Semantic Consistency in Model-Driven Development

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What is consistency of models?

Pragmatic intuition

Models are consistent if they can be jointly realised.

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Relational view

Let $\mathrm{MM}_1, \ldots, \mathrm{MM}_n$ be meta-models, interpreted as sets of valid models. A consistency relation is

$$\mathrm{CR} \subseteq \mathrm{MM}_1 \times \cdots \times \mathrm{MM}_n.$$

Models $m_1 \in \mathrm{MM}_1, \ldots, m_n \in \mathrm{MM}_n$ are consistent iff

$$(m_1, \ldots, m_n) \in \mathrm{CR}.$$

Consistency Specification

From relation to specification

A consistency relation defines which model tuples are consistent:

$$CR \subseteq MM_1 \times \cdots \times MM_n$$

A *consistency specification* is an artefact that induces such a relation.

How to specify

- constraints or predicates
- model transformations
- consistency checkers
- formal semantics
- domain-specific rules

Consistency becomes explicit by specifications that tools and engineers can use.

Consistency Preservation Rules

Before a change

The models are consistent:

$$(m_1, \ldots, m_n) \in \text{CR}$$

Then a developer changes one or more models:

$$\delta_1, \ldots, \delta_n$$

After preservation

A preservation rule derives adapted changes:

$$\delta'_1, \ldots, \delta'_n$$

such that consistency is restored:

$$(\delta'_1(m_1), \ldots, \delta'_n(m_n)) \in \text{CR}$$

Models in CPS

- Heterogeneous multidisciplinary models and analyses.
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Syntactic Consistency

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Semantic Consistency

- Meanings agree
- Behaviours are compatible
- Analyses use coherent assumptions
- **Overlapping** system properties are not contradicted

From SUM to *V-SUM*

SUM - Single Underlying Models

- Views over one single monolithic model
- Consistency by construction

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V-SUM - Virtual Single Underlying Models

[Ralf Reussner+'21]

- Multiple heterogeneous models
- Diverse specialised tools
- Cross-view dependencies

Analyses as First-Class Citizens

Heterogeneous models and analyses

- **Mechanical domain:**
  - Multi-body dynamics simulation → Mechanical models (mass, force)
  - Fault Tree Analysis (FTA) → System failure models
- **Electrical domain:**
  - Circuit simulation → Circuit models (voltage, current)
  - Failure Mode and Effects Analysis (FMEA) → Component failure models
- **Software domain:**
  - Verification → Behavioural models (state machines, specs)
  - Static code analysis → Source code
  - Code reviews and compliance checks → code, guidelines

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After model changes

- Which previous analysis results remain valid?
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Current practice is often conservative, leading to excessive reruns and delayed certification and updates.

Gap in current *V-SUM* theory

V-SUM integrates heterogeneous models through explicit mappings and consistency relations for multiple metamodels.

What existing *V-SUM* does well

- Models as first-class artefacts
- Consistency relations across models
- Propagation of model (syntactical) changes via consistency preservation rules

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- Dependencies between analyses are implicit
- No analysis-aware consistency management
- No formal basis for selective re-execution

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Our goal is to make analyses first-class citizens alongside models.

Formal model of an analysis

$$f : I \otimes C \otimes P \rightarrow \mathit{Validity} \otimes \mathit{Evidence}$$

Input

- I: input models subject to analysis
- C: preconditions, e.g., Java installed for JUnit tests
- P: properties for I, expressed with observables

Output

- $\mathit{Validity} \in \{\text{true}, \text{false}\} \Leftrightarrow i \vDash p$
- Evidence: proofs, traces, CEs, reports, ...

Observables: measurable or derivable properties of models (e.g. physical quantities, constraints).

Model relations between input artefacts and reusable analysis results.

Compositionality

Compositionality

Local analyses achieve local goals:

$$f_{g_1} \vDash g_1, \ldots, f_{g_n} \vDash g_n$$

Together they entail a global goal:

$$\bigwedge_i (f_{g_i} \vDash g_i) \Longrightarrow f_G \vDash G$$

Essential for safety assurance cases (e.g., ISO 26262): certification goals are built from local analyses.

