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# Testing and Enhancing the Scenario ADE in the Context of Building Energy Performance Simulations

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# Contents

1. Motivation & Problem
2. Research Questions
3. Background
4. Methodology
5. Schema Development
6. Results
7. Discussion
8. Conclusion

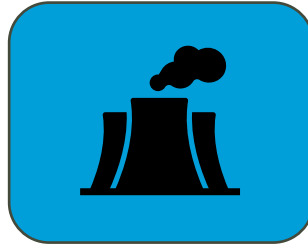
# Motivation – Modelling the Energy Transition

In the Netherlands...



**300k** home  
renovations per year  
(NL)

*Ebrahimigharehbaghi et al., 2019*



**-49%** greenhouse  
emissions by 2030; gas-free  
heating by 2050

*Klimaatwet, 2020*

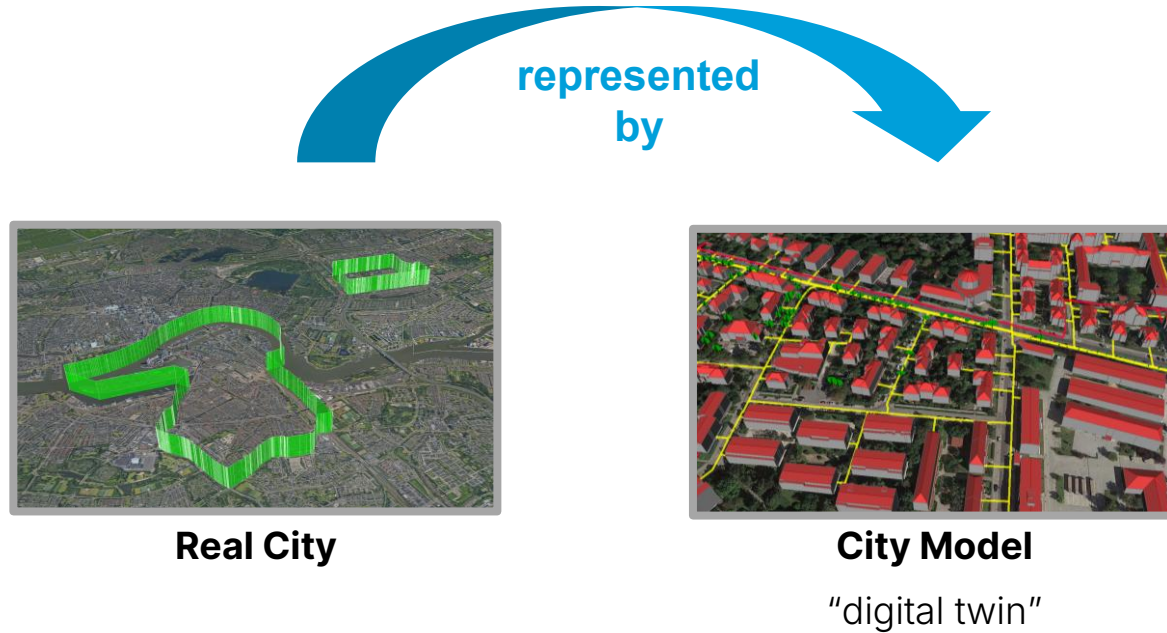


**Heating → Cooling**  
peak shift under future climate  
*KNMI'23*

Planning the energy transition means creating scenarios comparing many possible futures to make better decisions

