
IARIA
An Introduction
to
City Digital Twins
Prof. Robert Laurini
Academics Without Borders
Roberto.Laurini@gmail.com

City Digital Twins

- •The aim is to build a digital model of the city on which analyses and simulations can be carried out according to certain assumptions and conclusions for planning purposes.

- This is a new concept, although intuition (precursors) has existed since the 1970s with minor scopes
  - Urban data banks and databases
  - Development models
  - Geographic information systems
  - 3D digital models

Contents

- 1. Introduction, objectives
- 2. Technologies
- 3. Conclusions

1. Introduction, objectives

- There are many definitions of city digital twins

- Common purposes
  - Have a vivid digital image in all its complexity
  - Control it in real time in an optimal way

Different meanings of city digital twins

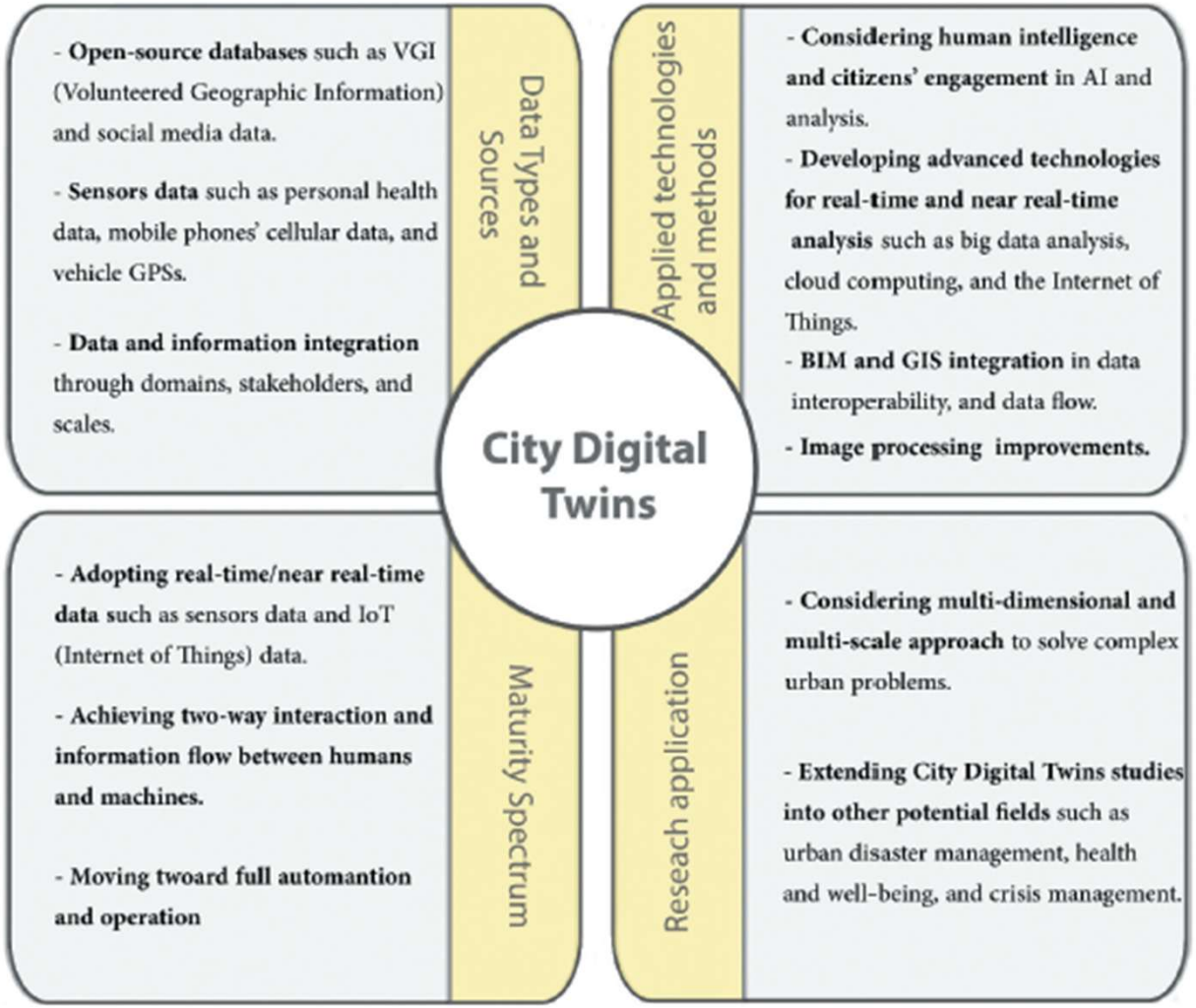
Table 1 Different understandings of "digital twin"

	Part of Understanding	Ideal Characteristics	Digital Twin Cities	Dimensions
1	a. Digital twins are 3D models b. Digital twins are copies of physical entities c. Digital twins are virtual prototypes	Multi-dimensional/multi-space-time/multiscale Dynamic/evolutive/interactive High fidelity/ Highly reliable/high-precision	Accurate Mapping	Model
2	a. Digital twins are data/big data b. Digital twins are PLM (Product Lifecycle Management) c. Digital twins are digital thread d. Digital twins are digital shadow	Total factor/all-service/ complete flow scheme/full life circle Virtual-real fusion/ multi-source fusion/heterogeneous integration Real-time update/real-time interact/real-time respond		Data
3	a. Digital twins are Physical union platform b. Digital twins are industrial Internet platforms	Bi-directional connection/interaction/driving Cross-agreement/interface/platform	Virtual-real Interaction	Connection
4	a. Digital twins are simulation b. Digital twins are virtual verification c. Digital twins are visualization	Model driven + Data driven Simulation verification/visualization/control/predict/optimize	Software Definition	Services/ Functions
5	a. Digital twins are pure digital representation or virtual bodies b. Digital twins are irrelevant to entities	models vary from object to object/data vary by feature/services and functions vary according to needs	Intelligent Feedback	Physical

Deren, L., Wenbo, Y. & Zhenfeng, S. Smart city based on digital twins. Comput.Urban Sci. 1, 4 (2021). https://doi.org/10.1007/s43762-021-00005-y 5

Figure 2. City digital twin potentials.

Shahat, E.; Hyun, C.T.; Yeom, C. City Digital Twin Potentials: A Review and Research Agenda. Sustainability 2021, 13, 3386. https://doi.org/10.3390/su13063386



Homa Masoumi, Sara Shirowzhan, Paria Eskandarpour & Christopher James Pettit (2023) City Digital Twins: their maturity level and differentiation from 3D city models, Big Earth Data, 7:1, 1-36, DOI: 10.1080/20964471.2022.2160156

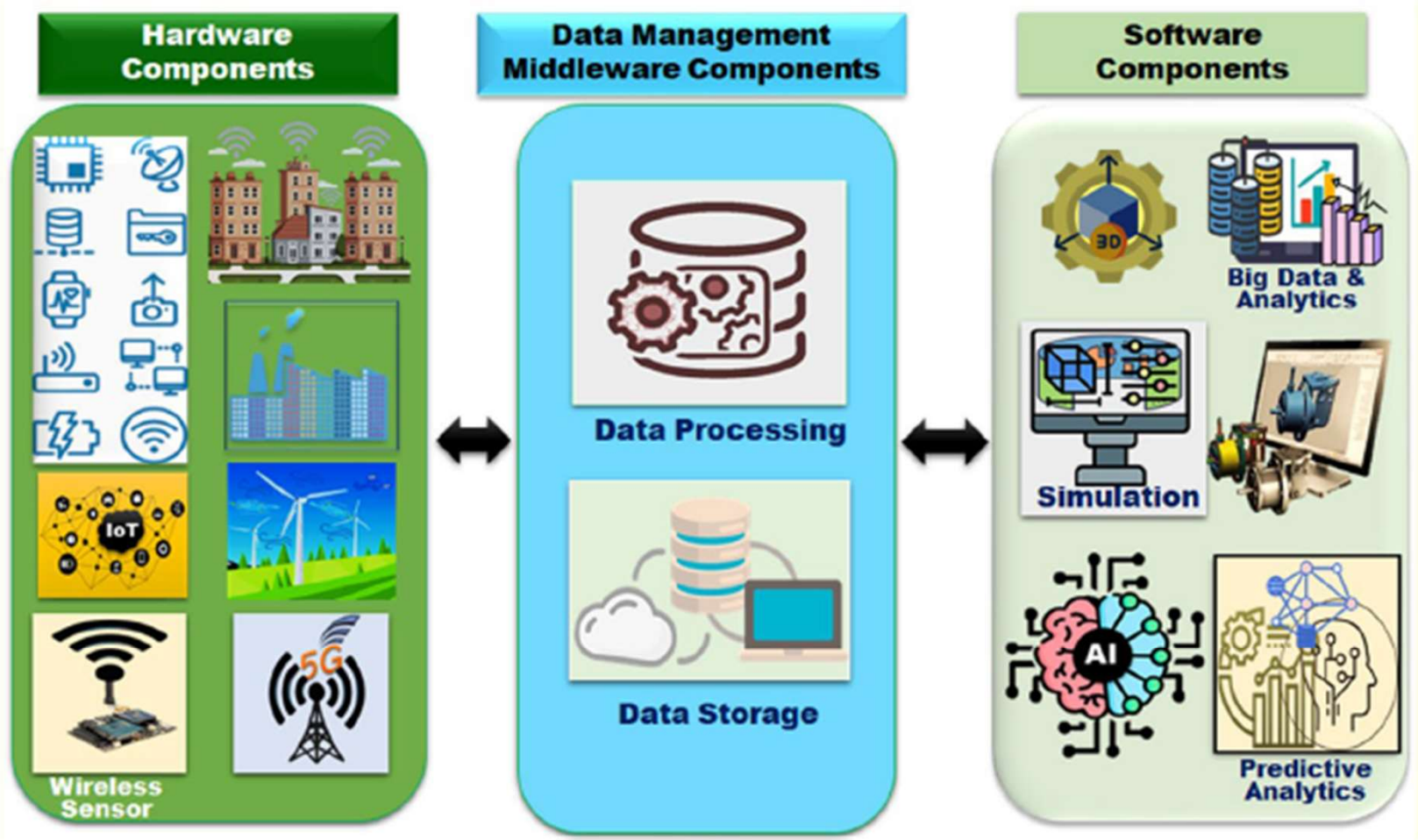
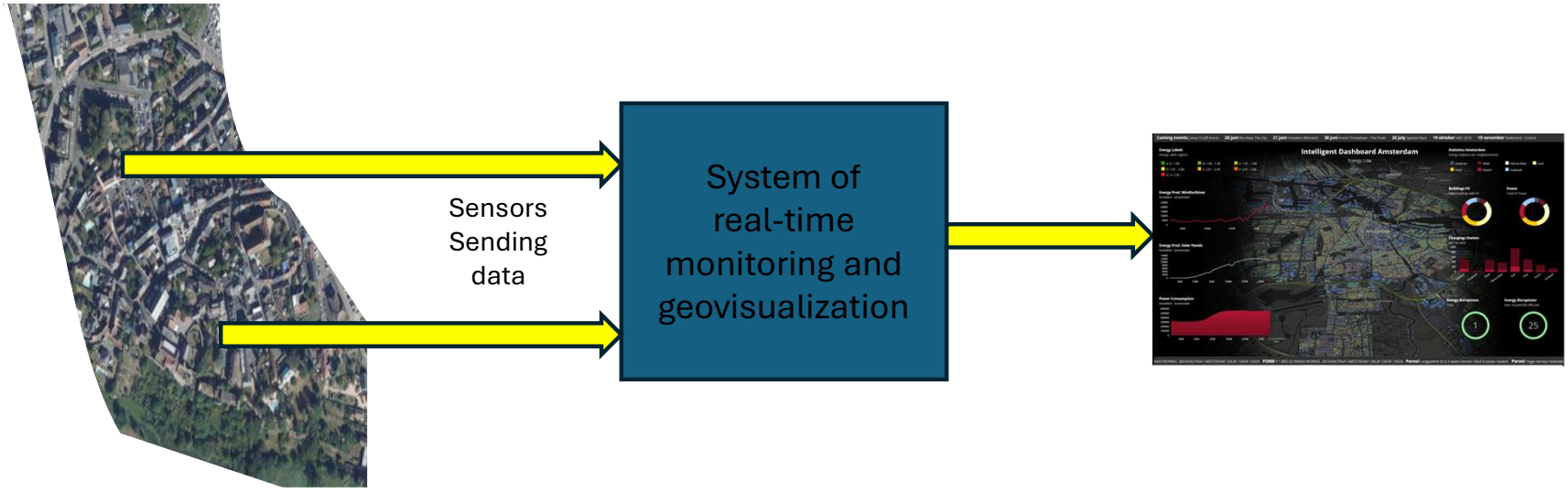


Fig. 1 Digital twin system structure. This diagram illustrates the essential components of a Digital Twin system, showcasing hardware with IoT sensors, middleware for data management, and a software analytics engine

Rasha F. El-Agamy, Hanaa A. Sayed, Arwa M. AL Akhatatneh, Mansourah Aljohani, Mostafa Elhosseini (2024) Comprehensive analysis of digital twins in smart cities: a 4200-paper bibliometric study. Artificial Intelligence Review (2024) 57:154 https://doi.org/10.1007/s10462-024-10781-8