Model consistency defined via analyses

General view

A tuple of heterogeneous models

$$m = \langle m_1, \ldots, m_n \rangle$$

is consistent w.r.t. a global goal G ($m \in CR_G$) if its set of analyses

$$F = \{f_{g_1}, \ldots, f_{g_n}\}$$

achieves local goals g_i and

$$\bigwedge_{i=1}^{n} g_i \Longrightarrow G$$

Observable-based view

- Analyses evaluate properties over observables of models
- Consistency requires compatibility of observables across models

$$CR_G = \left\{ \langle m_1, \ldots, m_n \rangle \;\middle|\; (Obs(m_1), \ldots, Obs(m_n)) \in R_G \right\}$$

R_G: cross-model compatibility relation of observables for goal G

Analysis Dependency Graph (ADG)

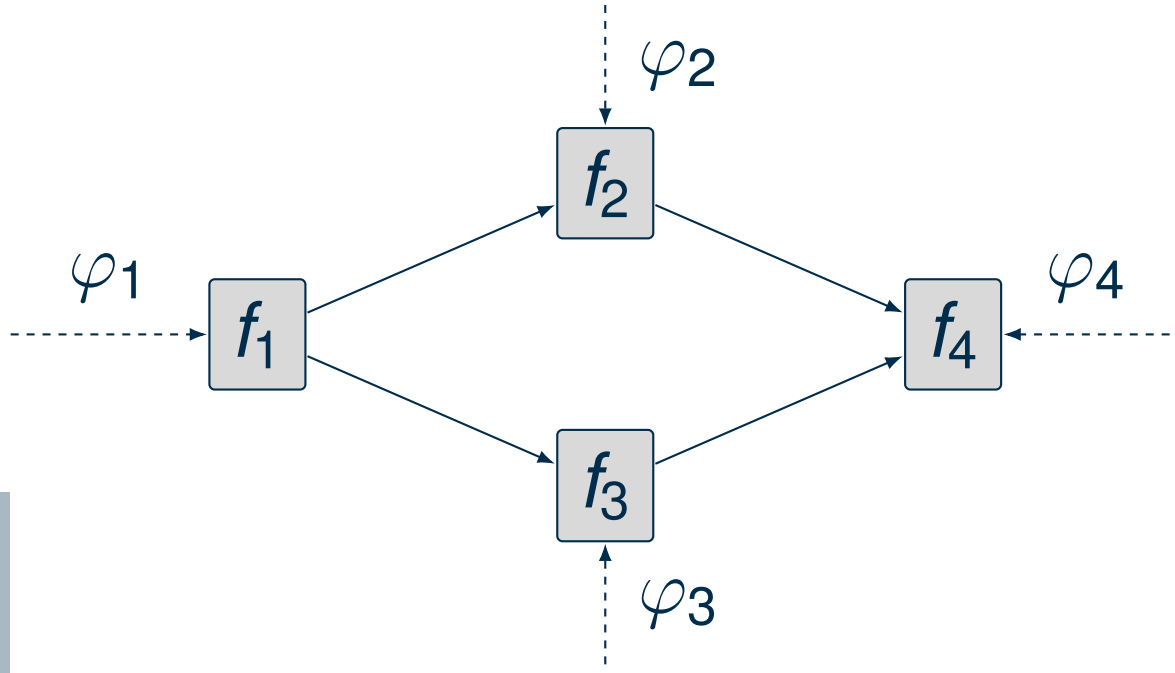
An ADG is a directed graph

$$A = (V, E, \Phi)$$

where:

- nodes = instantiated analyses
- edges = activation and dependency relations
- Φ = trigger functions inspect the model delta on observables. $\varphi(\Delta_{\text{weight}}) = |\Delta_{\text{weight}}| \geq 10$