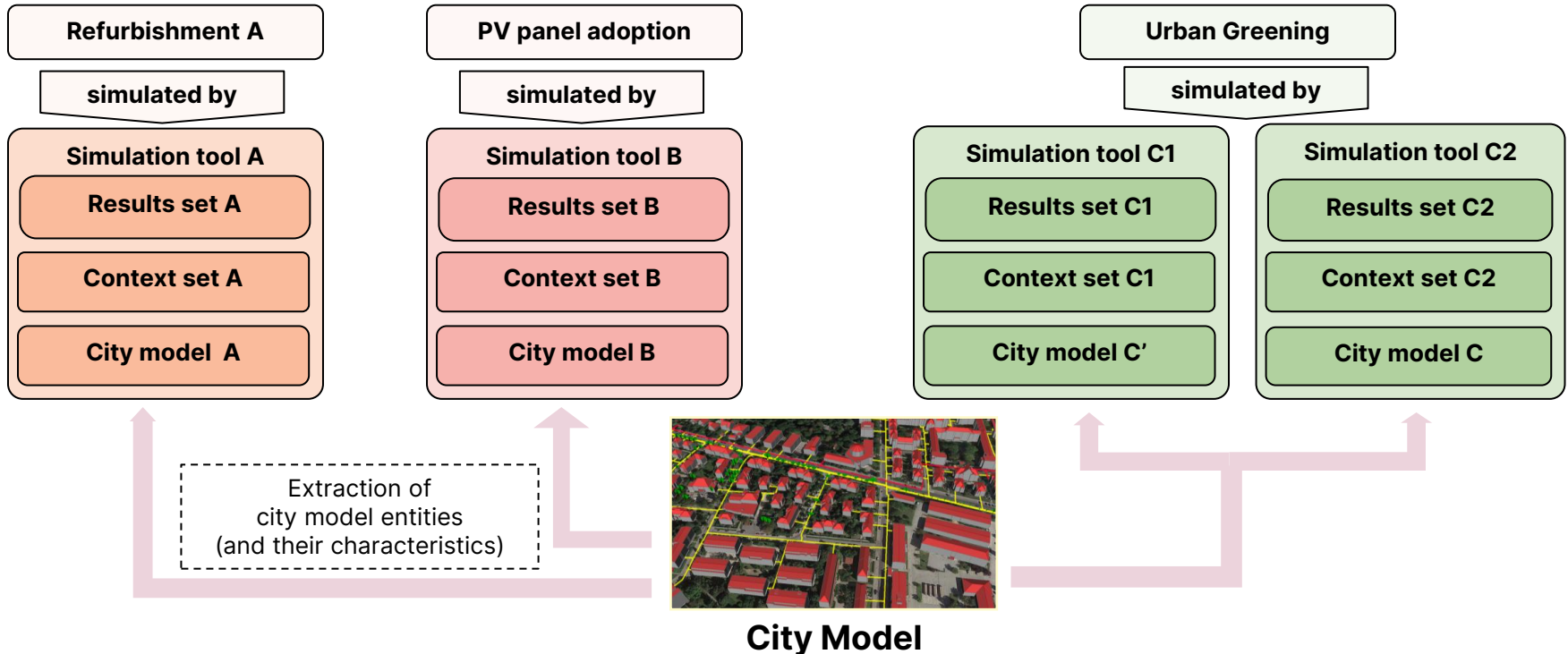
# Motivation - From City Model to Chaos

CityGML 2.0 represents cities as a single snapshot in time



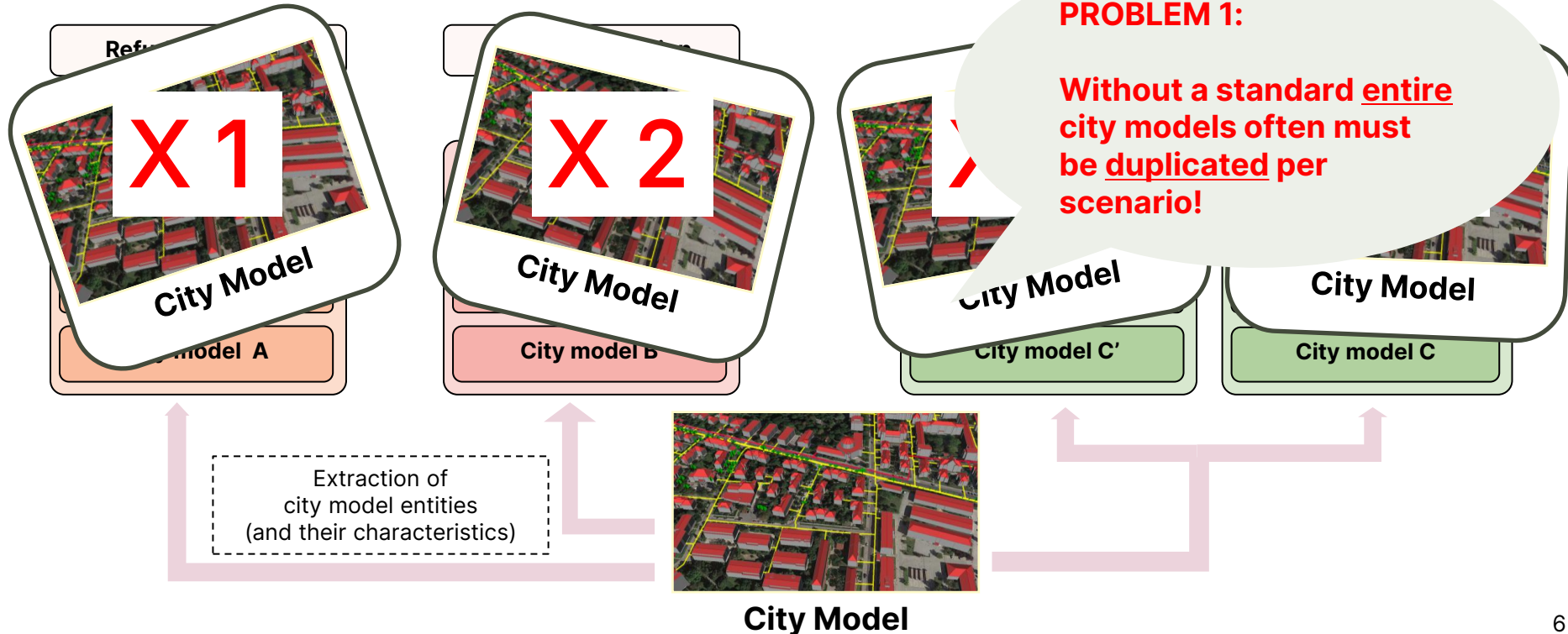
# Motivation - From City Model to Chaos

Urban energy planning requires evaluating multiple “what if” futures of the city model (refurbishment, PV adoption, climate change)



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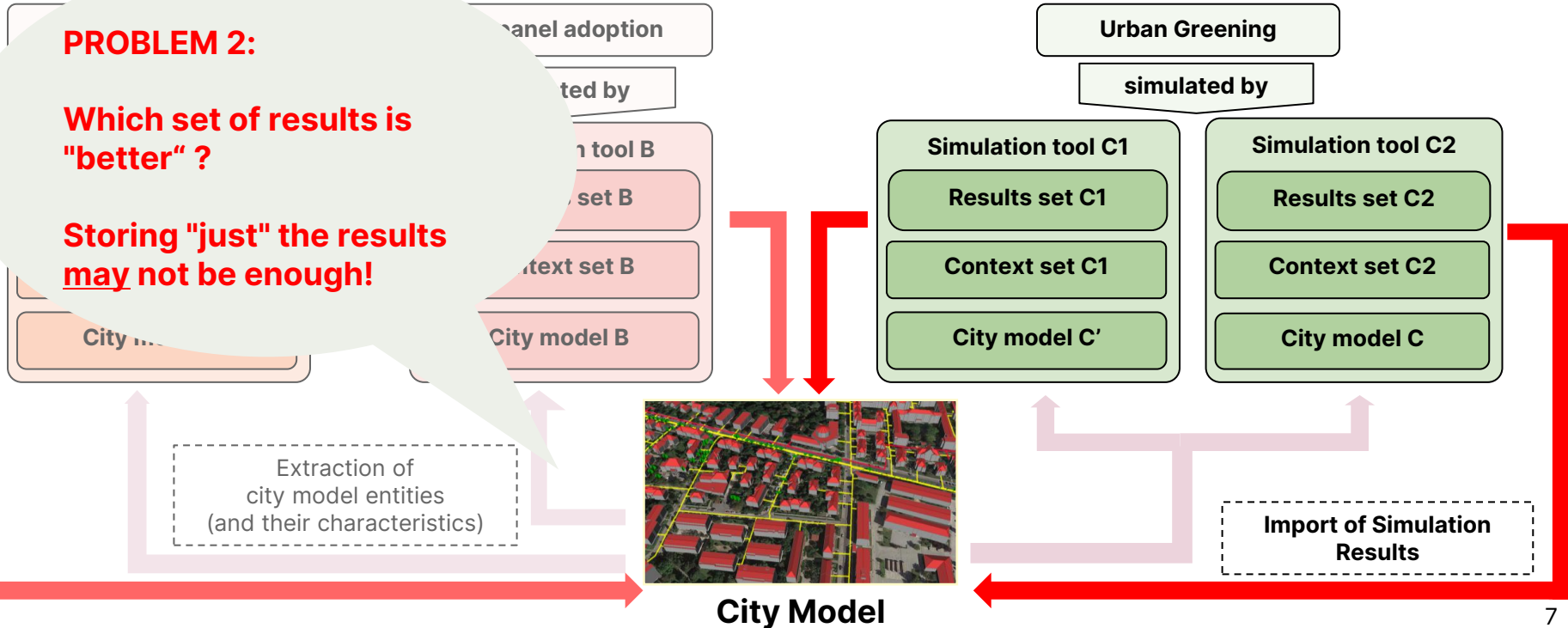


# Motivation - From City Model to Chaos

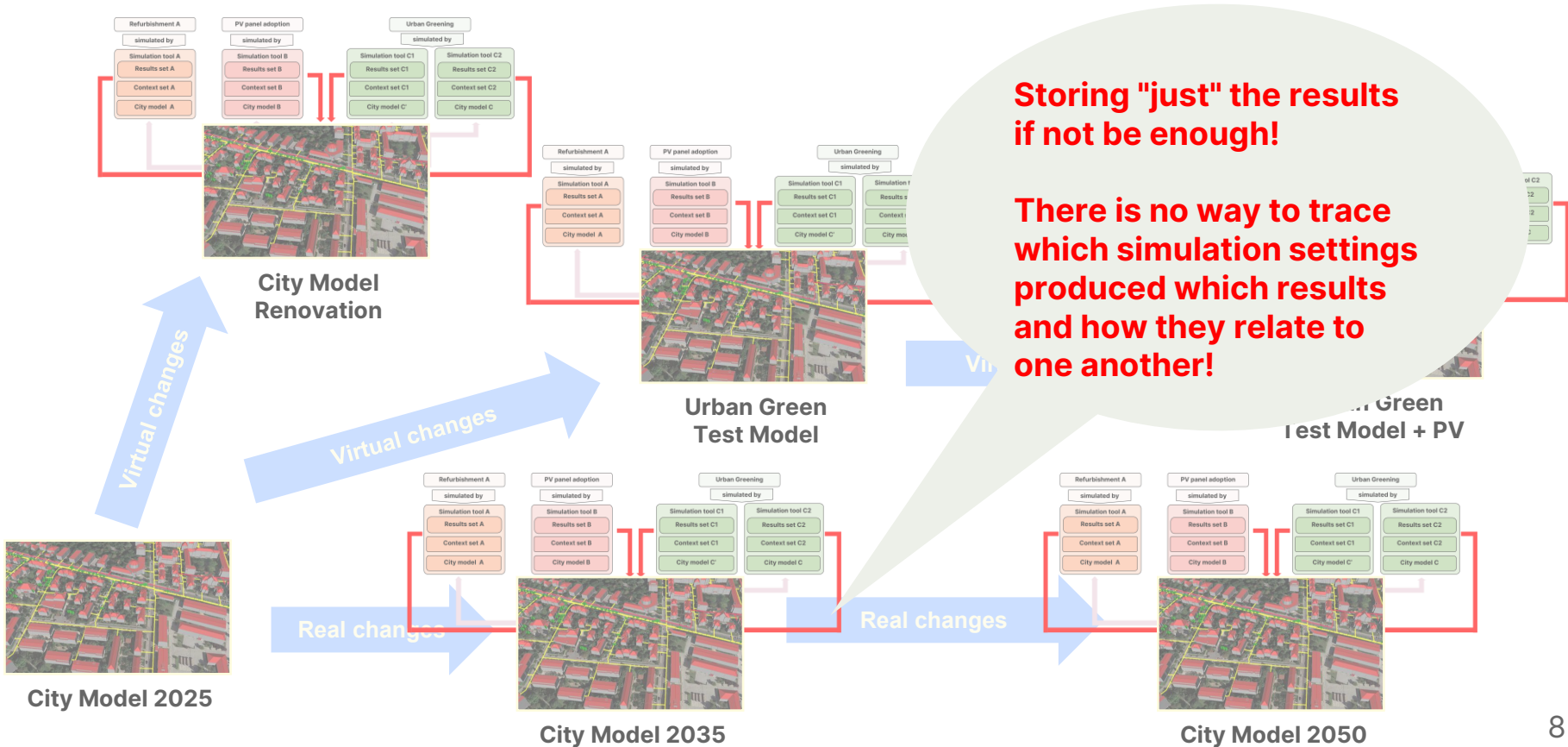
## PROBLEM 2:

Which set of results is "better" ?

