Design Ontology Supporting Model-based Systems-engineering Formalisms

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Model-based systems engineering (MBSE) provides an important capability for managing the complexities of system development. MBSE empowers the formalisms of system architectures for supporting model-based requirement elicitation, specification, design, development, testing, fielding, etc. However, the modeling languages and techniques are quite heterogeneous, even within the same enterprise system, which creates difficulties for data interoperability. The discrepancies among data structures and language syntaxes make information exchange among MBSE models even more difficult, resulting in considerable information deviations when connecting data flows across the enterprise. For this reason, this paper presents an ontology based upon *graphs*, *objects*, *points*, *properties*, *roles*, and *relationships* with *entensions* (GOPPRRE), providing meta models that support the various lifecycle stages of MBSE formalisms. In particular, knowledge-graph models are developed to support unified model representations to further implement ontological data integration based on GOPPRRE throughout the entire lifecycle. The applicability of the MBSE formalism is verified using quantitative and qualitative approaches. Moreover, the GOPPRRE ontologies are generated from the MBSE language formalisms in a domain-specific modeling tool, *MetaGraph* in order to evaluate its availiability. The results demonstrate that the proposed ontology supports both formal structures and the descriptive logic of the systems engineering lifecycle.

Index Terms—Formalism, knowledge graph, model-based systems engineering, interoperability, ontology.

I. INTRODUCTION

The increasing complexity of technological innovations and their interoperability requirements within systems of systems, systems, subsystems and components, have led to an over-complexity of architectures and data structures, which, in turn, has led to enormous research and development costs. The model-based systems engineering (MBSE) has been widely used to counter this trend by formalizing end-to-end systems engineering perspectives through models. Each interface between lifecycle phases poses communication challenges brought about by this increasing complexity [1]. Much of the complexity is the result of individual stakeholder interests; they may have different concerns about systems and artifacts of interest, and they may, in turn, demand unique informational and data-standard feedback. These results can often be seen within the architectural models themselves, as discrepancies among such models create a system-integration nightmare, resulting in barriers to communications, understandability, and, more importantly, operations. Apart from stakeholder nuances, the integration of model views is also challenged by different domain-specific knowledge base and systemsengineering taxonomies.

Across the entire lifecycle, enterprise data integration is the ultimate goal for a fully implemented MBSE. However, at the working levels, it is common for domain engineers to formalize their various domain problems using stovepiped domain-specific modeling languages and specifications. These various representations are difficult to piece together during collaborative development, and the results often lead to misinterpreted or inaccurate reporting. Therefore, there is a critical need to standardize information representations and data structures so that a complete model flow can be wielded across the lifecycle while meeting all stakeholder and engineering requirements.

System development is an iterative process that relies on a unified and authoritative data architecture built upon collaboration. Owing to advances in artificial intelligence (AI) and machine-learning (ML) techniques, the concept of MBSE is undergoing a digital transformation that will ultimately lead to advanced facilitation to complex system development [2]. Semantics web-data exchange is the basis for much current data and information integration via AI reasoning. Thus, it is critical that participants of the MBSE lifecycle work to ensure the completeness and consistency of the data that fuel decision-making and engineering task implementation. Based upon on an AI-driven data exchange, the knowledge management of the future aims to provide the required information to stakeholders whenever (or even before) they need it [3].

This paper focuses on a unified MBSE ontology based on a meta-meta model built upon six key concepts with extensions: Graph; Object; Point; Property; Role; and Relationship (GOP-PRRE). This ontology presents a formalization opportunity for MBSE modeling via a unified syntax and data structure to support systems-engineering information exchange via the integration of AI and ML. The main contributions of this defined ontology are as follows:

- It supports integrated architectural representation across the lifecycle.
- It promotes a MSBE tool built upon data interoperability and consistency.
- It provides potential solutions for developing AI/ML MBSE roadmaps.

In order to promote the scalability of the proposed ontology, it will be discussed and applied in the Industrial Ontologies

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Foundry Systems Engineering Working Group¹.