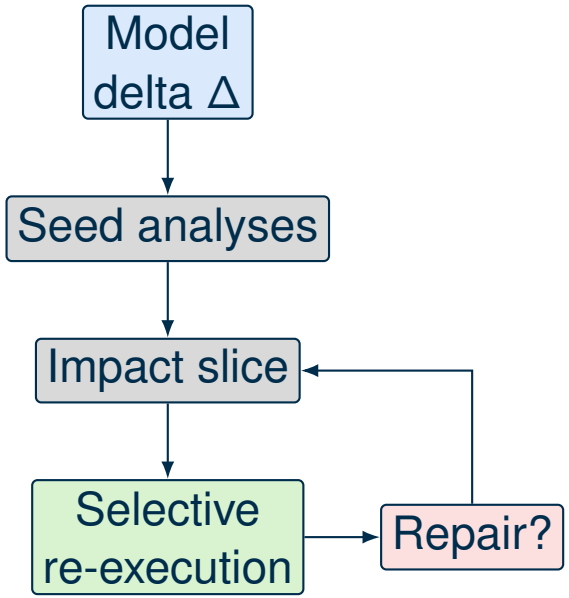
A change does *not* necessarily require a full rerun. Analysis slice detected using triggers and use-define relations over observables.



Incremental recertification by analysis slicing

1. **Find initially affected analyses by triggers**
2. **Compute the impact analysis slice (based on use-define relations over observables)**
3. **Rerun only the impact slice topologically**
4. **If repair introduces new deltas, slice again**

Only the semantically affected subset (i.e., core analyses) is re-executed.



Core analysis theorem

$$(F \models G) \iff (F_{\text{core}} \models G)$$

Why safe?

Analyses outside the slice:

- are unaffected by the change
- would reproduce the same result

Why complete?

All analyses that could influence G:

- are reached via dependencies
- are included in the slice

Integration into *V-SUM*

$$V\text{-}SUM^{+} = \langle M,\ F,\ CR,\ CR^{+} \rangle$$

Classical *V-SUM*

- ***M*: domain models**
- ***CR*: domain-to-domain consistency relations**

Our extension

- ***F*: analysis models**
- ***CR*$^{+}$: domain-to-analysis relations via triggers**

Result: consistency management becomes analysis-aware, not only model-aware.

Preliminary Evaluation

Model Change (Δ)	Re-executed	Saved
Software-development		
Comment-only change in code	f_{rel}	4
Decrease of coverage threshold ($\theta_{cov} \downarrow$)	f_{rel}	4
Method added	f_{stat}, f_{cov}, f_{rel}	2
Method removed	f_{stat}, f_{test}, f_{rel}	2
Test added	f_{test}, f_{rel}	3
Test removed	f_{cov}, f_{rel}	3
Safety-critical code changed	f_{stat}, f_{rev}, f_{rel}	2
Guideline rule added	f_{rev}, f_{rel}	3
Increase of coverage threshold ($\theta_{cov} \uparrow$)	f_{cov}, f_{rel}	3
Sum		**26/45**
Average (9 changes)		**2.9/change (58%)**
ISO 26262 safety-assurance		
Hazard or ASIL added	f_{hara}, f_{req}, f_{ver}	0
New or modified safety requirement	f_{req}, f_{ver}	1
Verification artefacts changed	f_{ver}	2
Sum		**3/9**
Average (3 changes)		**1.0/change (33%)**

Consistency between Requirements

Requirements come first

- Early system intent
- Shared stakeholder view
- Basis for models and code
- Mostly natural language

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Late-discovered requirement inconsistencies propagate into models, code, and tests.

Final integration stage ⇒ expensive repair.

