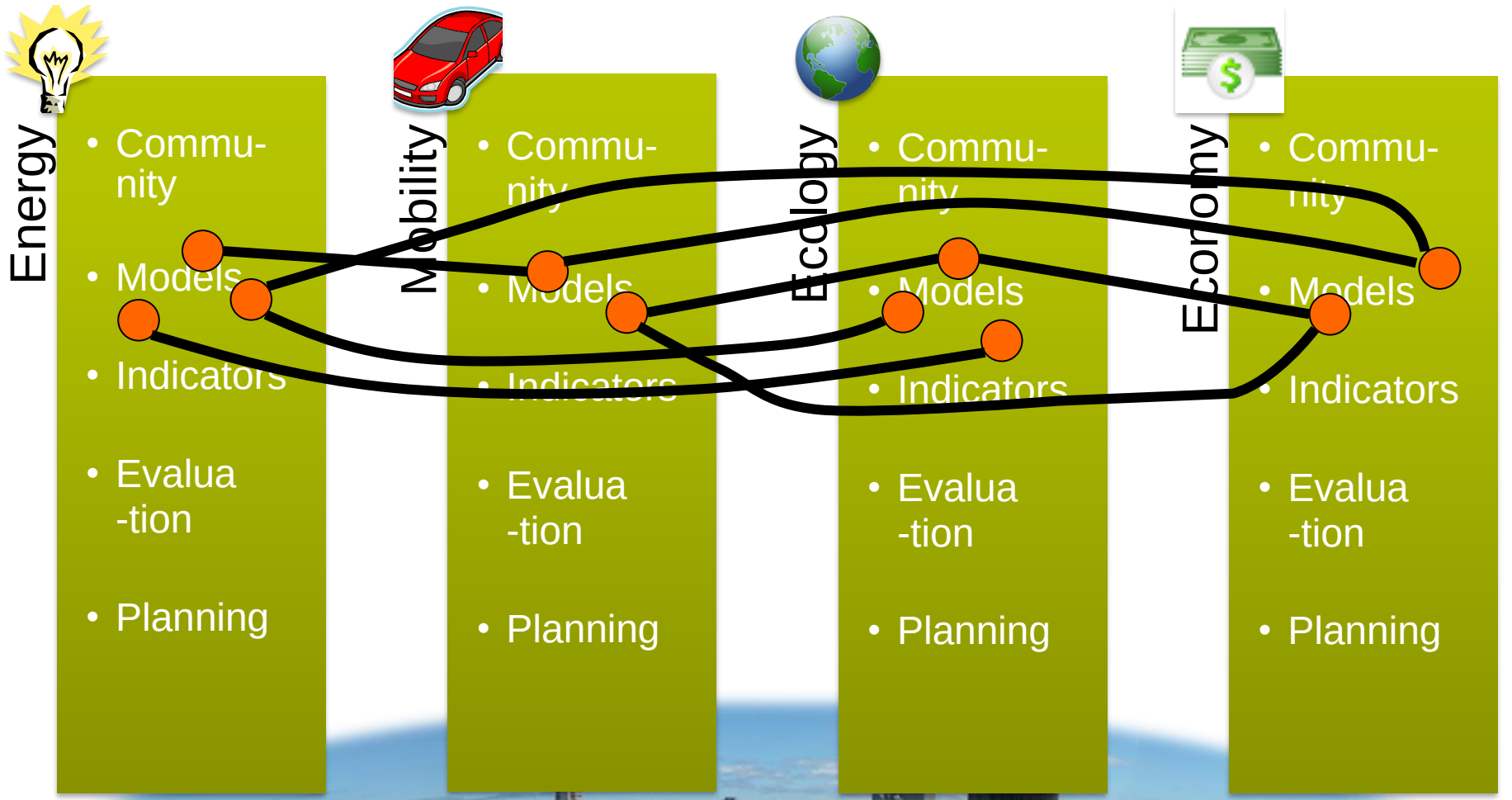
- Commu-nity
- Models
- Indicators
- Evalua-tion
- Planning

Economy

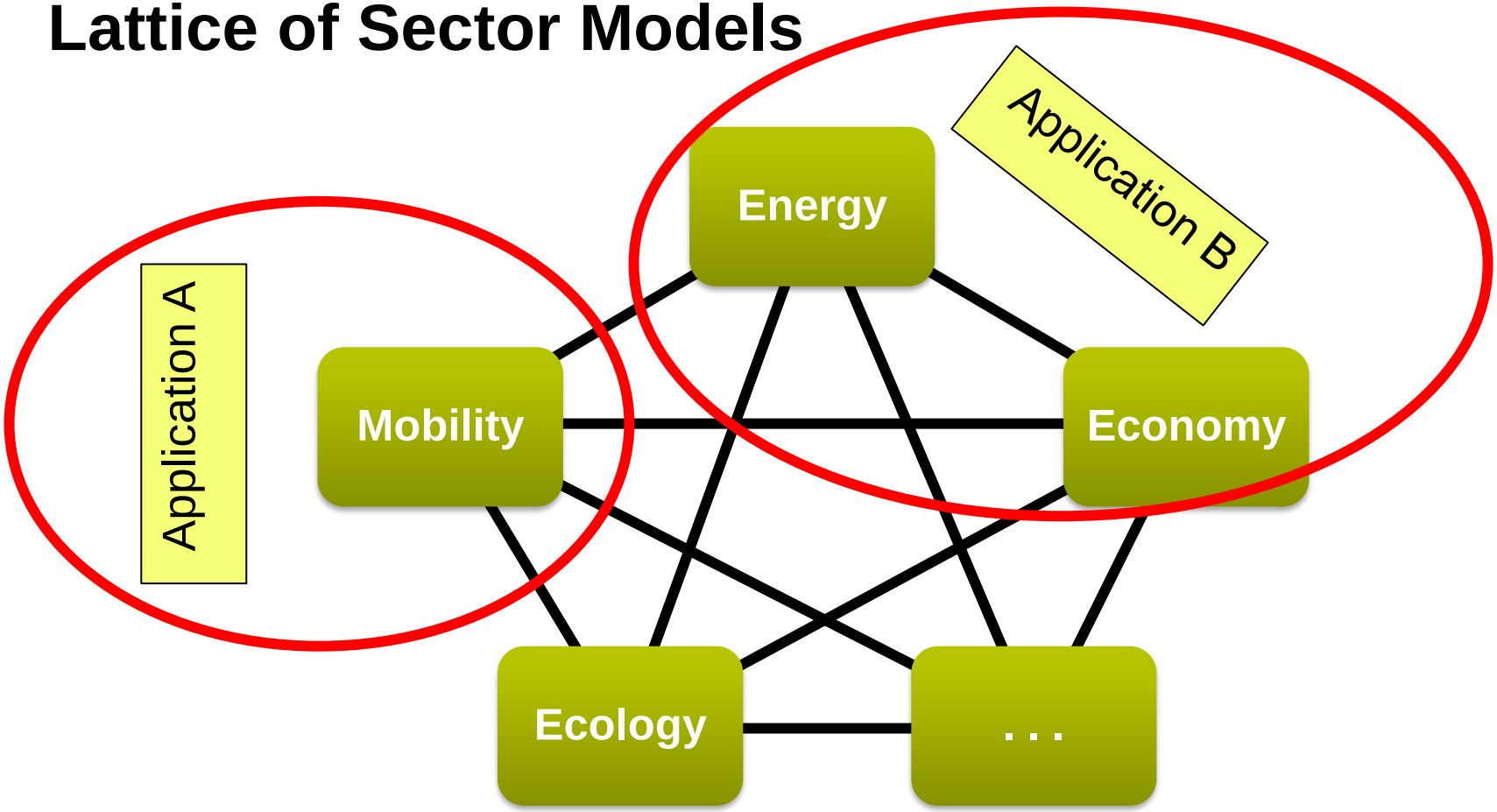
- Commu-nity
- Models
- Indicators
- Evalua-tion
- Planning

