From Simulation Outputs to Explainable C4I Insights

Neuro-Symbolic Approaches for MDO Planning and Critical-Sector Resilience

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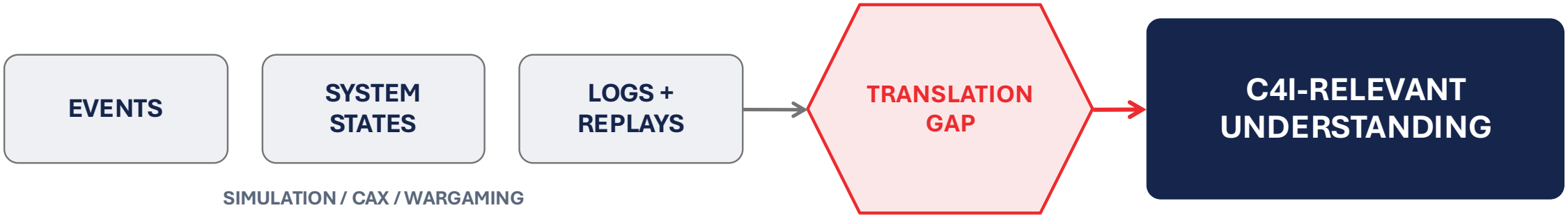
We do not lack outputs. We lack operational meaning.

Simulation evidence becomes useful only when its meaning, timing and assumptions remain visible.



SEMANTIC GROUNDING

TEMPORAL CONTEXT

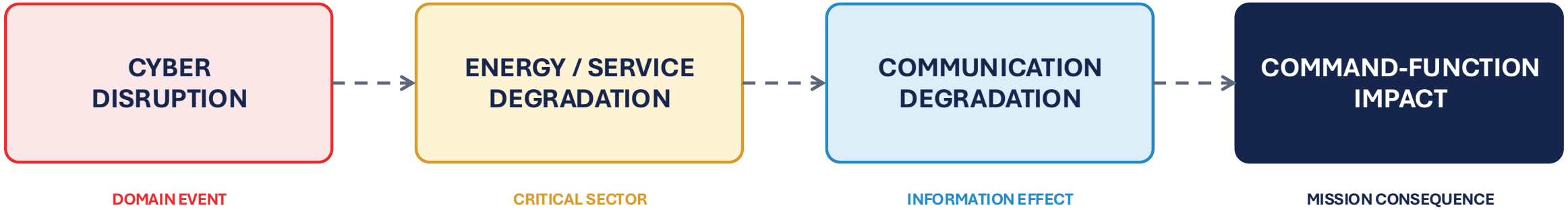
CONSTRAINTS + ASSUMPTIONS

TRACEABLE EVIDENCE

The analytical bottleneck is translation — not data volume.

MDO is a dependency problem

The operational meaning often lies in relationships between events—not in any isolated event.

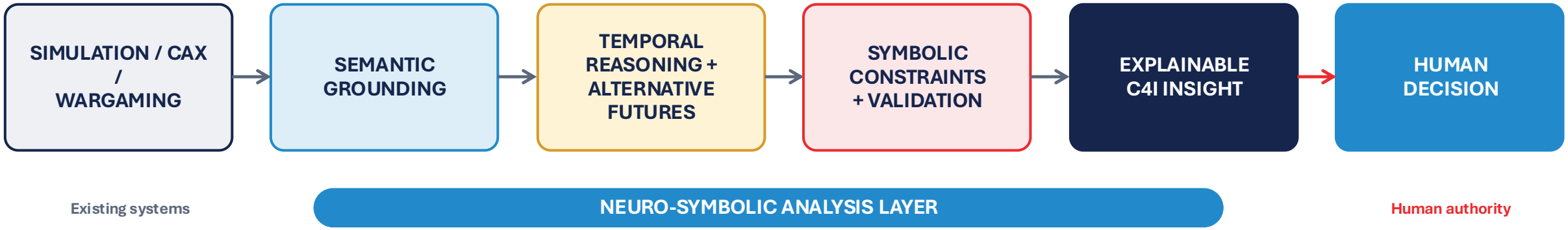


Illustrative pathway

Dependencies expose possible propagation paths; they do not establish deterministic causality.

A bridge, not a replacement

Preserve the full chain from simulated dynamics to human verification.