Example: Braking-system requirements

```
The braking system consists of a mechanical pedal/booster
assembly, an electronic sensing unit, and a software
controller. The driver's pedal effort is converted
mechanically into brake actuation force. The electronic
unit measures the resulting pedal force and produces a
digitised signal. The software controller consumes the
sensor signal and computes a brake torque command, which
is then provided to the actuator.
=== Mechanical Requirements Specification ===
MRS-001: The pedal effort produced by the driver shall be
within the range [0, 300] N.
=== Electronic Requirements Specification ===
ERS-001: The measured pedal force reported by the sensor
shall lie within the range [400, 500] N.
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SRS-001: The brake torque command shall be valid whenever
the reported pedal force is at least 50 N.
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Are these terms synonyms? In the context:

$$[0, 300] \cap [400, 500] = \emptyset$$

Requirements are inconsistent

Recall Observables

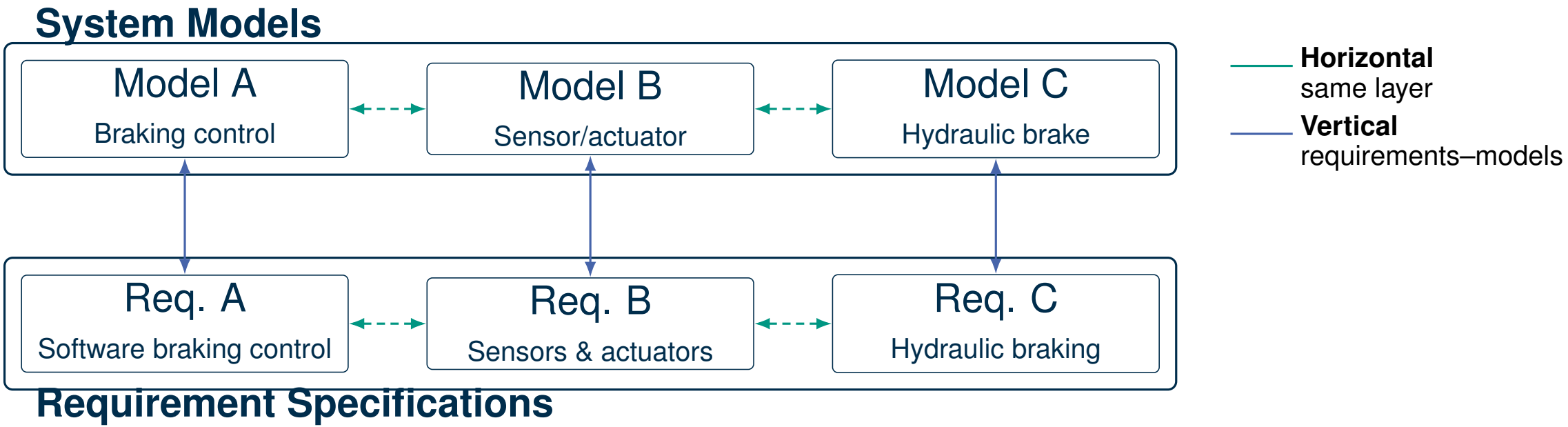
$$o = \langle n, T, C \rangle$$

- n: observable name
- T: observable type: numerical or categorical
- C: constraints over o (e.g., $[0, 300] \cup [400, 500]$)

$$\mathcal{O} = \{ o_1, \ldots, o_k \}$$

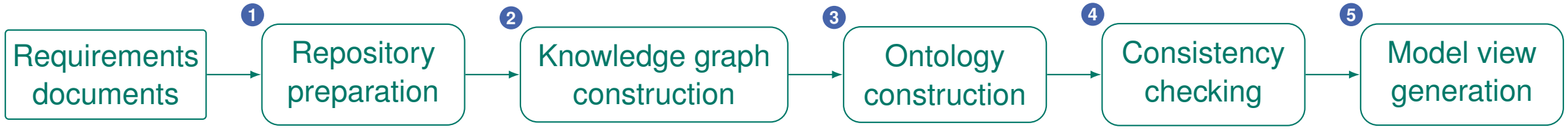
- Shared by requirements and models
- Common observable space between requirements and models
- Basis for solver-based reasoning

Horizontal and Vertical Consistency



All consistency relations are checked through shared observables.

RAG4C: A Semantics-Grounded Pipeline



LLMs extract; ontologies align; solvers decide.

Stage 1: Repository Preparation

What we remove

- Headers and footers
- Page numbers
- Administrative metadata
- Figures and diagrams

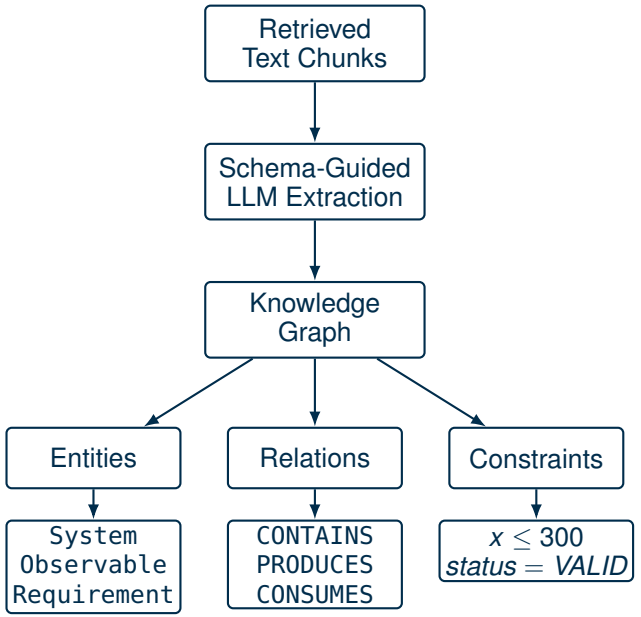
What we keep

- System descriptions
- Requirement statements
- Observable-bearing text
- Source document identifiers

Outcome