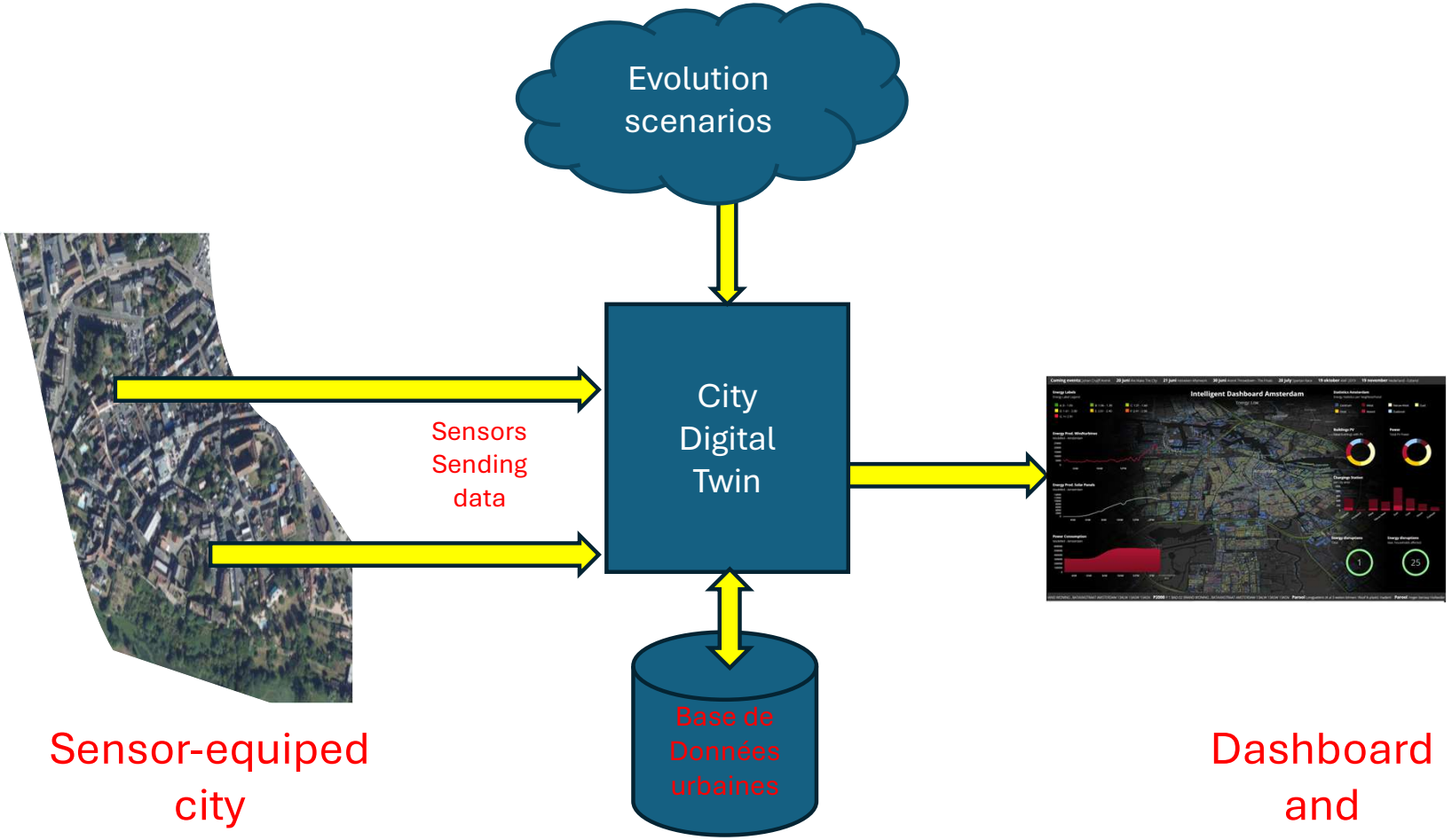
Principle of real-time monitoring and geovisualization systems

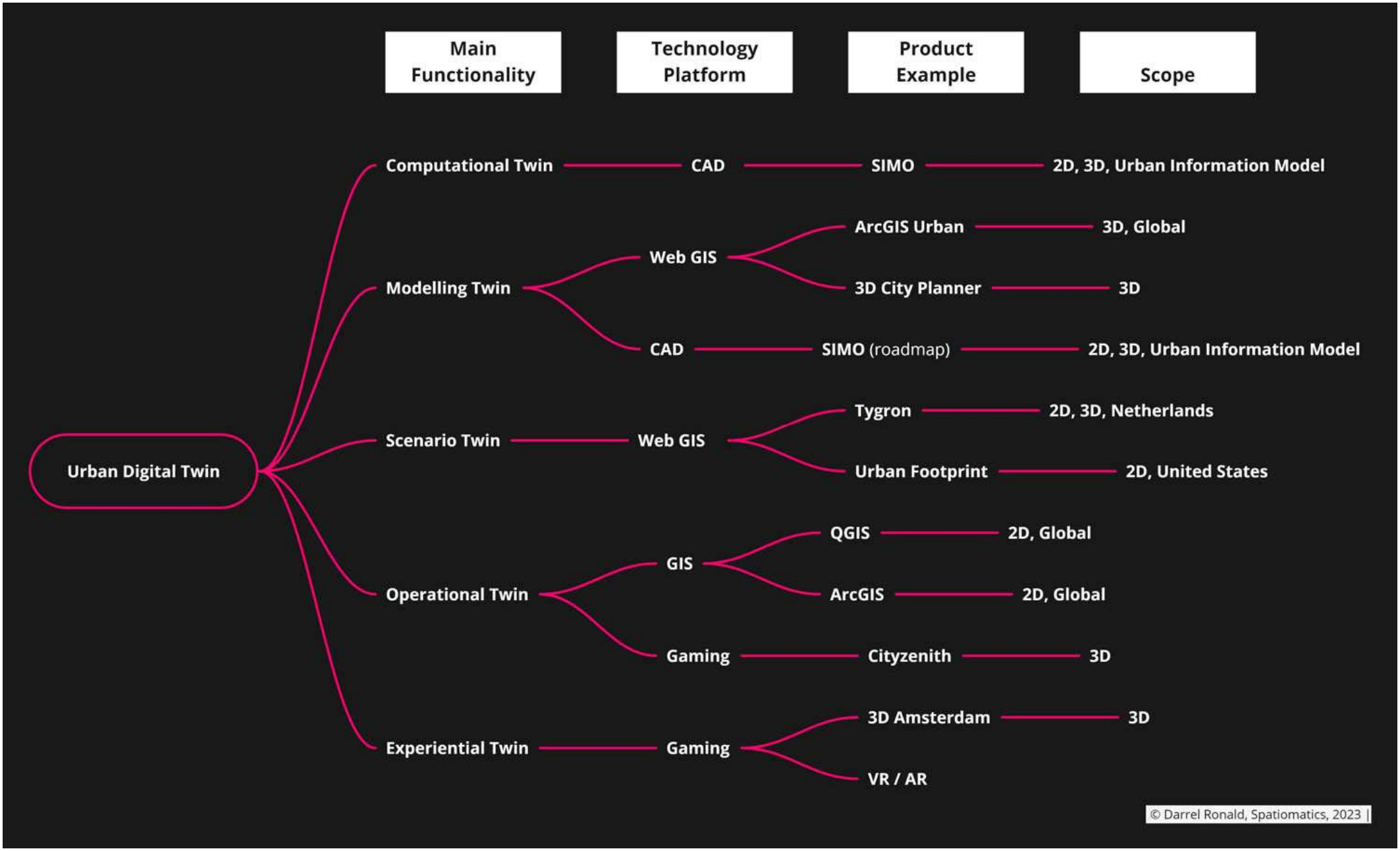


Sensor-equiped city

Real time dashboard

Principle of digital twin systems





https://aecmag.com/digital-twin/five-types-of-urban-digital-twins/

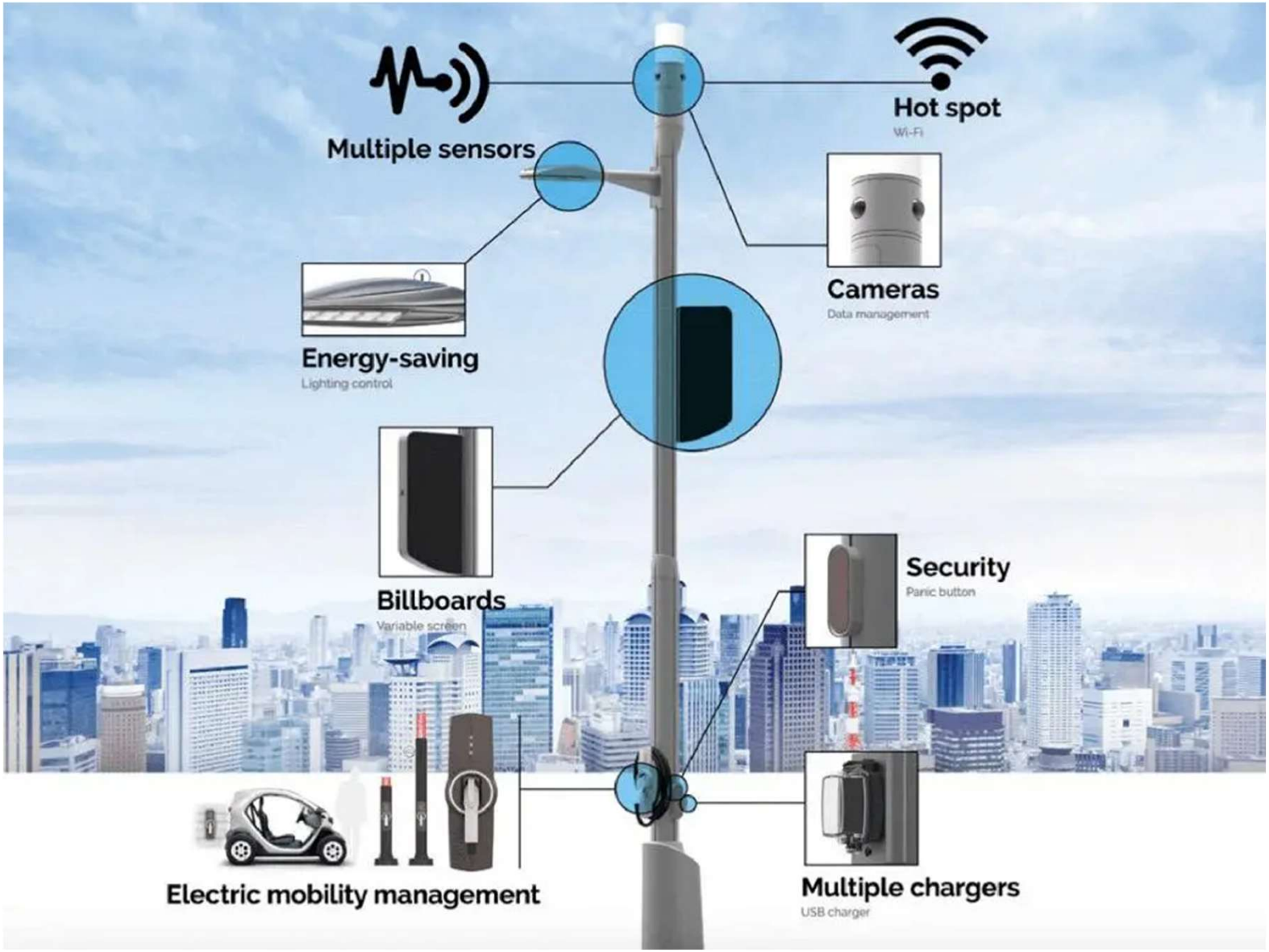
2. Technologies

- 2.1 Sensors
- 2.2 Urban IoT
- 2.3 Urban development models
- 2.4 3D Models
- 2.5 Geovisualization and dashboards
- 2.6 GeoAI
- 2.7 Digital Sovereignty

2.1 Sensors

- Depending on their function, they send signals
  - Often regularly
- Some have local storage options
- Particular type of distributed databases
- Often linked to the Internet of Things

