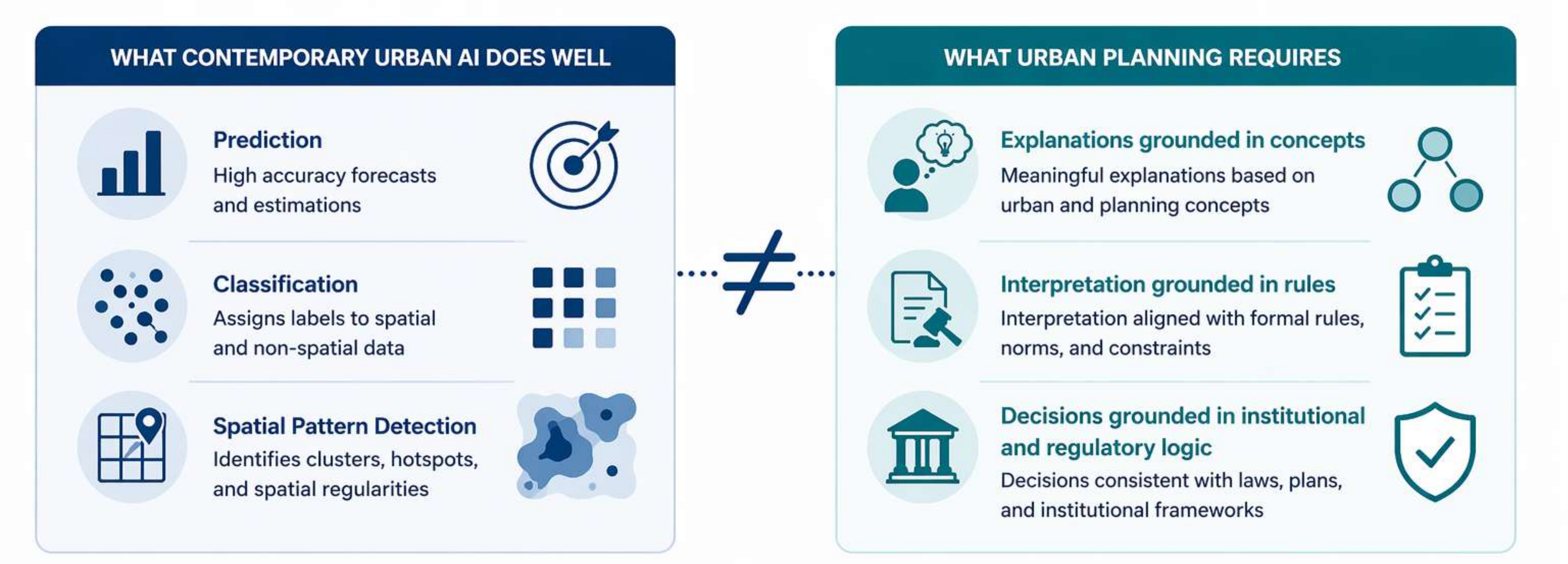
BEYOND LAYERS:

Neuro-Symbolic Spatial Reasoning in Urban Knowledge Graphs

Iwona Kaczmarek · Associate Professor · Wrocław University of Environmental and Life Sciences

What Urban AI can do?



Data-driven urban AI is not the same as planning-oriented reasoning

Where is the gap?

Explainability is not yet planning interpretation

Recent work on XGeoAI shows that explaining model outputs is useful, but still does not fully explain urban meaning, planning relevance, or regulatory context.

Implication: model explanation is not the same as planning-oriented interpretation.

Urban planning requires explicit concepts, relations, and rules

Urban planning decisions depend on land-use categories, spatial relations, regulations, and institutional logic that are not automatically captured by data-driven inference.

Implication: advanced analytics alone does not yet provide planning-relevant reasoning.

There is still a gap between analytics and urban reasoning

Even advanced urban analytics does not automatically provide the kind of interpretation needed for planning decisions.

Implication: the gap is not weak analytics, but limited planning-oriented interpretation.

From patterns to understanding

Central question

How can we move from detecting urban patterns to understanding what a given transformation means for the area in which it occurs?