The value is continuity: evidence, semantics, assumptions and constraints stay connected.

Why neural + symbolic + human?

The value comes from composition—each part resolves a different analytical limitation.

1

DATA-DRIVEN / GENERATIVE AI

Patterns
Temporal dynamics
Alternative futures

+

2

SYMBOLIC KNOWLEDGE

Meaning
Dependencies
Constraints + traceability

+

3

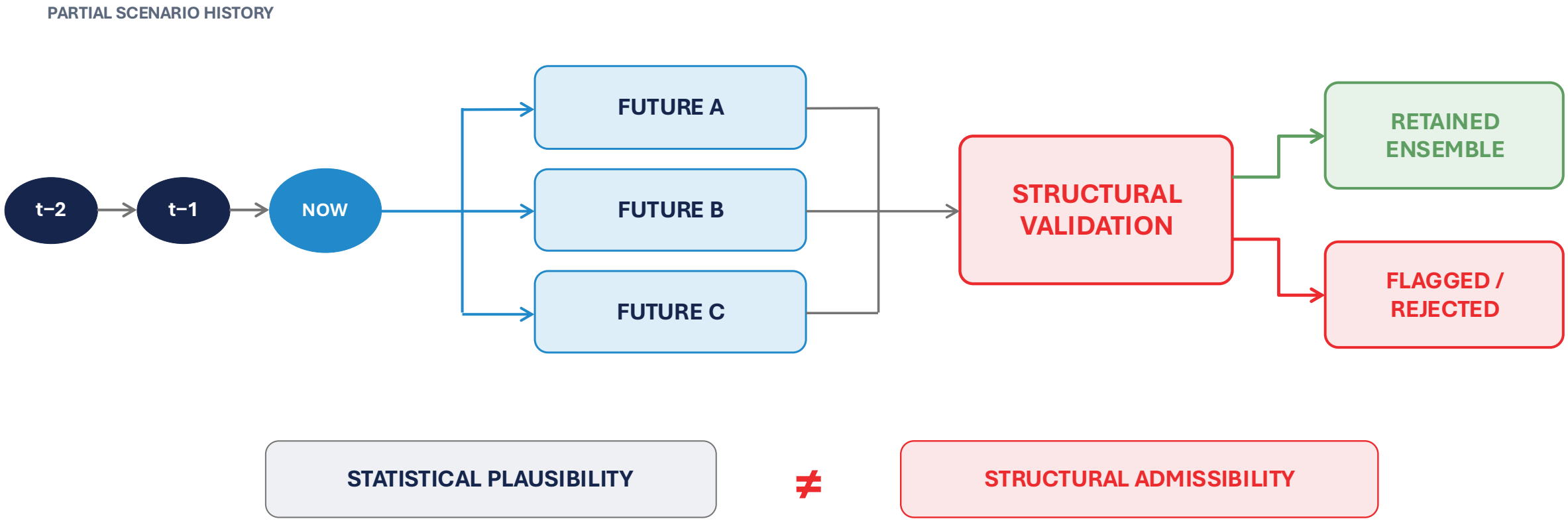
HUMAN JUDGEMENT

Context
Verification
Decision authority

No single component supplies pattern discovery, explicit admissibility and accountable judgement by itself.