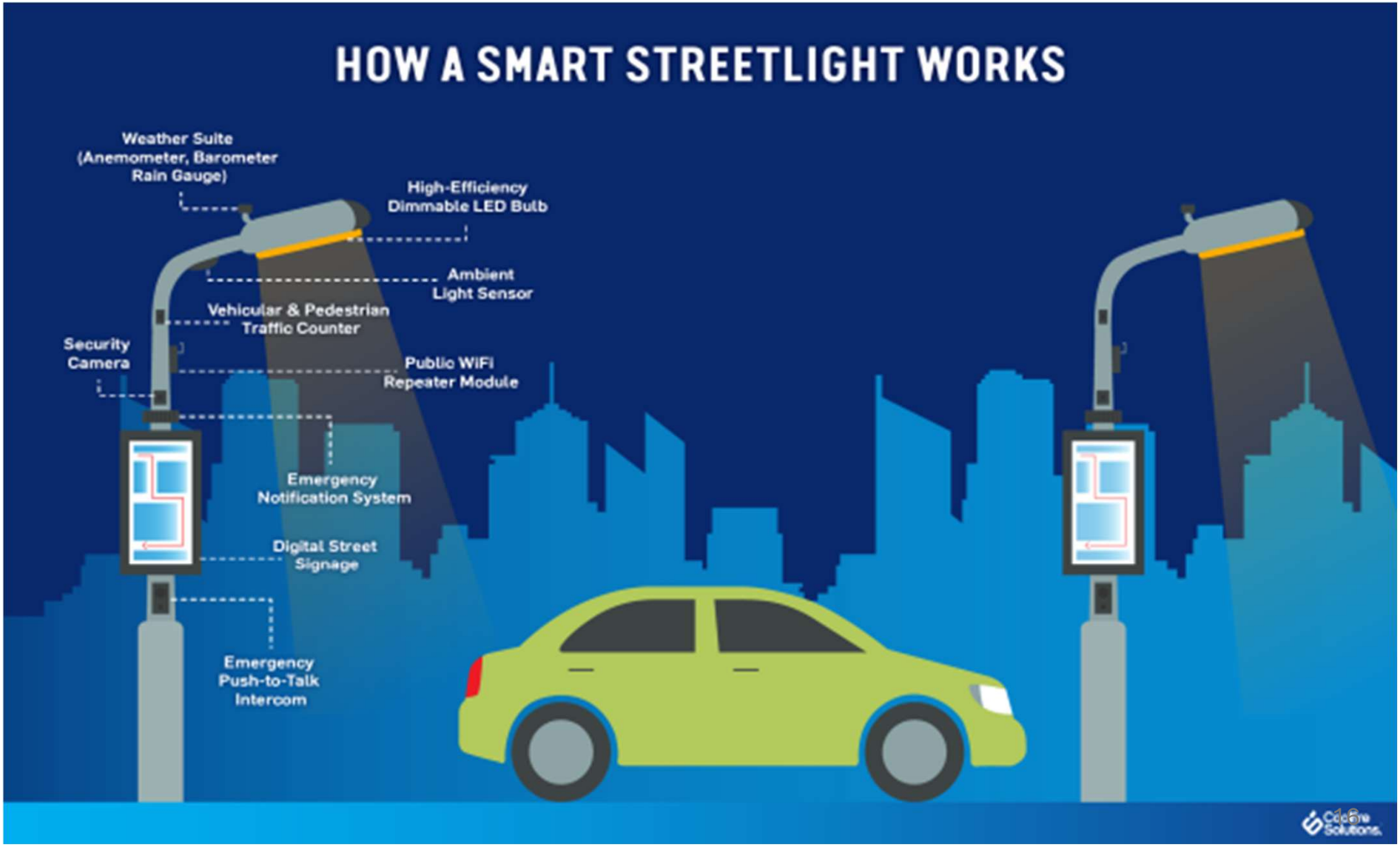
Intelligent lamppost



Intelligent streetlighting

- Principle: streetlights along the streets light up when a vehicle passes
- They send an order to the following streetlights to illuminate thus a light wave is created allowing the vehicle to move quickly.
- Need to manage multiple vehicles in both directions
- Sensors are installed in the streetlights
- They detect vehicles and their speed
- They inform the following streetlights according to the vehicle speed

Intelligent streetlighting



2.2 – Urban IoT

- Common street furniture
- Fixed urban connected objects
- Connected mobile urban objects

Common street furniture

- Street furniture includes various equipment installed in public spaces to serve and embellish the daily life of residents.
  - Benches
  - Streetlights
  - Garbage cans
  - Bus shelters
  - Decorations on the squares (sculpture, etc.)
  - Charging stations for electric vehicles road signs
  - etc.

Common street furniture

IoT in urban areas

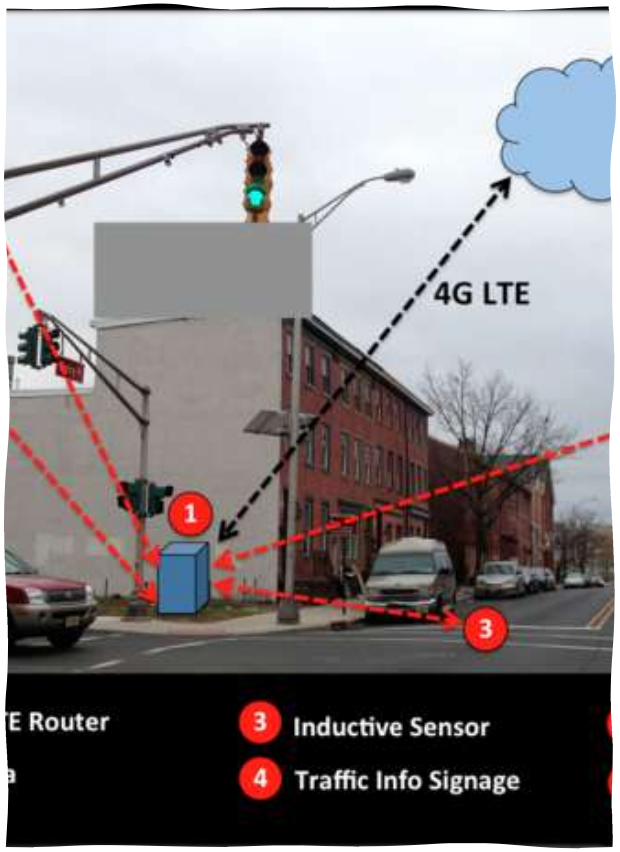
- Some objects can be connected
- Need to organize a specialized fiber network
- Sometimes linked to moving objects

Connected benches

Variable display panels

Connected Trash Containes

Crossroad lights



Videosurveillance

Connected mobile objects

- Public vehicles with specific missions
- Embedded systems
  - Equipped with sensors
  - Positioned by GPS
  - Linked to various information systems (including GIS)
  - Often connected to fixed furniture

Bus and shelters

SMART CITY TECHNOLOGIES

Centralized Control and Management via Web Based Software

- Visual Programming
- 24/7 Location and Speed Information
- Accident Damage Detection
- Route Control

4.5G/3G/GPRS

SERVER

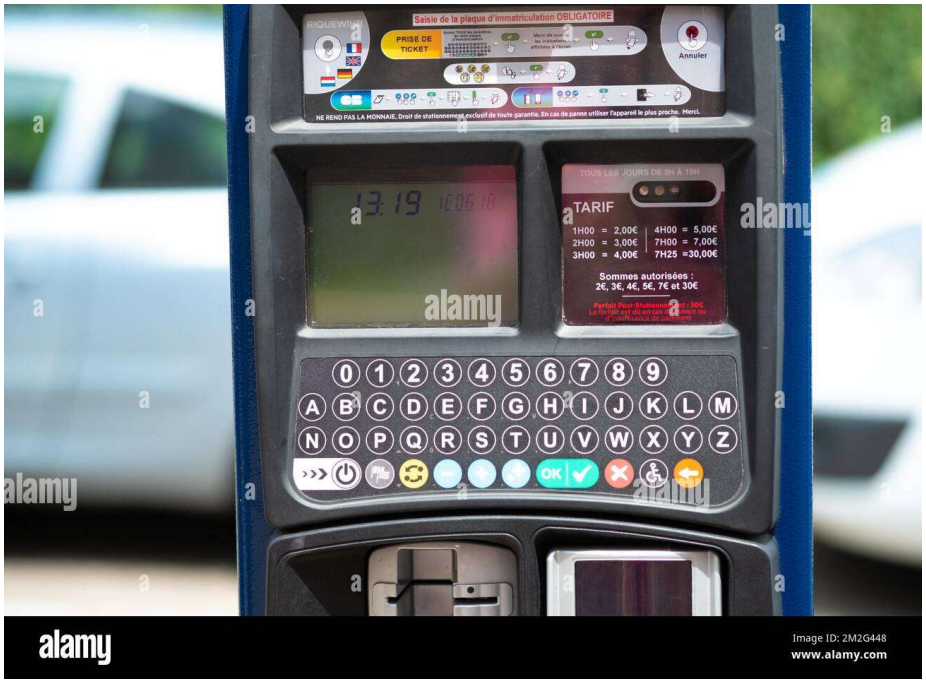
SQL

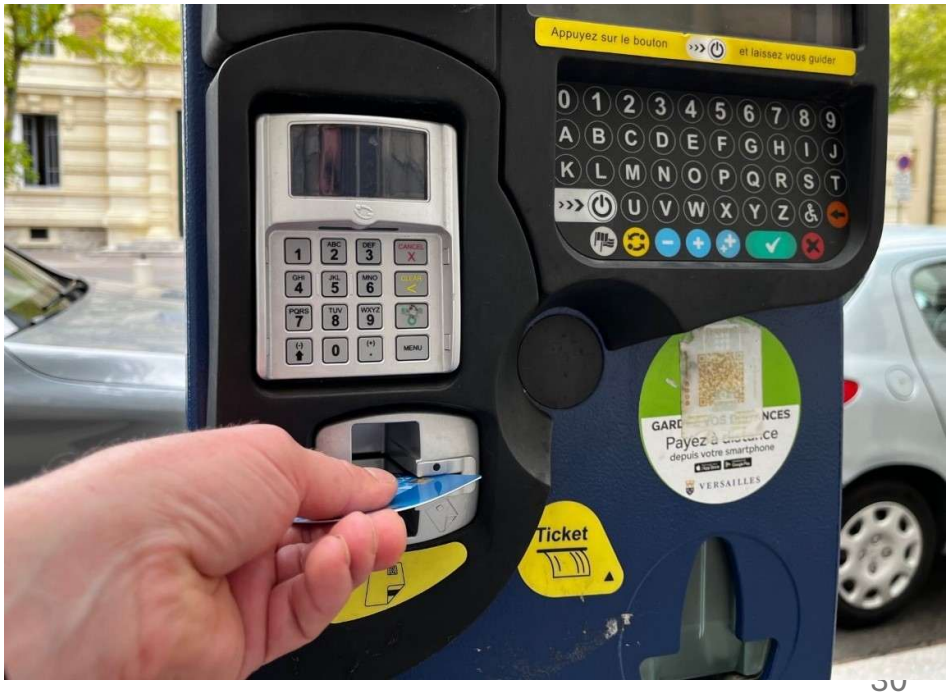
- Vehicle Tracking and Management
- Reporting

Bus Shelters

- Features
  - Waiting time for the next bus/tram
  - Viewing the schedules
  - Problems with connections
- Prior
  - Each bus is connected - on-board equipment
  - GPS positioning
  - Monitoring centre
  - Awareness of the positioning of all buses

Connected parking meter





Automatic reading of licence plates

Automatic reading of licence plates

- Automatic scanning of parked vehicles
- Verification
  - Whether vehicle stolen
  - Payment for parking
  - Compulsory insurance
  - Technical inspection
  - Etc.

Connected Urban Furniture

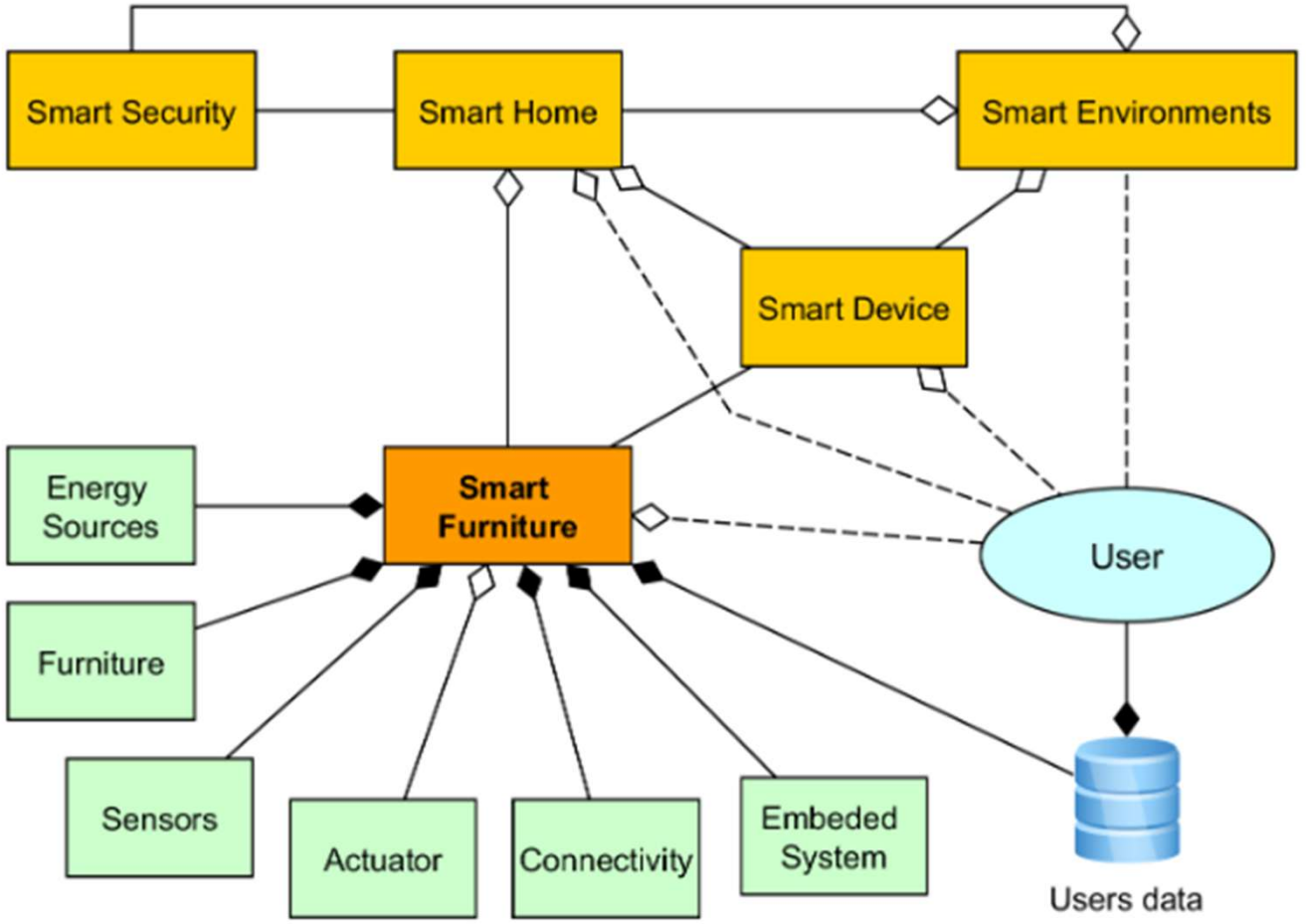


FIGURE 5. Role and position of Smart Furniture within the Smart City umbrella according to the UML design.