The rest of the paper is organized as follows. We discuss related works and the proposed research methodology in Section II. In Section III, the designed ontology is analyzed. A case study is presented in Section IV for the evaluation of our ontology using quantitative and qualitative approaches. Finally, we present our conclusions in Section V.

II. RESEARCH DESIGN

A. Literature review

Some researchers have provided ontology-based approaches to facilitating design automation for complex systems ([4], [5]). MBSE supports complex systems engineering and development efforts [6] by formalizing development processes, system architectures, and operational interrelationships. There are currently several such modeling languages in use (e.g., Systems Modeling Language (SysML) [7], Object Process Methodology [8], and Business Process Modeling Notation (BPMN) [9]), which provide modeling tools that can be used to describe real-world processes using graphic views. Recently, researchers have proposed an Object Management Group standard for model-driven engineering, comprising a four-layered architecture. The four layers are labeled M0-M3 and provide the modeling framework needed to support MBSE. The M0-M3 layers are described thoroughly in the "Ontology Design for MBSE Formalism" section of this paper. It applies the GOPPRR formalization of specific system views with new extensions [10]. Notably, several generic modeling environments also provide meta-modeling languages that can support complex system development based on unified modeling-language (UML) notation and object constraint language [11]. Advocates of these methods continue to seek a singular adaptive language that can be used to describe all system architecture views.

Yang *et al.* provided a unified ontology to describe a systems-engineering body of knowledge for the International Council on Systems Engineering ([12], [13]). Charlotte *et al.* proposed a formal method of safety analyses for systems engineering [14]. But these research were not involved with MBSE. Lu *et al.* developed an ontology to support automated co-simulation using an MBSE tool-chain. The ontology was used to implement MBSE models for integrated verification [15]. Most of the above ontological approaches, however, focused on domain-specific problems instead of modeling languages and data interoperability across the entire MBSE lifecycle.

MBSE was the basis for constructing a digital replication technologies and supporting virtual verification concepts ([16], [5]). It is further expected to provide potential solutions for combining systems engineering approaches and AI technologies. Some researchers provide an ontology-based approach facilitating design automation for complex systems ([4], [5]). Hao *et al.* proposed an ontology-based method to support knowledge management [17]. Ontology contributes to semantics descriptions and models that not only support decision-

making regarding system development, it also supports realtime operations via a universal system description and information transfer [18].

Currently, ontological methods are widely used to support lower-level tool and data interoperability and consistency issues. For example, an extensible XML Metadata Interchange (XMI) is used to support data exchange between SysMLs and multiple other tools [19]. Additionally, MBSE ontologies have been developed to formalize domain-specific concepts and their interrelationships using different languages ([5], [20]). In this paper, Web Ontology Language (OWL) is used to design a complete MBSE ontology based on a GOPPRRE approach that can support information exchange across the MBSE enterprise.

B. Summary

Several modeling languages have been used to formalize the different views and approaches found in the systems engineering lifecycle. Many challenges arise, however, when these different languages are adopted for different enterprises.

- Generic modeling languages have difficulty supporting the complete formalism of a specific domain; they do not support multiple system views in a unified way.
- Different language models pose integration challenges across different development phases.
- An ontology that supports MBSE formalisms will be the basis of the combination of systems-engineering processes and AI tools for enterprise knowledge management and decision-makings.

C. Case study

A case study was conducted to evaluate the designed MBSE ontology. Quantitative and qualitative approaches were separately applied [15], and two key measurements were considered:

1. The ontological completeness of the concrete syntax of MBSE formalisms:

- In the qualitative evaluation, SPARQL [21], a query language, was used to evaluate whether the ontology could completely represent the information generated from the MBSE models. To support this measurement, several metrics were defined:
 - *Graph-include-objects (relationship)* refers to a situation, wherein one model includes all information related to its components or connections.
 - Object (relationship)-include-points (roles) refers to a situation wherein one model component or connection includes all information related to its points or connection arrows.
 - Object (graph and relationship)-include-properties refers to a situation wherein one model (model component and connection) includes all information related to its attitudes.
- Using the quantitative approach, a domain-specific modeling tool, *MetaGraph*, was developed to support the required ontology generation [22]. The numbers of key elements in the modeling languages and specifications



Fig. 1. Overview of the ontology and MBSE formalisms

for which the ontology was formalized were analyzed to evaluate its completeness.