The challenge

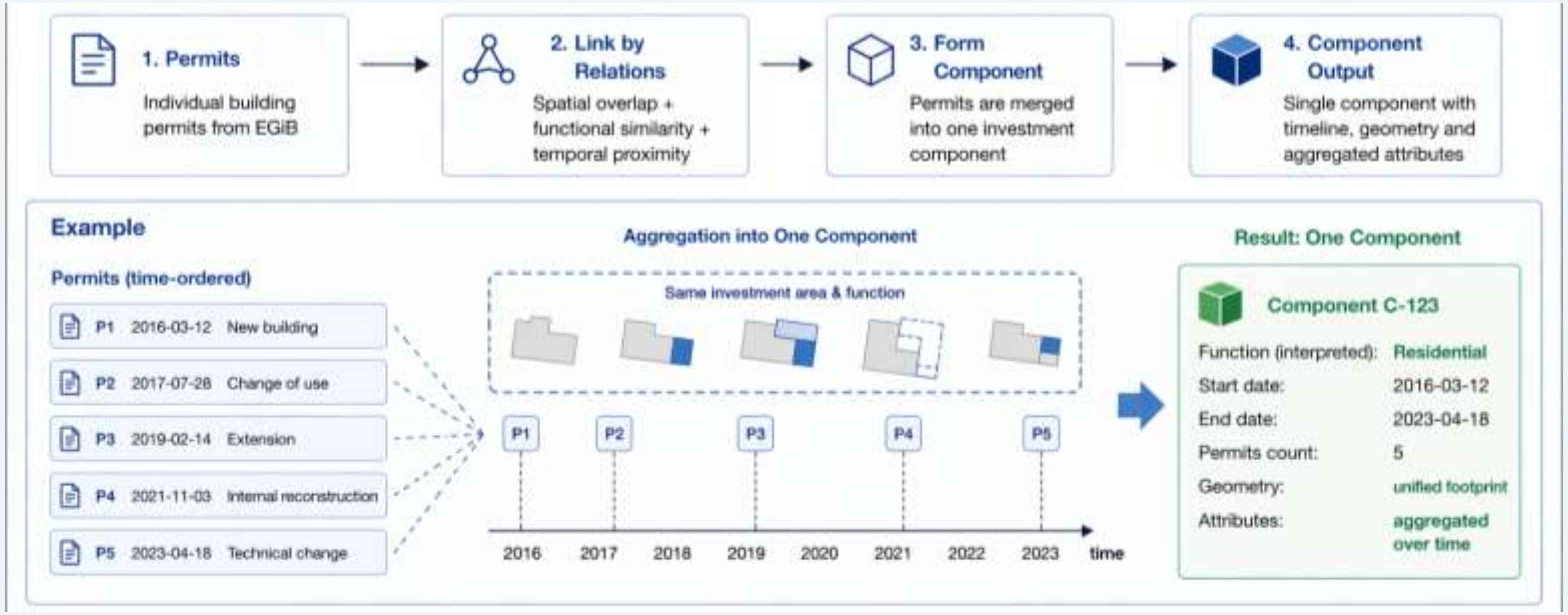
Advanced analytics can identify recurring forms of change, but not necessarily their functional meaning, local fit, or urban implications.

Key point

The issue is not only detecting that change occurs, but understanding **what kind of change it is and what it means in its urban context.**

Wrocław use case

Wrocław city
293 km² · 670,000 inhabitants · 17-year study (2006–2023) · Poland's 4th largest city



59,388
Building Permits (2006–2023)

31,356
Connected components of permits

12
Semantic Clusters (BERT)

9
Structural Clusters (AHC)

What patterns can we see?

Structural Clusters

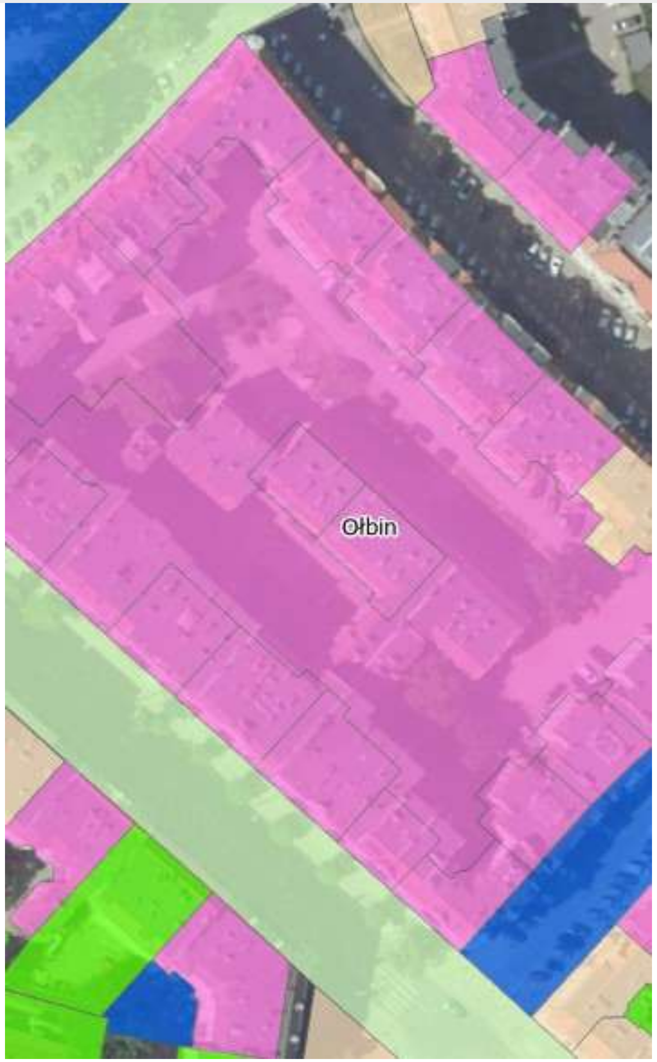
Groups of investment processes that share similar shape, duration, and decision sequence: revealing recurring patterns in how formal development unfolds.