Storing "just" the results may not be enough!

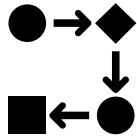


# Motivation - From City Model to Chaos

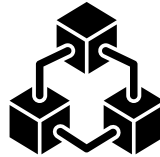


# Motivation - From need to objective

A way to track change in 3D city models that captures not only *what* changed but also *why* and under *which* assumptions.



Track how city models change and relate to one another over time



Let parallel alternatives live in one dataset, without duplication the city model for each



Tie every result back to the configuration that produced it and the city entities it is related to

**Objective:** Test and enhance the Scenario ADE for CityGML 2.0 so it can hold several alternative futures of one neighborhood in a single dataset and link each future to the simulation that produced it

# Contents

1. Motivation & Problem
2. Research Questions
3. Background
4. Methodology
5. Schema Development
6. Results
7. Discussion
8. Conclusion

# Research Questions

## MAIN RESEARCH QUESTION

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How can a Scenario ADE for CityGML 2.0 be **developed** and implemented to **support** the structured management, **analysis**, and **comparison of multi-temporal scenarios** in urban applications, using urban energy as the case study?

## SUB-QUESTIONS

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SQ  
1

Decompose

How can a scenario be formally decomposed into a structure of entities, properties, and relations that can be managed in the Scenario ADE?

SQ  
2

Refine

How can an existing Scenario ADE schema be iteratively refined to satisfy the design principles derived from scenario theory and empirical evidence?

SQ  
3

Operationalize

How can the Scenario ADE be operationalised through its physical encodings to support the management and comparison of urban energy scenarios?

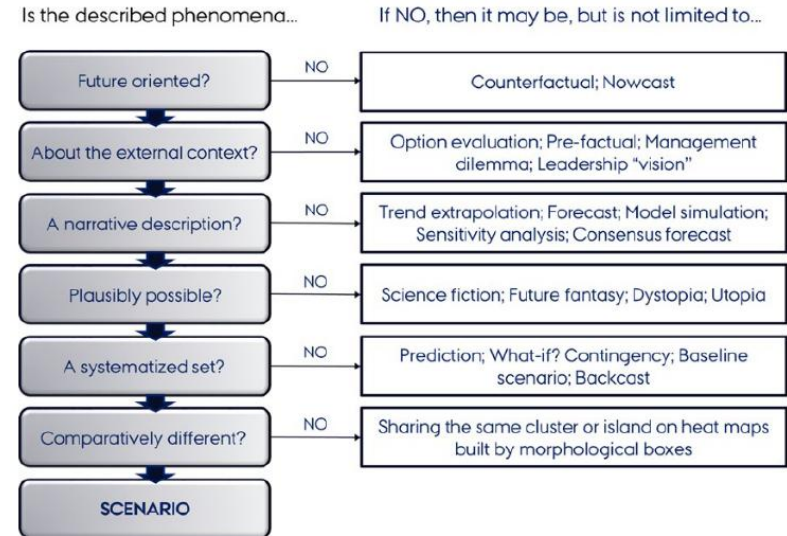
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1. Motivation & Problem
2. Research Questions
3. Background
4. Methodology
5. Schema Development
6. Results
7. Conclusion

# Background - What “counts” as a Scenario?

## The Definitional Chaos

- "Scenario" is used loosely; futures science has decades of “methodological chaos” (Bradfield et al. 2005)
- Spaniol & Rowland (2019) synthesized consensus from hundreds of definitions
- → **a scenario is about the external future context, not the actions you take.**
- But urban planners also need to test interventions (strategies)
- → **decouple the external context from the strategy / intervention** (XSP, Abou Jaoude et al. 2022)



*Classifying a phenomenon as a scenario (Spaniol & Rowland, 2019)*

*This context/strategy split becomes the Context and Strategy pillars of the data model*

# Background - why CityGML can't do this yet

## CityGML 2.0 + the ADE mechanism

- ADEs extend the schema for new domain data, but only describe the state — *not why or under what assumptions*

## What today's tooling tracks

- **CityGML 3.0 Versioning**: bitemporal model to track object lifecycles (Chaturverdi et al., 2017)
- **CityGML 3.0 Dynamizer**: Animates a single attribute over time (Kutzner et al., 2020)
- **CityJSON**: Offers a git-based versioning file-level deltas (Ledoux et al., 2019)
- **Provenance Standards (ISO19115, PROV)**: how data was created, *but no binding to changes, settings and assumptions*

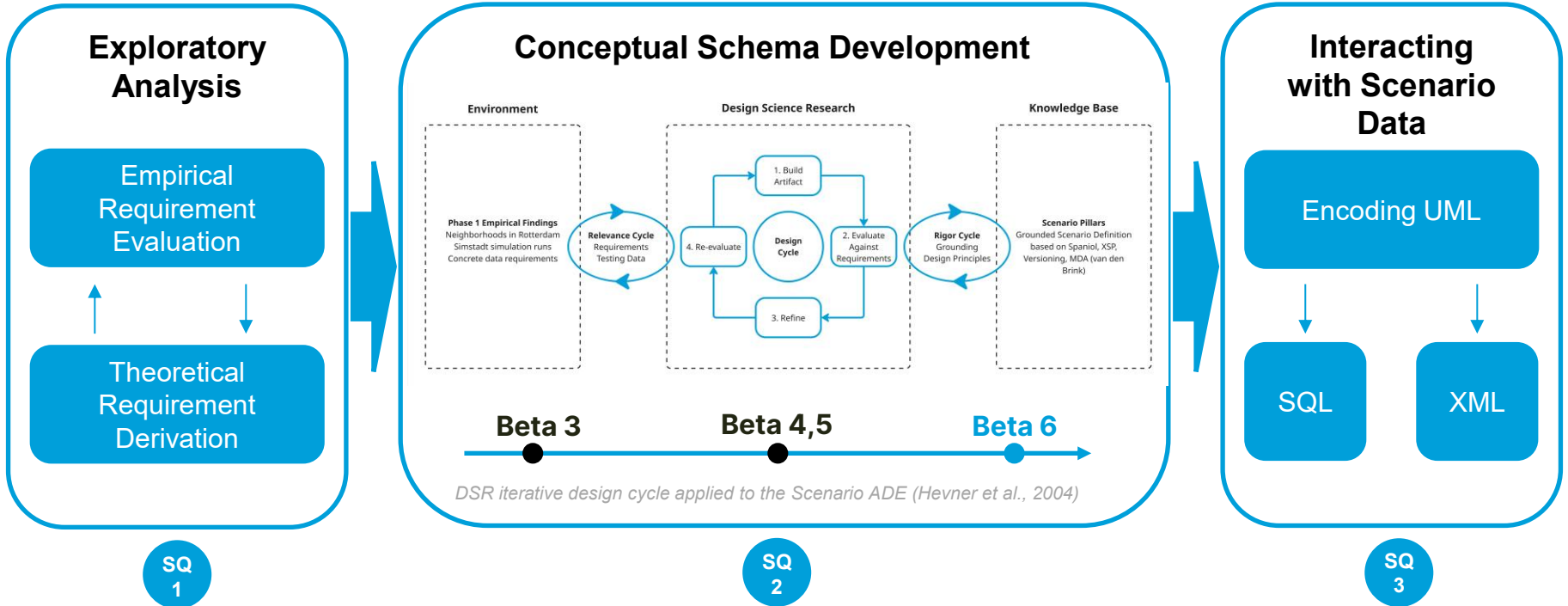
## The Limitation

- Currently none of the existing tools support 3D city models that captures not only **what** changed but also **why** and under **which** assumptions.

