A Constructed System of Analysis to Enable Automation and Reasoning in Multi-Model Analysis

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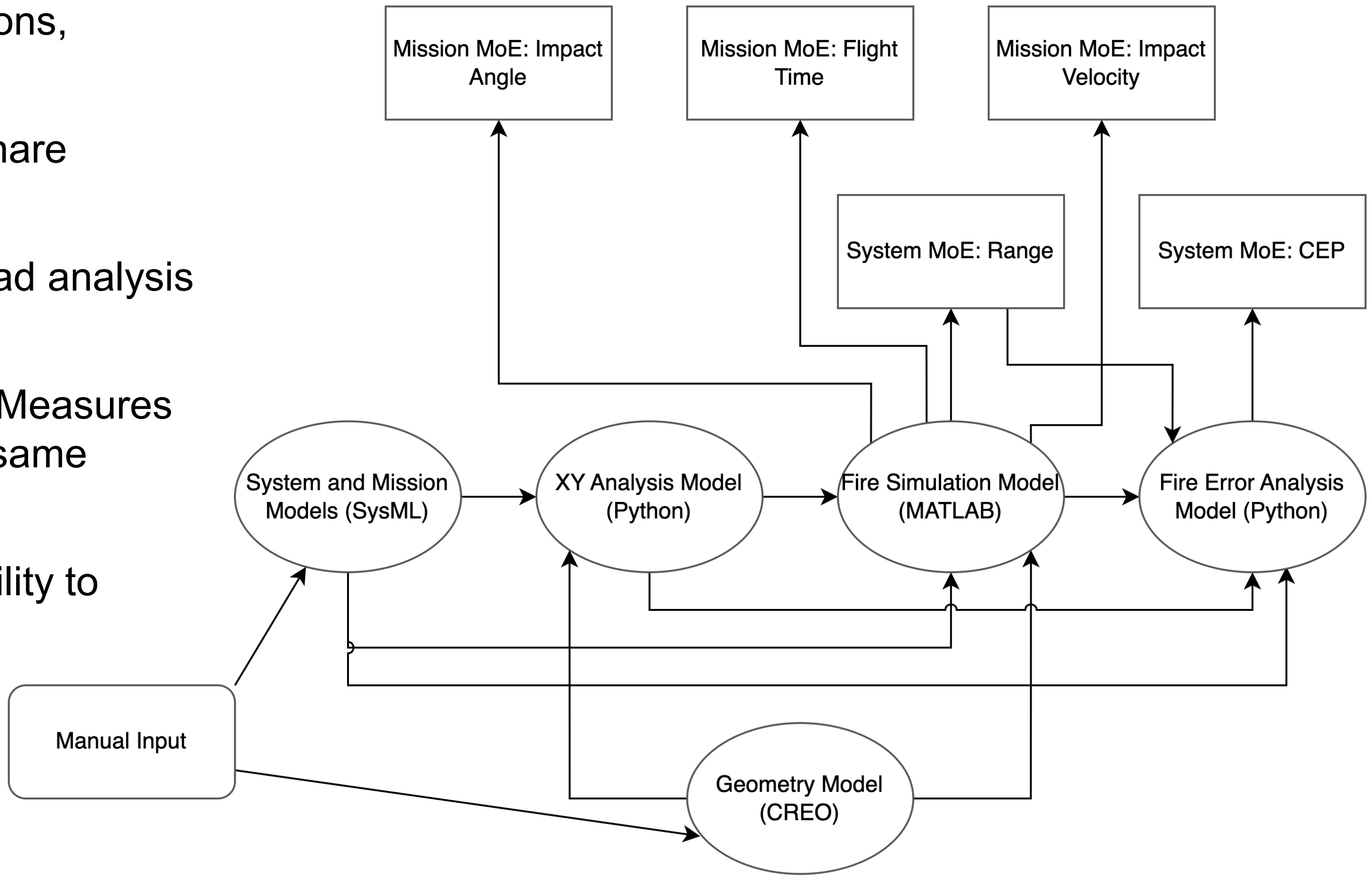
September 27, 2023

Cleared for Public Release

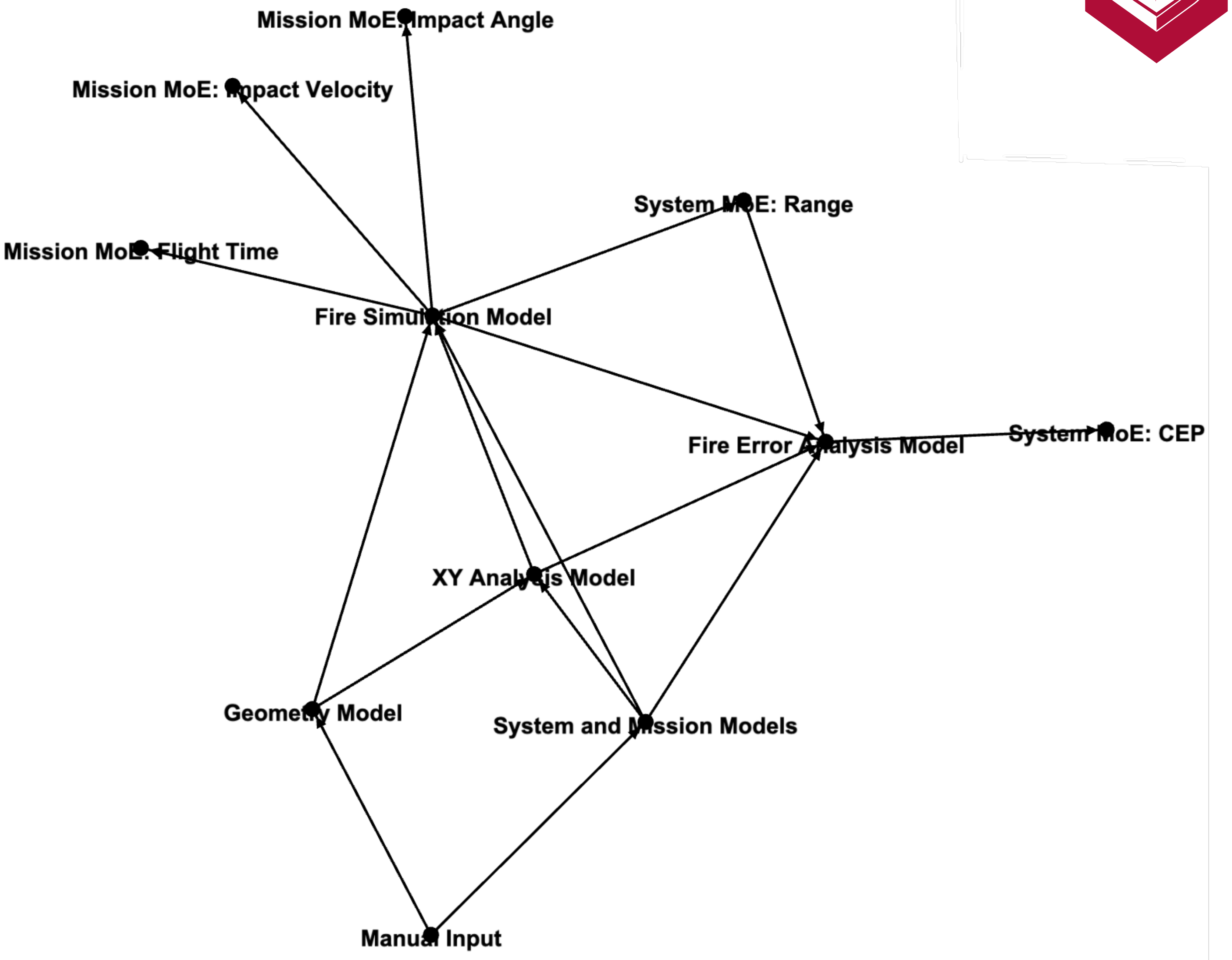
The Problem – Digital Thread and Higher Order Analysis