Semantic Clusters

Groups identified by the type of intervention described eg. renovation, new construction, infrastructure (capturing what the investment is about).

Recurring Investment Trajectories

Repeated urban development patterns emerging from both dimensions.



+ The study integrates two dimensions usually separated: the formal side shows how investment unfolds structurally; the semantic side shows what the investment is about.

Structural ≠ Semantic

AHC and LLM capture different dimensions of urban transformation

Expansion
Structural profile: 10 permits, 5 years, ICI=0.4
Semantic profile: Semantic dominance - New construction.

Revitalization
Structural profile: 8 permits, 6 years, ICI = 0.45
Semantic profile: Semantic dominance – Reconstructions, Renovations.

Urban Knowledge Graphs

An **Urban Knowledge Graph** is a structured, machine-readable representation of urban entities, their spatial and semantic relations, and the planning rules that govern them enabling inference over meaning, not just pattern.

Entities

- Investment processes (nodes)
- Components: construction, renovation, demolition
- Spatial units: parcels, zones, districts
- Actors: investors, authorities, planners
- Documents: permits, MPZP, decisions

Relations

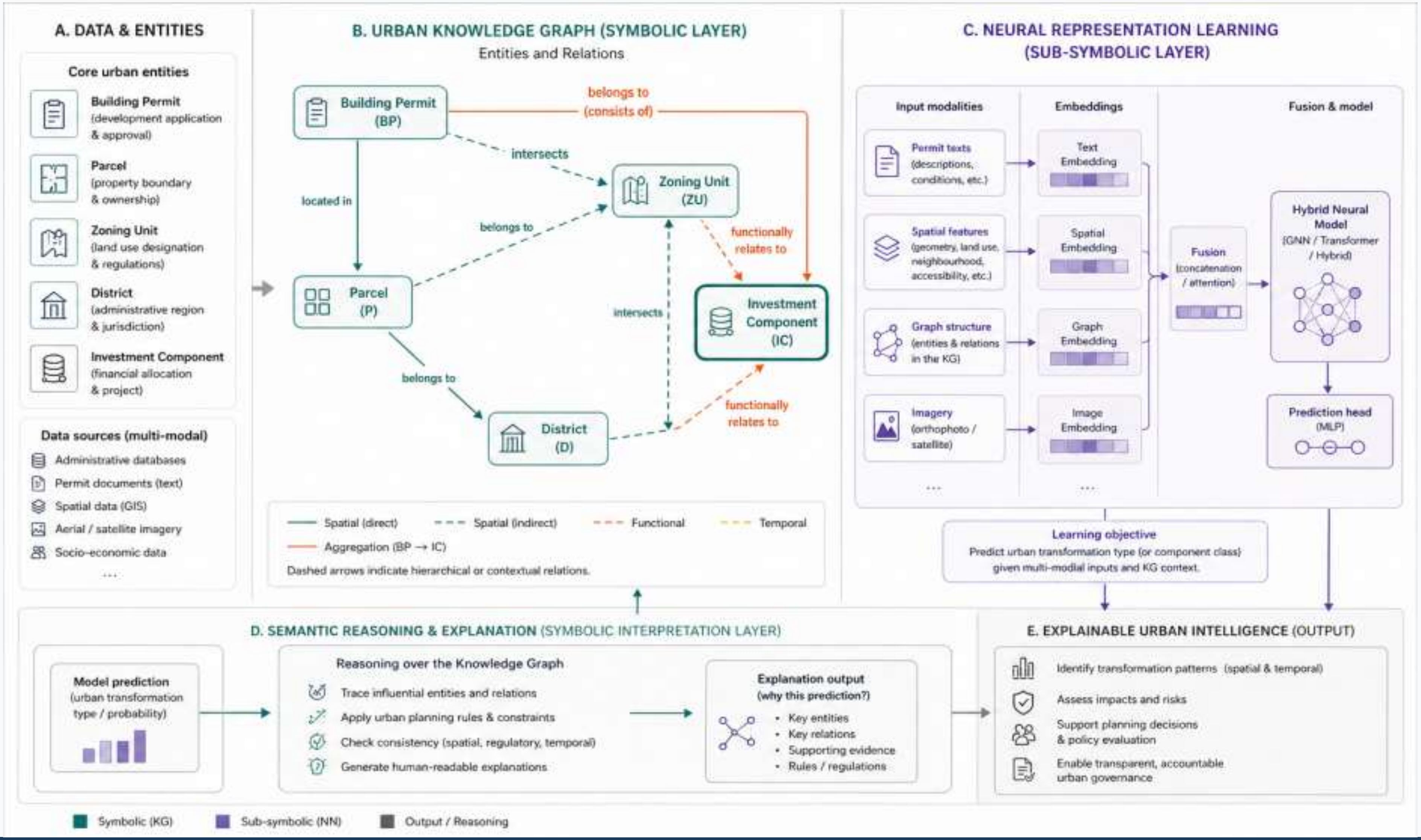
- isPartOf, contains, adjacentTo
- precedes, follows, triggers
- locatedIn, regulatedBy
- hasComponent, hasPermit
- conflictsWith, isCompatibleWith