# Contents

1. Motivation & Problem
2. Research Questions
3. Background
4. Methodology
5. Schema Development
6. Results
7. Discussion
8. Conclusion

# Methodology — Phases



# Methodology – Exploratory Analysis

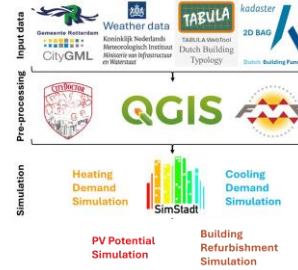
## Exploratory Analysis

Empirical Requirement Evaluation

Theoretical Requirement Derivation

SQ  
1

Conduct empirical simulation runs using a methodology adapted from Gao et al., 2025



Design principles and Concrete Requirements

Operationalize scenario definition and urban planning scenario development approach. (Abou Jaoude et al., 2022; Spaniol & Rowland, 2019)



### Context

*What past, present or future conditions are we in?*

- Climate projections (KNMI 2050)
- Socio-economic factors
- Grid constraints

e.g. KNMI 2050Hn weather file



### Strategy

*What intervention are we applying?*

- Envelope modifications (U-values)
- PV panel deployment
- Building demolition/greening

e.g. Advanced TABULA retrofit



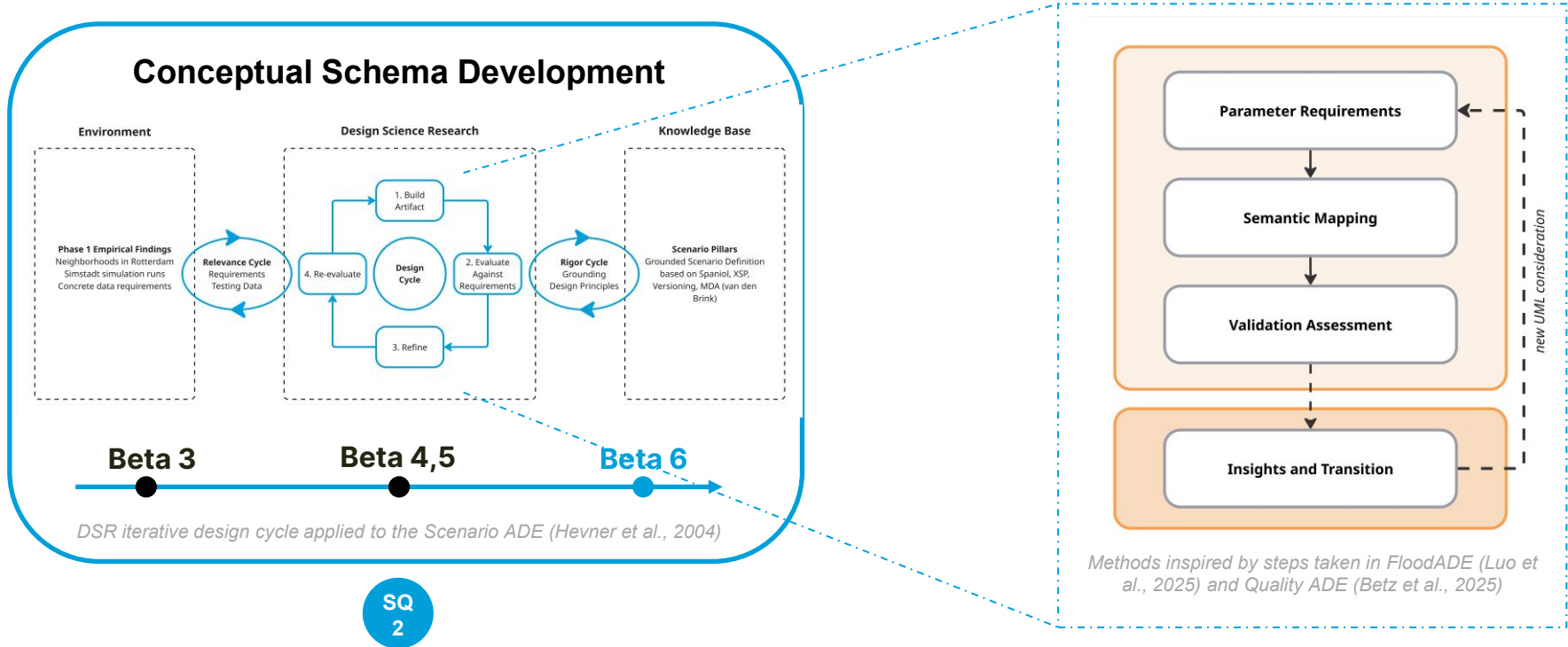
### Configuration

*How were the results computed?*

- Simulation engine & version
- Calculation standards (ISO)
- Temporal resolution

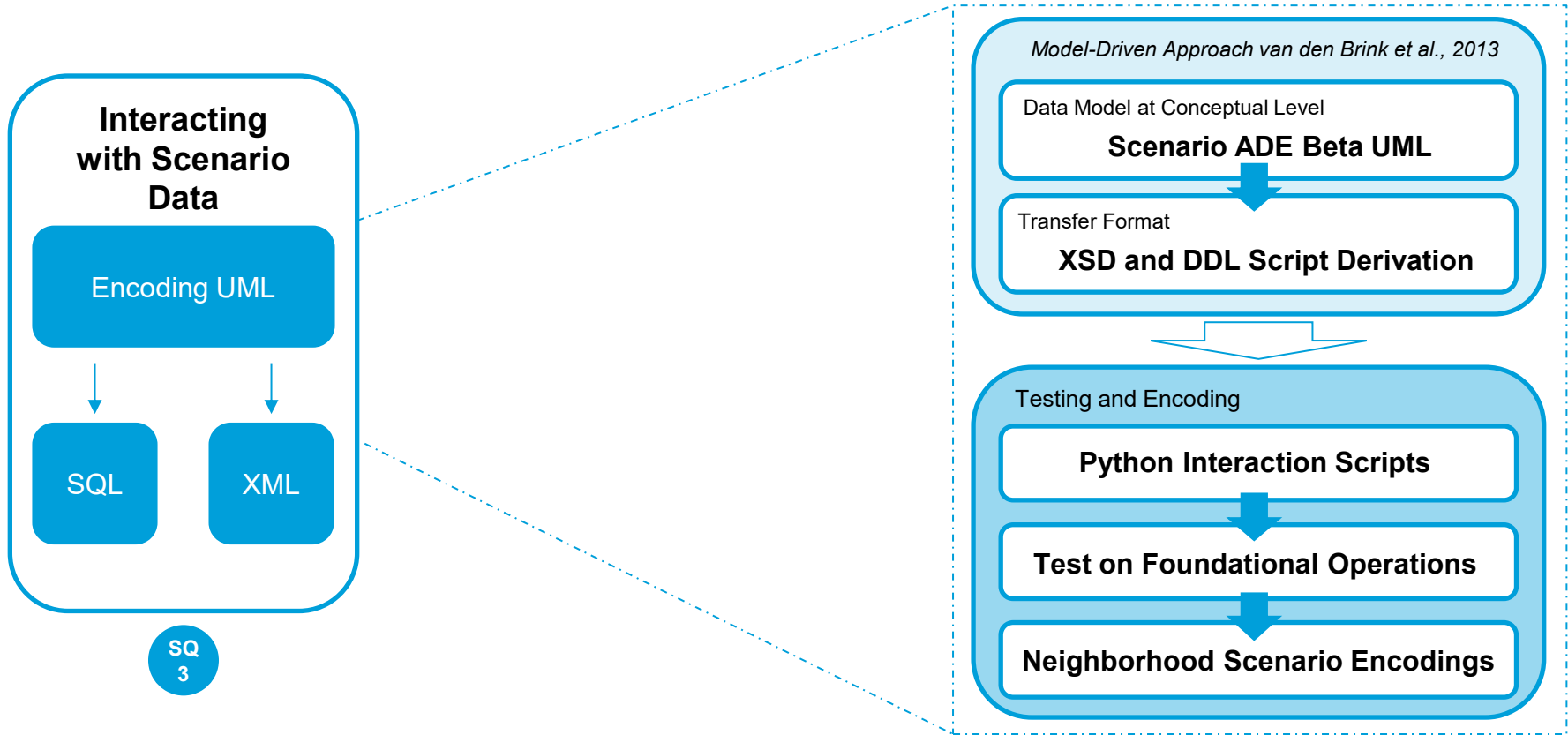
e.g. SimStadt + ISO 13790

# Methodology – Iterative Schema Refinement



SQ  
2

# Methodology – Generating Final Encodings



# Contents

1. Motivation & Problem
2. Research Questions
3. Background
4. Methodology
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6. Results
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# Schema Development – What the simulation runs demanded