- Analyses often involve multiple models, simulations, domains, etc.
- Multiple models can interact in different ways (share common parameters, inform one another, etc.)
- Different levels of abstraction can occur in a broad analysis context
    - Domain, System, and Mission models and Measures of Effectiveness (MoE) can be used in the same analysis context
- As an analysis increases in complication, the ability to verify analysis structure increases in difficulty



Digital Threads are Graphs

- Digital thread as simple, directed graph
  - Edges represent sequencing information
- Graph-Based Analysis can provide insight:
  - Cycles in the directed graph
  - Order for automation
  - Complexity
- Simple graph analysis only looks at simple edges



Ontology-Aligned Data

“An ontology is a directed labeled graph that is identified by a unique IRI (Internationalized Resource Identifier) and that describes a set of things by a set of propositional statements that are regarded to be true in some context.” (Wagner et. al)

- Multiple edge types enables representation of different relationships
- Has language and syntax to be ingested and interpreted by a computer
- Axioms for giving robust representation of a knowledge base
- Can conform to Description Logic, which enables entailments using formal mathematical logic

Wagner, D. A., Chodas, M., Elaasar, M., Jenkins, J. S., & Rouquette, N. (2022). Ontological Metamodeling and Analysis Using openCAESAR. In A. M. Madni, N. Augustine, & M. Sievers (Eds.), *Handbook of Model-Based Systems Engineering* (pp. 1–30). Springer International Publishing. https://doi.org/10.1007/978-3-030-27486-3_78-1

Digital Engineering Framework for Integration and Interoperability

Digital Engineering Framework for Integration and Interoperability (DEFII)[1]

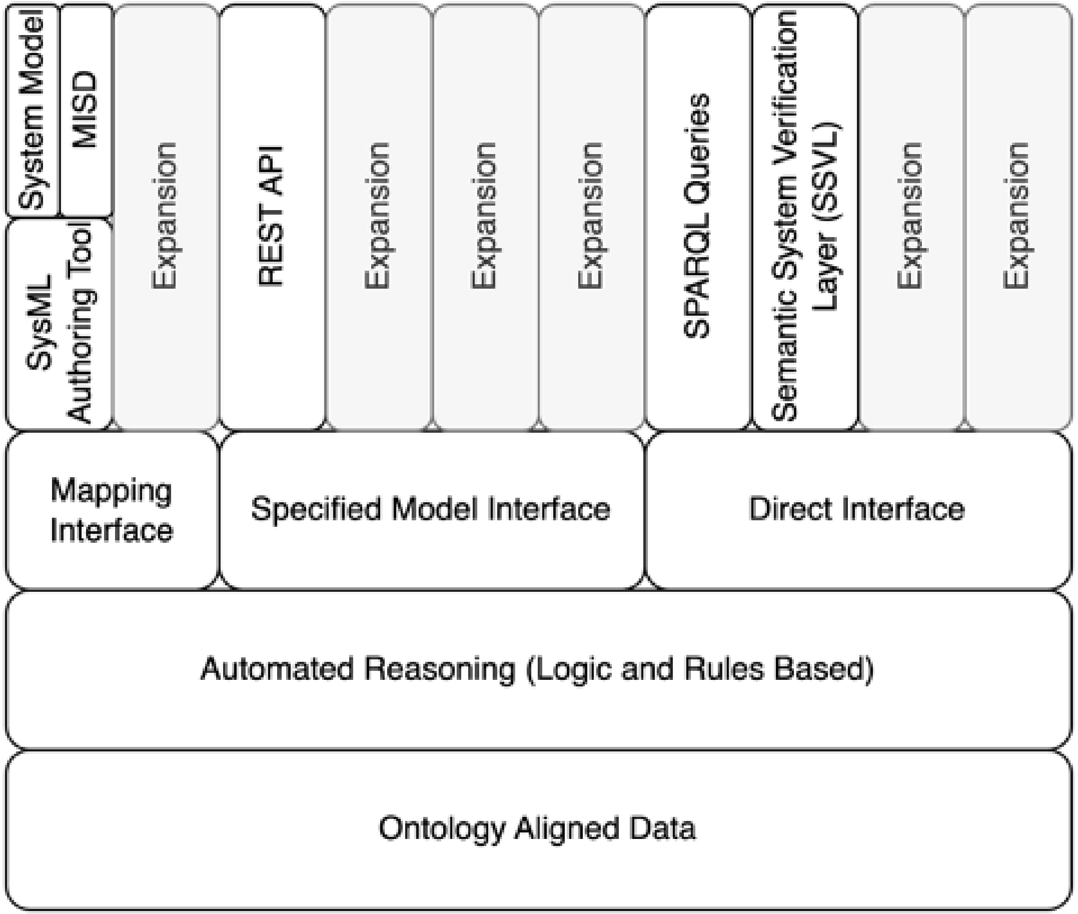
- Three different types of interfaces
    - Mapping Interface
    - Specified Model Interface
    - Direct Interface