Ondrej Krejcar et al. « Smart Furniture as a Component of a Smart City - Definition Based on Key Technologies Specification »

Connected street furniture

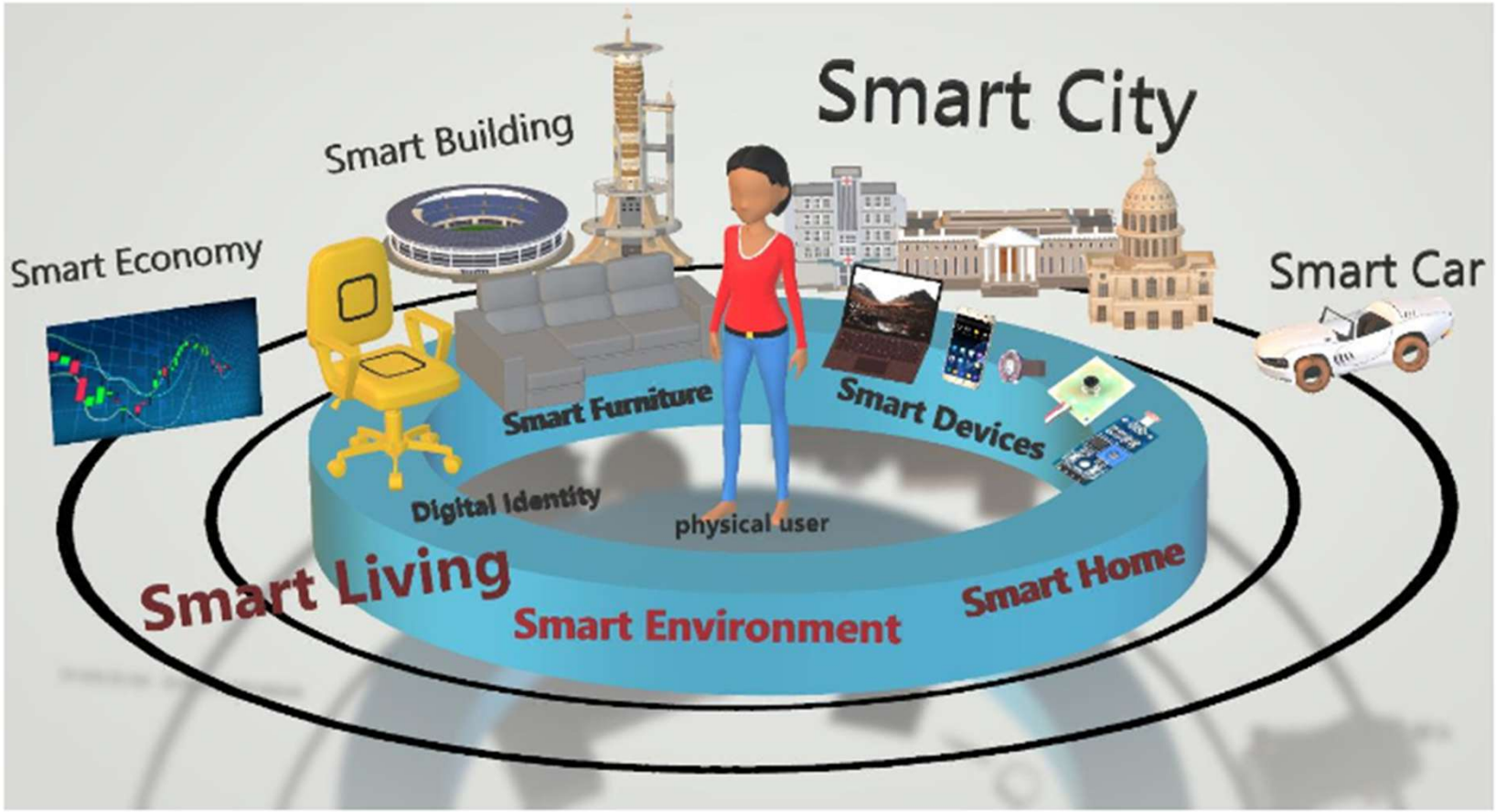


FIGURE 7. A user in a digital world of smart concepts (living, furniture, devices, home, environment, car, building, city, economy, etc.).

Ondrej Krejcar et al. « Smart Furniture as a Component of a Smart City - Definition Based on Key Technologies Specification »

2.3 Urban development models

- Very fashionable in the 70s-80s
- Winter for 30 years
- Back on the critical path of research
- Two types
  - **Static** (to understand and analyze the static relationships between urban components)
  - $\vec{V}(t) = f(a, b, c,)$
  - **Dynamics** (to understand and analyse developments)
  - $\vec{V}(t+1) = f(\vec{V}(t), e(t), d(t))$

Example: home-work commuting

- Commuting T_{ij}
- Model by A.G. Wilson
- City divided into n zones
- Knowing (where C_{ij} is the interzone distance)
  - $\sum_i^n T_{ij} = O_i \quad \sum_j^n T_{ij} = D_j$
  - $\sum_{ij}^n T_{ij} C_{ij} = C$
- It is enough to maximize the entropy under constraints
- $H = -\sum_{ij}^n T_{ij} ln T_{ij}$

Static example (cont'd)

- The Lagrangian is written
- $L = -\sum_{ij}^{n} T_{ij} ln T_{ij+} \sum_{j}^{n} \alpha_j \left(\sum_{i}^{n} T_{ij} - D_j\right)+$
  $\sum_{i}^{n} \delta_i \left(\sum_{j}^{n} T_{ij} - O_i\right) + \beta\left(\sum_{ij}^{n} T_{ij} C_{ij} - C\right)$

- To obtain the optimum, we put to zero he partial derivative of the Lagrangian
- $\frac{\partial L}{\partial T_{ij}} = 0$
- The solution is:
- $T_{ij} = A_i B_j \exp(-\beta c_{ij})$

About C_{ij}

- Distance interzone at bird's eye view
- Distance on the road network
- Distance taking into account track capacity

- If new route, change the concerned C_{ij}
- And make the calculations again

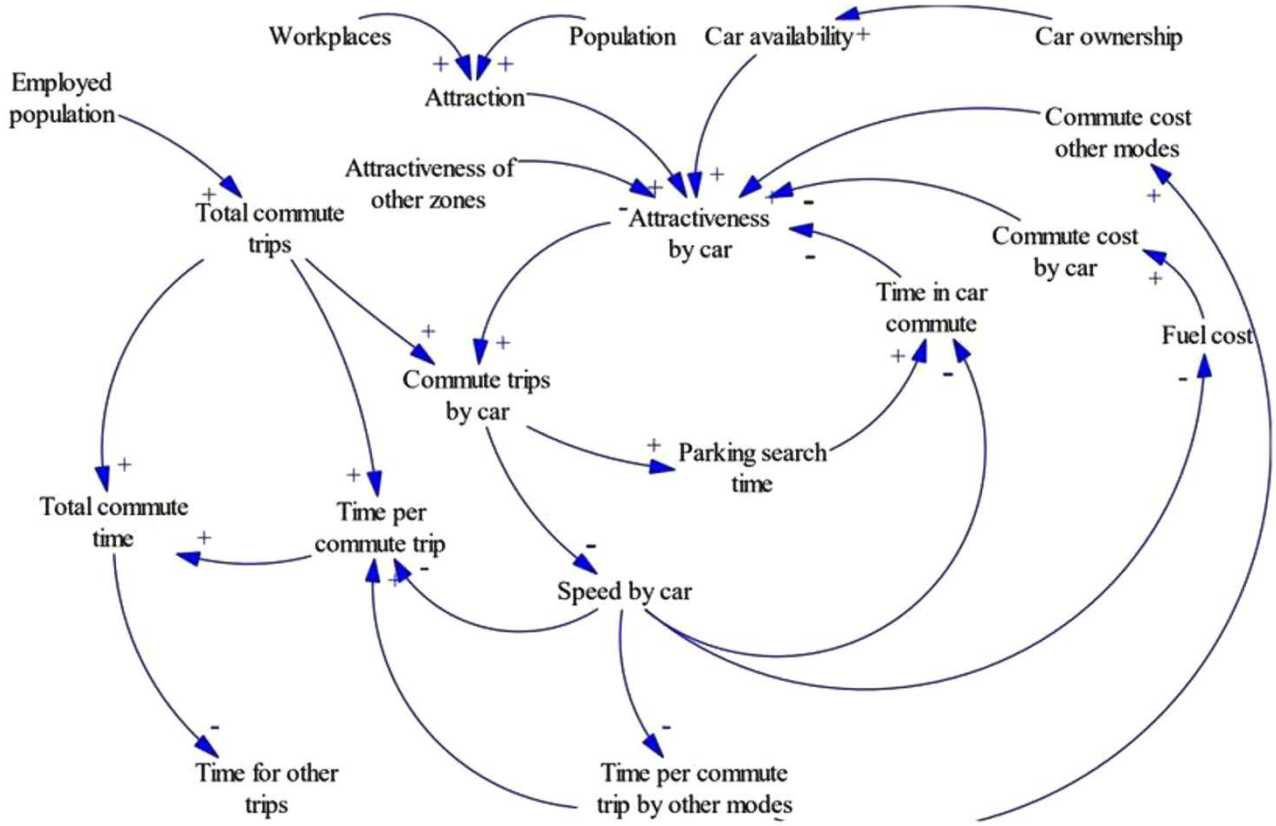
Dynamic model example

- Population growth in an area
- Vector $\overrightarrow{P(t)}$ population by age and sex

- Next year:
- $\overrightarrow{P(t+1)} = A\vec{P}\,(t) + \overrightarrow{E(t)} + \overrightarrow{S(t)}$

- With
  - $\overrightarrow{E(t)}$ are inputs (new comers)
  - $\overrightarrow{S(t)}$ are outputs (Those who left)