2. Ontology logic related to the abstract syntax of MBSE formalisms:

- In the qualitative evaluation, SQWRL [23], a query language, was used to evaluate its description logic, by querying OWL as its semantic web-rule language to design the rules needed to assign the *subject*, *predicate*, and *object* by their defined *predicates* [24]. It was adopted to evaluate whether the ontology could capture the information needed to define the abstract syntax of the MSBE models. Two metrics were thus considered:
 - Relationship definitions in the MBSE model: they
 present the connections (logic flows) with two ends
 in the MBSE models. The connections between model
 components or points define the basic logic for constructing one MBSE model.
 - Direction of relationship: it presents the start of each connection, which decides how the connection is linked to its two sides.
- Using the quantitative approach, *MetaGraph* was used to support ontology generation, wherein the numbers of key graphs could support connection rules of different modeling languages and specifications. They were identified to evaluate the logic supported by the designed ontology.

III. ONTOLOGY DESIGN FOR MBSE FORMALISM

A. Overview

The overall workflow of the proposed approach is shown in Fig. 1-A. The M0–M3 modeling framework is proposed to develop the MBSE ontology, including:

- M0: Meta-meta models that refer to basic elements of the constructed model compositions and their interconnections. We adopt GOPPRR meta-meta models and their extensions to support meta-model development.
- M1: Meta-models refer to the model compositions and connections needed to develop models.
- M2: MBSE models represent real-world systems.



Fig. 2. Meta-models of GOPPRRE

 M3: Real-world artifacts are considered, including complex systems and their development processes.

The developed ontology is transformed into semantics triples (i.e., subject, object, and predicate) to formalize systemsengineering models from three dimensions: disciplinary, system lifecycle, and system artifacts [25]. The disciplinary dimension includes several domains, such as control engineering, mechanical engineering, etc. Systems engineering refers to requirements, functions, architectures, etc., and the product lifecycle includes different phases of the complex system lifecycle.

As shown in Fig. 1-B, the MBSE formalisms include syntax and semantics [26]. Syntax refers to the representations of the MBSE formalisms, and semantics refers to the MBSE model meanings. The details are explained as follows:

- Abstract syntax refers to the compositions of MBSE models and their defined rules for connecting with each composition. It is realized using the core GOPPRRE concepts for the MSBE formalisms (introduced in Section III.B)
- Concrete syntax refers to the visual representations of the MBSE model compositions. It is represented in the knowledge-graph model as the annotation property, which is introduced in Section III.C.
- Semantics domain refers to the target of the semantic mapping, which implies the meanings of the MBSE models. It includes the three dimensions shown in Fig. 1-A. The formalisms are used to describe system-engineering concepts, product-lifecycle processes, and disciplinary knowledge needed to support information exchange during system development.
- Semantics mapping refers to the dependencies among MBSE models and their meanings according to the three dimensions.

B. GOPPRRE Concepts for MBSE Formalisms

The *GOPPRRE* approach uses the M0–M3 modeling framework, as inspired by the GOPPRR meta-meta models and their extensions, to construct the MBSE model syntax and semantics. We added one new concept, *constraint*, to the approach in order to define constraints of the abstract syntax. In Fig. 2, the details of the GOPPRRE concepts are introduced:

TABLE I INTERRELATIONSHIPS AMONG THE GOPPRR ELEMENTS

GOPPRR	$graph_a^{id}$	$object_b^{id}$	$relationship_d^{id}$	$role_c^{id}$	$point_e^{id}$
$graph_a^{id}$	-	decompose decompose explore explore		explore	decompose explore
$object_b^{id}$	include	-	-	connect	-
$relationship_{d}^{id}$	include	-	-	-	-
$role_c^{id}$	-	-	startFrom endTo	-	-
$point_e^{id}$	-	include	-	connect	-
$property_{f}^{id}$	have	have	have	have	have