Rules and Inference

- Zoning compliance rules (MPZP)
- Temporal sequencing constraints
- Function compatibility logic
- Normative evaluation criteria
- Spatial coherence checks

Example query: "Find investment processes in residential zones that include commercial components and have not been preceded by a change-of-use permit" - impossible with clustering, answerable with a KG.

Neuro-symbologic framework



Conclusions

1. Urban AI remains highly effective in detecting spatial patterns and supporting predictive analysis.
2. Current literature increasingly points beyond prediction toward richer forms of urban decision support, including scenario thinking and contextual interpretation.
3. Structured urban knowledge is emerging as an important complement to data-driven models.
4. AI is consistently framed as augmenting planners rather than replacing planning judgment.
5. The next methodological step is not replacing urban AI, but combining analytical strength with explicit urban knowledge.

Thank you for your attention

Department of Systems Research
Wroclaw University of Environmental and Life Sciences
Poland
iwona.kaczmarek@upwr.edu.pl

What is still missing?

Even when we combine formal and semantic clustering, we still do not get **reasoning**. Pattern detection cannot by itself represent:

01
Entities and Roles
Who are the actors? What is the investment component? What is its planning role in the city system?

02
Spatial Relations
Adjacency, overlap, containment, neighborhood context — relationships that define urban meaning

03
Planning Constraints
Zoning rules, land-use logic, MPZP regulations-institutional frameworks that govern development

04
Normative Evaluation
Is this transformation appropriate? Coherent? Desirable? These require value-laden urban logic

05
Rule-Based Inference
Step-by-step reasoning over context, rules, and relations — not statistical similarity

> We still cannot ask whether a transformation is contextually appropriate, compliant, or consistent with planning logic - this is why a new framework is needed.

Combining formal and semantic dimensions

FORMAL DIMENSION

Graph Aggregation
Permits aggregated into connected investment components

Structural Metrics
Duration, scale, sequence, diversity - Investment Complexity Index (ICI)

Structural Clustering (AHC)
Hierarchical clustering reveals recurring formal process patterns and investment trajectories

SEMANTIC DIMENSION

Permit Text Descriptions
Natural language descriptions of investment intent from administrative permit documents

BERT-Based Embeddings
Language model embeddings capture semantic similarity across intervention types

Semantic Clustering
Identifies intervention type and intention: renovation, new construction, infrastructure, change of use

+ The study integrates two dimensions usually separated: the formal side shows how investment unfolds structurally; the semantic side shows what the investment is about.

Kaczmarek & Iwaniak, 2026 | Land Use Policy. https://doi.org/10.1016/j.landusepol.2026.108039