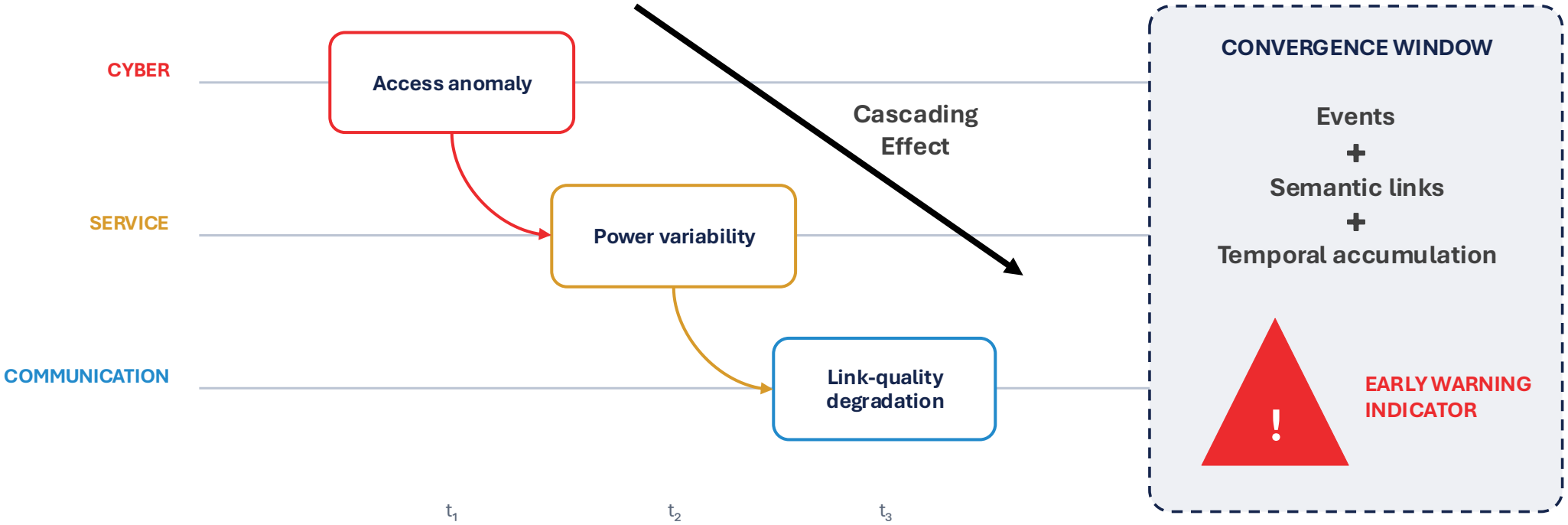
ENRICH — Explore alternative futures under constraints

Explore more futures without assuming that every generated future is valid.



WARN — See cascades before they converge

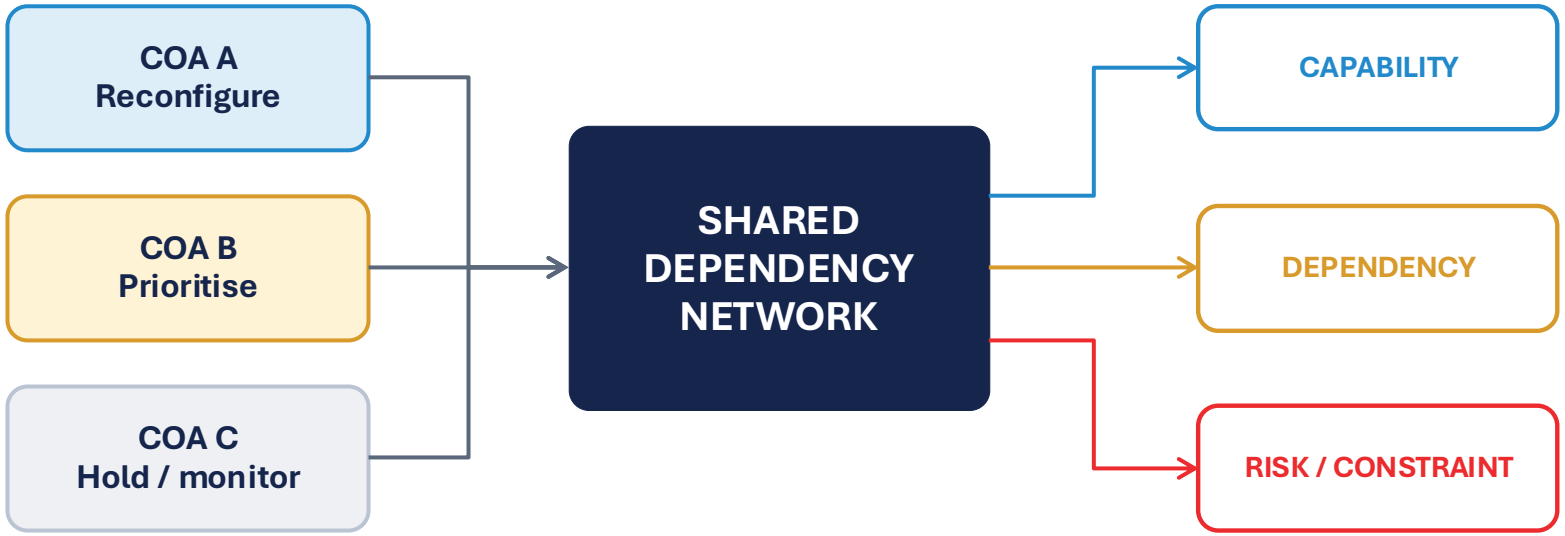
Individual signals may appear weak; their temporal and structural convergence may not.