- *Graph* is an entity collection of *Object*, *Relationship*, and *Role*, represented in one layout (e.g., a UML class diagram). The graph is either a visual diagram or another that was decomposed (explored) by one *Object*.
- *Object* is an entity that constructs a *Graph*.
- Point is one attached port in an Object.
- *Relationship* refers to one connection between the *Points* and/or *Objects*.
- *Role* is used to define the binding restrictions with the relevant *Relationship*. One *Relationship* is associated with two *Roles*. Through each role, the *Relationship* is defined as one that binds with one *Point* or one *Object* in its one end.
- *Property* is a specific attribute of meta-models that is attached to the other five meta-meta models.
- *Extension* refers to the additional *constraints* used to construct meta-models. In this paper, one constraint is developed as a *connector*. It refers to one binding between one *Point* or *Object* and one *Role* in one side of the *Relationship*.

Definition 1: Token ::= refers to a collection of elements. As shown in Table I, the GOPPRRE meta-meta models are identified, and their interrelationships are defined. Thus, the meta-model, Graph, is defined as

$$graph_{Tp} ::= \{\sum object^{obTp}, \sum relationship^{reTp}, \\ \sum role_{reTp}^{roTp}, \sum point_{obTp}^{poTp}, \sum property_{nonPro}^{proTp})\},$$
(1)

where $graph_{Tp}$ refers to the ontological concept of a metamodel, Graph, whose type is defined as Tp. $object_{obTp}$ refers to the ontological concept of the meta-model, object, where obTp is a type of object. The $relationship^{reTp}$ refers to the ontological concept of meta-model relationship, where reTpis a type of Relationship. $role_{reTp}^{roTp}$ refers to the ontology concept of a meta-model, Role, and reTp refers to the relationship that starts from (ends at) the Role, whose type is roTp. $point_{obTp}^{poTp}$ refers to the ontological concept of the meta-model, Point, and obTp refers to the object, including the point, whose type is poTp. $property_{nonPro}^{proTp}$ refers to ontological concept of the meta-model, Property, and nonPro refers to the nonproperty elements (nonproperty \subseteq {Graph, Object, Relationship, Role, andPoint}), having the Property of type, proTp. To define the connection rules among meta-models *Objects* and *Points* in each *Graph*, an additional constraint is defined as a *connector*:

$$connector(conId) ::= \{relationship^{reTp}, role_{reTp}^{roTp}, \\ object^{obTp}(\lor point_{obTp}^{poTp})\},$$
(2)

where the connector(conId) defines a rule that allows reTp, roTp, or obTp (or poTp in obTp) to be connected.

$$graph_{T_{p}}(gId) ::= \{\sum object^{obT_{p}}(obId), \sum relationship^{reT_{p}}(reId), \sum Role_{reT_{p}}^{roT_{p}}(reId, roId), \sum Point_{obT_{p}}^{poT_{p}}(obId, poId), \sum Property_{nonPro}^{proT_{p}}(nonproId, proId)\}$$

$$(3)$$

Definition 2: $graph_{Tp}(gId)$ refers to the model, gId, based on the meta-model of Graph Tp. In $graph_{Tp}(gId)$, $object^{obTp}(obId)$ refers to the Object instance, obId, based on the meta-model of Object obTp. $relationship^{reTp}(reId)$ refers to the Relationship instance, reId, based on the metamodel of Relationship reTp. $Role_{reTp}^{roTp}(reId, roId)$ refers to the Role instance, roId, based on the meta-model of Role roTp in the Relationship, reId, whose meta-model is Relationship roTp. $Point_{obTp}^{poTp}(obId, poId)$ refers to the Point instance, poId, based on the meta-model is obTp. $Property_{nonPro}^{proTp}(nonProId, proId)$ refers to the property instance, proId, based on the meta-model of Property proTp in the nonproperty element, nonProId, whose meta-model is nonPro;