A clean, traceable corpus for retrieval-augmented observable extraction.

Stage 2: Knowledge Graph Construction



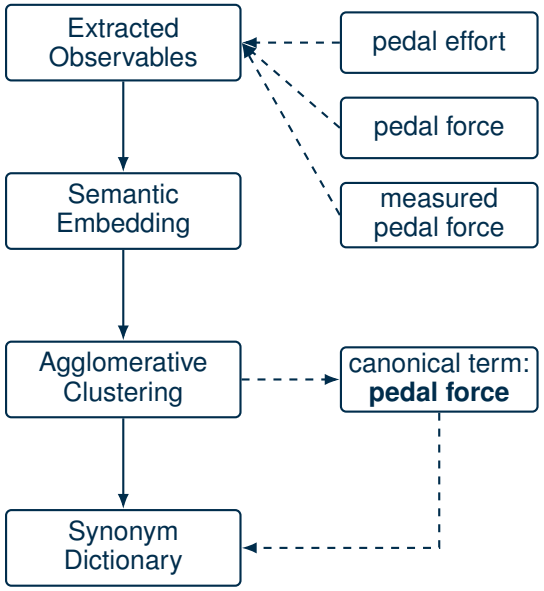
What happens?

- Requirements are processed as retrieval chunks
- LLM extracts only allowed entity and relation types
- Constraints are normalised into a machine-readable form

Outcome

A traceable knowledge graph that links requirement text to observables, systems, relations, and constraints.

Stage 3: Ontology Construction



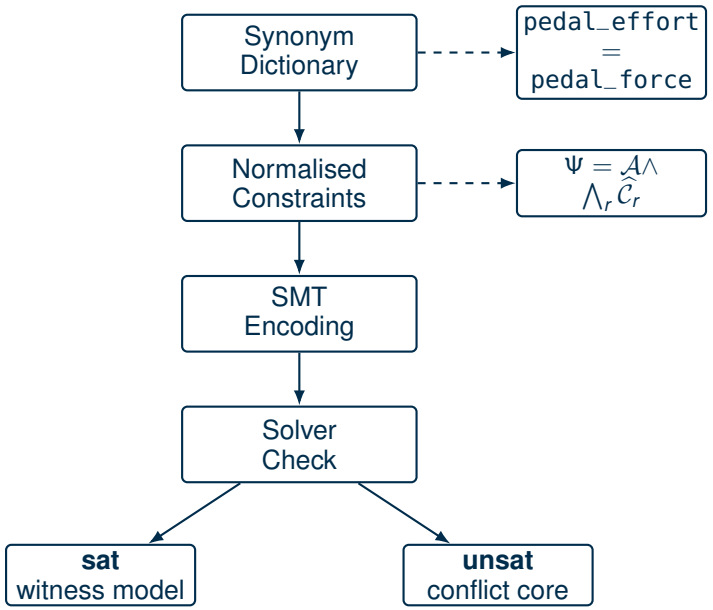
What happens?

- Extracted observables are embedded with their context
- Semantically close terms are clustered
- Each cluster receives one canonical ontology term
- Raw names remain traceable through the synonym dictionary

Outcome

A semantic vocabulary with unified terms.

Stage 4: Consistency Checking



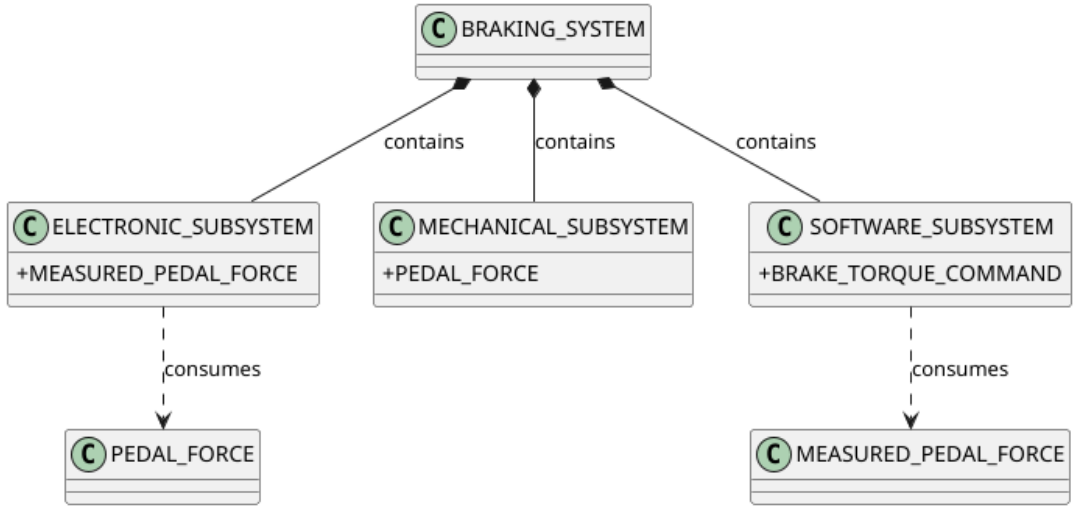
What happens?

- Aliases are encoded as equalities
- All constraints are rewritten using canonical observable names