Example of interactions

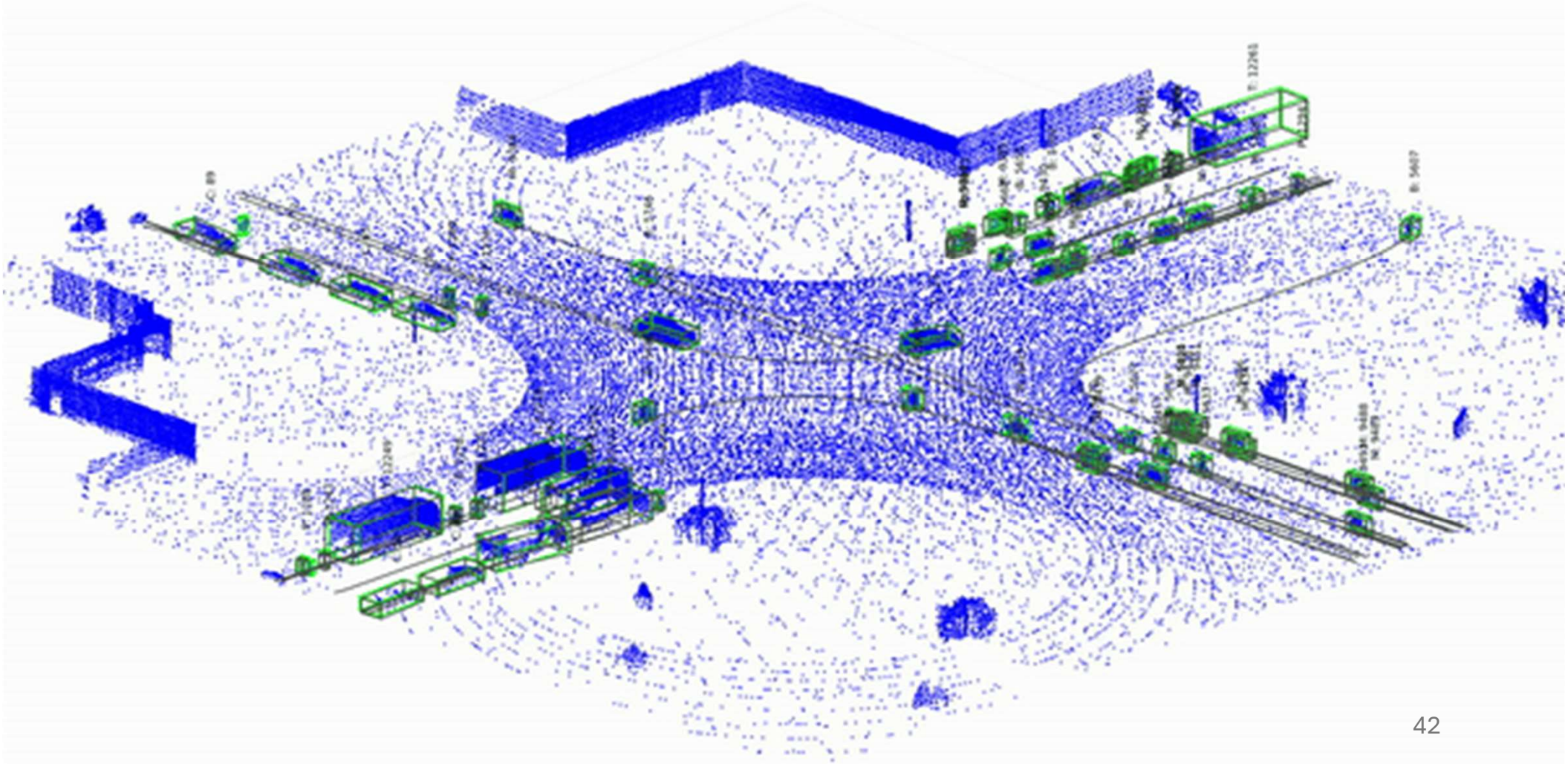


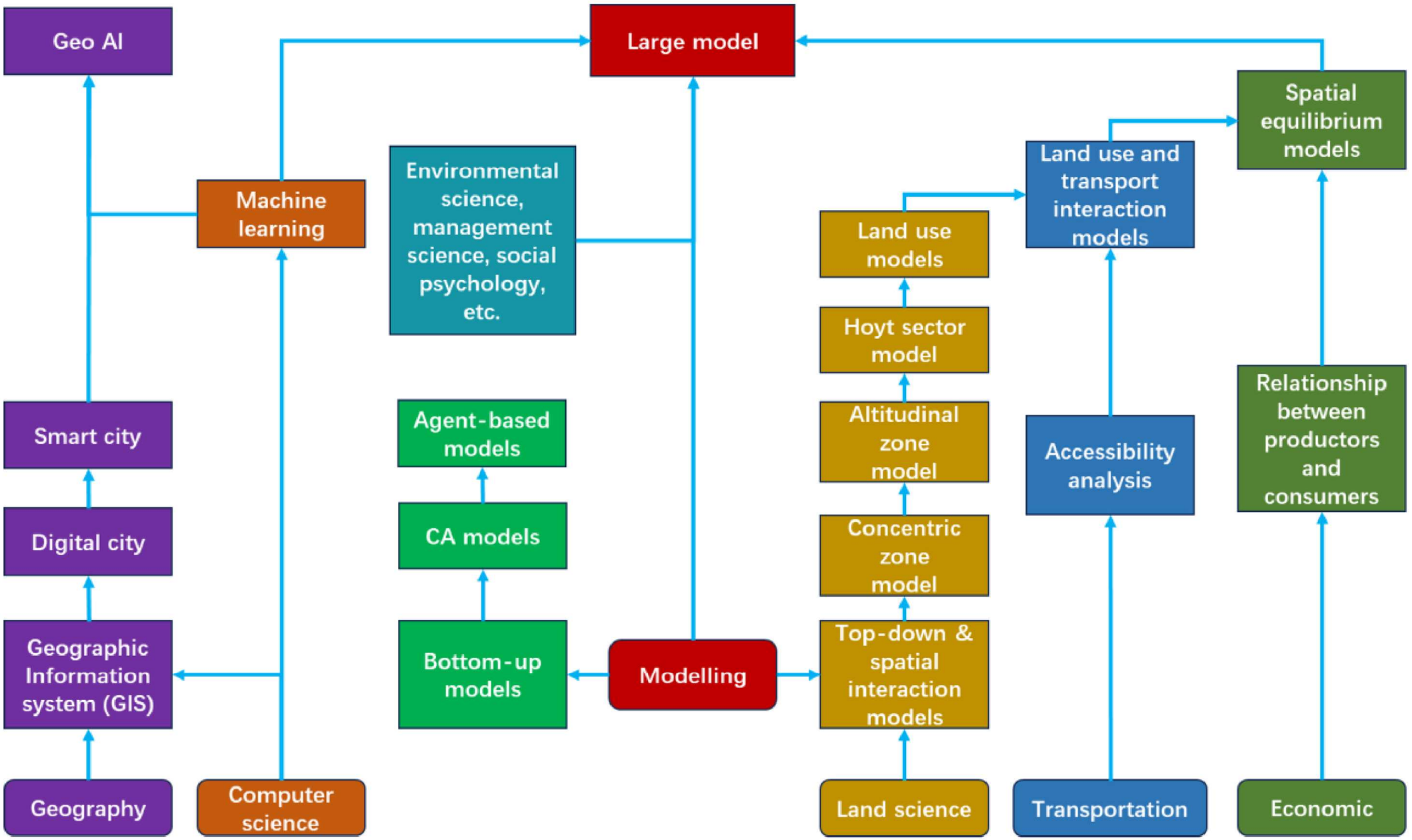
Jing Wang, Gengze Li, Huapu Lu, Zhouhao Wu (2024) Urban models: Progress and perspective Sustainable Futures 7 (2024) https://doi.org/10.1016/j.sftr.2024.100181

What-if models

- Model calibration based on real data
- Presentation of development scenarios
- Compare the results of various alternatives

Example of simulation





Jing Wang, Gengze Li, Huapu Lu, Zhouhao Wu (2024) Urban models: Progress and perspective Sustainable Futures 7 (2024) https://doi.org/10.1016/j.sftr.2024.100181

2.4 3D Models

- For some authors, 3D representation is the heart of digital twins
- Uses
  - Overall vision of the city
  - Visualization of urban projects
  - Visualization of risk consequences
  - Integration of new buildings
  - Simulation of wind effects
  - Location of photovoltaic panels
  - Location of rooftop gardens
  - Etc.

Example: Amsterdam

https://aecmag.com/digital-twin/five-types-of-urban-digital-twins/

Example: Singapour

https://eandt.theiet.org/2019/01/17/digital-urban-planning-twins-help-make-sense-smart-cities

3D of the underground

- Metrolines
- Engineering networks
- Subsoil car parks
- Underground City (Montreal)
- Underground galleries (catacomb, etc.)
- Geology
- Etc.

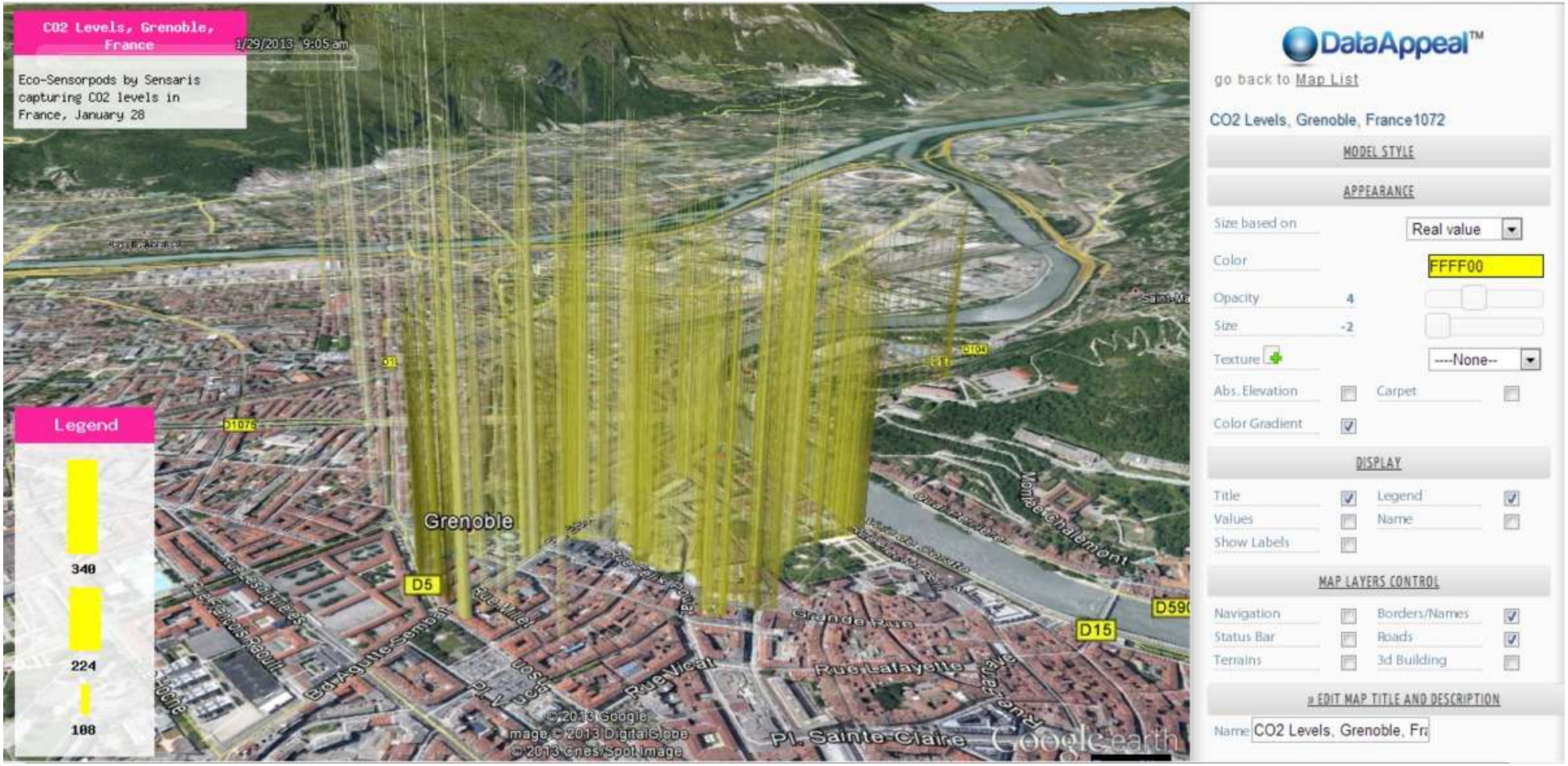
2.5 Geovisualization and dashboards

- Global visualization

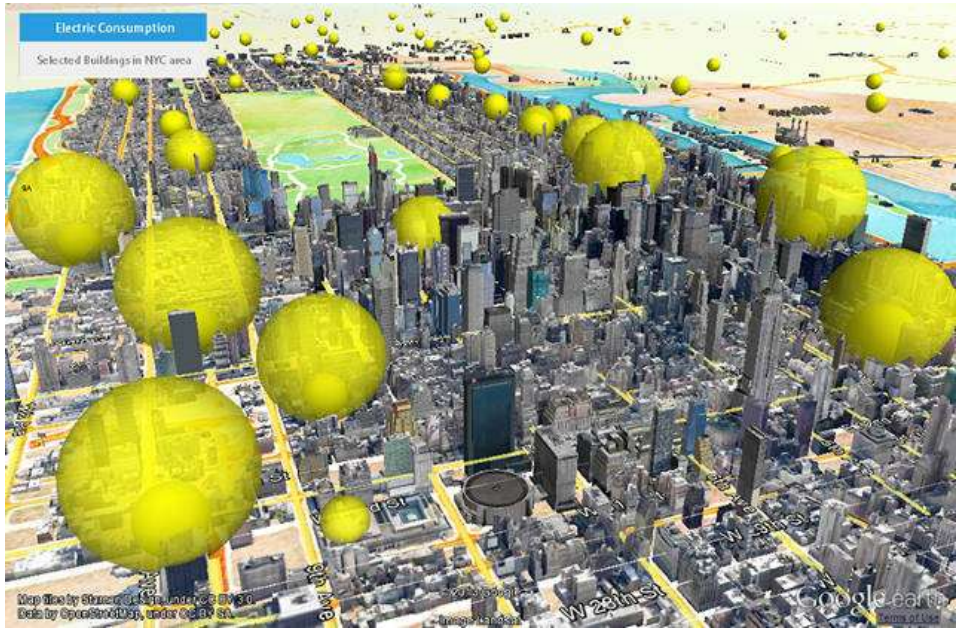
- Ben Schneiderman's Mantra
- "*Overview, zoom and filter, details-on-demand*"

- Geovisualisation
- Chorems
- Data landscape (datascape by Nadia Amoroso)
- Dashboards
- https://placesjournal.org/article/mission-control-a-history-of-the-urban-dashboard/?cn-reloaded=1