Model Interface Specification Diagram (MISD)[1]

- Packages system elements in a useful way for analysis
- Can be aggregated to form a System of Analysis (SoA)

Semantic System Verification Layer (SSVL)[2]

- Uses the Direct Interface to perform verification and/or validation operations on the ontology-aligned data



[1] Dunbar, D., Hagedorn, T., Blackburn, M., Dzielski, J., Hespelt, S., Kruse, B., Verma, D., & Yu, Z. (2023). Driving digital engineering integration and interoperability through semantic integration of models with ontologies. Systems Engineering, sys.21662. https://doi.org/10.1002/sys.21662

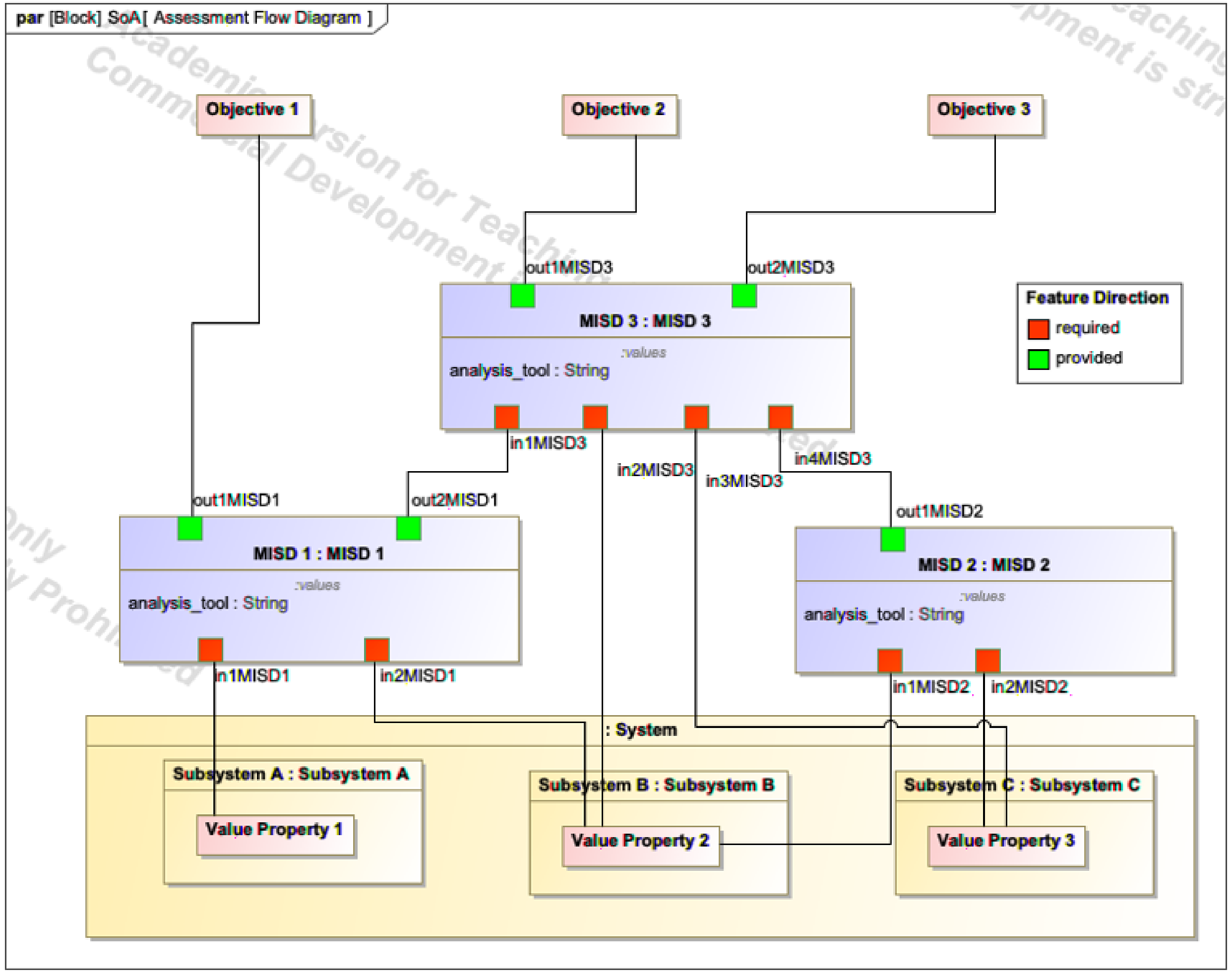
[2] Dunbar, D., Hagedorn, T., Blackburn, M., & Verma, D. (2022). Use of Semantic Web Technologies to Enable System Level Verification in Multi-Disciplinary Models. In B. R. Moser, P. Koomsap, & J. Stjepandić (Eds.), Advances in Transdisciplinary Engineering. IOS Press. https://doi.org/10.3233/ATDE220632

Abstract System of Analysis (SoA)

Value Properties identified as Objectives of the SoA

Intermediate Analyses defined through model interface specifications within SysML

Value Properties of System Under Analysis



Well-Formedness in System of Analysis

- What does well-formedness mean?
  - Working def. - a data model's adherence to a defined form or structure
  - Any definition will be context dependent, but ways of structuring a well-formedness definition exist and can provide guidance to our definition.
    - Rodano and Giammarco, "A Formal Method for Evaluation of a Modeled System Architecture."
    - Ernadote, "An Ontology Mindset for System Engineering."

Table 1: Summary of axioms for system model evaluation.

1. Decomposition Axioms	
1.1	Every activity not designated as a context activity shall have at least one parent. $(\forall a_1 \in A)[\neg context(a_1) \rightarrow (\exists a_2 \in A) decomposes(a_1, a_2)]$
1.2	No activity shall have exactly one child. $(\forall a_1 \in A)(\forall a_2 \in A)[decomposedby(a_1, a_2) \rightarrow (\exists a_3 \in A)(decomposedby(a_1, a_3) \wedge (a_2 \neq a_3))]$
1.3	No activity shall be decomposed by itself.

provided in the table to indicate the sources used in formulating them. The provided axioms are examples; architects may tailor their own collections of axioms and corresponding rationale and apply them as they see fit at appropriate stages of the architecture model maturity.