City System

Linking Sectors creates a Lattice of Models

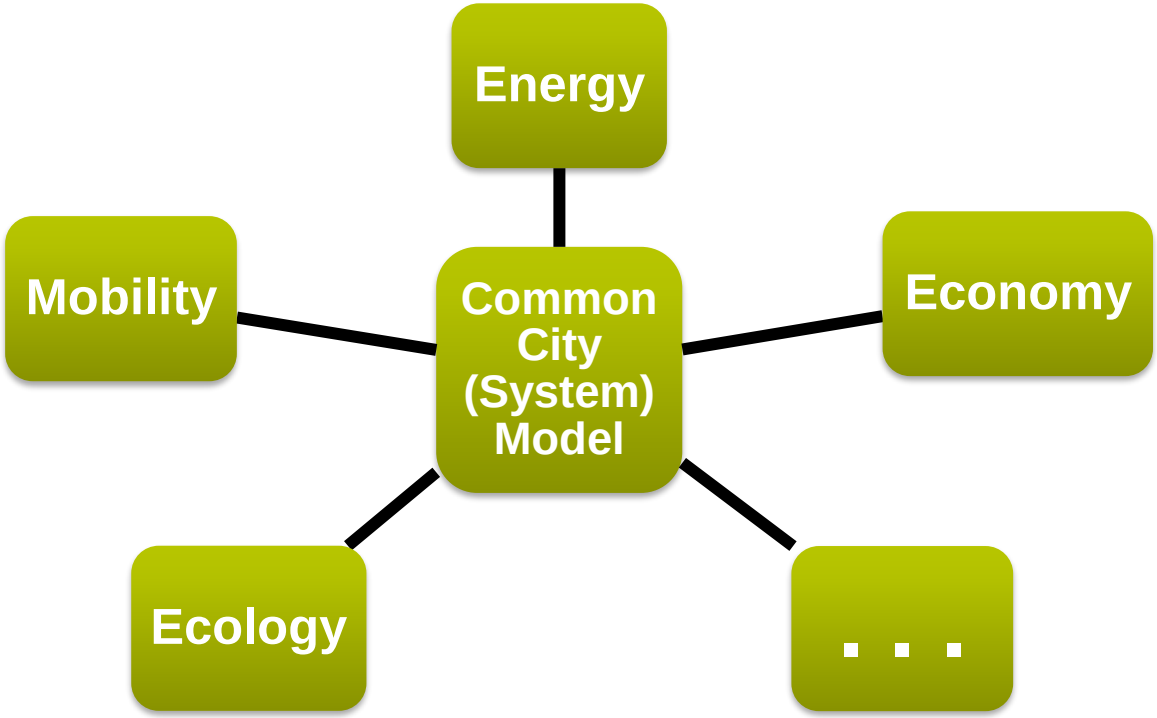


Lattice of Sector Models



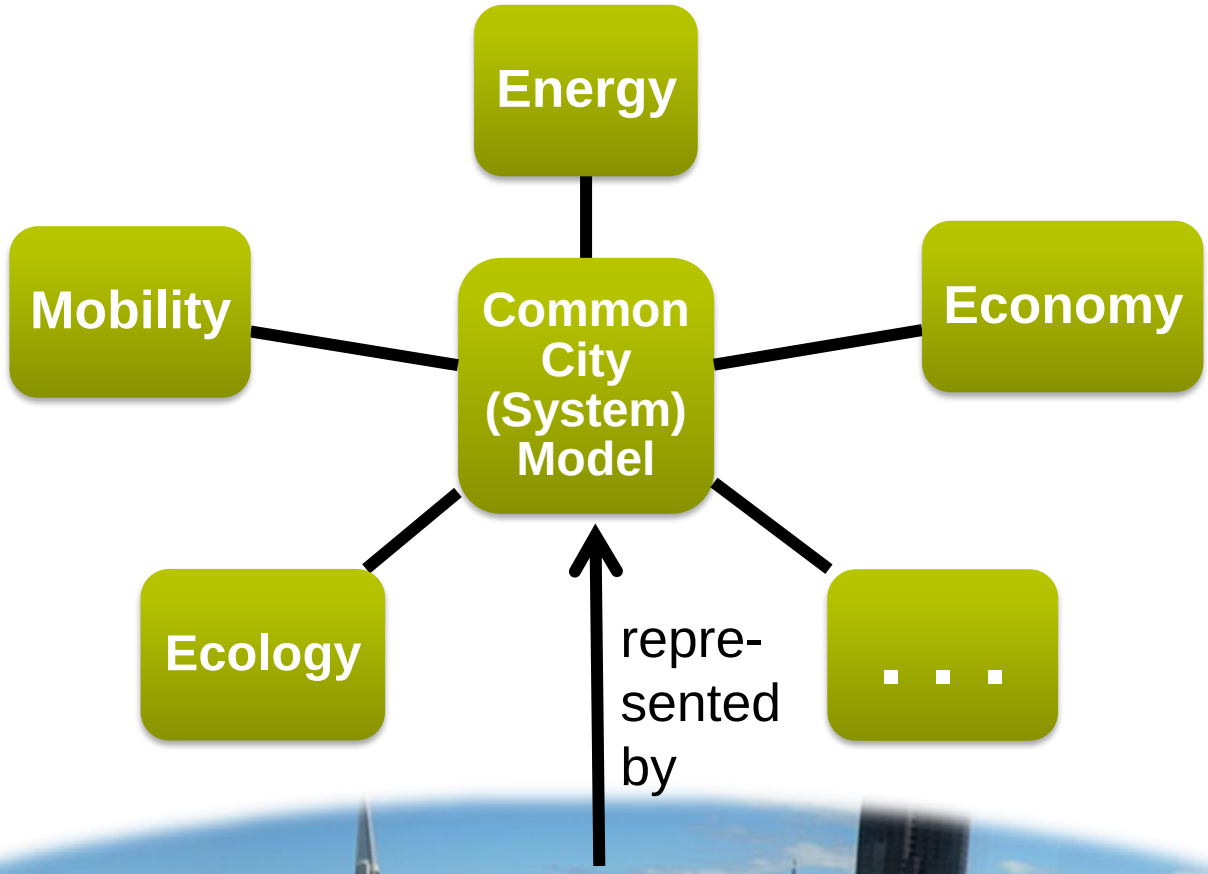
- *n* Sectors → **potentially n^2 connections!**
- difficult to express, to maintain, and to keep consistent

What if we could link to a Common Model?



- *n* Sectors → ***n* connections!**
- Sector models can be linked via the Common Model
- Sector models need to be aligned with the Common City System Model → **high degree of coherence required**

Is there such an integrative model? Candidates?

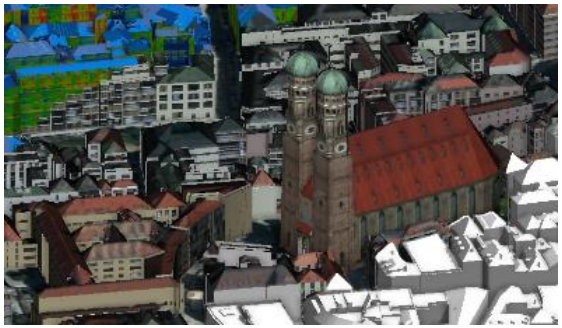


Spatial Digital City Models (→3D City Models)

- most **relevant urban objects are physical things**
- physical things **occupy space in the real world**
  - partitioning of the occupied real space → discrete objects
  - spatial properties: place (location & orientation), extent, shape
- **space as a unifying organizing principle** for urban information
- large-scale, area-wide **recording of the spatial configuration** possible **using sensors**
  - from satellites, airplanes, UAVs, vehicles, persons with cameras, laser scanners, tachymeters
  - automatic extraction of urban objects and decomposition into detailed sub-objects
- **intuitive visualization and exploration**
  - 3D depiction is more intuitive for people than 2D maps

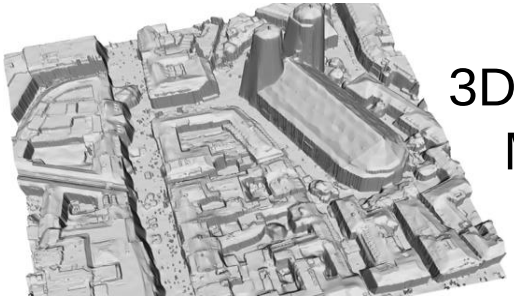
Digital 3D Models of the City

- There are different types, for example:

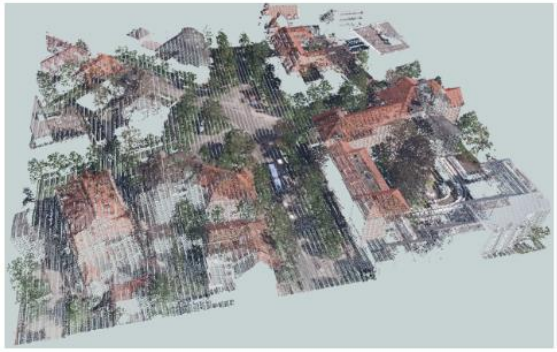


Semantic
3D City Models
e.g. CityGML

Building
Information
Modeling
e.g. IFC



3D Mesh
Models



3D Point
Clouds

- All have certain advantages and disadvantages, and cities nowadays employ more than one type to compensate for the weaknesses of the others

Spatio-Semantic City Modeling

3D Decomposition of Urban Space

- City is decomposed into meaningful objects with clear semantics and defined spatial and thematic properties
  - buildings, roads, railways, terrain, water bodies, vegetation, bridges
  - buildings may be further decomposed into different storeys (and even more detailed into apartments and single rooms)
  - domain specific data are attached to the objects as thematic attributes

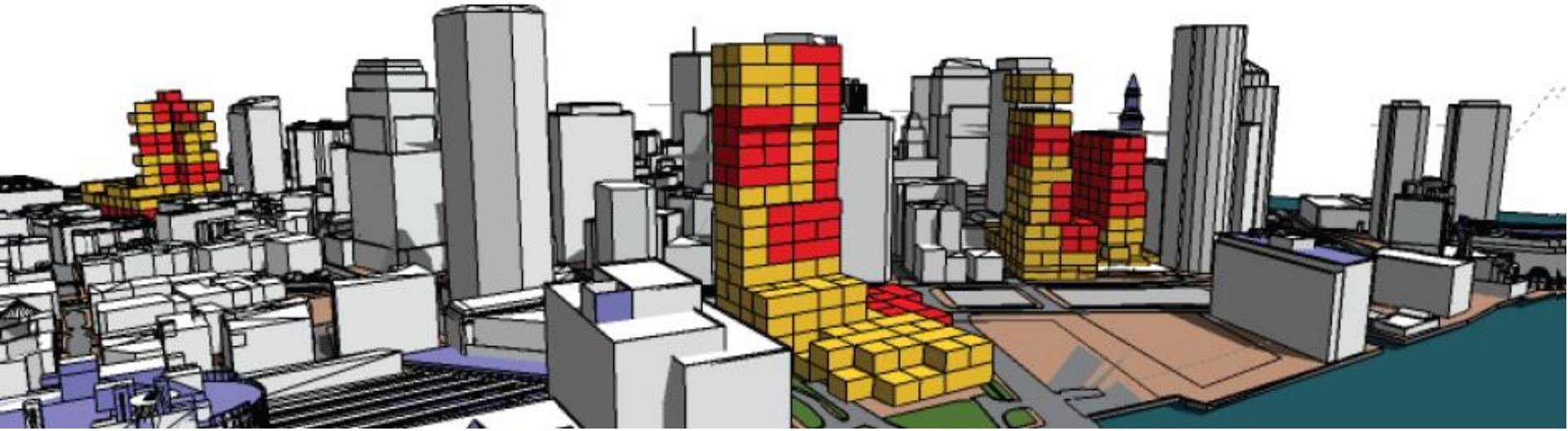


Image: Paul Cote, Harvard Graduate School of Design

Information Integration via 3D City Model Objects

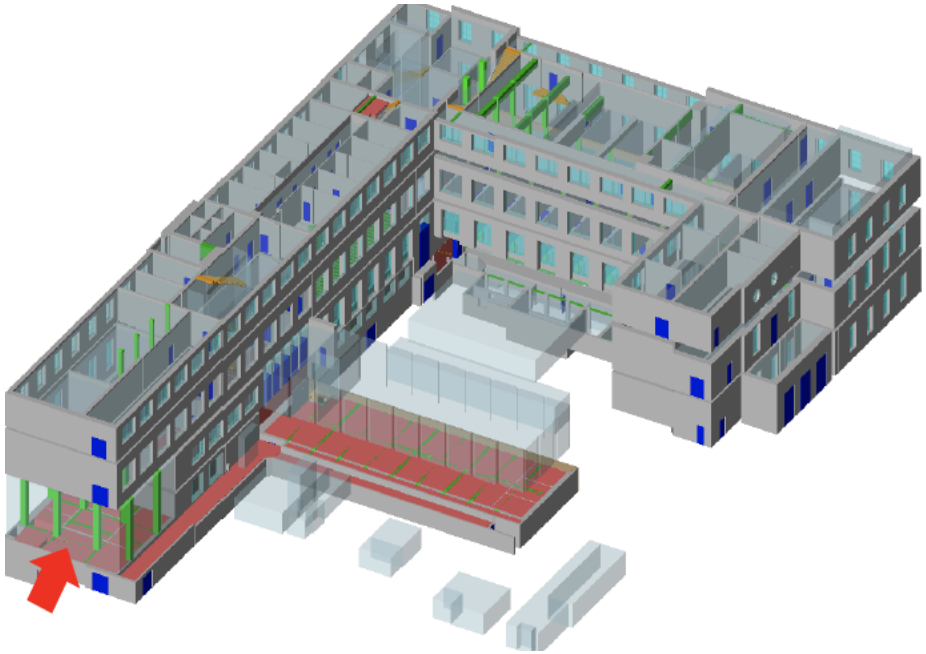
Energy
Heat energy demand
Energy demand for warm water
Electric power consumption