Air pollution



https://www.nadiaamoroso.com/creative-cartography

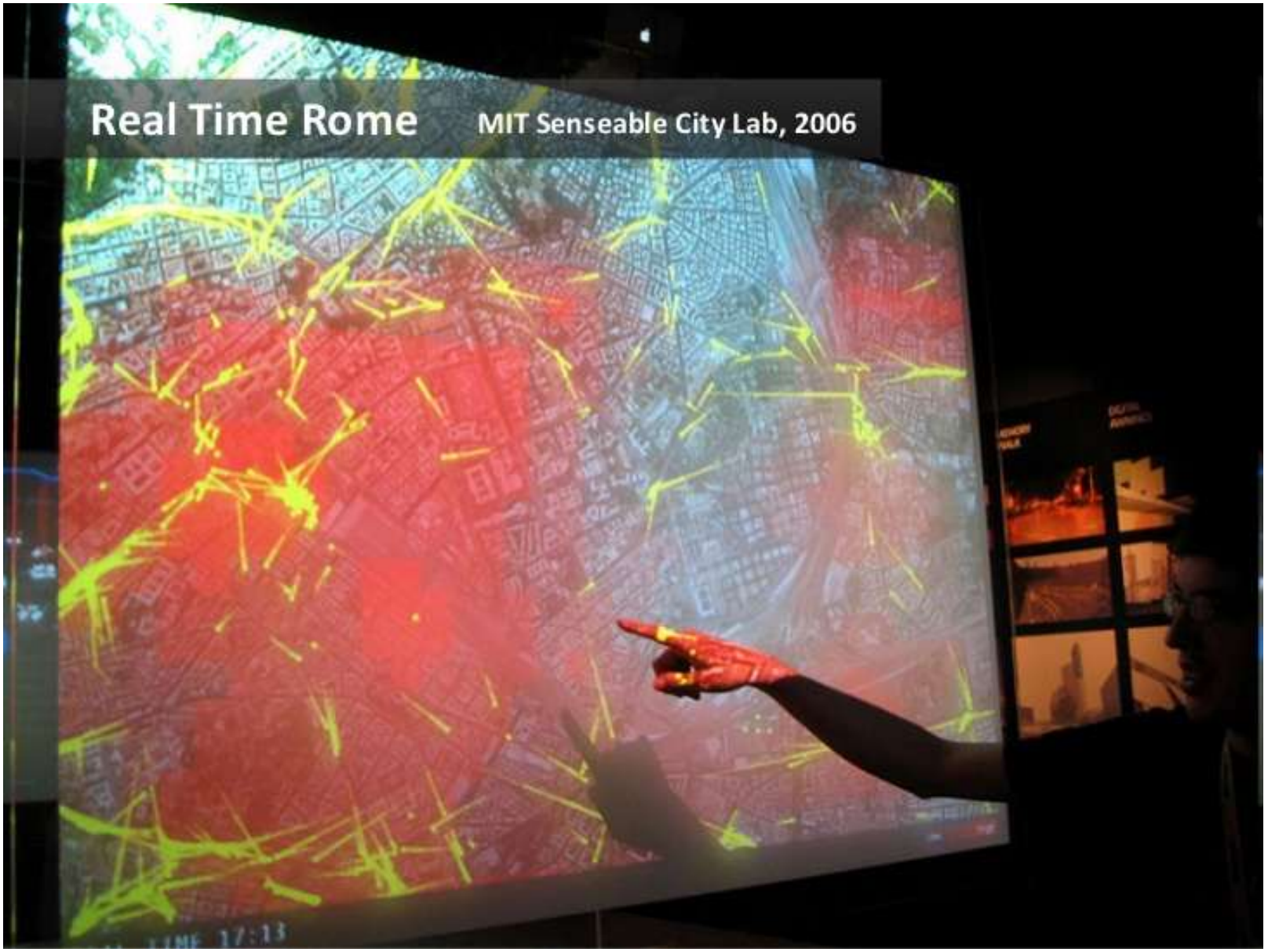

Electric Consumption
Selected Buildings in NYC area
W 28th St
Google earth


Burlingame Island
Laughton Island
Image © 2012 TerraMetrics
Google earth

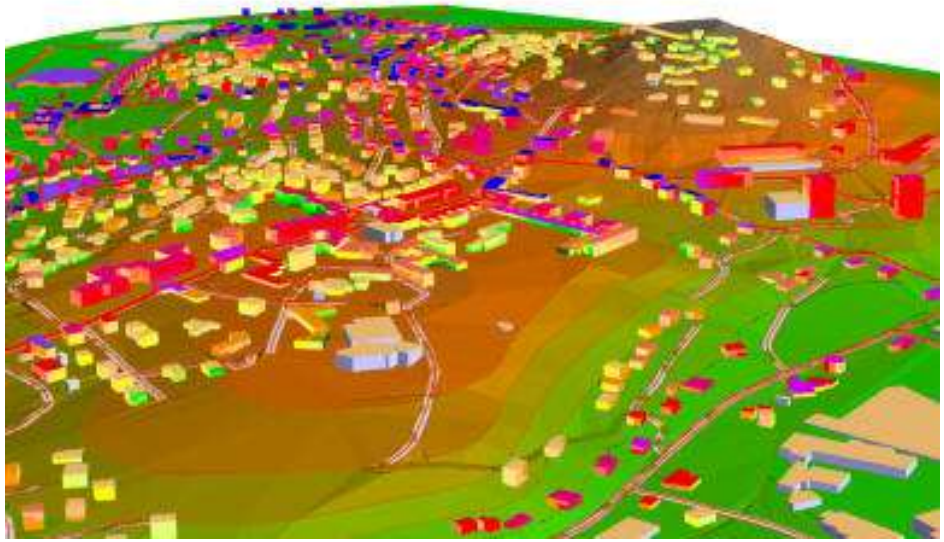

sensorpod data
Grenoble
D5
© 2013 Cnes/Spot Image
© 2013 Google
Google earth

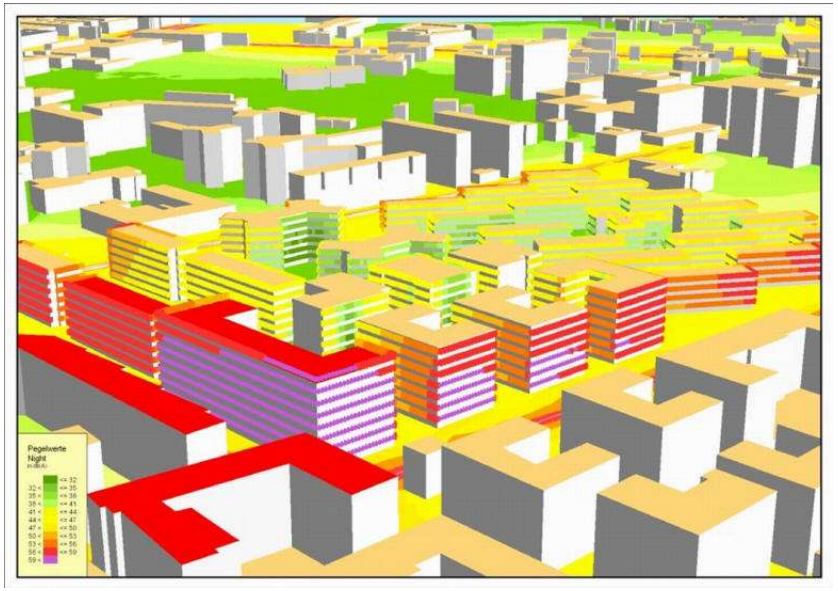

Oakland crimespotting
Stamen, 2009
CRIME TYPE
Show All | Hide All
Aggravated Assault
Murder
Robbery
Simple Assault
Disturbing the Peace
Narcotics
Alcohol
Prostitution
Theft
Vehicle Theft
Vandalism
Burglary
Arson
TIME OF DAY
Show All | Hide All
Light | Dark [nearest hour]
Commute | Nightlife
Day | Night | Swing Shift
NOON
AM
PM
MIDNIGHT
DATE
Past Week
Mar
2010
MAR 8 2010
MAR 15 2010
MAR 22 2010
Lakeside Park
19th St Oakland BART
Lake Merritt BART Station
Map tiles © CloudMade, Map data CC-BY-SA OpenStreetMap.org

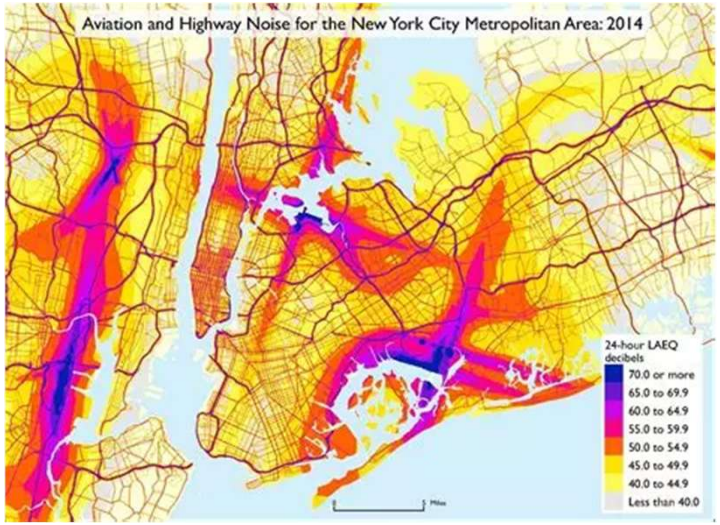
Virtual Singapore. Solar Panel Production.
Source: National Research Foundation,
Prime Minister's Office Singapore.


Real Time Rome
MIT Senseable City Lab, 2006

Examples of noise visualization







Example: Zurich

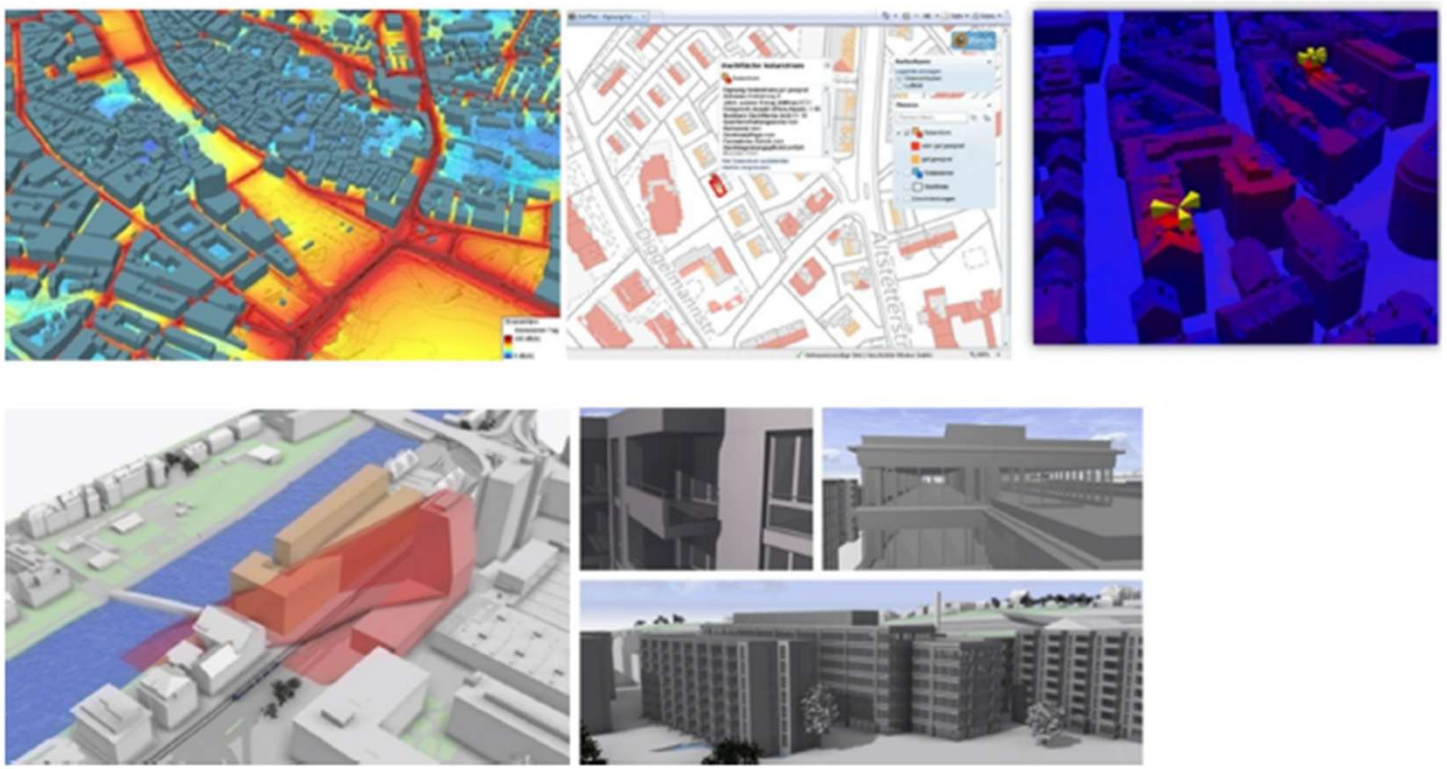


Fig. 7 Established applications: noise (upper left), air pollution (upper centre), mobile phone radiation (upper right), solar potential (lower left), visualization of construction projects (lower right) (source: City of Zurich)

Gerhard Schrotter · Christian Hürzeler (2020) The Digital Twin of the City of Zurich for Urban Planning. PFG (2020) 88:99–112
https://doi.org/10.1007/s41064-020-00092-2

https://www.sciencedirect.com/science/article/pii/S1071581920300331#:~:text=City%20dashboards%20use%20a%20suite%20of%20visual%20analytics%20-%20dynamic

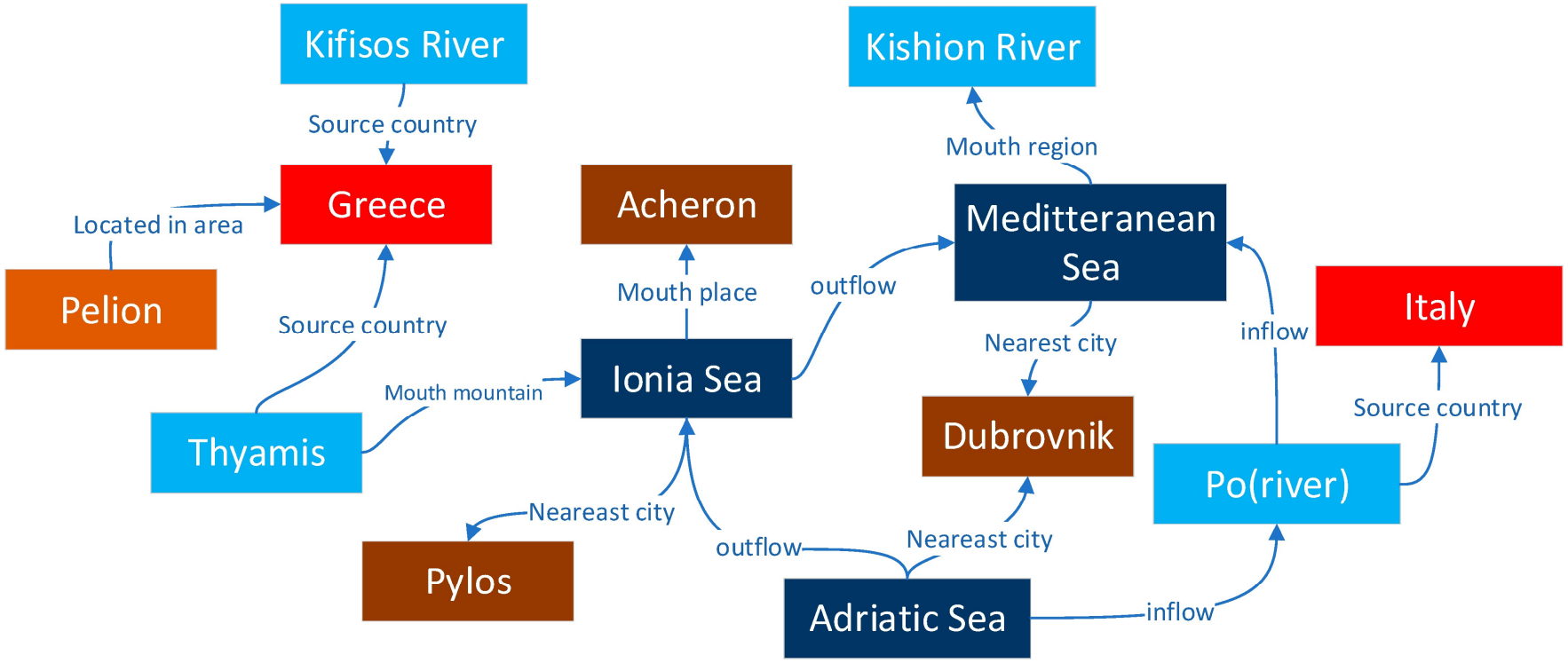
2.6 GeoAI

- Little AI work for urban planning
- Rules-based systems
- Geographic knowledge graphs (GeoKG)
- Deep learning
- Generative AI;
- Large language models
- LLM ↔ GeoKG ?