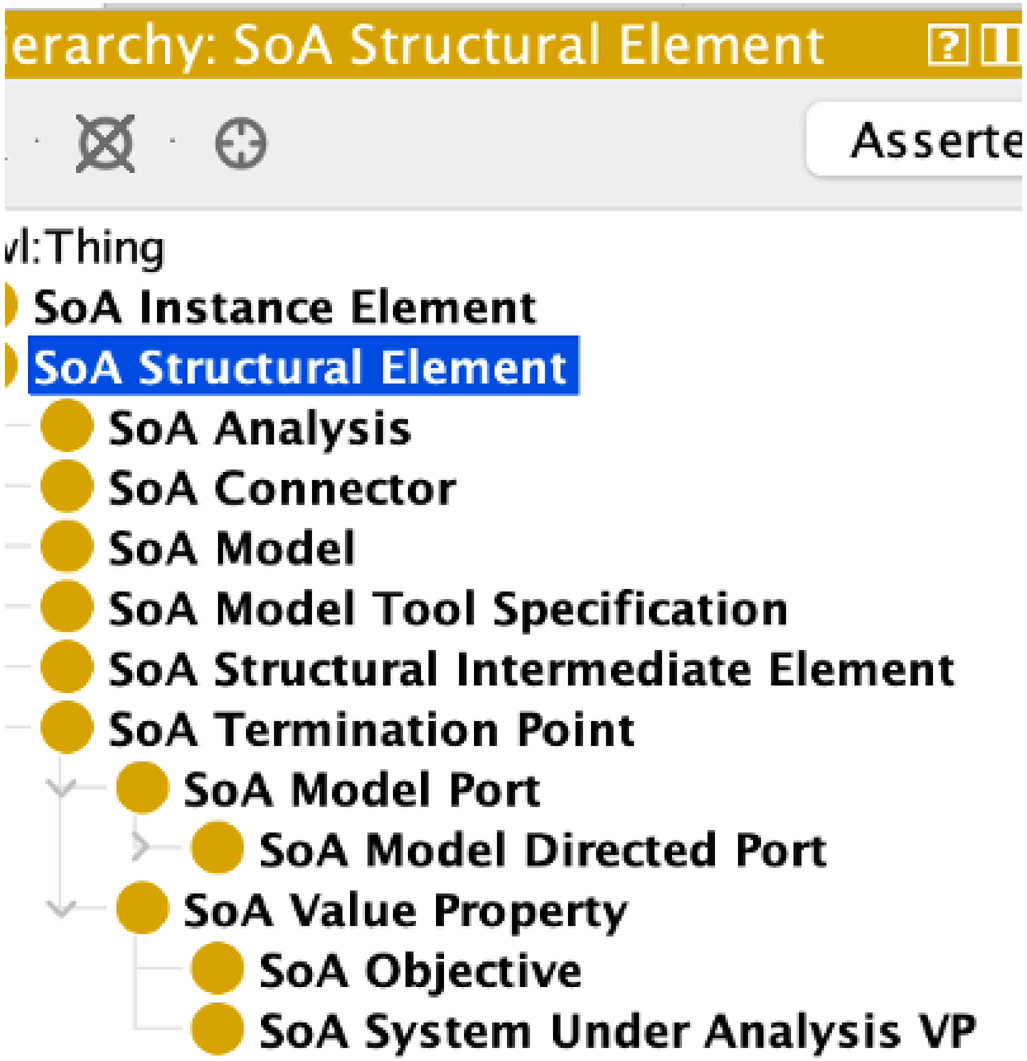
Rodano, M., & Giammarco, K. (2013). A Formal Method for Evaluation of a Modeled System Architecture. *Procedia Computer Science*, *20*, 210–215. https://doi.org/10.1016/j.procs.2013.09.263

Well-Formed Ruleset – Construction Journal part 1

Axiom Num	Axiom Description	Requirement Category	Assessment Approach	Context Dependent
1	Termination points cannot connect to like points (input-input, output-output, value property-value property)	Allowed Connection	DL-Reasoning	No
2	Each SoA Connector should be terminated at exactly two unique points	Allowed Connection	DL-Reasoning, SHACL	No
3	Each SoA Connector must be connected to a minimum of one <<model>> element	Allowed Connection	SHACL	No
4	Models cannot connect to themselves	Allowed Connection	DL-Reasoning	No
5	At least one analysis objective should be present	Specification	SHACL	No
6	Tool specification should be included	Specification	SHACL	Yes
7	All value properties should be tagged with a value in the loaded ontologies	DEFII	SHACL	No
8	Models should be instantiated (there should be a value associated with every entry from the AFD)	DEFII	SHACL	No
9	Constraint Parameters must be directional (in SysML - have <<DirectedFeature>> stereotype with provided or required applied)	DEFII	SHACL	No
10	SoA should form a Directed Acyclic Graph (DAG) when ordered by sequence	Graph Based	Graph Analysis	Yes