Reason over distributed evidence—not only isolated alerts.

COMPARE — Make COA consequences inspectable

Do not ask only which option looks best. Ask what supports each assessment.



INSPECTION QUESTIONS

- What assumptions support it?
- Which capabilities become critical?
- Which constraints activate?
- Where can second-order effects emerge?
- What evidence supports the assessment?

Transparent comparison—not automated selection of a ‘best’ COA.

Incremental integration with the CAX ecosystem

Add an analysis layer without rebuilding the simulation, C4I or command stack.

POTENTIAL EXCHANGE PATHS

HLA	C2SIM	MSaaS
Federation path	Semantic exchange path	Service-delivery path

CONCEPTUAL COMPATIBILITY ≠ IMPLEMENTED INTEROPERABILITY ≠ OPERATIONAL DEPLOYMENT

Wargaming and CAX as a validation environment

Use WG & CAX experiments to test analytical value, verification burden and integration assumptions.

EXPERIMENTAL INPUTS

- Scenario variants
- Degraded / uncertain data
- Roles + decision tasks

INSTRUMENTED WG/CAX EXPERIMENT

Human players • structured state • logged decisions
optional semantic / temporal / validation services

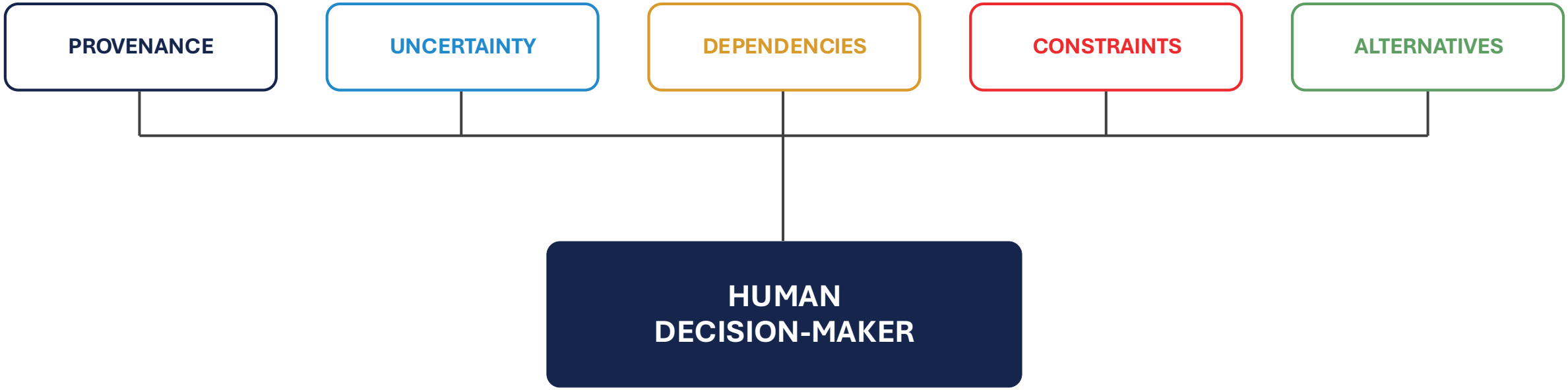
EVALUATION EVIDENCE

- **Traceability**
  Can users recover the basis?
- **Timeliness**
  Does insight arrive early enough?
- **Verification burden**
  Can staff challenge it in practice?

Compare baseline and augmented workflows.
Evaluate each service before making integrated capability claims.

Explainable means inspectable

An explanation is useful only if evidence and assumptions remain recoverable.



A viable path to verification—not merely a final approval button.

From research components to collaborative capability

WHAT WE HAVE STUDIED

- Ontology-centred architectures
- Ontology-guided information structuring
- Temporal structural reasoning
- Learned scenario continuation + validation
- Digital human-in-the-loop wargaming

WHAT WE STILL NEED TO TEST TOGETHER

- Integrated CAX workflows + interoperability
- Larger heterogeneous simulation environments
- Degraded and uncertain semantic conditions
- Operator interaction + human factors
- Operationally meaningful validation criteria

M&S + INTEROPERABILITY

AI + KNOWLEDGE ENGINEERING

HUMAN-CENTRED C4I

From simulated events to trusted operational evidence.

