The Composition of Digital Twins for Systems-of-Systems: A Systematic Literature Review

Mennatullah T. Khedr and John S. Fitzgerald
m.t.y.a.khedr2@newcastle.ac.uk,
john.fitzgerald@newcastle.ac.uk,
mengwei.xu@newcastle.ac.uk.

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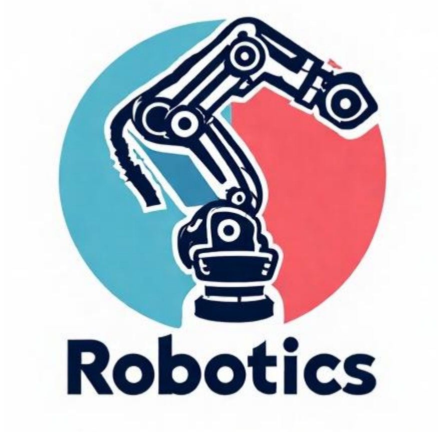
1. **Background & Motivation**

Background: CPS and SoS

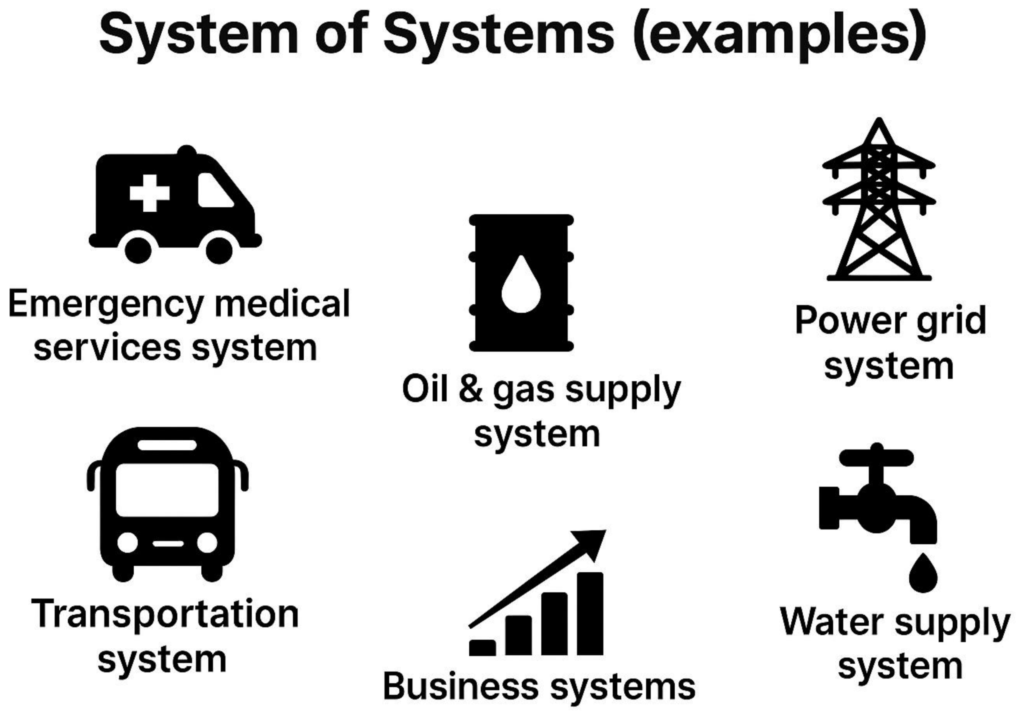
Cyber-Physical Systems (CPS): Interacting computational & physical processes.