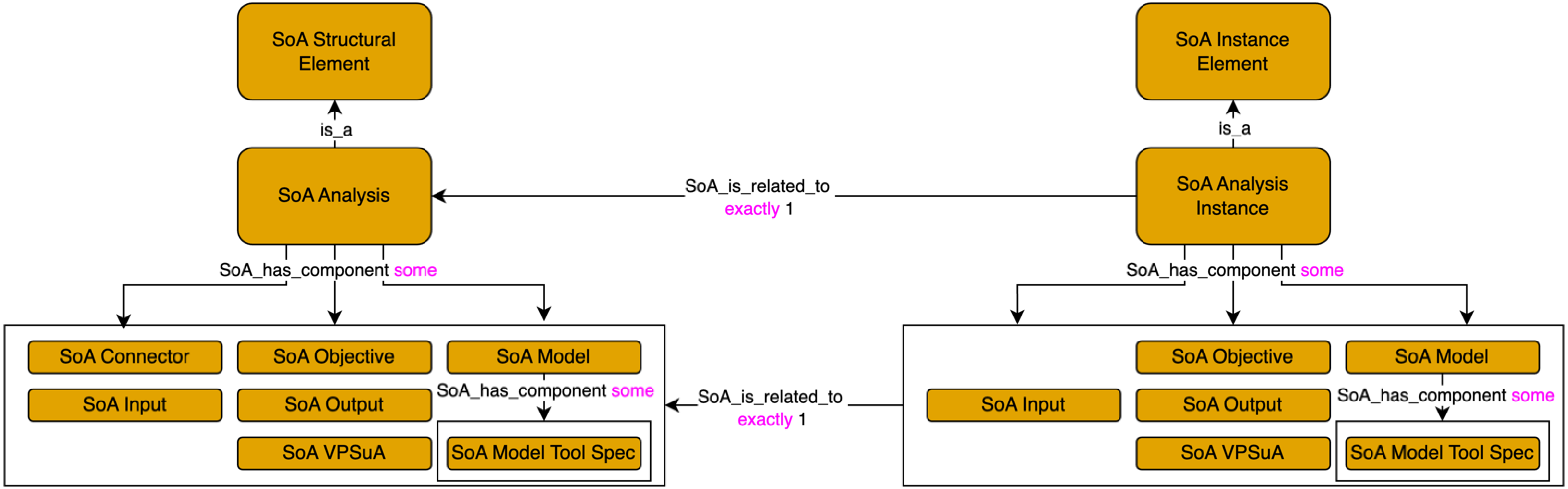
SoA Ontology Development

- Application Ontology
  - Not BFO aligned because its scope is confined to SoA analysis
  - Avoids multiple inheritance issues
  - Not software application specific (Cameo or SysML v1)
- Includes classes and axioms to provide knowledge representation from an SoA perspective
- Reduced Scope (SoA Repository for Catapult is 10.6% the size of Domain Mapped Repository)
- Can also use Semantic Web Rule Language (SWRL) to expand ABOX based on two-variable logic



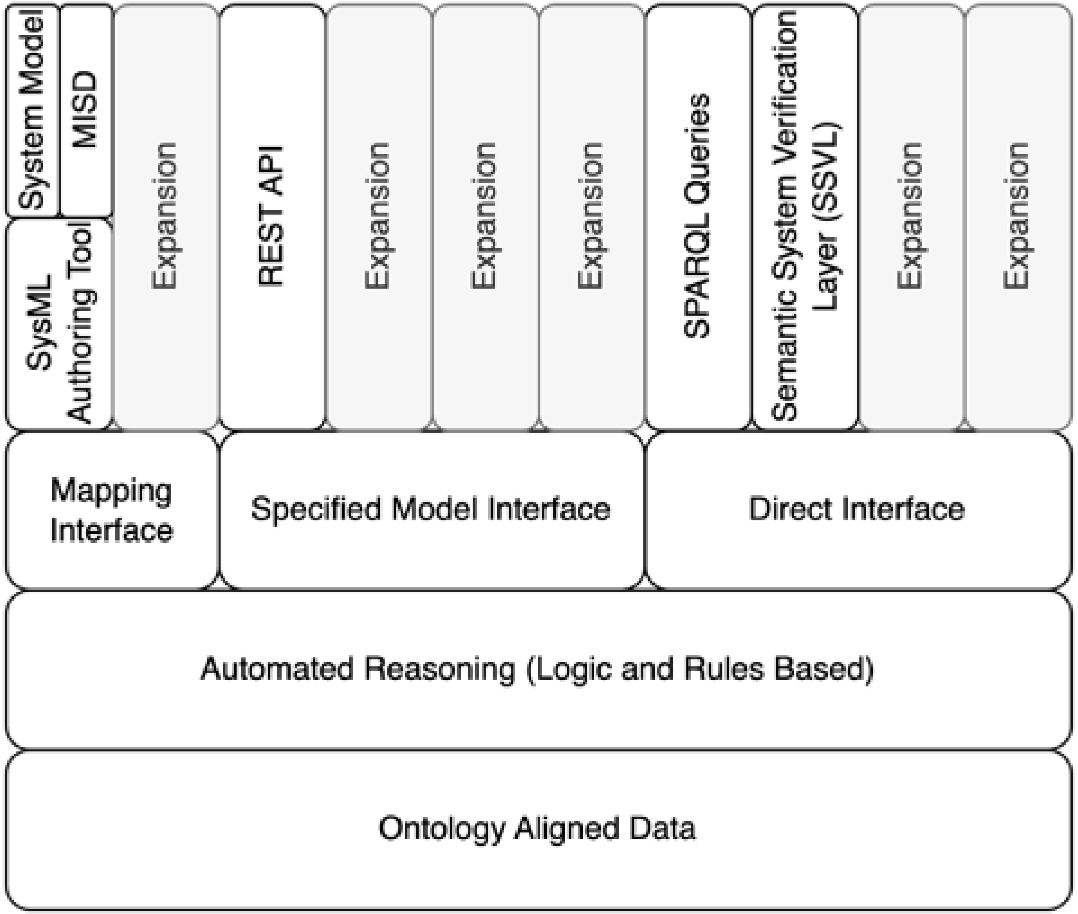
Ontology-Aligned Data

Structural and Instance Element Classes



Mapping to the SoA Ontology

- Previous research uses the SysML Stereotype for explicit tagging
  - Allows for flexibility in naming and general applicability
- SoA is expressly being used to check for well-formed construction
- Many elements are clearly identified by the form:
  - SysML Binding Connectors in the AFD Parametric Diagram
- To reduce load on designer/analyst (and reduce human error), many elements of the SoA can be pulled out with no additional effort on the modeler
- Exceptions:
  - SoA Objective
  - SoA Model Tool Specification



Extension of the SSVL

Three-Pronged Approach to Verification Task

1. Description Logic Reasoning
    - Uses Open World Assumption (OWA)
    - Can check for satisfiability of ontology and consistency of ontology-aligned data
2. Constraint Based Analysis using the Shapes Constraint Language (SHACL)
    - Can analyze data using Closed World Assumption (CWA)
    - Checks data based on constraints defined in “shapes”
3. Graph Based Analysis
    - Focuses on subgraph portions of ontology-aligned data
    - Uses advances in graph analysis developed in other domains

Analysis Approach – DL Reasoning

- Rich Axioms in ontology development
  - Cardinality Restrictions
  - Irreflexive Object Properties
  - Functional Properties
  - Domain/Range
  - Class Disjoints
  - Composition

Description: SoA Connector

Equivalent To

SubClass Of

- 'SoA Structural Element'
- (SoA_connected_to min 1 'SoA Model')
  and (SoA_connected_to max 2 'SoA Model')
- (SoA_connected_to_source some 'SoA Model') or (SoA_connected_to_source some 'SoA Value Property')
- (SoA_connected_to_target some 'SoA Model') or (SoA_connected_to_target some 'SoA Value Property')
- (SoA_terminated_to min 1 'SoA Model Port')
  and (SoA_terminated_to exactly 2 'SoA Termination Point')
  and (SoA_terminated_to max 1 'SoA Input')
  and (SoA_terminated_to max 1 'SoA Output')
  and (SoA_terminated_to max 1 'SoA Value Property')
  and (SoA_terminated_to max 2 'SoA Model Port')
- SoA_connected_to exactly 2 ('SoA Model' or 'SoA Value Property')
- SoA_terminated_to_source some 'SoA Termination Point'
- SoA_terminated_to_target some 'SoA Termination Point'