Definition 3: With the definition of connector, the concept connection is defined as a link between Objects or Points in a Graph model, which is realized as a Relationship. Token a => b is defined as a connection that is linked from a to b, created based on two connector constraints. Thus, the connection, reTp, refers to one link realized by the Relationship individual, reTp, in the MBSE models, which is defined as follows:

$$connection_{reTp}(reId) ::= connector(conId') => connector(conId) = \{object^{obTp'}(obId')(\vee Point^{poTp'}_{obTp'}(obId', poId')), Role^{roTp'}_{reTp'}(reId', roId'), relationship^{reTp}(reId)\}, => \{relationship^{reTp}(reId), Role^{roTp}_{reTp}(reId, roId), object^{obTp}(obId)(\vee Point^{poTp}_{obTp}(obId, poId))\}$$
(4)

where the *connection* is defined for *Relationship* instance *reId* whose type is reTp based on connector(conId') and connector(conId).

C. GOPPRRE Concept Mappings to Knowledge Graph Models

As shown in Fig. 3, a workflow for transforming the GOPPRRE core concepts to knowledge-graph models based on OWL is demonstrated. The class for each GOPPRR concept represents the GOPPRRE meta-meta models (i.e., Graph, Object, Relationship, Role, Property, Point, and Connector). Their interrelationships are transformed to object-property concepts in the knowledge graph model. Meta-models based



Fig. 3. Abstract syntax transformations

on each GOPPRRE concept are then transformed to sub-class concepts. Models are transformed to individuals based on their related sub-classes. Based on the object-property concepts, the interrelationships among individuals are defined. Moreover, the data property is used to define the value of each *Property*. The data property type is used to define the data type of each attribute. Finally, the MBSE models representing the realworld views are transformed to the ontology defined by the knowledge-graph models using individuals, data properties, and object properties.

Apart from the abstract syntax, the concrete syntax of metamodels and models is described by the annotation and data properties.

- *annotation property*: used to represent the abstract syntax of meta-models, such as their original *icon paths*.
- *data property*: used to define the abstract syntax of models, such as the *icon path* of objects in the models. This differs from the annotation property, because, when building MBSE models, the original icon of meta-models may be reconfigured.

IV. CASE STUDY

Quantitative and qualitative analyses were performed to evaluate the completeness of the concrete syntax and logic of the abstract syntax. During quantitative analysis, a domainspecific modeling tool, *MetaGraph*, was developed to evaluate the ontology using several MBSE languages [22], as shown in Fig. 4. Several meta-models were developed with the *Meta-Graph* based on five existing MBSE language specifications. In the qualitative approach, SQWRL and SPARQL were used to evaluate the completeness and logic of the developed ontology through reasonings.

A. Quantitative analysis

When implementing the quantitative analysis, the *Meta-Graph* was used to develop MBSE models based on the proposed ontology, as shown in Fig. 4. Moreover, five general MBSE languages were developed to evaluate whether the ontology could provide enough information for the MBSE constructions. As shown in Table II, meta-models of five general MBSE languages were built to compare the four existing tools.

From the results, we found that the ontology could formalize almost all meta-models of the related languages. All graphs were developed based on the five MBSE language specifications. Some objects were different from the existing tools, because some elements in their tools were not defined as objects in our approach. For example, in Magic draw, some properties were defined as elements in their diagram-building environment so that the users could easily configure an object's property. The concrete syntax of all languages were completely transformed to the developed ontology in *MetaGraph*.

Apart from the concrete syntax, the abstract syntax was also evaluated by comparing the connection rules with different languages in other tools. In the MetaGraph, the connectors between relationships and objects were compared with the rules for connecting different elements in other tools. This was done to determine whether the ontology can formalize the logic flow between different MBSE model elements. As shown in Table III, connection rules refer to the specifications used to define how to connect model compositions and their ports for the five existing languages in other tools. The connectors were used to create connections between Objects and Points in our approach. From the results, we found that almost all connection rules were defined based on the given ontology, although the number of connectors was not twice the connection rules of different MBSE languages. This occurred because of the discrepancies of constructing the Graph meta model. For example, in BPMN, the number of connectors was 11 fewer than twice the number of connections, because the linkings between the text Object and other 12 Objects in the BPMN specification required one Role for the text Object and 12 roles for other Objects in our approach, compared with the 12 connection rules in other tools.