Noise immission
Noise levels on the facade
Number of inhabitants

Economy
Assessed real estate value
Available rental support

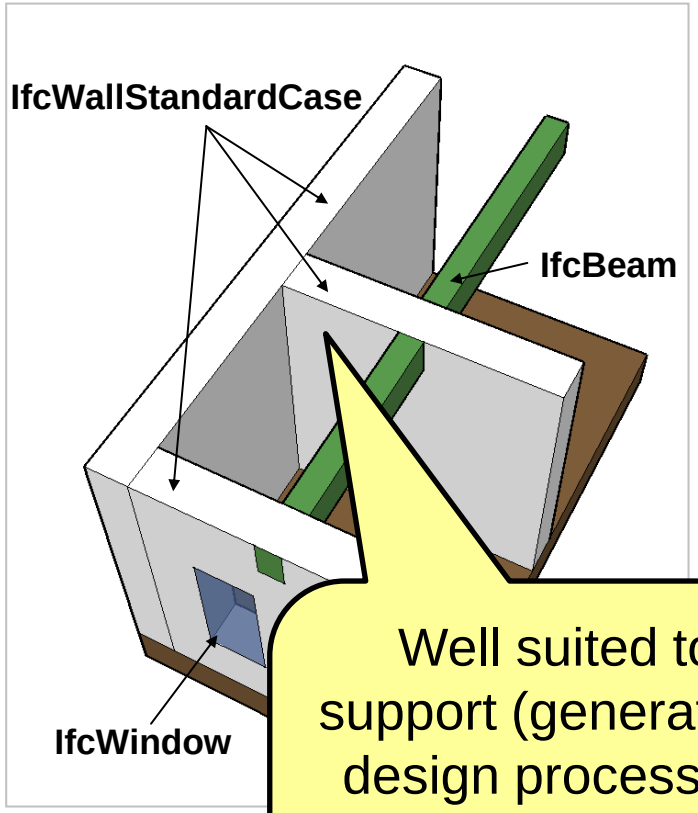
Semantic 3D Models of the Built Environment

- On the scale of individual sites:
  Building Information Modeling (BIM)
- On the scale of city quarters up to entire regions:
  Semantic 3D City Models (*Urban Information Models*)



Differing Object Modeling Paradigms

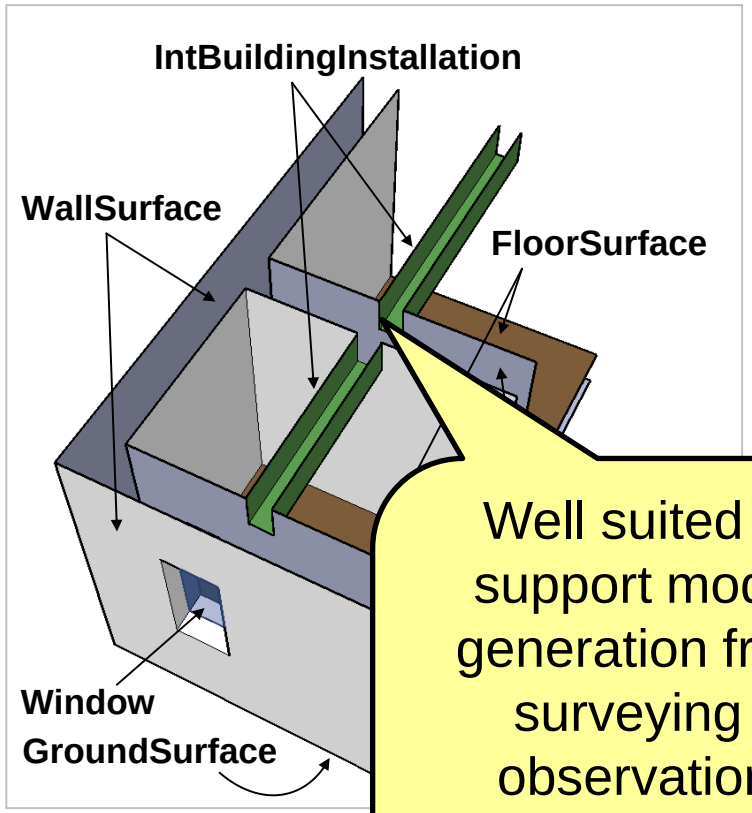
BIM (e.g., IFC)
Constructive Solid Geometry



Volumetric, p
representing the
of

Well suited to support (generative) design processes, hence, to create **models for planned objects**

3D GIS (e.g., CityGML)
Boundary Representation



Accumulation of obs
topograph

Well suited to support model generation from surveying / observation, hence, to create **models for existing objects**

Standardized Access to Semantic City Models

Mapping the state of a city at time t_i →

CityGML

← Virtually carrying out planned actions by changing the city model accordingly

- Energy Demand & Production Estimation
- Noise Immission Simulation & Mapping
- Real Estate Management & Urban FM
- Vulnerability Analysis & Disaster Management

CityGML

City Geography Markup Language – CityGML

Application independent Geospatial Information Model
for semantic 3D city and landscape models

- comprises **different thematic areas** (buildings, vegetation, water, terrain, traffic, tunnels, bridges etc.)
- **Data model (UML) + Exchange format** (based on GML3)

CityGML represents

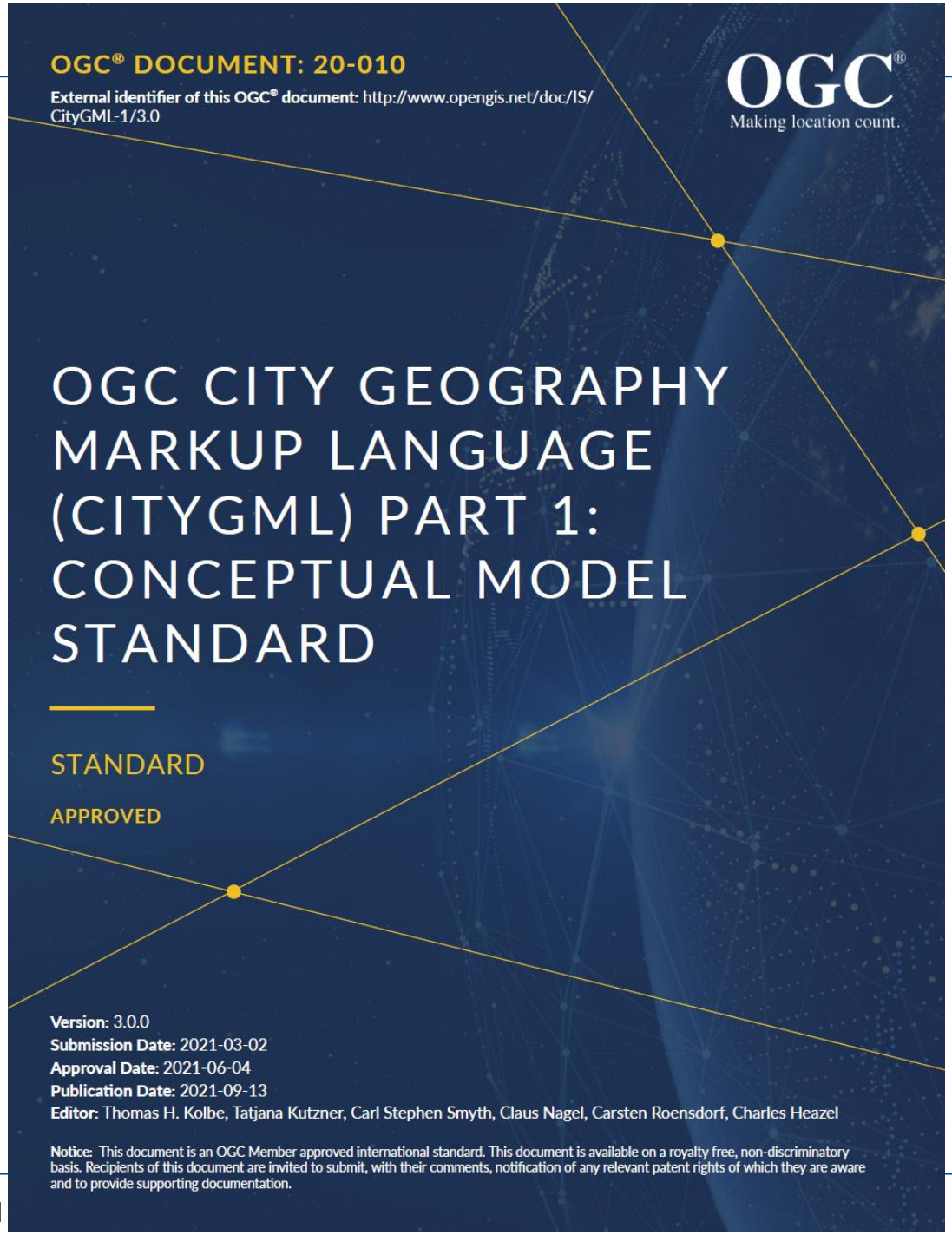
- 3D geometry, 3D topology, semantics, and appearance
- in 5 discrete scales (Levels of Detail, LOD)

International Standard of the Open Geospatial Consortium

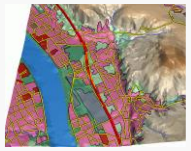
- Version 2.0.0 was issued in 3/2012
- **Version 3.0 issued in 2021 (Conceptual Model) + 2023 (Encoding)**

The recent version CityGML 3.0

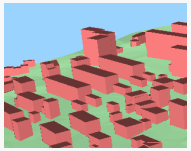
- On 13 September 2021, after eight years of development, the OGC published version 3.0 of the international standard CityGML
- The new version can be downloaded here: https://docs.ogc.org/is/20-010/20-010.html



Five (respectively four) defined Levels of Details



LOD0 – Regional, landscape model **+ interior**
- 2.5D Digital terrain model



LOD1 – City, regional model
- Prismatic buildings without roof structures **+ interior**