Background: CPS and SoS

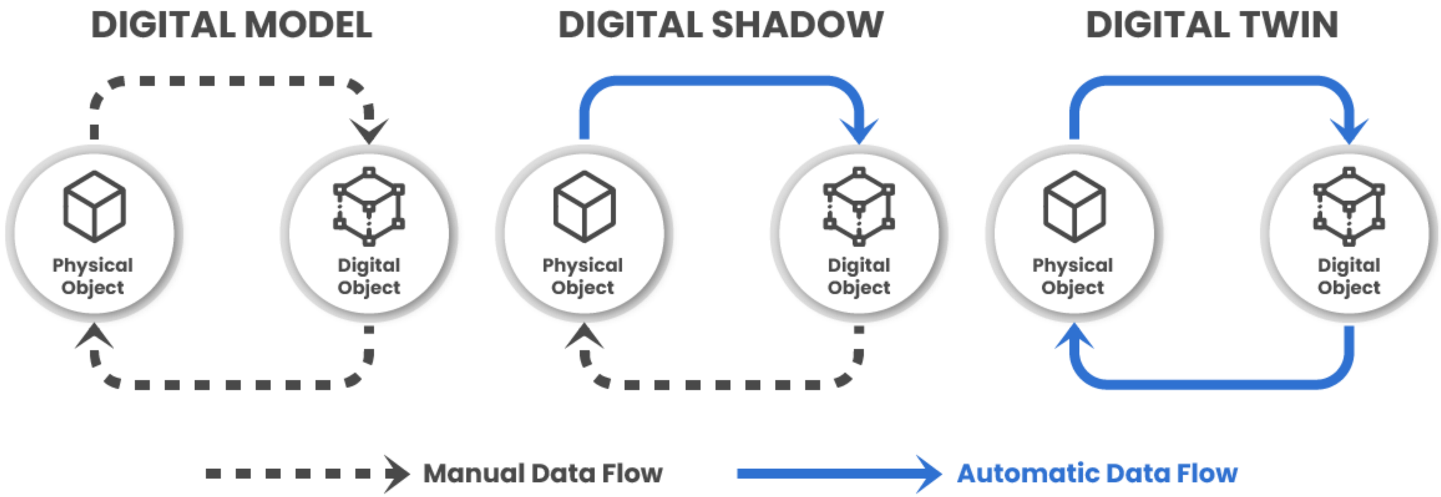
Integrating CPSs form a System-of-CPSs (SoCPSs)

- **Systems-of-Systems (SoS):** Independently managed constituent systems.
- **SoS Engineering** face challenges from heterogeneity, complexity, dynamic/uncertain environments.



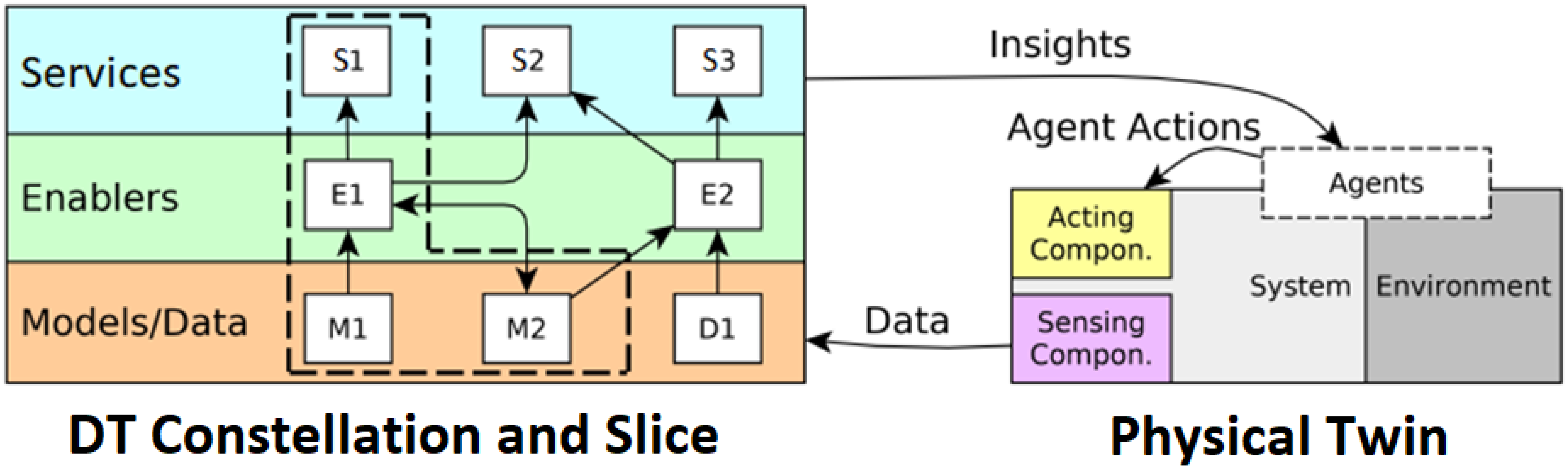
Digital Twins

- **DT:** Synchronized virtual representation of a system (Physical Twin).
- **Core:** Abstract model(s) of PT aspects for purpose/context.



The Role of Digital Twins

- **Value:** Analysis, simulation, optimization for performance, fault prediction, decision-making.