## ▪ Store inputs

Simulation inputs must be stored with the engine

## ▪ Native Resolution

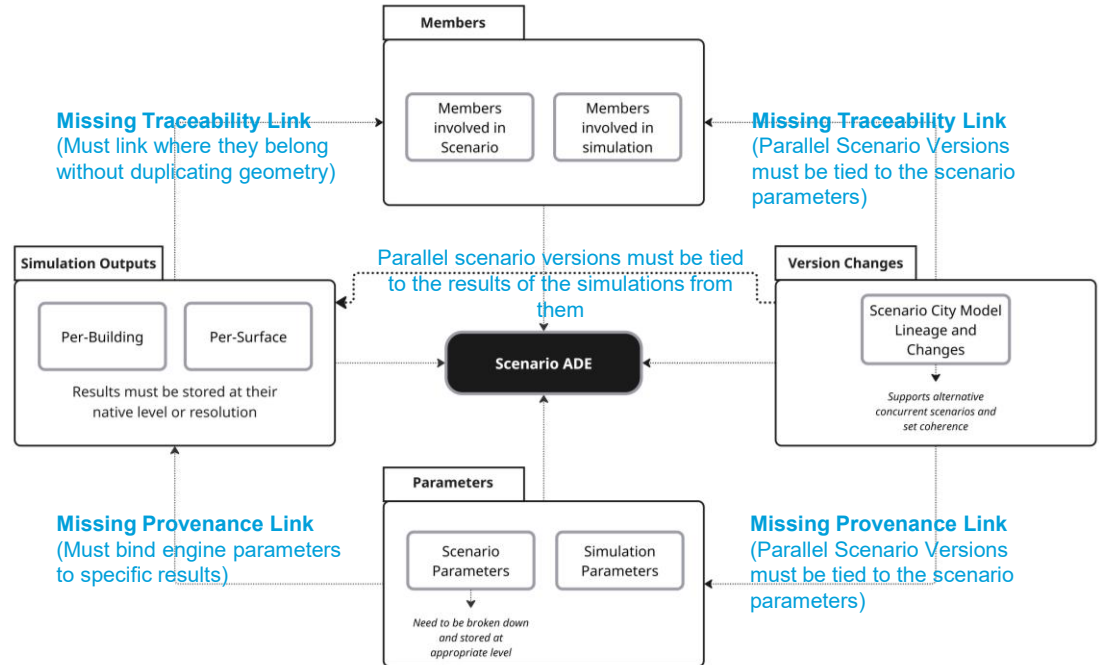
Results must be stored at their native level of resolution

## ▪ Bind every result

Each results must be linked to what produced it

## ▪ Trace enrichment

Data must be traceable to specific features



# Schema Development – The Intentions and the design principles

## Intentions

Foundational Intentions

**F1**

Domain agnostic layer over any CityGML module

**F2**

Scenario set coherence – comparison of scenarios

**F3**

Forward compatible with CityGML 3.0

## Context

External Boundary Condition

**C1**

Boundaries remain independently retrievable

**C2**

Horizons & narratives travel with parameters

**C3**

Parameters carry role metadata (input vs. result)

## Strategy

Intervention

**ST1**

Interventions without duplicating base geometry

**ST2**

Attribute changes point unambiguously to target

## Configuration

Simulation + Reproducibility

**CF1**

Simulation settings separable & reusable

**CF2**

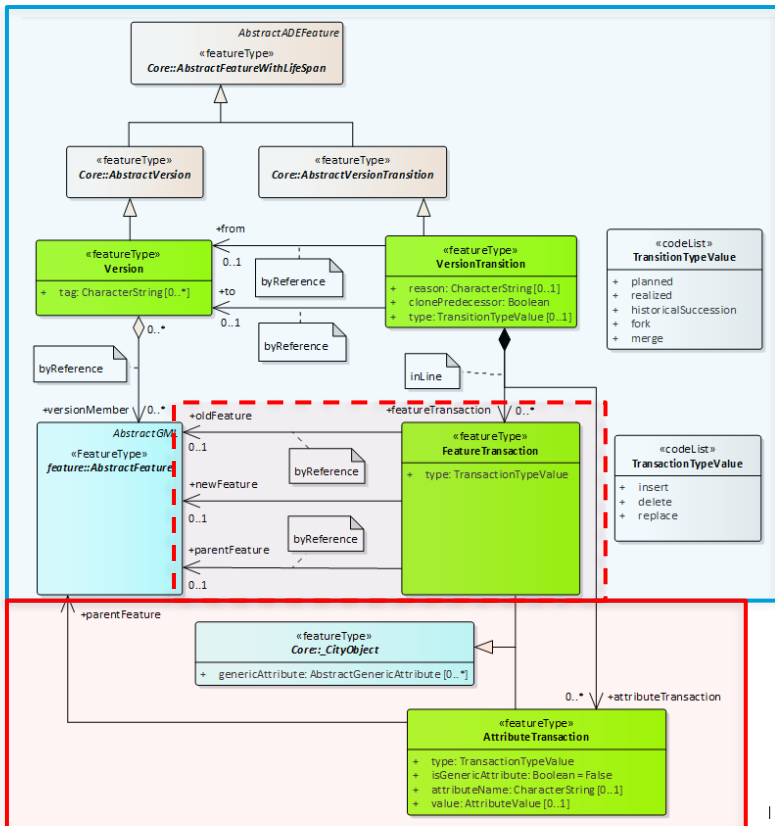
Results traceable to object + run

**CF3**

Multiple result types structurally distinguishable



# Schema Development – Versioning Module



Backported from CityGML 3.0 Versioning Module

- **Version, VersionTransition and Transaction**

Beta 6 added functionality

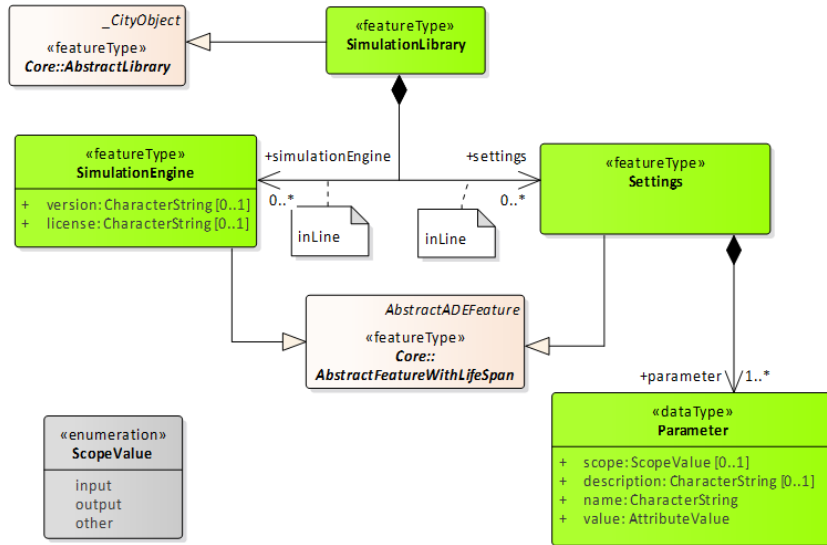
- **AttributeTransaction**

- Supports Attribute Modifications for root and child features.