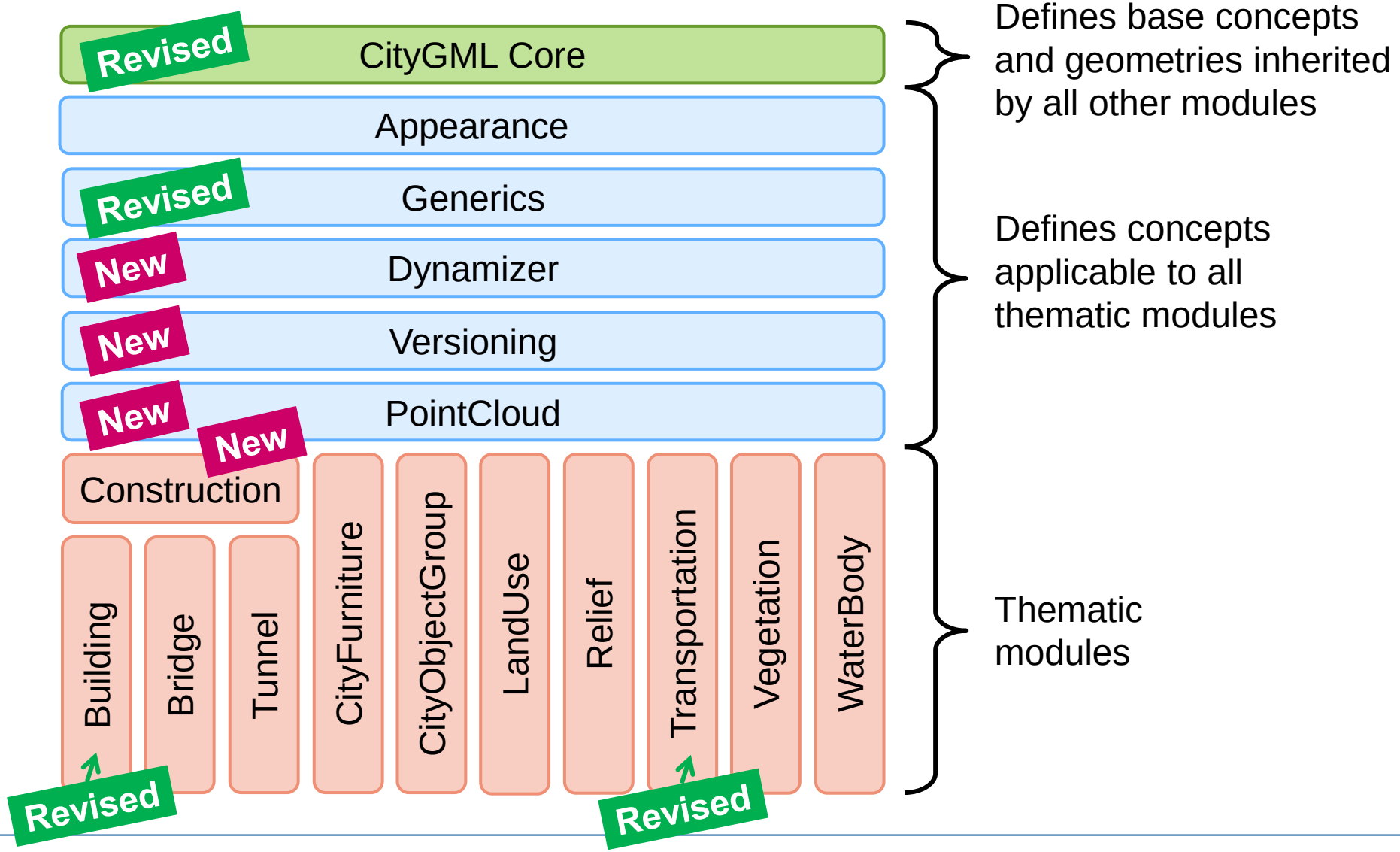
LOD2 – City districts, site model
- Simple buildings with detailed roof structures **+ interior**

LOD3 – Architectural models (exterior) **+ interior**
- Detailed architectural models

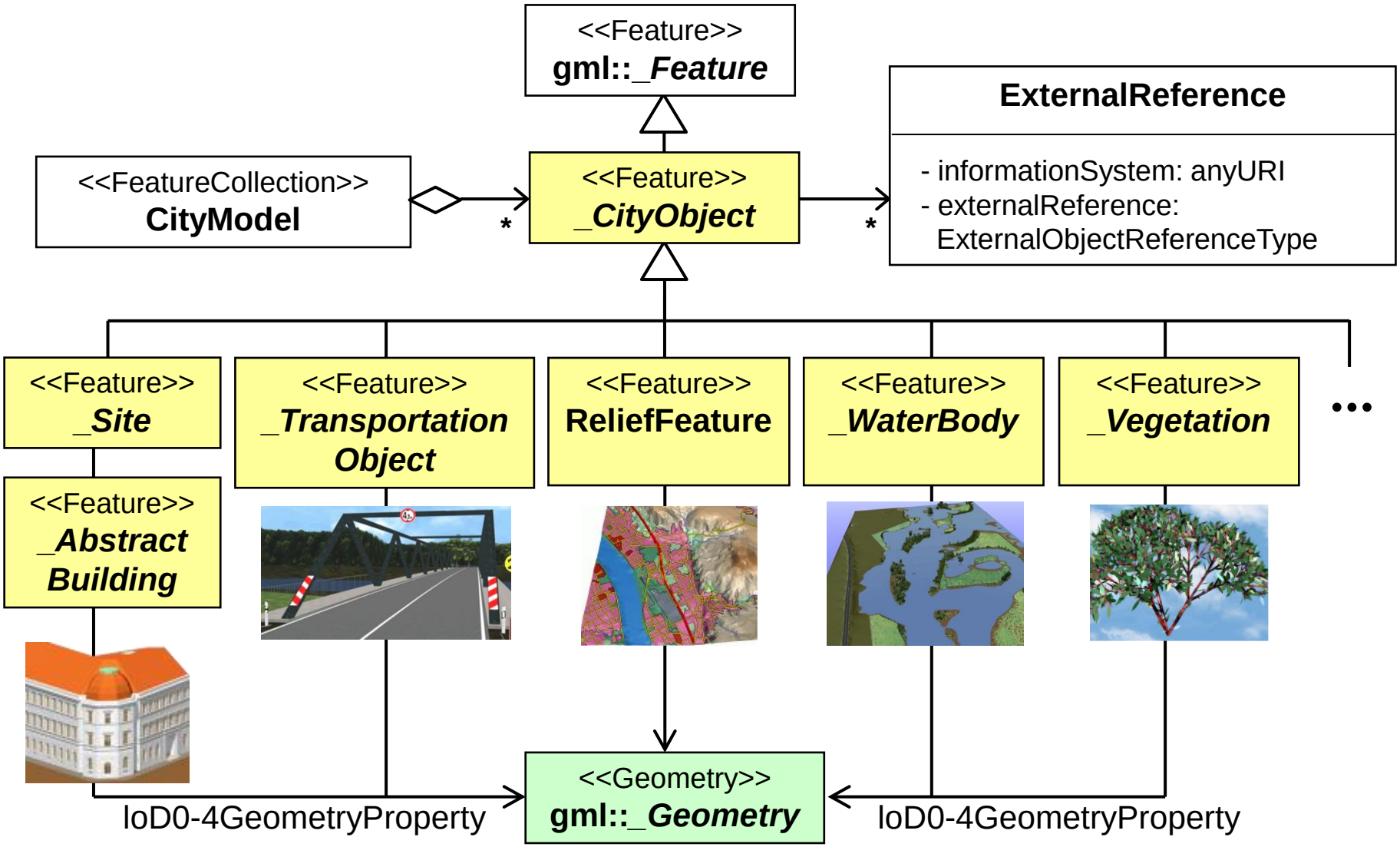
LOD4 – Architectural models (interior)
- "Walkable" architectural models

- CityGML 3.0 allows for representing the interior of buildings, tunnels and bridges in LODs 0-3 as well.
  → E.g., the exterior can now be modelled in LOD1, whereas the interior is represented in LOD2 or 3
- Supports the use of 3D city models in applications which require detailed representations of the indoor, but not necessarily of the outdoor, e.g. indoor navigation, energy applications, smart homes