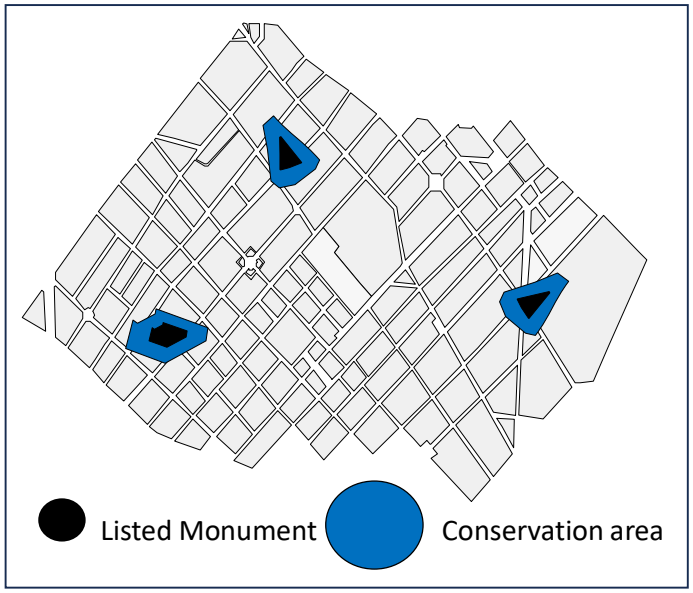
Definition of geographic knowledge

- Knowledge = information that can be used to solve a problem or facilitate decision-making
- For a territory, geographic knowledge is information potentially useful for: explain
  - Manage
  - Monitor
  - simulating the future
  - and plan

Example of semantic networks



Example of rules around historical monuments



$$\forall\ T \in Earth, \forall\ B \in PROJECT, \exists\ M \in Geo\text{-}Objects,$$

$$\text{Type}\ (B) = \text{“Building”},$$

$$\text{Type}\ (M) = \text{“Listed\_Monument”},$$

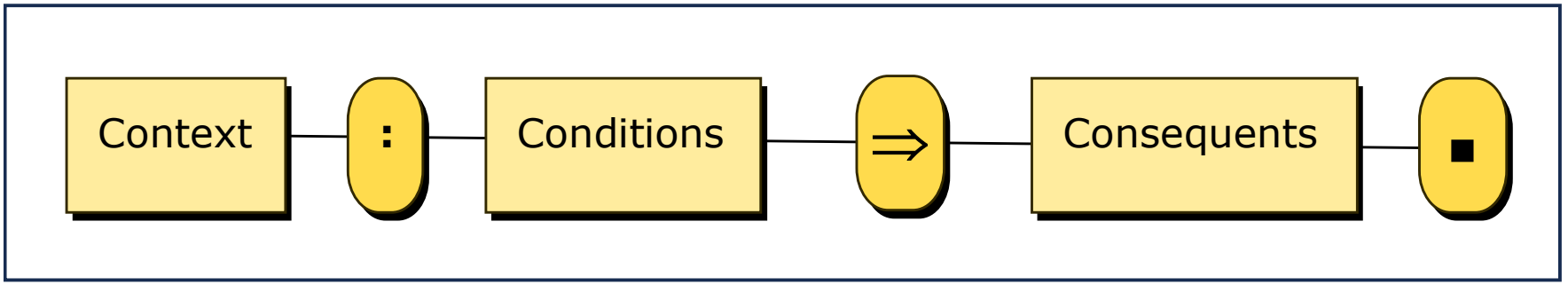
$$\vDash Inside\ (Geom\ (B), T), Inside\ (Geom\ (M), T)$$

$$:$$

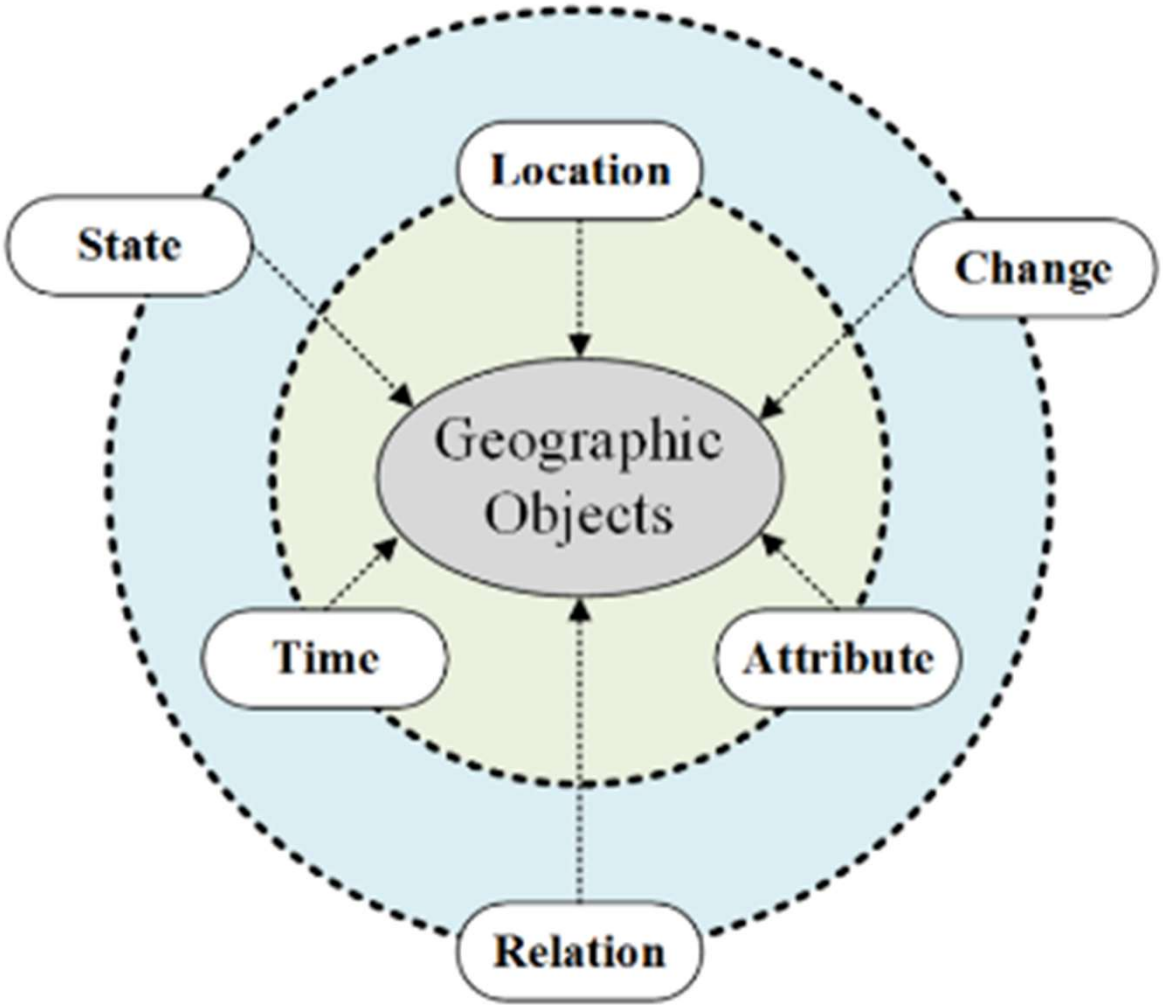
$$Disjoint\ (\text{Geom}(B), Union\ (Buffer\ (Geom\ (M), 100)))$$

$$\Rightarrow$$

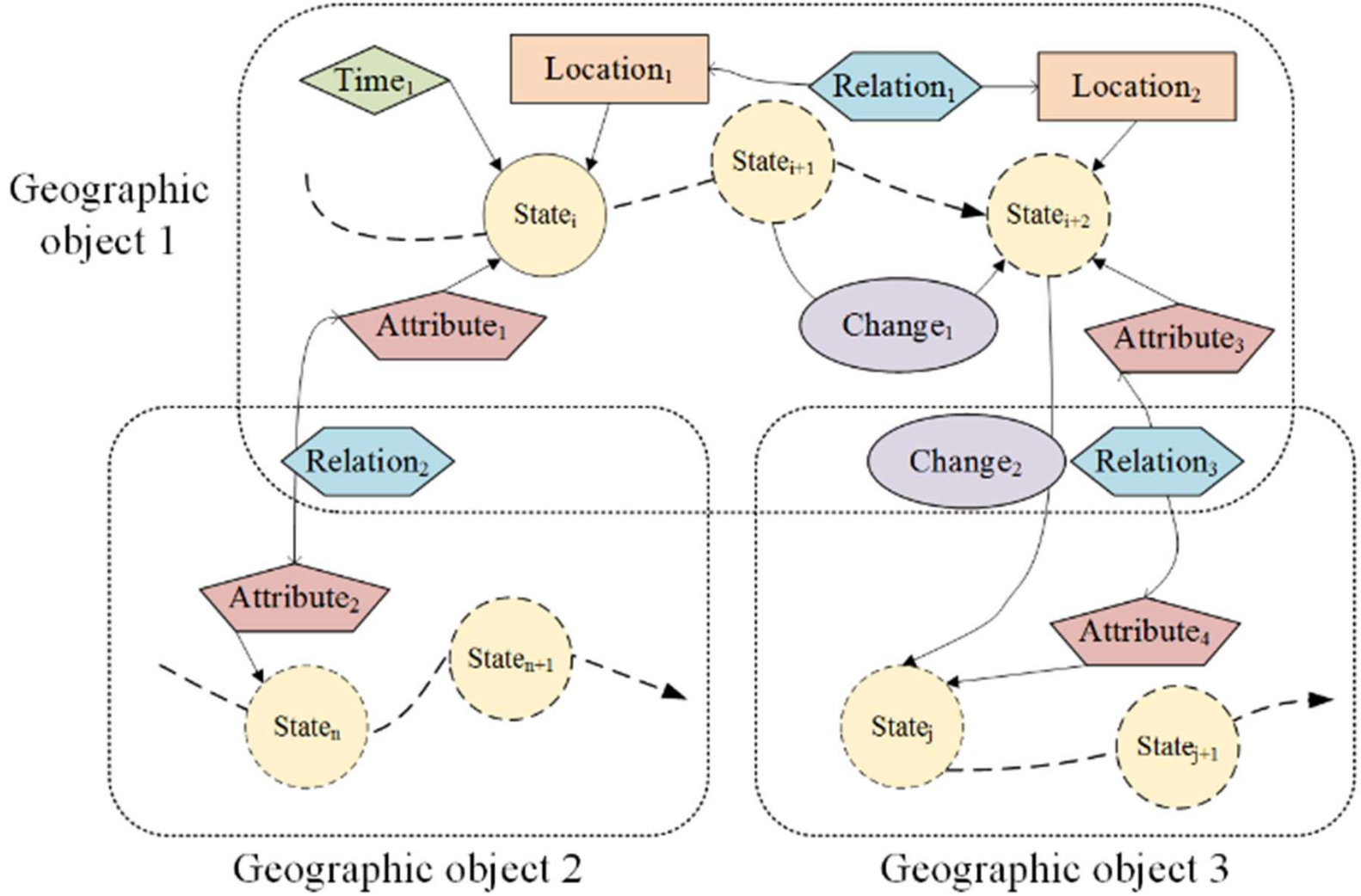
$$State\ (B) = \text{“LM\_Approved”}$$



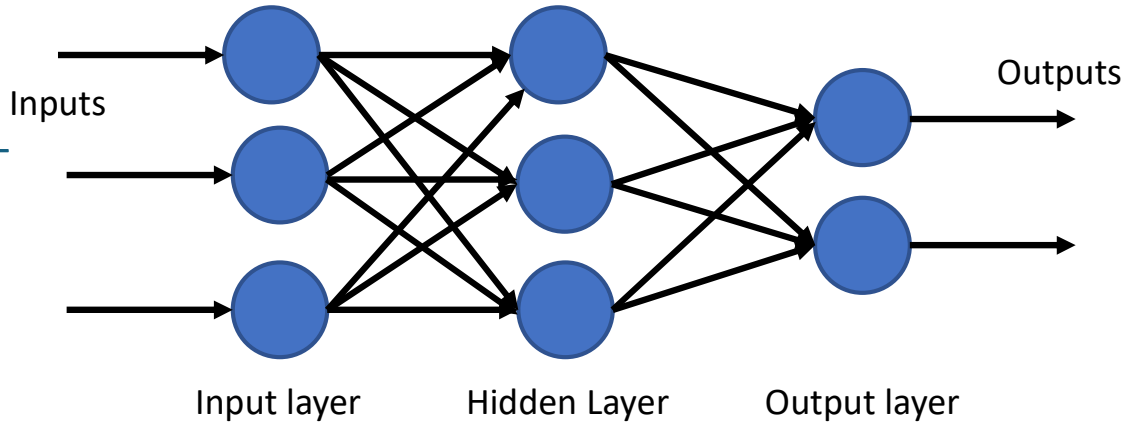
Geo-KG (Shu Wang 2019)