Motivation

- Increasing CPSs / SoSs complexity demands robust Digital Twins.
- **Key Gap:** Lack of formal Validation & Verification (V&V) frameworks for Digital Twins in SoSs.

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Research Questions

1. What are the current approaches and **integration patterns** used in the **composition of DTs** within SoS contexts?

2. What **system-level properties and quality attributes of DTs** are addressed in studies focusing on their V&V?

3. What are the existing **approaches for verifying and validating DTs** within SoS contexts?

4. What **challenges** are identified in the **verification and validation of DTs** within SoS environments?

Protocol & Information Sources

Sources: ACM Digital Library - IEEE Xplore - Scopus – Web of Science - Engineering Village

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles, conference papers, and book chapters	Duplicates across multiple databases
Publications on DT composition.	Studies not discussing DTs as the main topic
Explicit discussion of V&V of DTs of CPSs, SoSs, or complex systems	Publications not discussing verification/validation or composition
2021 onwards	
English	

Search Results

Data Source	#Papers
Scopus	164
Web of Science	120
IEEE Xplore	43
ACM Digital Library	35
Engineering Village	28

Publications were classed as:

- Relevant
- Maybe Relevant
- Irrelevant.

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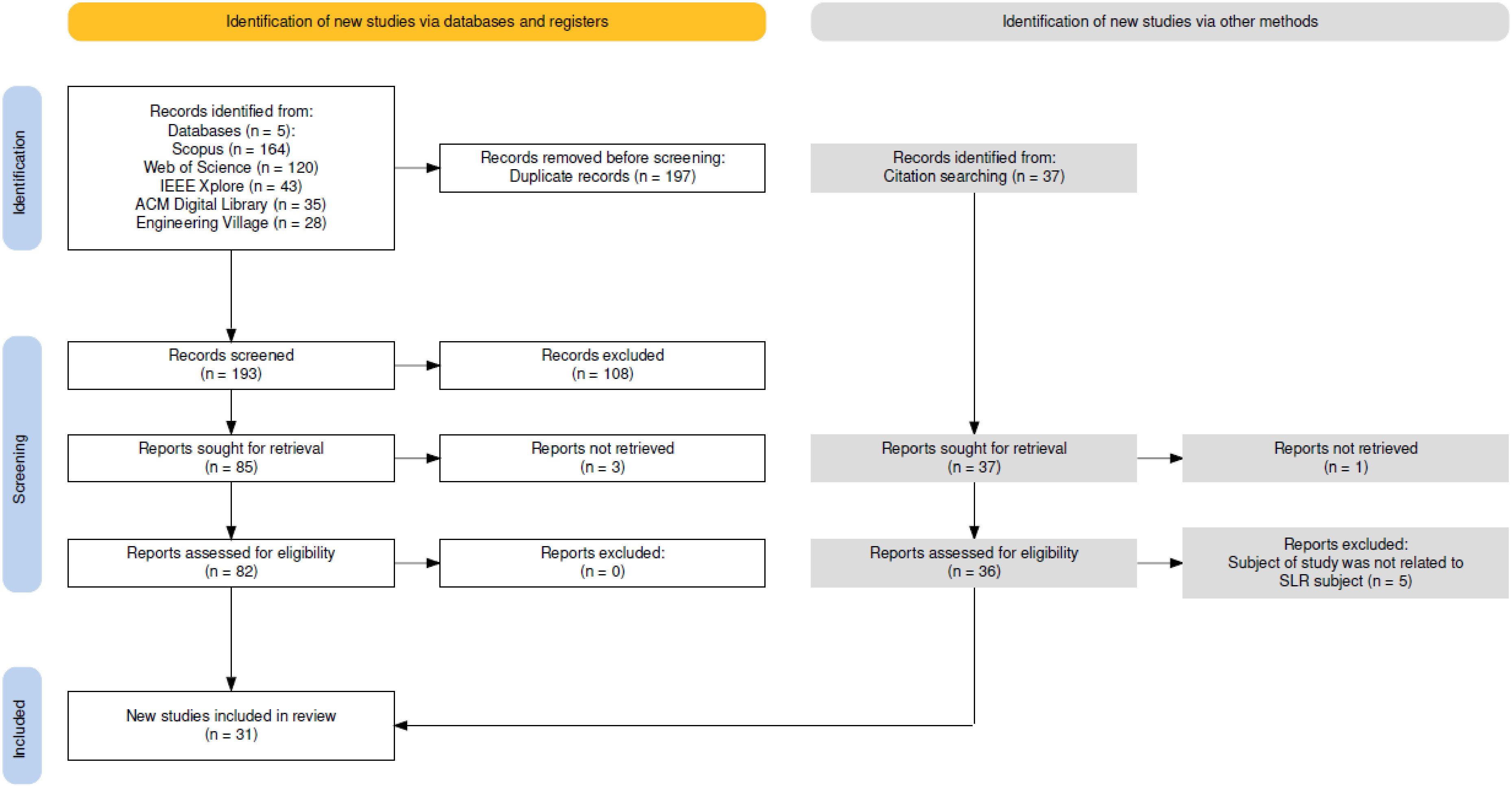
PRISMA 2020 flow diagram for the SLR