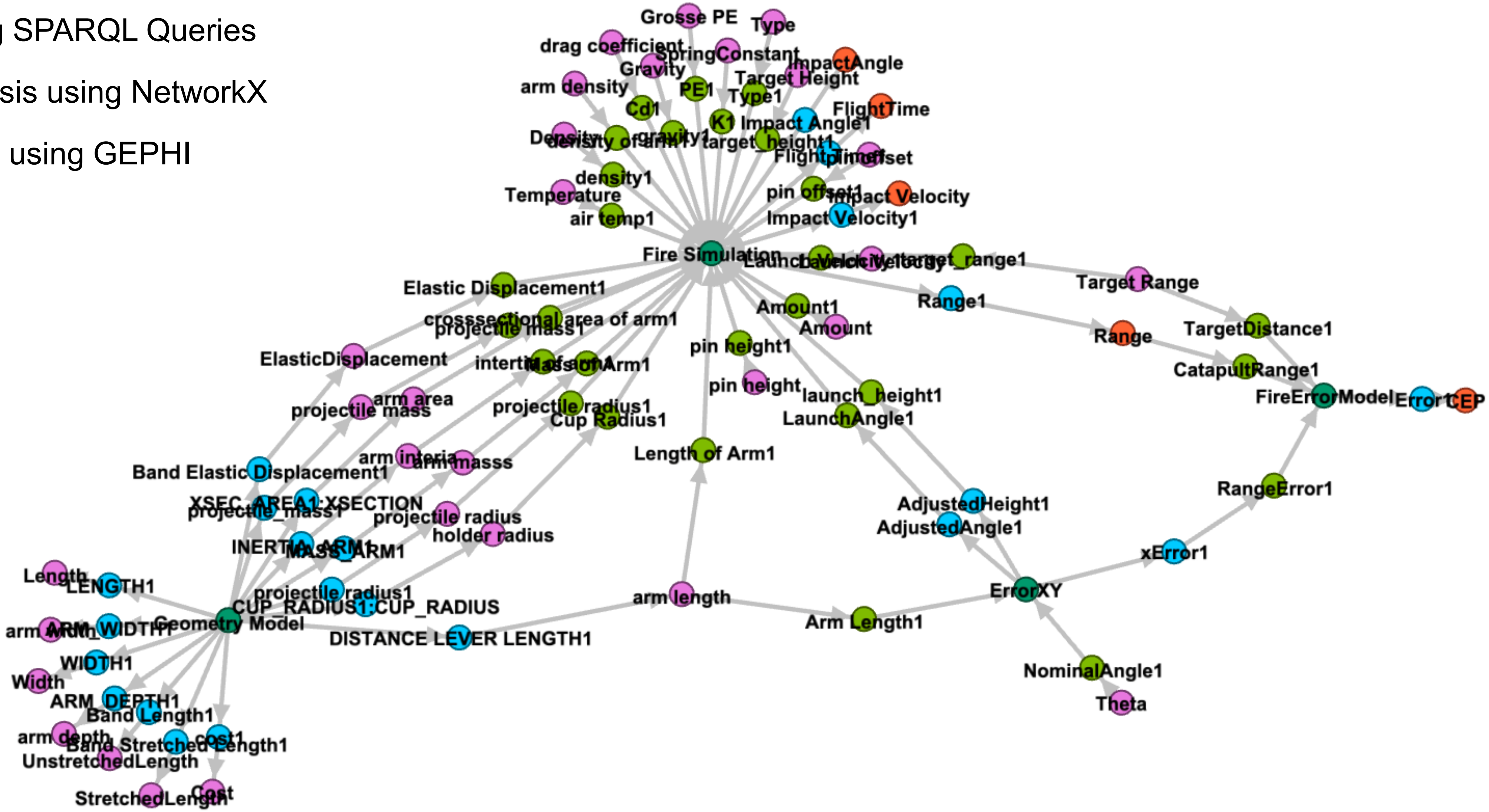
Analysis Approach - SHACL

- Define constraints using SHACL Shapes
  - Advanced SHACL features allow for use of SPARQL to define constraints

```
SoA:TaggedValuePropertyInOntologies                    # Axiom 7b-c
    a sh:NodeShape ;
    sh:targetClass SoA:SoAValueProperty;
    sh:sparql [
        a sh:SPARQLConstraint ;
        sh:message "Violation: Axiom 7 - Value Property: '{?vpLabel}' is not tagged with a loaded ontology term" ;
        sh:select  """
            PREFIX SoA: <http://www.systemofanalysis.org/resources/ontology/SoA.owl#>
            PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
            PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
            PREFIX owl: <http://www.w3.org/2002/07/owl#>
            select * where {
                ?this a SoA:SoAValueProperty .
                ?this SoA:SoA_label ?vpLabel .
                OPTIONAL {
                    ?this SoA:SoA_exists ?check
                }
                FILTER (!bound(?check))
            }
        """ ;
        ] .
```

Analysis Approach – Graph Analysis

- Pull subgraph using SPARQL Queries
- Graph Based Analysis using NetworkX
- Graph Visualization using GEPHI