Questions

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GOOGLE SCHOLAR

ORCID

Research foundations

Five connected studies support the workflow:

SEMANTIC ARCHITECTURE [1] → **ONTOLOGY-GUIDED STRUCTURING** [2] → **TEMPORAL REASONING** [3] → **SCENARIO CONTINUATION + VALIDATION** [4] → **DIGITAL WARGAMING** [5]

[1] Romei de Socio, Pozzato & Merlo — A Scalable Ontology-Driven Architecture for Situational Awareness and Decision Support in Multi-Domain Operations.

[2] Romei de Socio, Pozzato & Merlo — When Ontologies Guide LLMs: A Controlled Study of Zero-Shot Schema-Aligned Information Extraction.

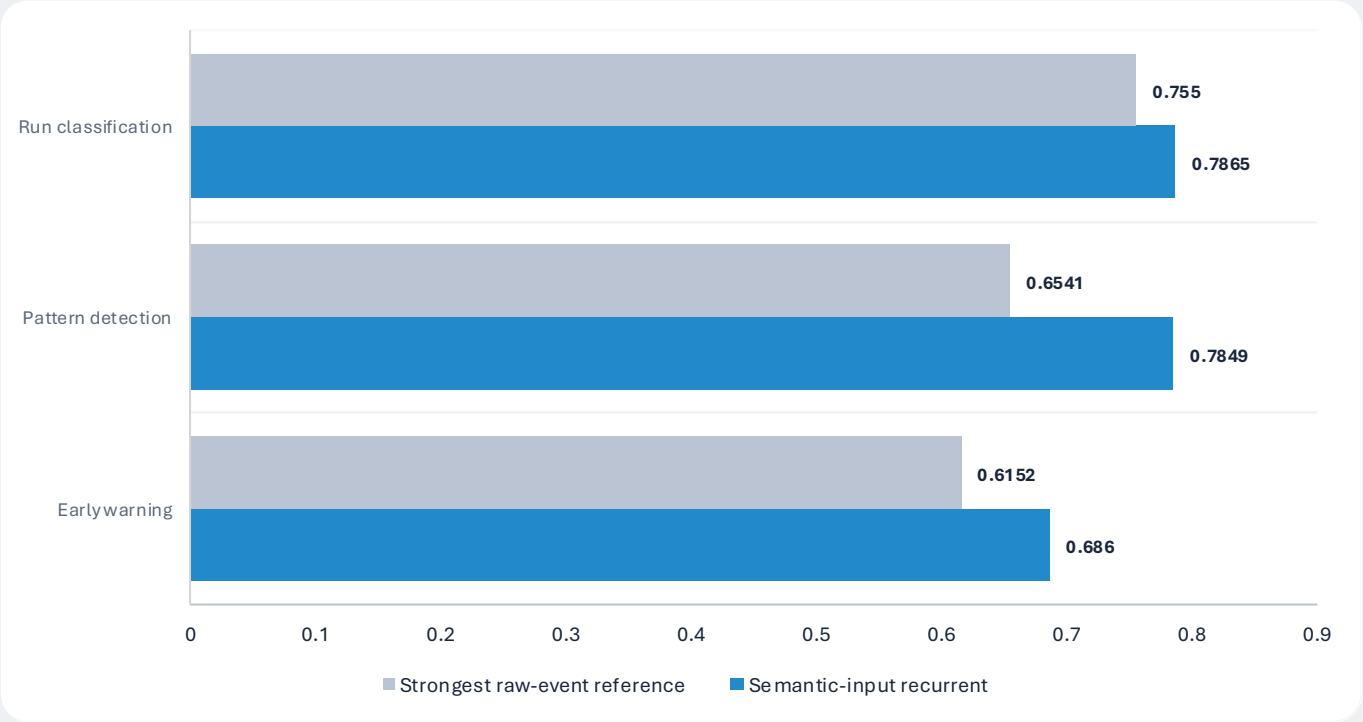
[3] Romei de Socio, Pozzato & Merlo — TRACTA: Benchmarking Temporal Reasoning over Semantic Trajectories.