- The conjunction is checked by an SMT solver
- Results are mapped back to source requirements

Outcome

Consistency becomes a satisfiability question, with evidence for both consistency and inconsistency.

Stage 5: Model View Generation



What happens?

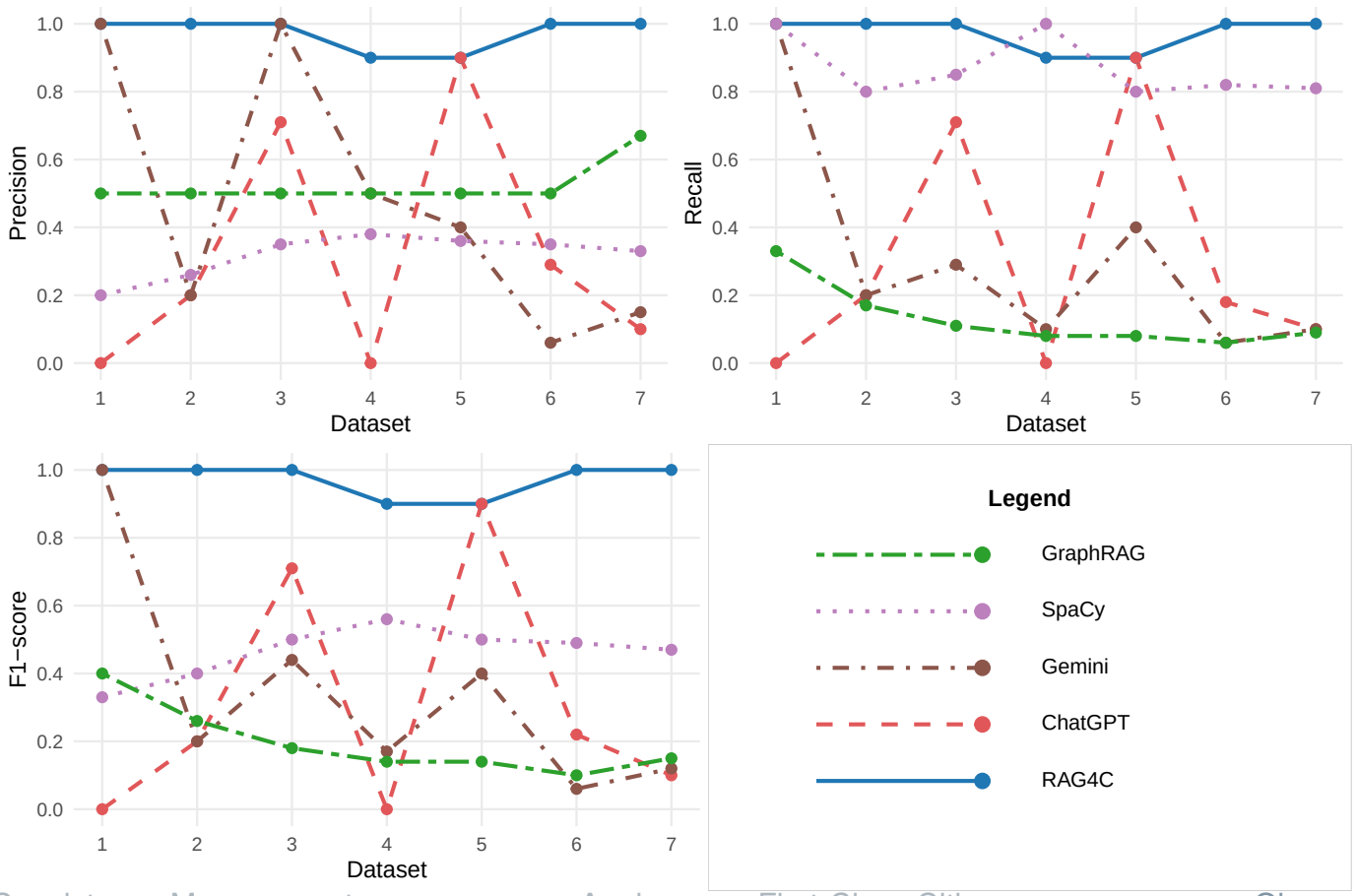
- Transform the extracted graph into a structural model view
- Map `System` entities to classes
- Map observables to attributes
- Map relations to associations

It is not the final design, but helps engineers inspect the extracted systems, observables, and dependencies.

Evaluation setting

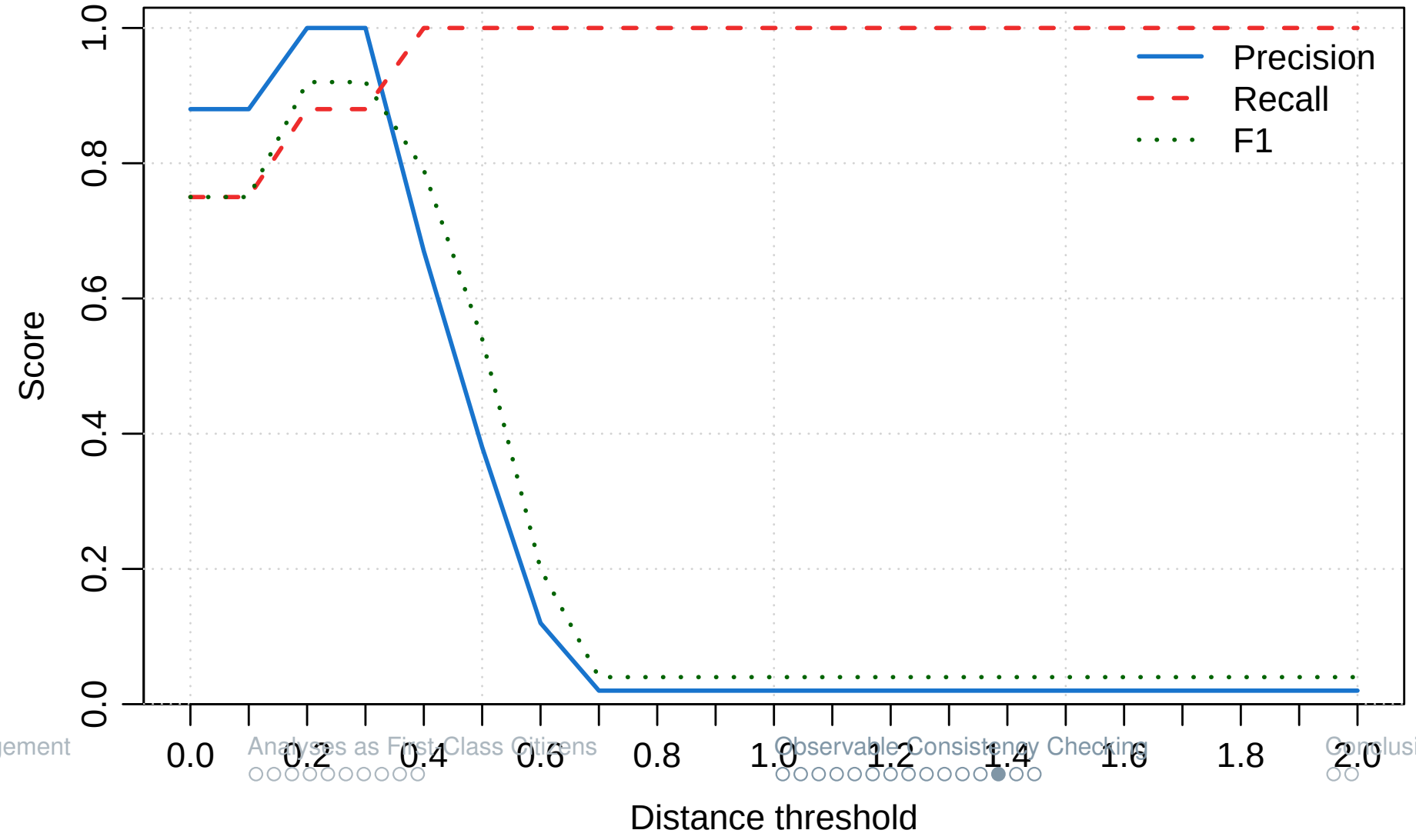
- Synthetic automotive datasets: 7 small human-validated sets + 3 larger scalability sets (A, B, C).
- Industrial requirements: EU project AI$_4$CSM deliverables.
- Baselines: ChatGPT, Gemini, spaCy, and GraphRAG.

Evaluation: observable extraction and synonym groupin



- Observable extraction: macro/average F1 0.99
- Synonym grouping: macro/average F1 0.97

Evaluation: trend of clustering distance threshold



Evaluation: scalability

Data	#Req	Time	Result
A	30	25.3s	UNSAT
B	300	82.7s	UNSAT
C	3000	414.9s	UNSAT
AI_4CSM	151	232.3s	SAT

Most runtime is spent on knowledge-graph construction

$>$ 2 days manual check *V.S.* about 2 minutes automated check + 1 hour manual check.

What have we learned?

Observables
make heterogeneous artefacts comparable.

LLMs
extract candidates, but do not decide on consistency.

Ontologies
make terminology explicit across disciplines.

Solvers
provide evidence: assignments or conflicts.

What are the main contributions?

- Formalisation of analyses and dependencies
- Incremental recertification procedure
- Analysis-aware *V-SUM*
- Ontology-driven extraction of observables and constraints
- Observable consistency across requirements and models

What remains?

- Modular analysis specification language (in progress)
- Unit normalisation and dimensional analysis (in progress)
- Domain-specific trigger function construction (in progress)

Thank you!