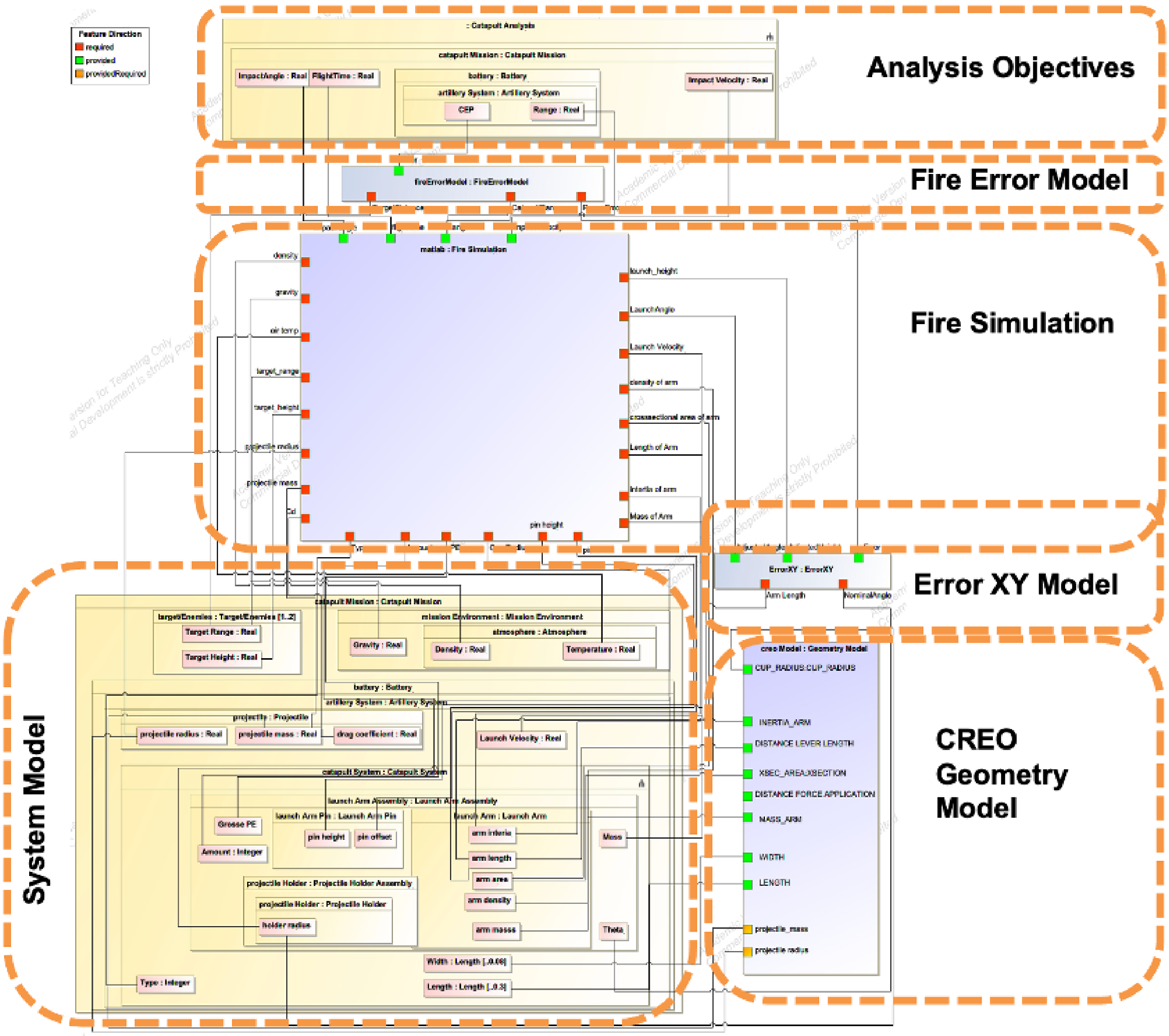


Catapult Analysis System of Analysis

The AFD has the System Under Analysis, the analysis models, and the Analysis Objectives.

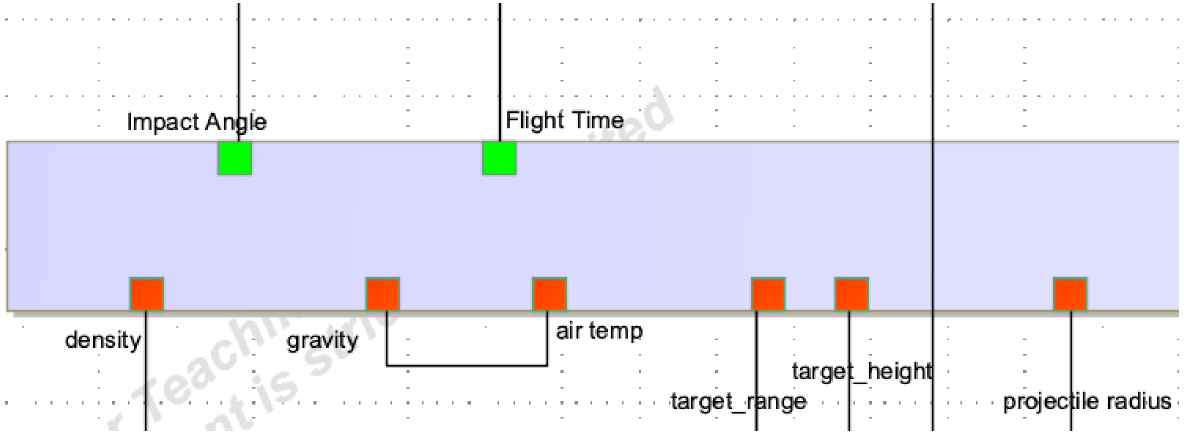
Allows for explicit connection between individual parameters, intermediate models, and final objectives.

The AFD is the basis for the graph-based representation of the SoA.



Open-World Reasoning

Scenario Name	Scenario Description	DL-Reasoning	SHACL	GRAPH	Pellet Message
C10	Gravity to Air Temp Inputs on Fire Simulation Model	1	0	0	1) Functional SoA_terminated_to_target 09de70c2-0dfd-4599-8ebe-1dfaab9b7d61_SoA SoA_terminated_to_target 69ec40fc-3edd-4635-8e56-f21431071a86_SoA 09de70c2-0dfd-4599-8ebe-1dfaab9b7d61_SoA SoA_terminated_to_target a4f578a8-ce36-4417-ad15-81f982ebf855_SoA