- **FeatureTransaction**

- Additionally allows storing features inside Scenario Container

# Schema Development – Simulation Module

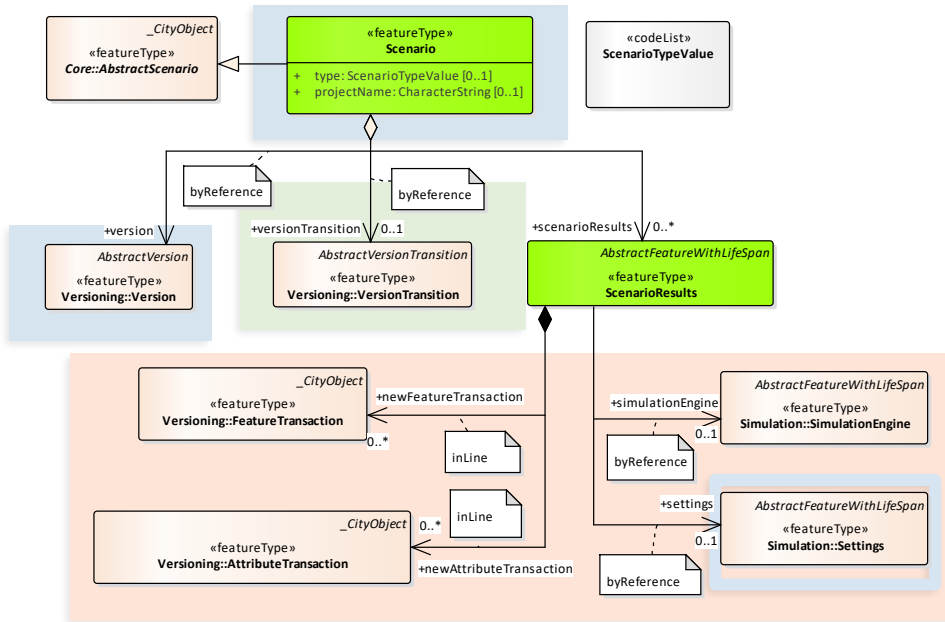


Allows for the storing of scenario configurations

## SimulationLibrary

- Holds all **SimulationEngine** and **Settings**
- **Settings** is composed of Parameters that can be:
  - Input, outputs or other

# Schema Development – Scenario Module



The Scenario Module holds all of the scenario components:



## Context

Stored amongst different classes.



## Strategy

Represented by the **VersionTransition** holding all strategy changes required to arrive at the **Version** of the Scenario



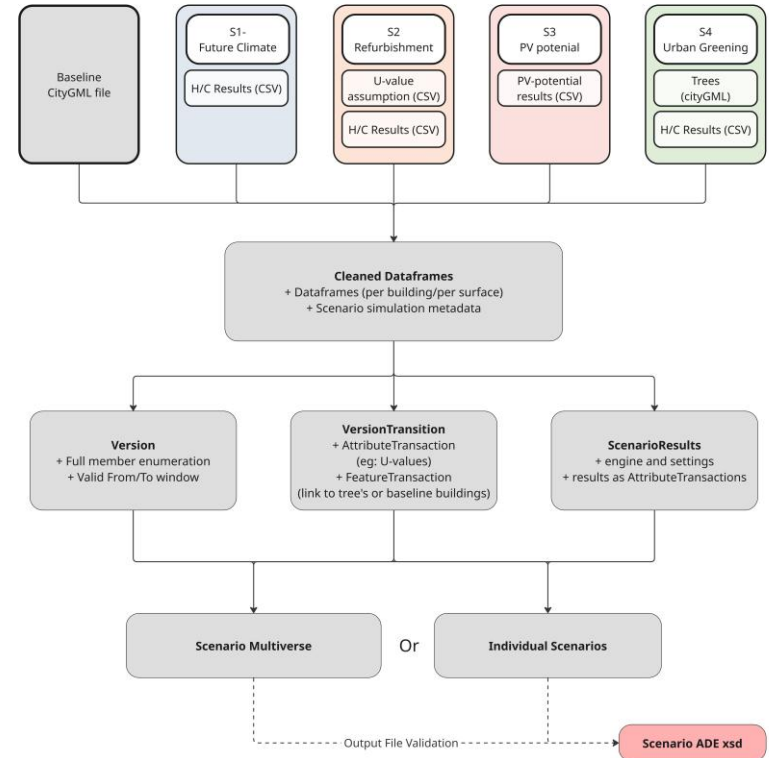
## Configuration

Represented by the **ScenarioResults** which holds a unique combination of a **SimulationEngine**, **Settings** and **Transactions** to insert results tied to scenariomembers

# Schema Development – Generating the XML and SQL Encoding

- The 4 case scenarios were encoded for Feyenoord using the following:
- **XML:** First test on foundational operations, then neighborhood scale
- **SQL:** First for 10 buildings in Feyenoord, then neighborhood scale




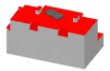
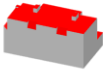




The 4 scenarios are:



# Contents

1. Motivation & Problem
2. Research Questions
3. Background
4. Methodology
5. Schema Development
6. Results
7. Discussion
8. Conclusion

# Results – Foundational Operations

+	-	↔
Insert	Delete	Replace
 <b>Root Feature</b> Add a new building	 <b>Root Feature</b> Demolish a building	 <b>Root</b> New building design
 <b>Child Feature</b> Add PV panels to roof	 <b>Child Feature</b> Remove a solar panel	 <b>Child</b> New roof / green roof
 <b>Property Attribute</b> Add U-Value of Wall	 <b>Property Attribute</b> Remove U-Value of Wall	 <b>Property Attribute</b> Replace Wall to Window Ratio: 7%→20%

C1  
C2  
C3

```

8 <scn:Scenario gml:id="id_scenario_case8">
9 <gml:description>U-value attribute removed after facade replacement</gml:description>
10 <scn:identifier>id_scenario_case8</scn:identifier>
11 <scn:validFrom>2026-06-01T00:00:00</scn:validFrom>
12 <scn:validTo>2030-12-31T23:59:59</scn:validTo>
13 <scn:type codeSpace="http://.../1.0/codeLists/ScenarioType.xml">explorative</scn:type>
14 <scn:projectName>ScenarioADE Beta6 - Test Suite</scn:projectName>
15 <scn:version xlink:href="#id_version_case8_v2"/>
16 <scn:versionTransition xlink:href="#id_vt_case8"/>
17 </scn:Scenario>

```

Scenario

```

20 <scn:VersionTransition gml:id="id_vt_case8">
21 <gml:description>Stale wall U-value attribute deleted</gml:description>
22 <scn:reason>Facade replaced - pre-renovation U-value no longer valid, pending new measurement</scn:reason>
23 <scn:clonePredecessor>true</scn:clonePredecessor>
24 <scn:type codeSpace="http://.../codeLists/VersionTransitionType.xml">planned</scn:type>
25 <scn:from xlink:href="#id_version_case8_v1"/>
26 <scn:to xlink:href="#id_version_case8_v2"/>
27 <scn:attributeTransaction>
28 <scn:AttributeTransaction gml:id="id_at_case8_delete">
29 <gml:description>Delete stale wallUValue_M_m2K generic attribute after facade replacement</gml:description>
30 <scn:type codeSpace="http://.../codeLists/AttributeTransactionType.xml">delete</scn:type>
31 <scn:parentFeature xlink:href="#BAG_059910000654922"/>
32 <scn:attributeType>cityGMLGenericAttribute</scn:attributeType>
33 <scn:attributeName>wallUValue_M_m2K</scn:attributeName>
34 </scn:AttributeTransaction>
35 </scn:attributeTransaction>
36 </scn:VersionTransition>

```

AttributeTransaction  
VersionTransition

```

39 <scn:Version gml:id="id_version_case8_v1">
40 <gml:description>Building with pre-renovation wallUValue_M_m2K attribute</gml:description>
41 <scn:validFrom>2026-01-01T00:00:00</scn:validFrom>
42 <scn:tag>baseline</scn:tag>
43 <scn:versionMember xlink:href="#BAG_059910000654922"/>
44 </scn:Version>

```

Version 1 (baseline)

```

47 <scn:Version gml:id="id_version_case8_v2">
48 <gml:description>Building with stale wall U-value attribute deleted after facade replacement</gml:description>
49 <scn:validFrom>2026-06-01T00:00:00</scn:validFrom>
50 <scn:tag>scenario</scn:tag>
51 <scn:versionMember xlink:href="#BAG_059910000654922"/>
52 </scn:Version>