B. Qualitative analysis

To qualitatively verify the ontology, SPARQL and SQWRL were used to evaluate the completeness and logic of MBSE models through reasoning. As shown in Fig. 4-A, a SysML model was transformed to the defined ontology (Fig. 4-B, C, and D) generated by *MetaGraph*. The completeness and logic of the given SysML model were evaluated separately using Algorithms 1 and 2.

Algorithm 1 is a SPARQL query algorithm developed to verify completeness of the generated ontology. As shown in Fig. 4, the ontology generated from the SysML model was used to verify the completeness of the ontology. Based on Algorithm 1, the SPARQL script was developed to verify the three metrics mentioned in Section II. As shown in Fig. 5-B, the query results demonstrated that all *Objects* and *Relationships* representing the SysML model were captured in the ontology to describe its model structure. Moreover, *Properties* was also identified in different meta-models. From the results, we can infer that the completeness of the ontology was verified, because all the information related to the SysML model was completely transformed into the ontology model.

Algorithm 2 is a SQWRL algorithm used to verify the logic flows in the given SysML model. To capture the *connections* among *object*^{obTp}(*obId*), *relationship*^{reTp}(*obId*), and *point*^{reTp}(*obId*, *poId*), which are defined as the individuals representing the the *Object*, *Relationship*, and *Point* concepts



Fig. 4. Ontology modeling using MetaGraph

Language	Graph	Object	Point	Property	Relationship	Role	Referred tools
SysML	9(9)	73(64)	11(11)	10(10)	31(31)	31(31)	(Magic draw) [27]
BPMN	1(1)	81(77)	0(0)	51(46)	5(3)	10(0)	(BPM Camunda) [28]
UPDM (Unified Profile	52(52)	100 (123)	7(6)	84 (06)	57 (50)	54 (0)	(Magie draw) [27]
for DoDAF/MODAF)	52(52)	100 (123)	7(0)	84 (90)	37 (30)	54 (0)	(Wagie uraw) [27]
EASTADL	10(9)	67(62)	17(17)	93(93)	23(21)	68(64)	(MetaEdit+) [10]
OPM	1(1)	3(3)	0(0)	9(8)	15(15)	12(4)	(OPCAT) [29]

 TABLE II

 Meta models described by the GOPPRRE approach.

in the model, Algorithm 2 was used to capture the related information. All individuals representing the SysML model were queried using the object properties listed below:

- graphIncludingConnector refers to the connector developed in a graph associated with *Relationship*, *Role*, and *Object (Points)*, as shown in Equation (2).
- *linkFromRelationship* refers to the relationship linked to one connector, where one *Relationship* has one *Role* as its end, as described by *linkRelationshipAndRole*.
- *linkToObject* refers to the connector linked to one *Object*,

where one *Role* is connected to one *Object* or one *Point* described by *roleBindingObject* or *roleBindingPoint*. If *Points* are not involved in the connection, the *Object* is defined as the end of the relationship or vice versa.

• *connect* refers to that one connector (start) linked to another connector (end). It is used to describe the direction of the relationship.