Large interactions between urban objects with Geo-KG (Shu Wang 2019)

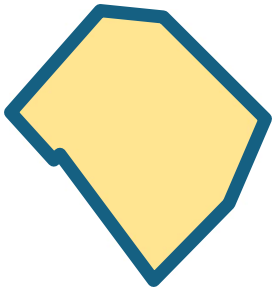


Learning
Ex: Mass plan



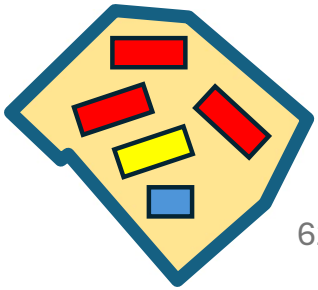
Request input

- Shape of the plot of land
- Number of buildings
- Other services



Response to the request

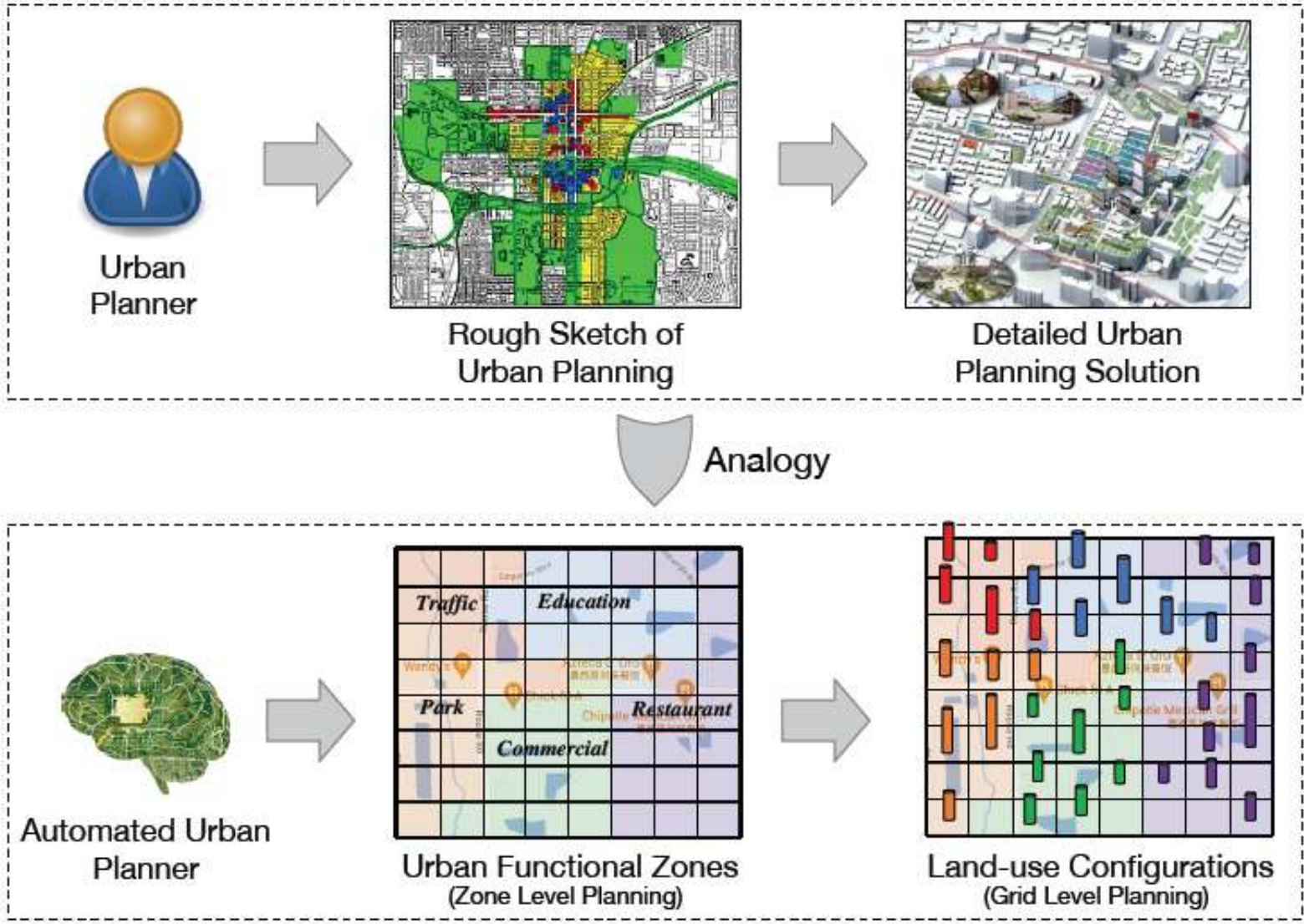
- Proposal for several mass plan



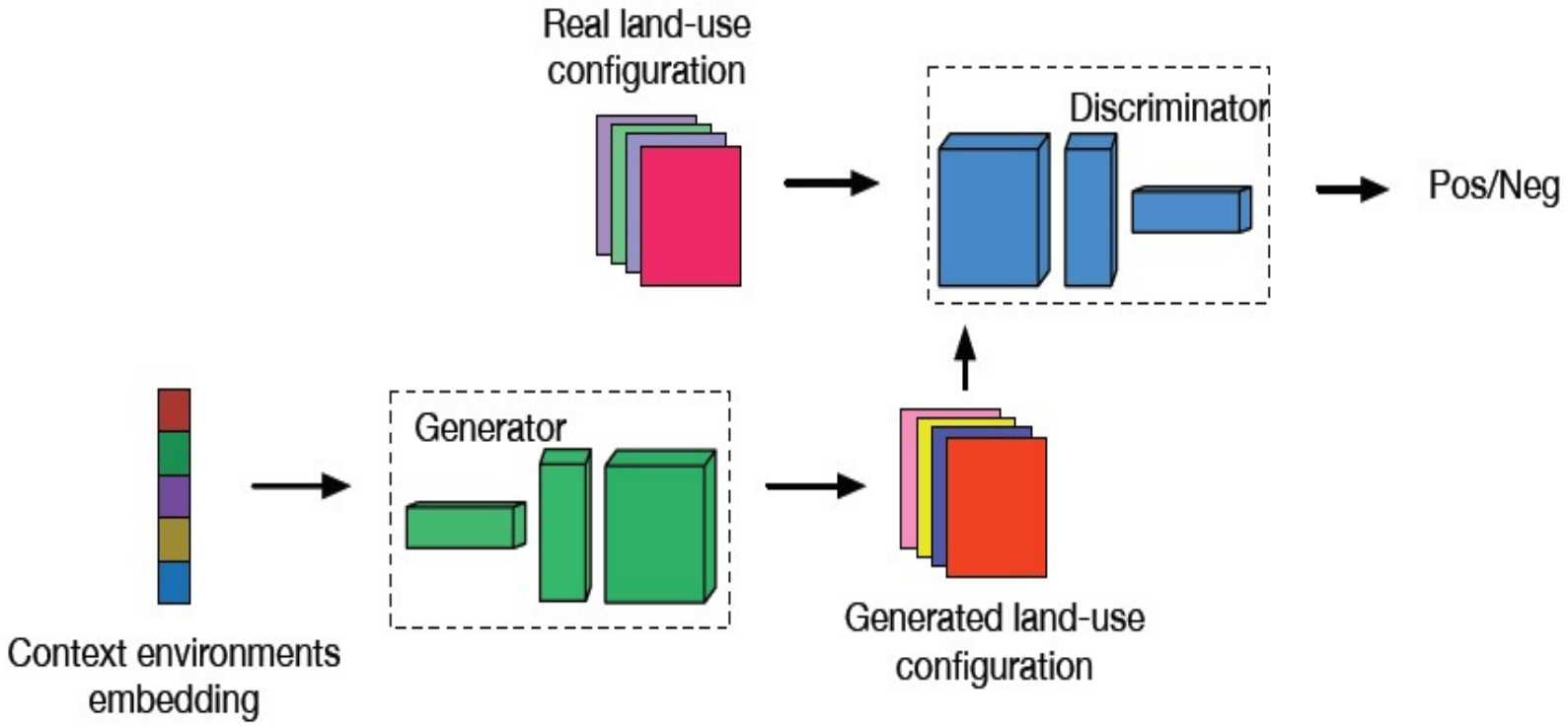
Foundation Models

- Chatbots based on large models
  - Large sets of training texts
  - Token (part of a word) (N-gram)
  - Statistics between tokens
  - Well-suited for text, images etc.
- What about space?
  - Raster: aerial photos and satellite images
  - Vector: 2D and 3D

Approach from Dongjie Wang et al. (2023)



Automatic land use configuration planner



- Wang D., Fu Y., Wang P., Huang B., & Lu C.T. (2020). Reimagining City Configuration: Automated Urban Planning via Adversarial Learning. In 28th *International Conference on Advances in Geographic Information Systems* (SIGSPATIAL '20), November 3–6, 2020, Seattle, WA, USA. ACM, New York, NY, USA, 10 pages.

After YOUSEF KHALILI, Tonomos

CCO / President Professional Services Unit

2.7 Digital Sovereignty

- The State’s current system allows us to see that DS means essentially three things:
- 1) The power to set boundaries around incoming information
- 2) Trade protectionism in the digital sector
- 3) Strengthening the State’s authority over residents' online accounts, data and personal information

And for a city?

- Have full control over your own data
- Effective fight against cyberattacks

3. Conclusions

- Promising new concept
- Intuition for several decades
- Assembly of technologies
- Lack of a comprehensive conceptual framework
- Multiple acceptions of the concept
- Several ways of achieving
- No success story yet

Two possible evolutions

- In the filiation of "enlightened despotism”
  - Techno-authoritarianism

- In the democratic filiation
  - Tools for participation

Bibliography 1/2

- Caldarelli, G., Arcaute, E., Barthelemy, M. et al. (2023) "The role of complexity for digital twins of cities". Nat Comput Sci 3, 374–381 (2023). https://doi.org/10.1038/s43588-023-00431-4
- Caprari, G. '2022) "Digital Twin for Urban Planning in the Green Deal Era: A State of the Art and Future Perspectives". Sustainability 2022, 14, 6263. https://doi.org/10.3390/ su14106263
- Darko Šiško, Vlado Cetl, Hrvoje Matijević (2024) Developing of a Digital Twin for Urban Planning in an International Context Tehnički glasnik, Vol. 18 No. si1, 2024.https://doi.org/10.31803/tg-20240910101801
- Ehab Shahat, Chang T. Hyun and Chunho Yeom (2021)"City Digital Twin Potentials: A Review and Research Agenda". Sustainability 2021, 13(6), 3386; https://doi.org/10.3390/su13063386
- Fabian Dembski, Uwe Wössner, Mike Letzgus, Michael Ruddatand Claudia Yamu (2020) "Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany" Sustainability 2020, 12, 2307; doi:10.3390/su12062307
- Homa Masoumi, Sara Shirowzhan, Paria Eskandarpour & Christopher James Pettit (2023) "City Digital Twins: their maturity level and differentiation from 3D city models", Big Earth Data, 7:1, 1-36, DOI: 10.1080/20964471.2022.2160156
- Jaume Ferré-Bigorra, Miquel Casals, Marta Gangolells (2022) "The adoption of urban digital twins". Cities 131 (2022) 103905
- Jing Wang, Gengze Li, Huapu Lu, Zhouhao Wu (20) "Urban models: Progress and perspective" Sustainable Futures 7 (2024) 10018, https://doi.org/10.1016/j.sftr.2024.100181
- Li Deren, Yu Wenbo and Shao Zhenfeng (2021) "Smart city based on digital twins" Computational Urban Science (2021) 1:4 https://doi.org/10.1007/s43762-021-00005-y
- Livebardon, M., Machado, V., Samuel, J., Chanfray, D., Toussaint, J.-Y., and Gesquiere, G. (2024) “IMUV: A Digital Twin for Mediation to Discover and Exchange on Territories", ISPRS Ann.

Bibliography 2/2

- Mousavi, Y.; Gharineiat, Z.; Karimi, A.A.; McDougall, K.; Rossi,A.; Gonizzi Barsanti, S. (2024) Digital Twin Technology in Built Environment: A Review of Applications, Capabilities and Challenges". Smart Cities 2024, 7, 2594–2615. https://doi.org/10.3390/ smartcities7050101
- Ondrej Krejcar et al. “Smart Furniture as a Component of a Smart City - Definition Based on Key Technologies Specification” in IEEE Access, vol. 7, pp. 94822-94839, 2019, doi: 10.1109/ACCESS.2019.2927778.
- Rasha F. El-Agamy, Hanaa A. Sayed, Arwa M. AL Akhatatneh, Mansourah Aljohani, Mostafa Elhosseini (2024) "Comprehensive analysis of digital twins in smart cities: a 4200-paper bibliometric study". Artificial Intelligence Review https://doi.org/10.1007/s10462-024-10781-8
- Schrotter, Gerhard, Hürzeler, Christian, (2020) "The Digital Twin of the City of Zurich for Urban Planning" Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 2512-2819, https://doi.org/10.1007/s41064-020-00092-2
- Tianhu Deng, Keren Zhang, Zuo-Jun (Max) Shen (2021)"A systematic review of a digital twin city: A new pattern of urban governance toward smart cities", Journal of Management Science and Engineering,Volume 6, Issue 2, Pages 125-134, ISSN 2096-2320, https://doi.org/10.1016/j.jmse.2021.03.003.
- World Economic Forum (2022) "Digital Twin Cities: Framework and Global Practices" can be downloaded from https://www.weforum.org/publications/digital-twin-cities-framework-and-global-practices/


Thanks for your attention!
Prof. R. Laurini
Can be downloaded from
www.laurini.net/ftp/IARIA25.pdf