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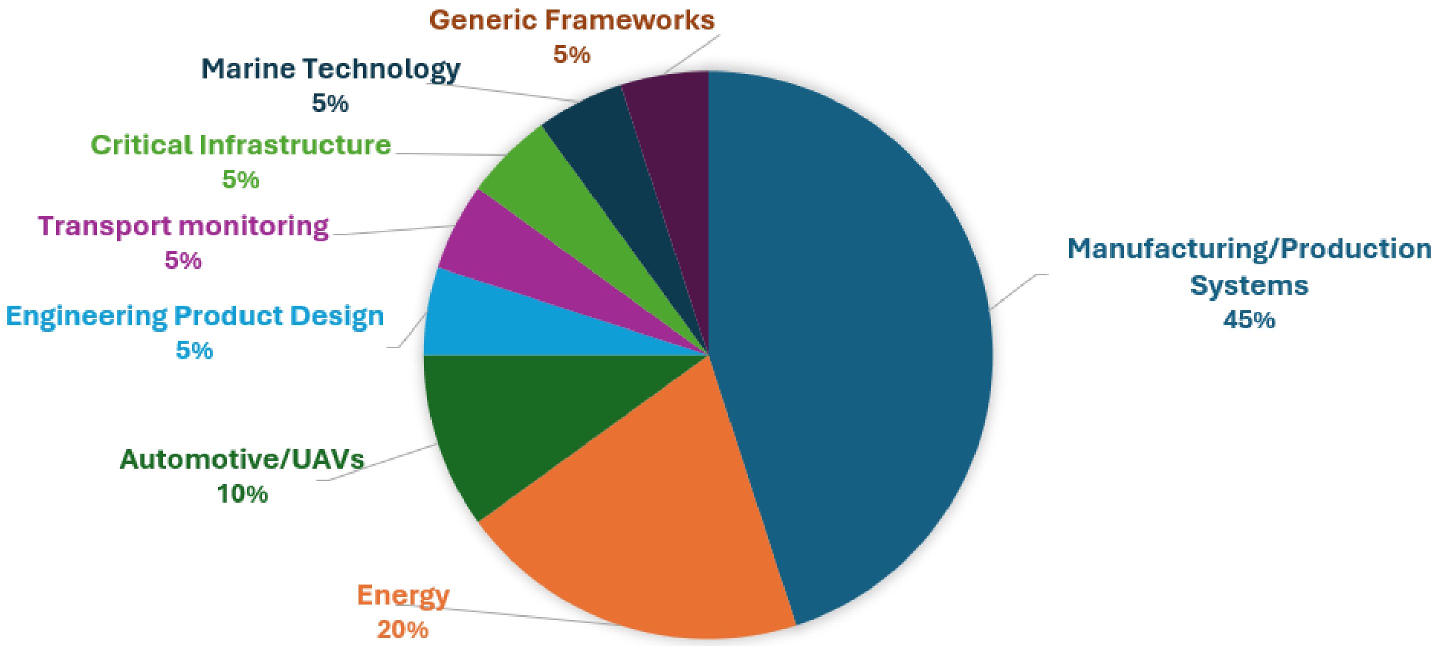
1. Background & Motivation
2. Literature Review
3. **Outcomes**:
   i. Composition Approaches (RQ1)
   ii. DT Properties and Qualities (RQ2)
   iii. V&V Approaches (RQ3)
   iv. V&V Challenges (RQ4)

RQ1 – DT Composition Approaches

- **Dominant domain:** Manufacturing/Production Systems (45%), followed by Energy (20%).
- **Key integration approach:** Orchestrated (centralized management).
- **Other approaches** include federated, service-based, hierarchical, and co-simulation.