[4] Romei de Socio, Pozzato & Merlo — Learning and Structurally Validating Simulation Scenario Continuations in Dynamic Graph Systems.

[5] Romei de Socio, Bernardi & Merlo — From Tabletop to Web Application: A Lightweight and Modular Architecture for Politico–military Digital Wargaming.

Selected experimental evidence

TRACTA — semantic-input recurrent configuration vs strongest raw-event reference [3]



SCENARIO CONTINUATION [4]

Medium-complexity synthetic regime

Generated invalid mass 15.59%

Hard filter retained 84.41%

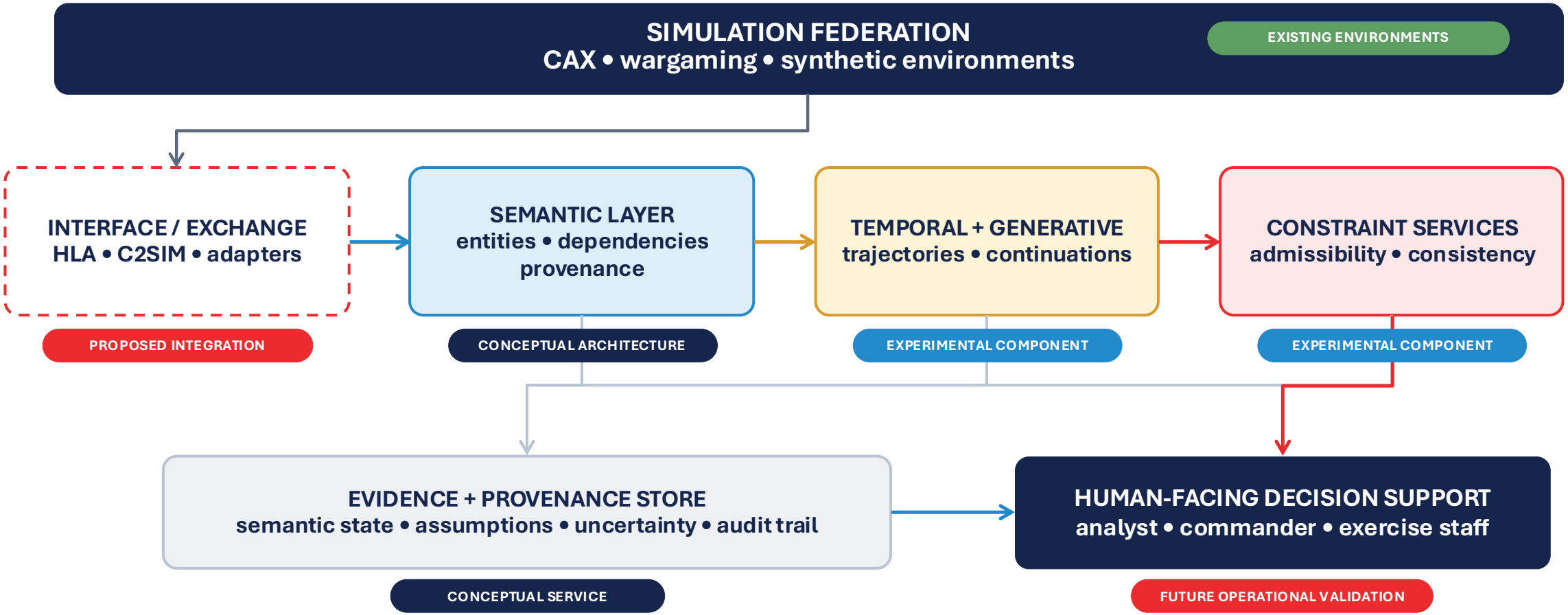
Invalid mass after hard filter 0% in retained ensemble

Both studies use synthetic data. Results support method feasibility—not operational effectiveness.

[3] Romei de Socio, Pozzato & Merlo — TRACTA: Benchmarking Temporal Reasoning over Semantic Trajectories, https://doi.org/10.48550/arXiv.2607.22365.
[4] Romei de Socio, Pozzato & Merlo — TRACTA: Benchmarking Temporal Reasoning over Semantic Trajectories, https://doi.org/10.48550/arXiv.2607.21421.

BACKUP 3 — Integration architecture and maturity

Every status label applies to its own block; arrows show the proposed evidence flow.



No status applies to the complete diagram as an integrated deployed system.