As shown in Fig. 5-C, the query results identify the *Relationship* individuals between different *Object* individuals and *Point* individuals. Moreover, the direction of the *Relationship*

Algorithm 1 SPARQL Algorithm for verifying the completeness of the MBSE models

 $\begin{array}{l} PREFIXowl: < http://www.w3.org/2002/07/owl \# > \\ PREFIXrdf: < http://www.w3.org/1999/02/22 - rdf \\ -syntax - ns \# > \\ PREFIXxsd: < http://www.w3.org/2001/ \\ XMLSchema \# > \end{array}$

PREFIXse < http://www.zkhoneycomb.com/formats/ metagInOwl# >

// If Graph includes Objects(Relationships)
select ?graph ?object ?relationship
where {

?graph se:graphIncludingObject(graphIncludingRelationship)
?object(relationship)

}

// If Objects(Relationships) includes Points(Roles)
select ?object ?point ?relationship ?role
where {

?object(relationship) se:linkObjectAndPoint(linkRelationship AndRole) ?point(role)

}

// If Object(Graph and Relationship) includes Properties
select ?graph ?object ?point ?relationship ?role ?property
where {

?graph(object, point, relationship or role) se:hasProperty ?Property

}

Algorithm 2 SQWRL Algorithm for verifying the logic of the MBSE models

// Query relationships in the MBSE models				
graph(?Graph) Λ connector(?Connector1) Λ				
connector(?Connector2) Λ relationship(?Relationship)				
Λ object(?ObjectInput) Λ object(?ObjectOutput)				
Λ graphIncludingConnector(?Graph, ?Connector1)				
Λ graphIncludingConnector(?Graph, ?Connector2)				
Λ linkFromRelationship(?Connector1,?Relationship)				
Λ linkFromRelationship(?Connector2,?Relationship)				
Λ linkToObject(?Connector1,? ObjectInput) Λ				
linkToObject(?Connector2, ?ObjectOutPut) Λ				
connect(?Connector1, ?Connector2)				
-> sqwrl:select(?Relationship,?ObjectInput,?ObjectOutput)				
// Query the direction of each relationship				

-> sqwrl:select(?Graph, ?Relationship, ?ObjectInput)

TABLE III CONNECTION RULES COMPARED WITH CONNECTORS IN THE GOPPRRE APPROACH

Language	Connection rules	Connectors
SysML	31	62
BPMN	72	133
UPDM	396	792
EASTADL	215	233
OPM	39	54

is identified based on its starting role from *Object* individuals.

C. Discussion

From the quantitative and qualitative analyses, we found that the ontology based on the GOPPRRE approach could formalize at least five MBSE modeling languages used to model systems of systems (e.g., UPDM), system architectures (e.g., SysML), business processes (e.g., BPMN), and domainspecific knowledge for the architectural description language of automotive embedded systems, for example. Thus, we can infer that the designed ontology can support the MBSE formalisms for the entire lifecycle.

This ontology enables the promotion of data interoperability. *GOPPRR* provides one the most powerful approaches available to describe domain-specific characteristics, whose meta-meta models have better descriptive capabilities [30] than others. Moreover, from the results shown in Tables II and III, we found that the current GOPPRRE ontology could integrate at least five existing MBSE languages. To support data exchange among these languages, the GOPPRRE ontology can be used as the middleware for the MBSE community.

OWL is widely used to support ML and AI techniques, and its ontology, generated from MBSE models, can be used to support reasoning and to analyze target modeling systems. For example, Algorithms I and II enable information capture from MBSE models for knowledge management. Moreover, the ontology generated from MBSE models are directly used to construct cognitive twins to support decision-making, system development, and operations [18]. With this ontology, AI and ML algorithms can be developed to support system development based on MBSE model information.

Scalability is an important issue regarding the application of the developed ontology. Thus, it will eventually require adoption by the Industrial Ontologies Foundry Systems Engineering Working Group.

V. CONCLUSION

In this paper, we designed an ontology based on the GOP-PRRE approach that supports MBSE formalisms using OWL methodologies for model integration. First, we demonstrated the GOPPRRE concepts using an M0–M3 modeling framework. Then, we developed a transformation rule between them and ontology based on OWL. Based on the transformation rules, OWL models were generated from five existing MBSE languages by a domain-specific modeling tool *MetaGraph*. Qualitative and quantitative approaches were used to evaluate



Fig. 5. SPARQL and SQWRL query results

the completeness and logic of the generated ontology models. From the results, we found that the designed ontology could support MBSE formalisms, showing the potential of this method to become the standardized ontology for the MBSE community in the future.

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