RQ1 – DT Composition Approaches: SoS Characteristics

The most frequently addressed SoS characteristics in DT composition were:

- Emergence
- Heterogeneity
- Distributed nature
- Managerial independence
- Complexity

RQ2 - DT Properties and Qualities

- **Key Properties:** Fidelity, latency, real-time synchronization, modularity, scalability

- **Key Qualities:** Verifiability, reliability, adaptability, interoperability (most common)

RQ3 - DT V&V Approaches

V&V Formality Levels:

- **Formal:** High Rigor, Low Scalability, High abstraction (5 studies)
  - e.g. Model Checking and Theorem Proving
- **Semi-formal:** Most Common, Balanced Approach (12 studies)
  - e.g. Simulation-based testing and Co-simulation
- **Informal:** Practical, Limited Guarantees (11 studies)
  - e.g. Experimental validation and Case studies

RQ3 – DT V&V Approaches: V&V Scope

The primary focus areas of DT V&V in the reviewed literature are:

- Behavioural Correctness (66.7%)
- Model Fidelity (52.4%)
- Integration Validation (42.9%)
- Performance Assessment (38.1%)
- DT-PT Consistency (33.3%)

RQ4 – DT V&V Challenges

V&V Challenges fall into categories:

- **Technical** (e.g., Model Uncertainty, Real-time Synchronization, Scalability)
- **Methodological** (e.g., Lack of Standards, Multi-domain Verification)
- **Formal Verification Complexity**
- **Data-Related** (e.g., Data Quality and Availability)
- **Practical** (e.g., Resource Constraints, Tool Interoperability)

Conclusion

- Formal composition and rigorous V&V are underdeveloped.
- Future focus: Formal support for DT composition, standardized/domain-independent V&V methods for trustworthy, interoperable DTs.

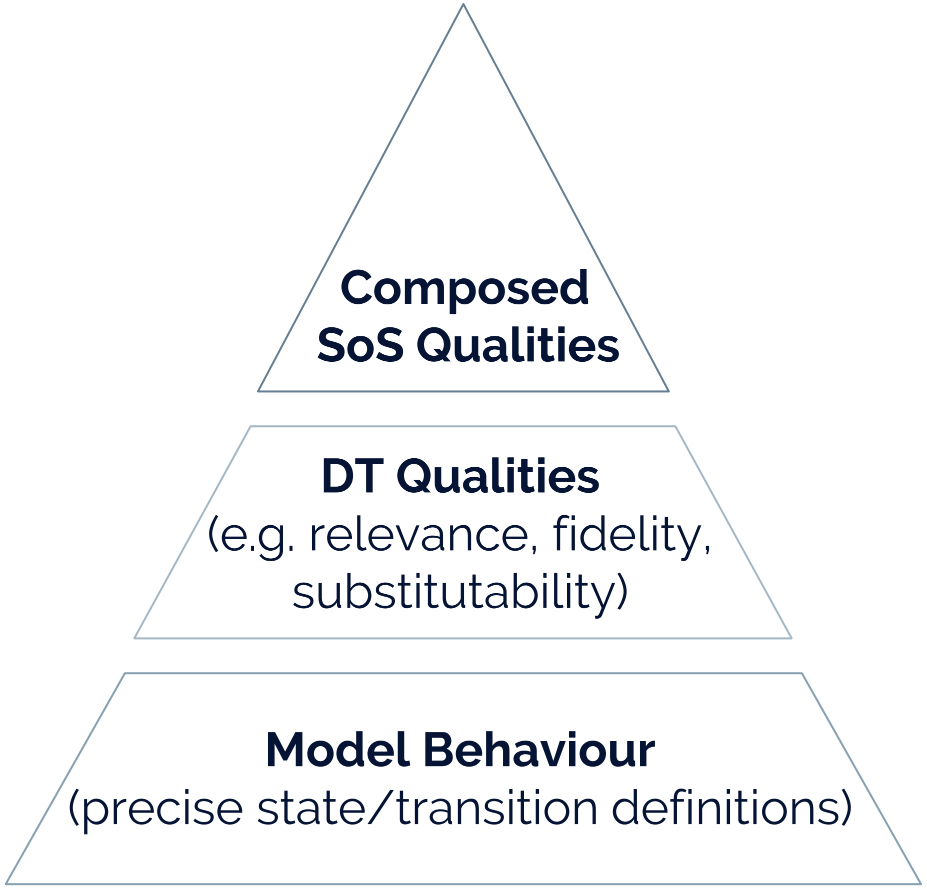
Future Direction: Bridging the Abstraction Gap in DT V&V