```

Version 2 (scenario)

# Results – Alternative options for storing results

Simulation results can be stored as:

- **AttributeTransaction – Generics Module**
  - Supports total freedom
- **AttributeTransaction – Simple Attribute**
  - For existing attributes defined by CityGML or used in any ADE

Also, a result as an ADE Feature, a root element or a child can sit in-line a scenario **Transaction** to be linked to a building.

```
12 <scn:newAttributeTransaction>
13 <scn:AttributeTransaction gml:id="v3_BAG_0599100000618982_yearlyCoolingDemand">
14 <gen:measureAttribute name="yearlyCoolingDemand">
15 <gen:value uom="kWh/a">7800.0</gen:value>
16 </gen:measureAttribute>
17 <scn:type codeSpace="http://.../1.0/codelists/TransactionTypeValue.xml">insert</
18 <scn:parentFeature xlink:href="#BAG_0599100000618982"/>
19 <scn:attributeType>cityGMLGenericAttribute</scn:attributeType>
20 </scn:AttributeTransaction>
21 </scn:newAttributeTransaction>
22
23 <scn:newAttributeTransaction>
24 <scn:AttributeTransaction gml:id="v3_BAG_0599100000618982_yearlyCoolingDemand">
25 <scn:type codeSpace="http://.../1.0/codelists/TransactionTypeValue.xml">insert</
26 <scn:parentFeature xlink:href="#BAG_0599100000618982"/>
27 <scn:attributeType>simpleAttribute</scn:attributeType>
28 <scn:attributeName>yearlyCoolingDemand</scn:attributeName>
29 <scn:value>
30 <scn:AttributeValue>
31 <scn:measure uom="kWh/a">7800.0</scn:measure>
32 </scn:AttributeValue>
33 </scn:value>
34 </scn:AttributeTransaction>
35 </scn:newAttributeTransaction>
36
37 <scn:newFeatureTransaction>
38 <scn:FeatureTransaction gml:id="ft_v3e_BAG_0599100000618982_yearlyCoolingDemand">
39 <scn:type codeSpace="http://.../codelists/TransactionTypeValue.xml">insert</
40 <scn:parentFeature xlink:href="#BAG_0599100000618982"/>
41 <scn:newFeature>
42 <nrg3:Energy gml:id="nrg_BAG_0599100000618982_yearlyCoolingDemand">
43 <nrg3:operationType codeSpace="http://.../codelists/
44 ResourceOperationTypeValue.xml">demands</nrg3:operationType>
45 <nrg3:amount uom="kWh/a">7800.0</nrg3:amount>
46 <nrg3:year>2026</nrg3:year>
47 <nrg3:isAmountNormalized>false</nrg3:isAmountNormalized>
48 <nrg3:type codeSpace="http://.../codelists/EnergyTypeValue.xml">useful</
49 nrg3:type>
50 <nrg3:endUse codeSpace="http://.../codelists/
51 EnergyEndUseValue.xml">spaceCooling</nrg3:endUse>
<nrg3:energyCarrier codeSpace="http://.../codelists/
EnergyCarrierValue.xml">electricity</nrg3:energyCarrier>
</nrg3:Energy>
</scn:newFeature>
```

(Imaginary @Existing attribute)

(1) Generics Module

(2) Simple Attribute

(3) Energy ADE

# Results – Neighbourhood Scale Encoding



Category	File	Lines	Bytes	Smaller vs. sum (%)
Individual	Future Climate (S1)	120,626	6,380,915	–
Individual	PV Adoption (S2)	86,391	4,310,510	–
Individual	Refurbishment (S3)	133,775	7,462,885	–
Individual	Urban Greening (S4)	169,699	9,178,187	–
Sum of individual	(4 files combined)	510,491	27,332,497	–
Multiverse	Scenario Multiverse	332,836	19,490,515	–
Savings (multiverse vs. sum)		177,655	7,841,982	28.7%

```

1 <core:cityObjectMember>
2 <scn:Scenario gml:id="scn_future_climate">
3 <!-- Future Climate Scenario-->
4 </core:cityObjectMember>
5 <core:cityObjectMember>
6 <scn:Scenario gml:id="scn_pv_adoption">
7 <!-- PV Adoption Scenario-->
8 </core:cityObjectMember>
9 <core:cityObjectMember>
10 <scn:Scenario gml:id="scn_refurbishment">
11 <!-- Refurbishment Scenario-->
12 </core:cityObjectMember>
13 <core:cityObjectMember>
14 <scn:Scenario gml:id="scn_urban_greening">
15 <!-- Urban Greening Scenario-->
16 </core:cityObjectMember>
17 <scn:SimulationLibrary gml:id="lib_simstadt">
18 <scn:simulationEngine>
19 <scn:SimulationEngine gml:id="eng_simstadt">
20 <!-- SimStadt Engine (name and version) -->
21 </scn:simulationEngine>
22 <scn:settings>
23 <scn:Settings gml:id="ss_future_climate">
24 <!-- Future Climate Scenario Settings -->
25 </scn:settings>
26 <scn:settings>
27 <scn:Settings gml:id="ss_refurbishment">
28 <!-- Refurbishment Scenario Settings -->
29 <!-- PV Adoption Scenario Settings -->
30 <!-- Urban Greening Scenario Settings -->
31 </scn:settings>
32 </scn:SimulationLibrary>
33 </core:cityObjectMember>
34 <gml:featureMember>
35 <scn:VersionTransition gml:id="vt_future_climate">
36 <!-- Future Climate Scenario -->
37 </gml:featureMember>
38 <gml:featureMember>
39 <scn:VersionTransition gml:id="vt_refurbishment">
40 <!-- Refurbishment Scenario -->
41 <!-- PV Adoption Scenario Version Transition-->
42 <!-- Urban Greening Scenario Version Transition-->
43 </gml:featureMember>
44 <gml:featureMember>
45 <scn:Version gml:id="v_base_line">
46 <!-- BaseLine Version -->
47 </gml:featureMember>
48 <gml:featureMember>
49 <scn:Version gml:id="v_future_climate">
50 <!-- Future Climate Version -->
51 </gml:featureMember>
52 <gml:featureMember>
53 <scn:Version gml:id="v_refurbishment">
54 <!-- Refurbishment Version -->
55 <!-- PV Adoption Version -->
56 <!-- Urban Greening Version -->
57 </gml:featureMember>
58 <cityObjectMember>
59 <blgd:Building gml:id="BAG_059910010001S100">
60 <!-- All buildings, building parts, and tree's belonging to the base citymodel (omitted) -->
61 </blgd:Building>
62 </cityObjectMember>
63 </cityModel>
  
```

The 4 Scenarios  
SimulationLibrary (1 Engine & 4 Settings)  
The 4 Version/Transitions  
The 5 Versions (baseline + 4 scenarios)

# Results – SQL Encoding

- Applied the same neighbourhood scale encoding in SQL
  - **5** Version, **4** VersionTransition, **1** SimulationEngine, **4** Settings, **4** Scenario

#	objectclass_id	class_name	n_rows
1	20100	Version	5
2	20110	VersionTransition	4
3	20120	FeatureTransaction	1599
4	20130	AttributeTransaction	30763
5	20200	SimulationLibrary	1
6	20210	SimulationEngine	1
7	20220	Settings	4
8	20300	Scenario	4
9	20310	ScenarioResults	4

# Results – Tracking Scenario Lineage



#	depth	version_gmlid	via_transition_gmlid	scenario_gmlid	scenario_project
1	0	v_baseline	-	-	-
2	1	ver_scn_future_climate	vt_scn_future_climate	scn_future_climate	Feijenoord Future Climate DIN18599 H+C demand under projected climate
3	2	ver_scn_pv_adoption	vt_scn_pv_adoption	scn_pv_adoption	Feijenoord PV Adoption per-surface PV yield + irradiance
4	2	ver_scn_refurbishment	vt_scn_refurbishment	scn_refurbishment	Feijenoord Tabula Advanced Refurbishment surface U-values + post-refurb H/C demand
5	2	ver_scn_urban_greening	vt_scn_urban_greening	scn_urban_greening	Feijenoord Urban Greening trees + post-greening H/C and PV results

# Results – Comparing scenario results

- Scenario Results can be compared directly with SQL directly inside a 3DCityDB instance

#	target_class	target_gmlid	attr_name	uom	Refurbishment_Scenario_2050	Future_Climate_Scenario_2050	delta	pct_change
1	Building	BAG_0599100 000618980	yearlyCoolin gDemand	kWh/a	4026	5314	1288	32
2	Building	BAG_0599100 000618982	yearlyCoolin gDemand	kWh/a	9623	10042	419	4
3	Building	BAG_0599100 000618983	yearlyCoolin gDemand	kWh/a	2792	3607	815	29
4	Building	BAG_0599100 000618984	yearlyCoolin gDemand	kWh/a	21220	25322	4102	19
5	Building	BAG_0599100 000654922	yearlyCoolin gDemand	kWh/a	23625	34791	11166	47

- So, as far as these 4 Feyenoord buildings go, refurbishing buildings does appear to reduce the yearlyCoolingDemand...