Closed-World Reasoning

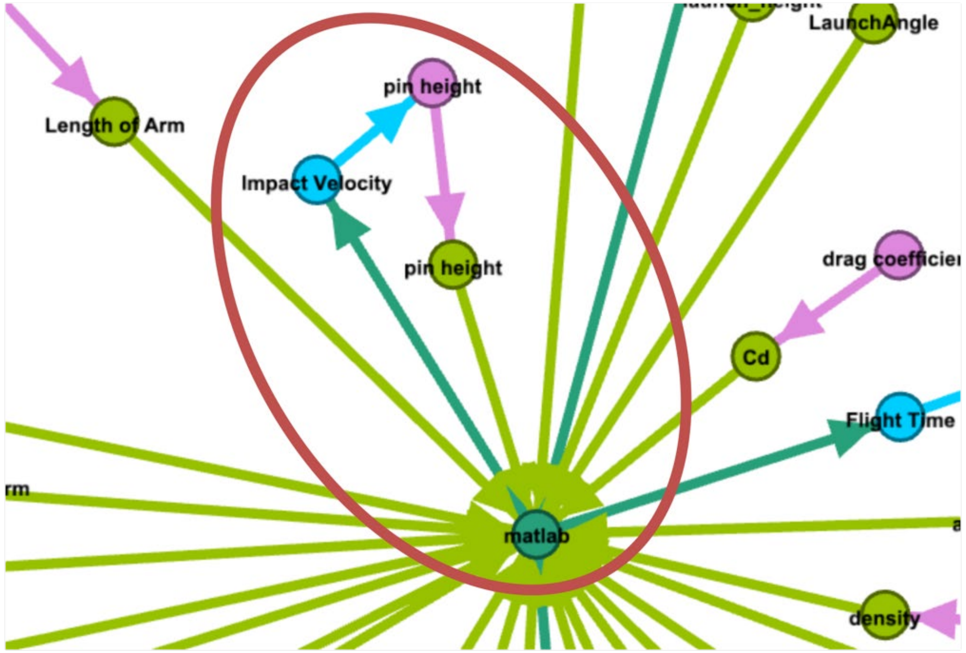
Scenario Name	Scenario Description	DL-Reasoning	SHACL	GRAPH	SHACL Messages
C16	Removed CircularErrorProbability (CEP) from objective	0	1	0	Violation: Axiom 7 - Value Property: 'CEP' is not tagged with a loaded ontology term

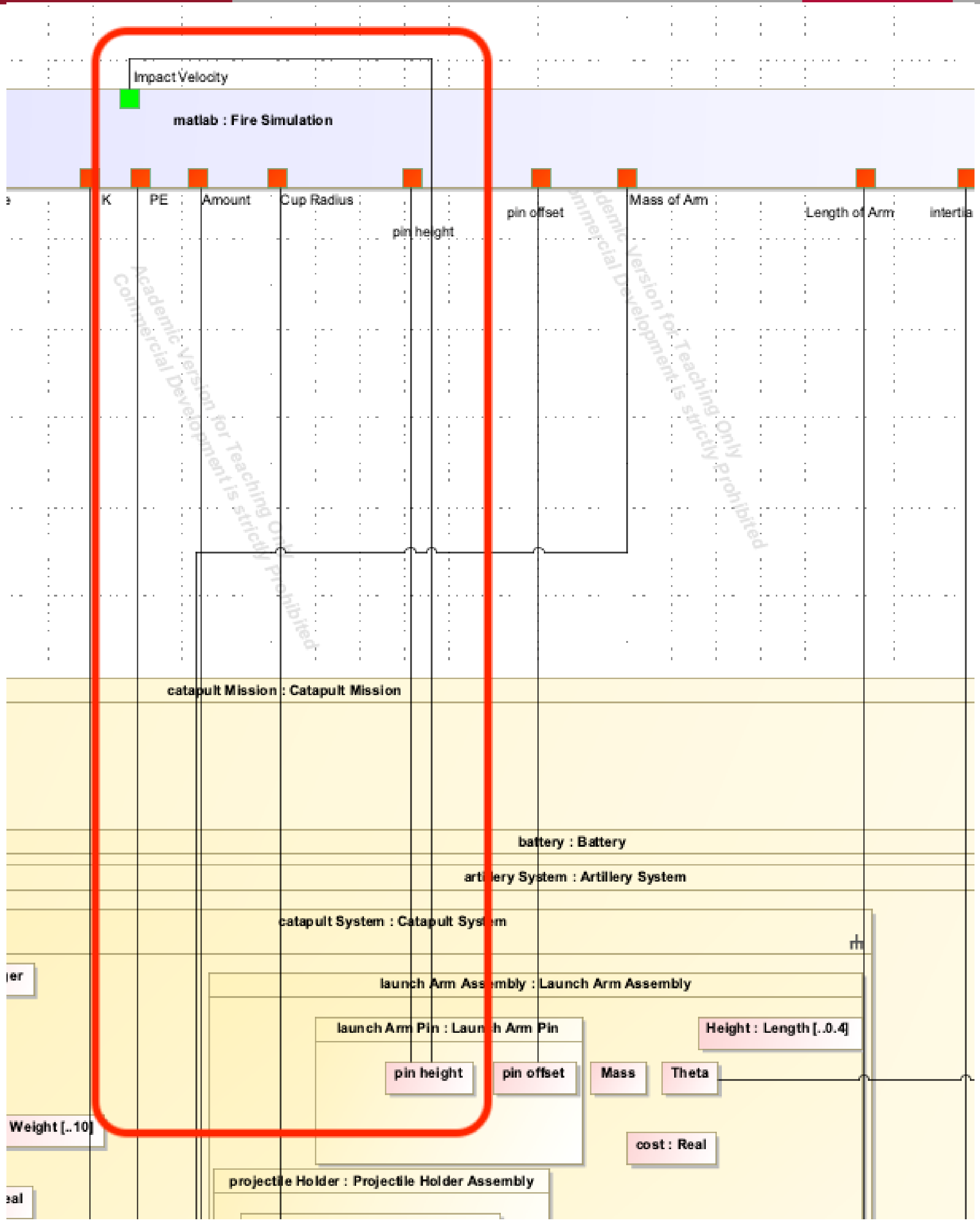
- SoAObjective Stereotype separate from the domain aligned stereotypes

Value Property	
Name	CEP
Owner	Artillery System [Mission]
Qualified Name	Mission::Artillery System::CEP
Type	
Type Modifier	
Visibility	public
Default Value	0
Applied Stereotype	ValueProperty [Property] [MD Customization SoAObjective [Element] [Ontology]
Multiplicity	(Unspecified)

Graph Analysis

Scenario Name	Scenario Description	DL-Reasoning	SHACL	GRAPH
C26	Cycle from Impact Velocity to Pin Height	0	0	1





Conclusion

- Three-Pronged Verification in expanded SSVL gives opportunity for robust analysis
  - DL-Reasoning
  - SHACL Constraint Analysis
  - Graph-based analysis
- The expanded SSVL can provide verification functionality to many problem spaces
- The System of Analysis ontology and defined constraints enables richer insight to a particular instantiation of the Digital Thread

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