CityGML 3.0 Module Overview

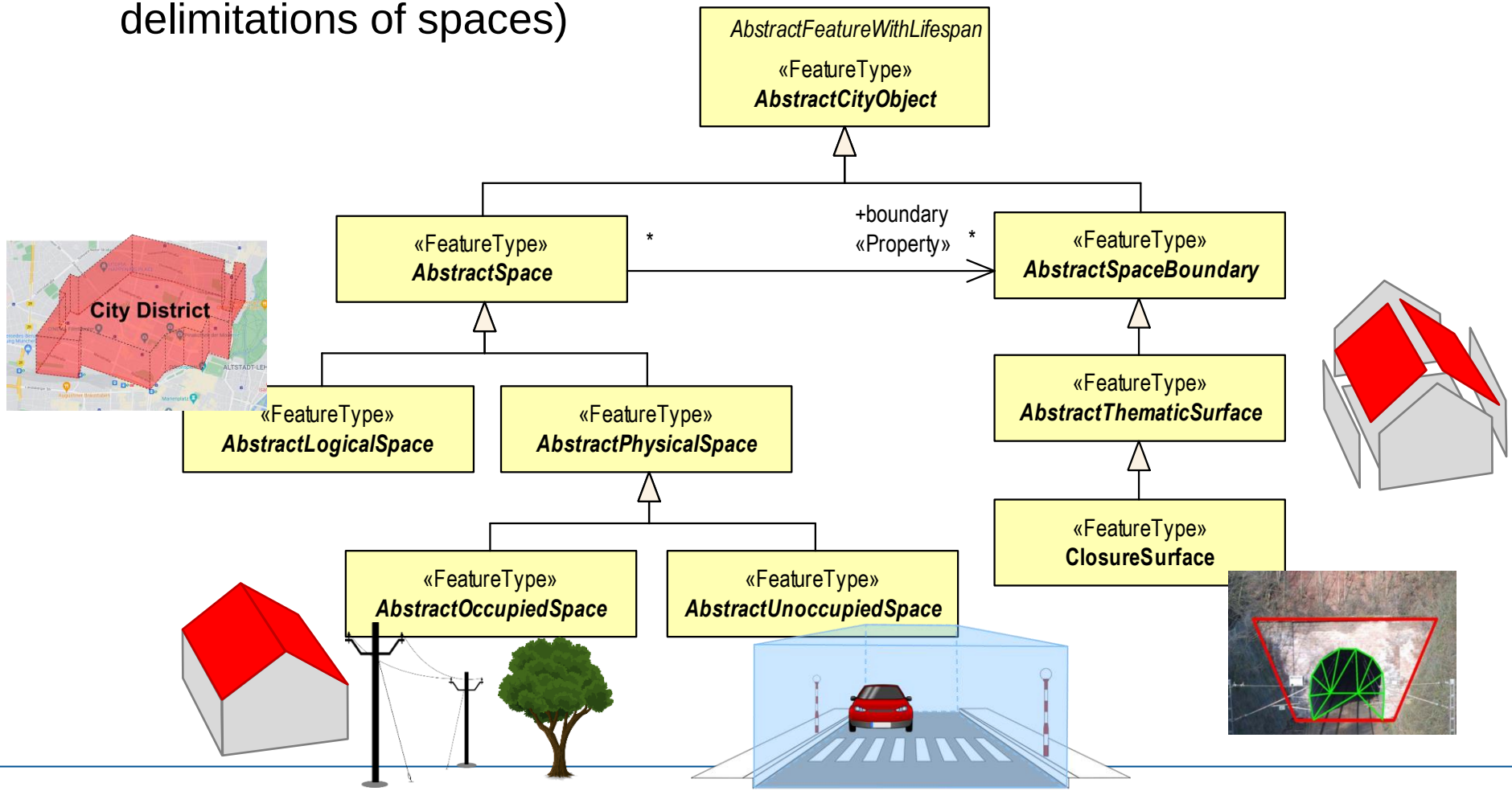


Thematic Modeling in CityGML



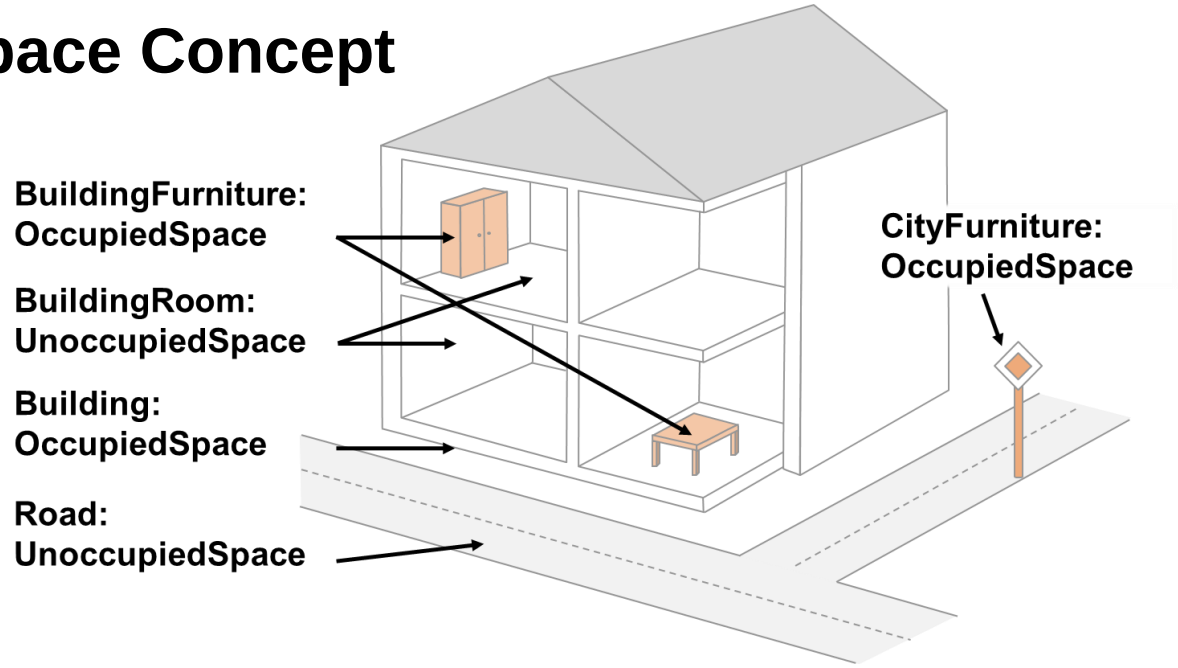
CityGML 3.0: Introduction of a Space Concept

- All thematic objects are now either categorized as **spaces** (objects with volumetric extent in the real world) or **space boundaries** (areal delimitations of spaces)



Advantages of the Space Concept

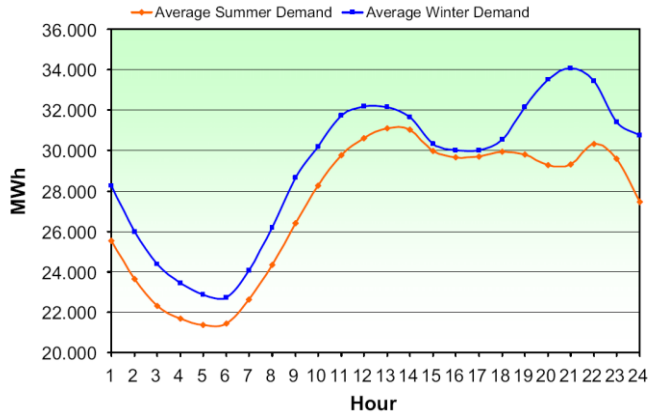
- Occupied and unoccupied spaces (OccupiedSpace, UnoccupiedSpace) **can be nested** within each other
- Supports the **analysis of navigable indoor and outdoor spaces** (e.g. to derive IndoorGML from CityGML data; but can also be used for airspace)



- Explicit modeling of **topological, geometric, and thematic relationships** between Spaces and Spaces, Spaces and Space Boundaries, Space Boundaries and Space Boundaries.
- Qualified attributes allow to provide **specific volume and area measures for Space objects and specific area measures for SpaceBoundary objects** (for example, for buildings and floors, the living area, net and gross floor areas, and net and gross volumes can be specified)

Changes in the context of semantic 3D city models – Highly dynamic changes

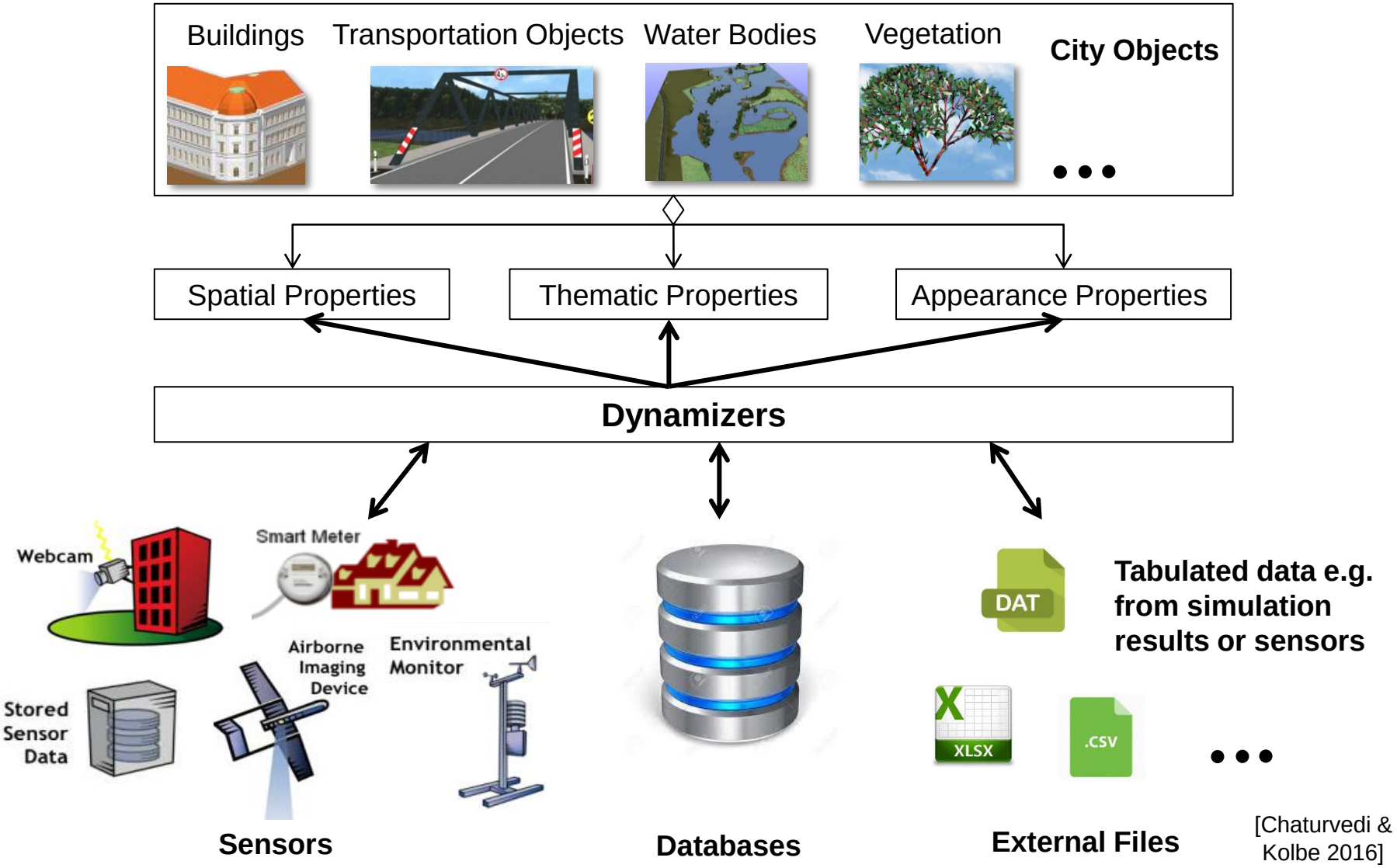
- **Variations of spatial properties**: change of a feature's geometry, both in respect to shape and to location (e.g. moving objects)
- **Variations of thematic attributes**: changes of physical quantities like energy demands, temperatures, solar irradiation
- **Appearance**: e.g. raster images showing air quality
- **Variations with respect to sensor or real-time data**



Source:C. García-Ascanio and C. Maté, "Electric power demand forecasting using interval time series: A comparison between VAR and iMLP,"*Energy Policy*

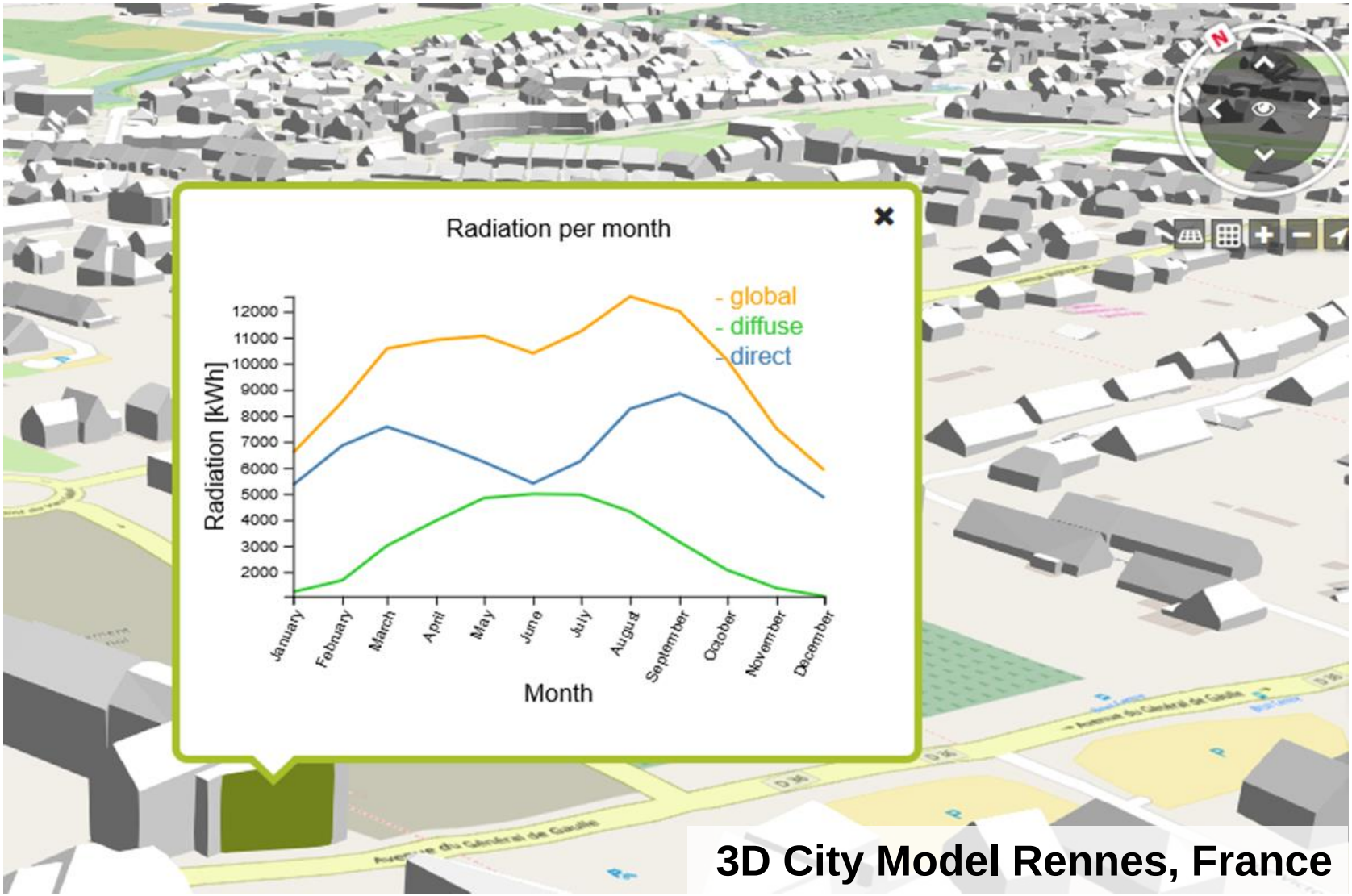
Source: MOREL M., GESQUIÈRE G., "Managing Temporal Change of Cities with CityGML". In UDMV (2014)