# Results – did the schema meet its intentions?

## Trajectory

- From mostly unmet in Beta 3 to **8 out of 11** met in Beta 6

## Three remain partial:

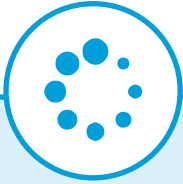
- C1** context stored by naming, not structure
- C2** narrative on inherited description
- ST2** generic-attribute targeting

Design principle	Beta 3	Beta 5	Beta 6
F1 Domain agnosticism	<i>unmet</i>	<i>met</i>	<i>met</i>
F2 Scenario set coherence	<i>partial</i>	<i>unmet</i>	<i>met</i>
F3 Forward compatibility	<i>unmet</i>	<i>met</i>	<i>met</i>
C1 Context independently retrievable	<i>unmet</i>	<i>partial</i>	<i>partial</i>
C2 Horizons & narratives travel	<i>partial</i>	<i>partial</i>	<i>partial</i>
C3 Parameter role (input vs result)	<i>partial</i>	<i>partial</i>	<i>met</i>
ST1 No base-geometry duplication	<i>partial</i>	<i>deferred</i>	<i>met</i>
ST2 Attribute change targets feature	<i>met</i>	<i>deferred</i>	<i>partial</i>
CF1 Reusable simulation settings	<i>unmet</i>	<i>partial</i>	<i>met</i>
CF2 Results traceable to object & run	<i>unmet</i>	<i>unmet</i>	<i>met</i>
CF3 Result types distinguishable	<i>unmet</i>	<i>unmet</i>	<i>met</i>

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2. Research Questions
3. Background
4. Methodology
5. Schema Development
6. Results
7. Discussion
8. Conclusion

# Discussion



## Interpretation

- From scenario theory to scenario data
- Conflation of context and configuration
- Domain agnosticism versus semantic rigidity



## Implications

- Addressing the gap
- Borrowing a provenance standard
- Possible CityJSON Encoding



## Limitations

- Validation in one domain (energy, SimStadt)
- Residual schema gaps
- Interaction is script driven



## Schema Recommendations

- Complete codelists
- Add context value to parameter scope
- Optional narrative slot on *Scenario*
- Generalise configuration class

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# Conclusion – Main research question

How can a Scenario ADE for CityGML 2.0 be **developed** and **implemented** to support the **structured management, analysis, and comparison** of multi-temporal **scenarios** in urban applications, using urban energy as the case study?

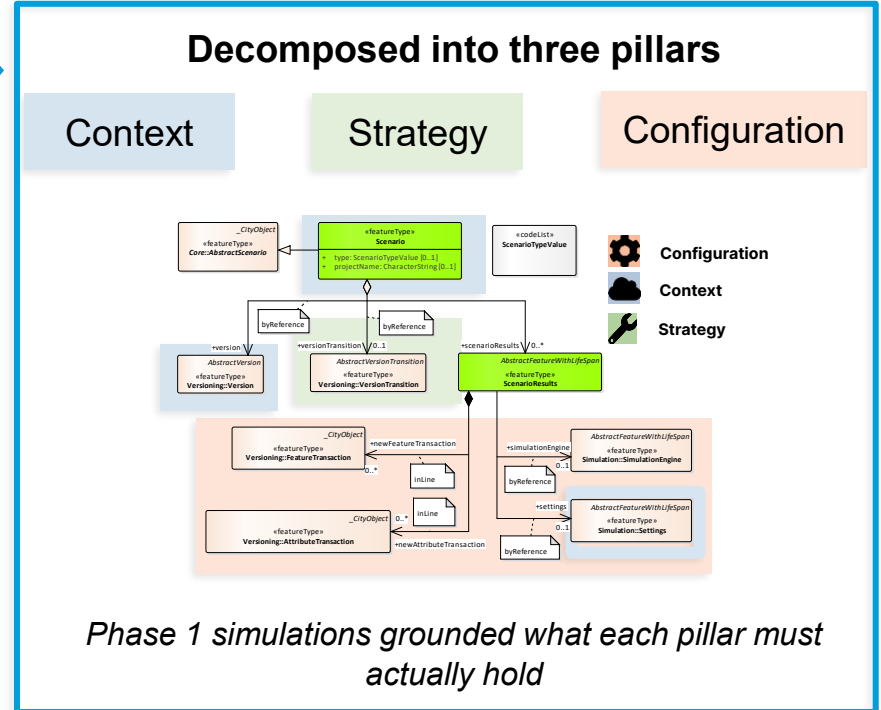
- **Beta 6:** a working Scenario ADE for CityGML 2.0
- Holds several alternative futures of one neighbourhood in a single dataset
- Binds each result back to the run that produced it
- Validated in energy simulations; C1, C2, ST2 still partial

*Contribution: Not a new versioning mechanism, but the binding around one*

# Conclusion – Sub Questions

SQ  
1

How can a scenario be formally decomposed into a structure of entities, properties, and relations that can be managed in the Scenario ADE?



# Conclusion – Sub Questions

SQ  
2

How can an existing Scenario ADE schema be iteratively refined to satisfy the design principles derived from scenario theory and empirical evidence?



- Refined over three Design Science Research Iterations
- From mostly unmet to **8 out of 11** principles met

Design principle	Beta 3	Beta 5	Beta 6
F1 Domain agnosticism	<i>unmet</i>	<i>met</i>	<i>met</i>
F2 Scenario set coherence	<i>partial</i>	<i>unmet</i>	<i>met</i>
F3 Forward compatibility	<i>unmet</i>	<i>met</i>	<i>met</i>
C1 Context independently retrievable	<i>unmet</i>	<i>partial</i>	<i>partial</i>
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CF3 Result types distinguishable	<i>unmet</i>	<i>unmet</i>	<i>met</i>

# Conclusion – Sub Questions

SQ  
3

How can the Scenario ADE be operationalised through its physical encodings to support the management and comparison of urban energy scenarios?



- Two physical encodings: XML and SQL
- Nine foundational operations are possible and XSD valid
- Four Feijenoord scenarios → one shared multiverse which is **28.7% smaller** than separate files
- Lineage recovered in both directions
- Cooling demand compared across scenarios in a single query

#	target_class	target_gmlid	attr_name	uom	Refurbishment_Scenario_2050	Future_Climate_Scenario_2050	delta	pct_change
1	Building	BAG_0599100 000618980	yearlyCoolin gDemand	kWh/a	4026	5314	1288	32
2	Building	BAG_0599100 000618982	yearlyCoolin gDemand	kWh/a	9623	10042	419	4
3	Building	BAG_0599100 000618983	yearlyCoolin gDemand	kWh/a	2792	3607	815	29
4	Building	BAG_0599100 000618984	yearlyCoolin gDemand	kWh/a	21220	25322	4102	19
5	Building	BAG_0599100 000654922	yearlyCoolin gDemand	kWh/a	23625	34791	11166	47

# Future Work

## Direct Improvements

- Apply the recommended refinements
  - Context scope, Narrative slot, Codelists

## Future Work

- Test a non-energy domain (flood / mobility / policy)
  - Is the schema really domain agnostic?
- Test generalizing configuration pillars to a generalized provenance standard (ISO19115 / W3C PROV)
- Migrate to CityGML 3.0, then add a CityJSON encoding.
- Build an application layer / GUI

Thank you!

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