Key Issue

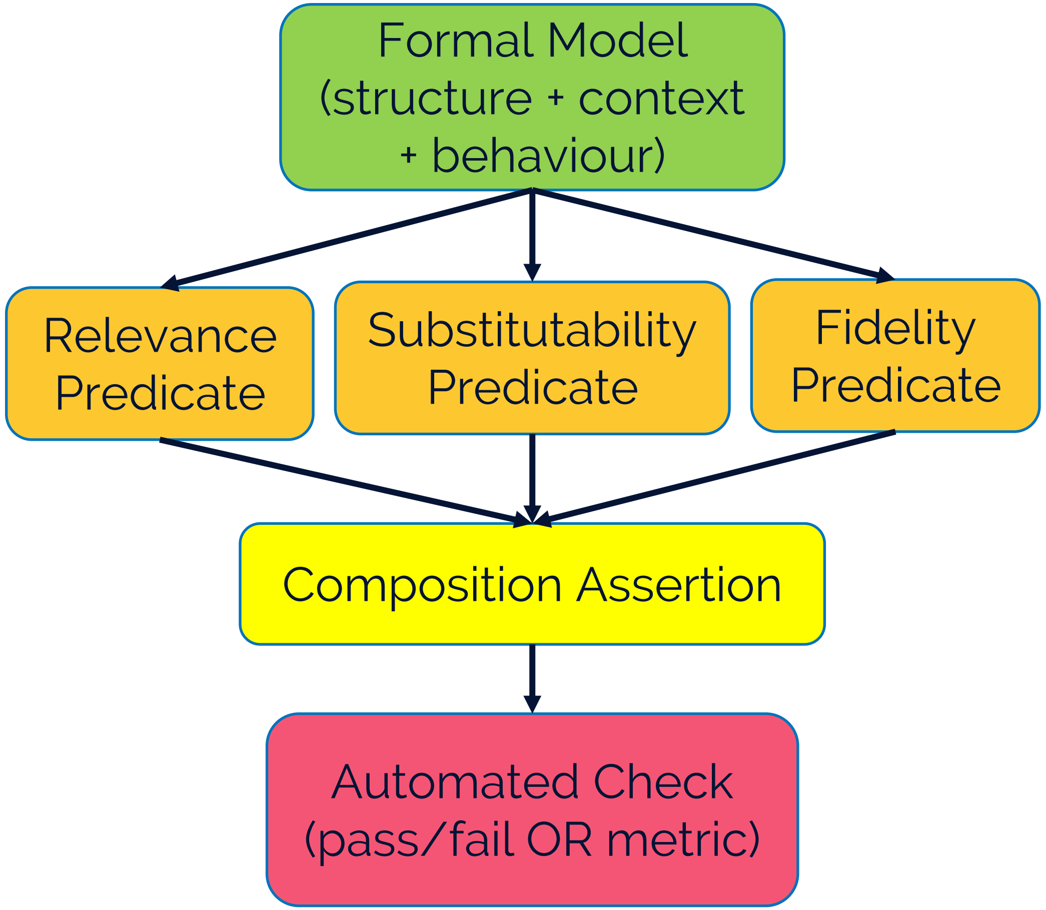
1. Conceptual qualities (fidelity, relevance, substitutability) are loosely defined.
2. Current V&V practices lack a clear link from model definitions to system-level guarantees.

Future Direction: Develop a **layered formalization** that:

- Defines model behaviour in precise terms
- Builds up to individual DT quality specifications
- Extends to composed DTs within System-of-Systems (e.g. cyber-physical consistency across twins)



Future Directions: Formalizing Models and Quality Attributes



Goals

- Precisely capture each DT model's **structure**, **context**, and **behaviour** in a simple formal notation.
- Define quality predicates for single twins **and** their composition
- Keep all checks simple enough to run automatically.

Approach

1. Introduce a minimal formal language (e.g. states + transitions + quality predicates).
2. Map model elements to quality predicates (e.g. "model state X implies correct output Y").
3. Ensure checks remain **computationally feasible** for real-world systems.

Future Directions: Bridging the Abstraction Gap in V&V

- Practical Quality Confirmation
- Operationalize Quality Assessment
- Develop Self-Adaptation Frameworks for autonomous quality violation detection
- Enable dynamic Model Configuration

Thank you!

Q&A