New CityGML 3.0 Dynamizer module



[Chaturvedi & Kolbe 2016]

Visualization of Time-dependent Solar Potentials

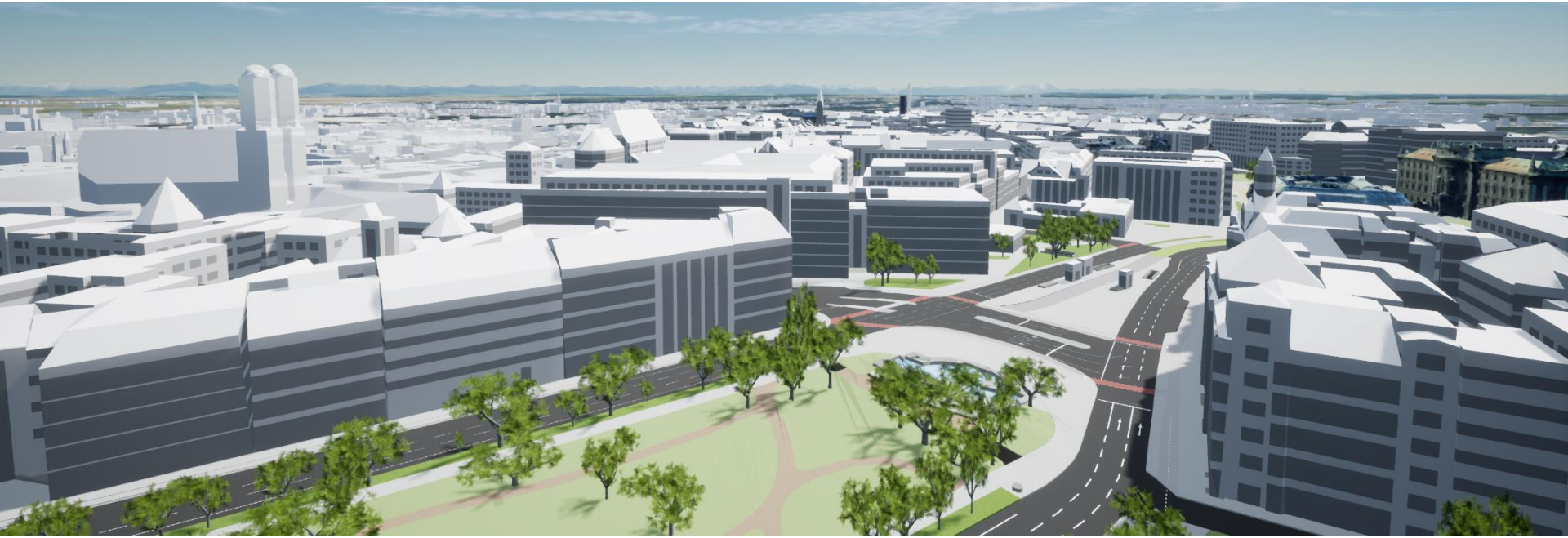


CityGML 3.0 Streetspace Modeling Example 1

- Streetspace model of Ingolstadt automatically generated from OpenDRIVE data
- Open-source OpenDRIVE to CityGML 2/3 converter r:trån https://github.com/tum-gis/rtron

CityGML 3.0 Streetspace Modeling Example 2

- Project: Urban Digital Twin Munich
- Representation of the streetspace and dynamic streetspace activities



CityGML Usage (mostly Version 1.0/2.0 so far)

- CityGML is already successfully used at national scale
  - The official national and municipal 3D geoinformation standards of Germany and the Netherlands base on CityGML 1.0/2.0
  - Japan published 3D city models for >100 cities based on CityGML and the i-Urban Revitalization Application Domain Extension
- Many cities worldwide use CityGML for their 3D city models
- List of Open CityGML Datasets: https://github.com/OloOcki/awesome-citygml
  - from 18 countries, in different Levels of Detail, most data are officially maintained 3D city models
- CityGML extensions like the Energy ADE and the Noise ADE are used internationally

Applications of 3D/4D City Models

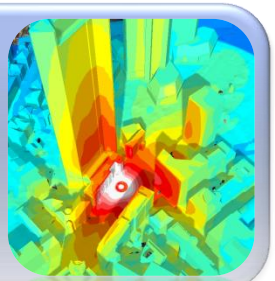
Urban Simulations using 3D/4D City Models: Situation Assessment + 'What-if' Scenarios

Flooding

River flooding
coastal flooding
Tsunami

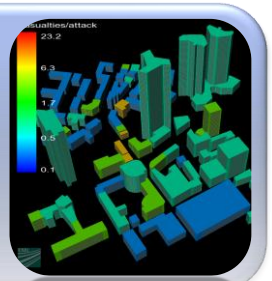
Blast

Detonation
pressure wave
propagation



Vulnerability

Risk-based
vulnerability
assessment

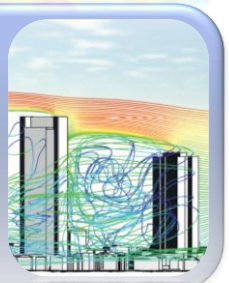


Crowd

Crowd dynamics
for events and
evacuations

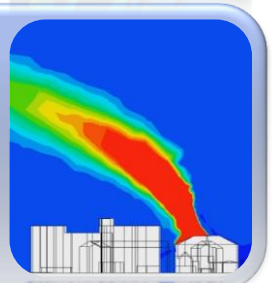
Wind Field

Turbulent wind
fields and thermal
stratification



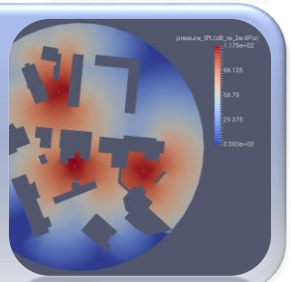
Air Quality

Smoke and
pollution
propagation



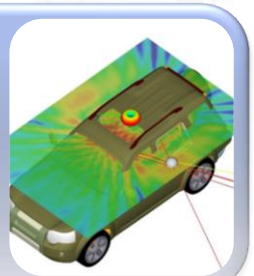
Acoustics

3D urban
noise
protection



Mobility

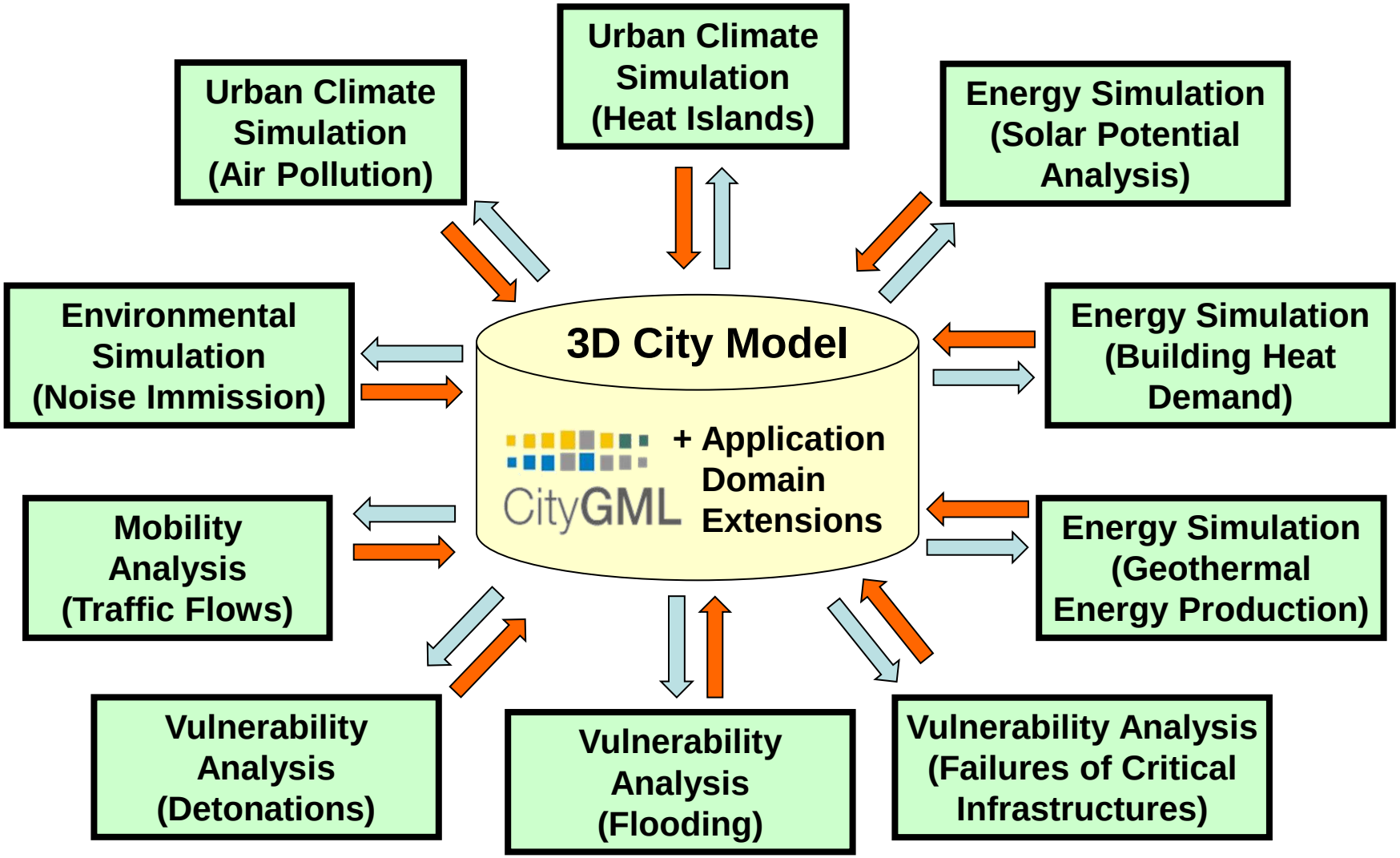
Autonomous
driving, traffic
and wireless
communication



Source:

virtualcitySYSTEMS
CADFEM®

Multi-Simulations with 3D/4D City Models



Projects that were carried out by or with participation of my teams so far

Is this it?

Are these models the Urban Digital Twin?

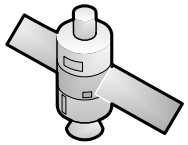
No, of course not!

- **Digital models** of the physical environment are just one **key element**
- But what about
  - the actors and stakeholders?
  - use cases and applications?
  - processing and analytical tools / simulators?
  - real-time measurements using sensor devices and services?
  - the many different sectors / thematic domains like mobility, energy, living, social aspects, environment, finances?
- The **Urban Digital Twin** is the set of **all digital resources about the city**, **distributed** across **all resource holders**.
  - clearly cannot be managed explicitly in a platform or a single database

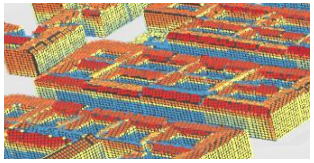
  → We need an infrastructure. And SDIs are a very good starting point!

City / District as a Complex System


Noise dispersion simulation

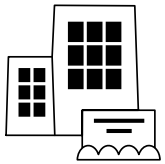

Satellite sensors

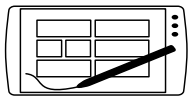

Citizens


Solar potential analysis

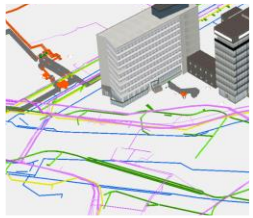

Municipality

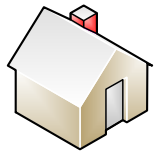

Weather sensors

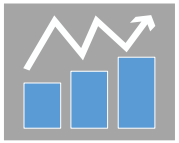

Real estate firms

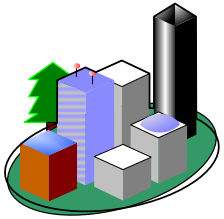

City Dashboard


Citizen engagement


Networks


Energetic building refurbishment


Energy demand estimation


Virtual 3D City model

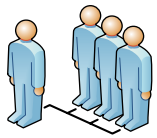

Flood simulation


Transportation service providers


Air quality monitoring

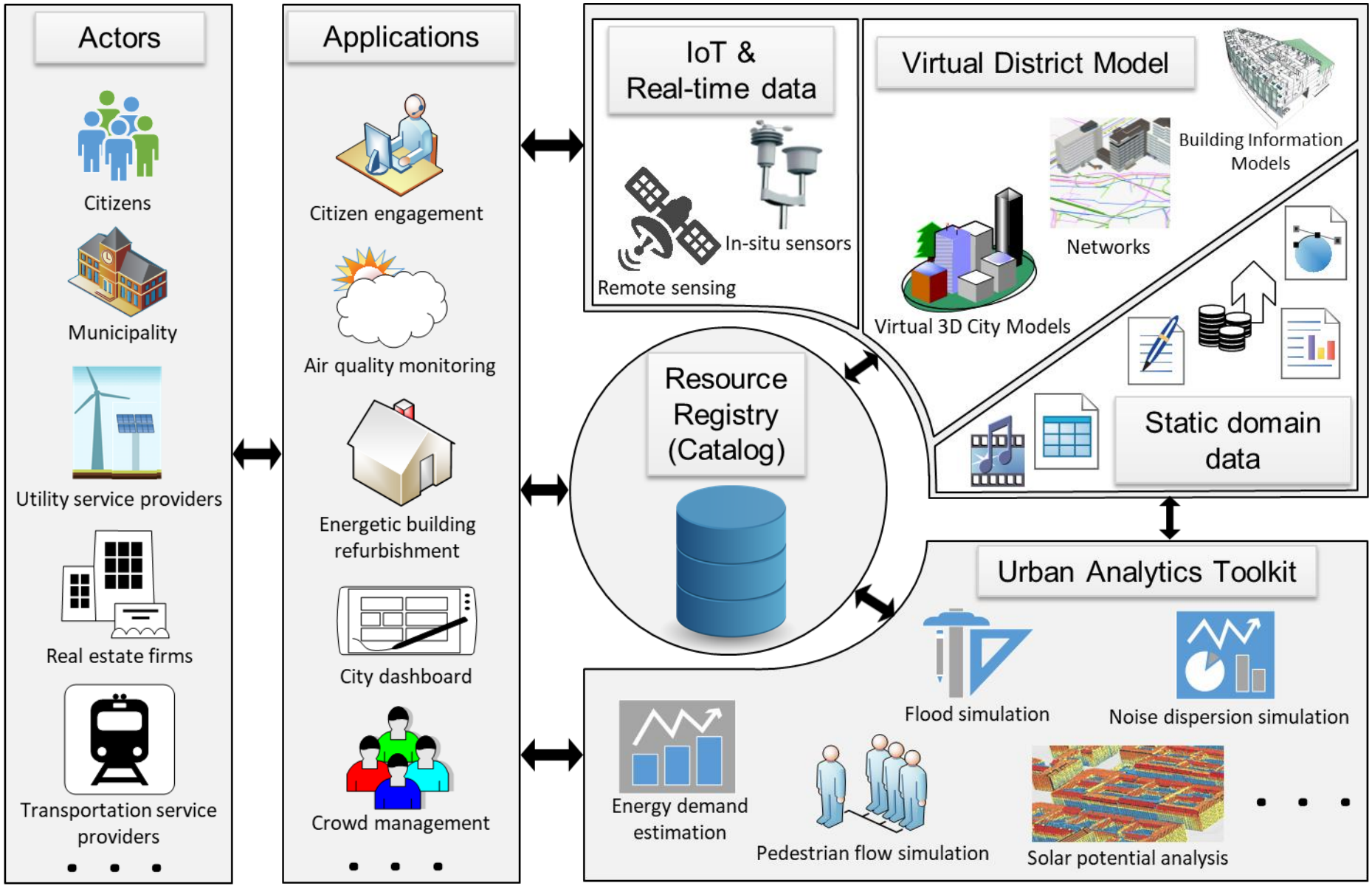

Utility service providers


Crowd management

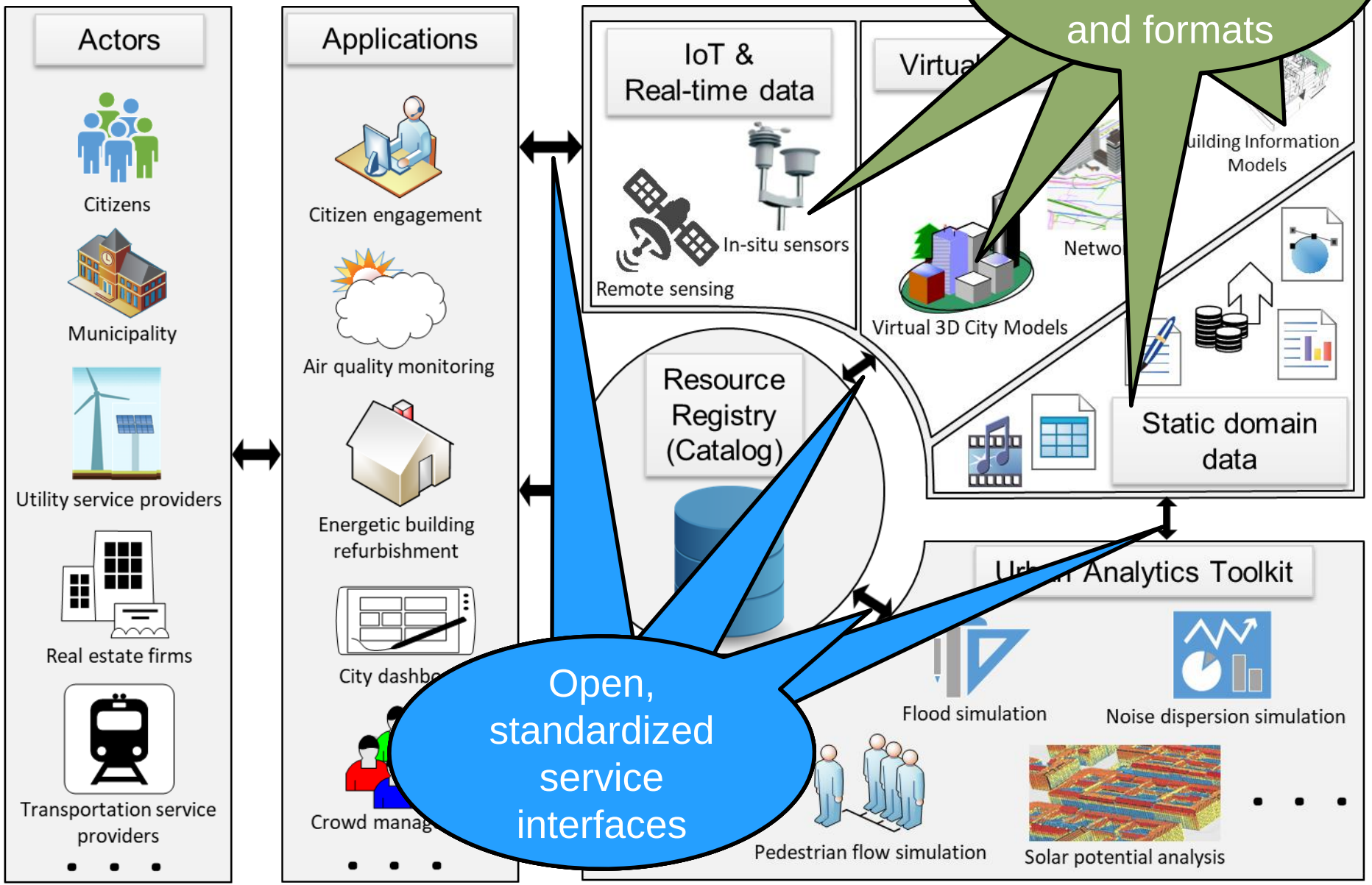

Pedestrian flow simulation

Smart District Data Infrastructure (SDDI)

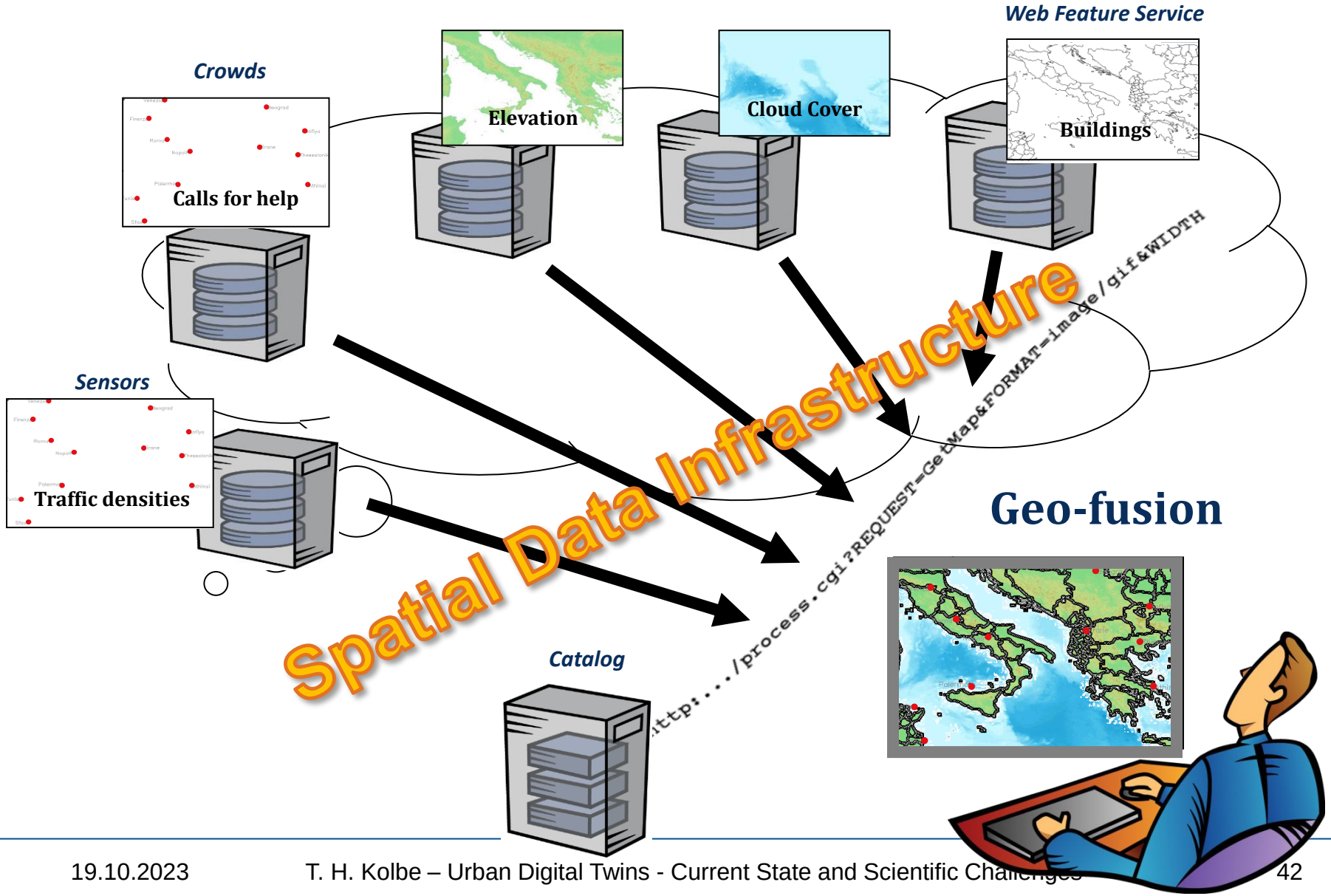
Smart District Data Infrastructure (SDDI)



Smart District Data Infrastructure (



SDDI – Realisation as a network of distributed services



SDDI Catalog

- We (TUM-GIS) have developed an improved catalog service to manage all kinds of distributed information resources of Urban Digital Twins
- **Open Source**; based on the **CKAN** Data Platform software
  - specific extensions: spatial & temporal metadata and search, GUI to link catalog entries, navigating linked catalog entries, DCAT2
  - supported information resources: digital twin, project, thing, geoobject, method, software, online service, online application, dataset/document
- Production ready; easy deployment in Cloud Environments
  - Docker images: https://github.com/tum-gis/ckan-docker

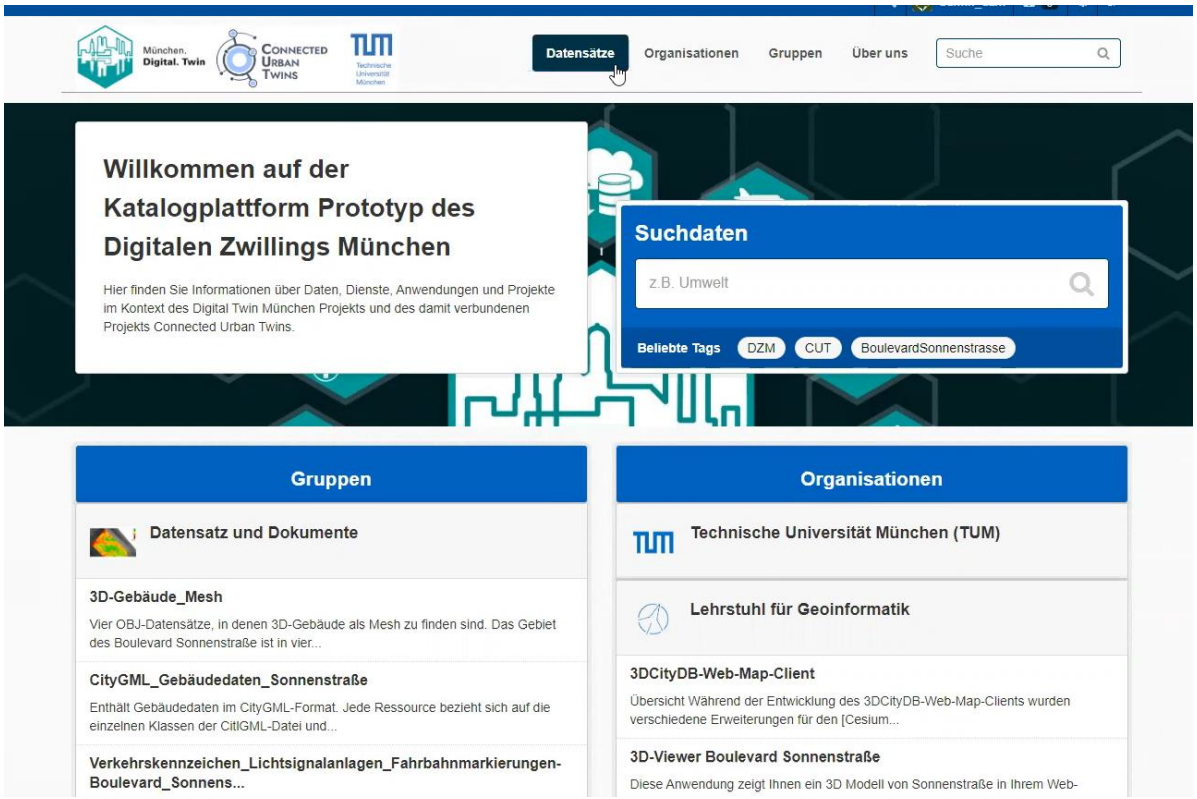
SDDI CKAN for Kubernetes

- Helm charts for easy deployment of application stack in a Kubernetes Cluster: https://github.com/tum-gis/sddi-ckan-k8s
- Tested & running on MS Azure, T-Systems Cloud, Minikube, Docker Desktop
- Branding is easy

SDDI ckan-docker

Examples for running SDDI Catalog instances

- Catalog platform for the Digital Twin Munich (ongoing work):



CUT

- Link to an open, running catalog for the project SAVeNoW: https://catalog.savenow.de/ *(Give it a try!)*

Summary – Key Elements of Urban Digital Twins

- **Stakeholders / Actors** (Consumers, Producers, Prosumers)
- **Distributed digital resources** of the cities/regions
  - **Digital models of the physical environment**
  - **Dynamic data** from all domains (e.g. provided by sensor services)
  - **Static data** from all domains
  - **Analytical tools** from all domains
- **Joint catalog** to register and find all resources
- **Interoperability** of all components and data representations
- **Organizational & operational framework**
  - Spatial Data Infrastructures (SDIs) and their institutional background are good starting points → existing & sustainably operated
    - **Extend SDIs to become SDDIs**

Coming to the end…

Key Challenges of Urban Digital Twins

- **Many stakeholders** / interests + **many thematic sectors**
  - coping with distributed information and systems is unavoidable; no single point of truth, no unique information owner
  - governance (organization, legal) is complex
- Cities are **highly dynamic environments**
  - rise & fall of objects; changes of object properties & relations
- Capturing & representing the **physical urban environment**
  - updating → change detection and interpretation
- **Many different models, processes**
- **Interoperability** within a heterogeneous data infrastructure
- Integration / **acceptance with humans and society**

Scientific Challenges & Development Areas (1)

- **Models / Modeling**
  - digital **models of the physical environment** (3D + time)
    - meta modeling („developing the models for urban digital models“)
    - automated digital model acquisition from sensor data (e.g. images, 3D point clouds); Scan to BIM; object reconstruction for 3D/4D city models
    - keeping models consistent 1) with reality, 2) with each other; updating
    - planning tools
  - digital **models for the different application fields**
    - alignments with the models of the physical environment
  - "What-if" scenarios → **digital triplets**
    - automation supported generation of scenarios (e.g. procedural modeling, generative AI-based modeling)

Scientific Challenges & Development Areas (2)

- **Data Management**
  - data federation over distributed resources
  - managing access rights & control; transactions; accounting; billing
  - ongoing research: **data spaces** – but this is technologically & organizationally too complex for most municipalities
- **Urban Data Fusion & Analytics**
  - computation of **urban indicators** directly based on the UDT;
  - dealing with **multiple representations** of the same object, object properties or phenomenon (e.g. observed, planned, simulated)
  - maintaining and propagating **data quality & lineage** along processing chains
  - generating **projections and predictions**

Scientific Challenges & Development Areas (3)

- **The Human Factor**
  - **Acceptance**, e.g. by ensuring relevance, good data quality, and trust
  - **Human-in-the-Loop**, e.g. by (public) participation
  - **Interacting with humans**
    - visualization (e.g. VR/AR, web-based 4D visualization)
    - user interfaces (e.g. VR/AR input devices, natural language and speech recognition)
- **Governance**
  - **Legal and economic aspects** of mixing of public and private data & tools (”public-private partnerships 4.0”)
  - **Business Models; Financing**

My take on defining "Urban Digital Twins"

- The digital twin of a city / neighborhood / region (**Urban Digital Twin, UDT**) is a **comprehensive framework** for organizing and making usable the diverse data
  - about the city,
  - its physical components and logical structures,
  - as well as the actors involved and their processes.

  Technical, organizational and legal aspects play a role.
- UDTs are created for specific purposes. The **specific compilation of digital resources** is therefore determined by the dedicated use of the UDT. The compilation digitally maps all aspects of the real world required for its purpose and makes them accessible, analyzable and visualizable for applications and users. The goal is to enable gaining essential insights into the state of the city / neighborhood / region and its development based on the analysis of the UDT, thus supporting planning and decision-making.
- **Digital resources include various types of data and digital models**, but also functionalities such as **analyses, simulations and visualizations**.
- An essential feature is the **systematic, bidirectional synchronization between the Urban Digital Twin and the real world**.