Ontological Integration of Semantics and Domain Knowledge in Energy Scenario Co-simulation

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Abstract: The transition of the power system to more decentralized power plants and intelligent devices in a smart grid leads to a significant rise in complexity. For testing new technologies before their implementation in the field co-simulation is an important approach, which allows to couple diverse simulation models from different domains. In the planning and evaluation of co-simulation scenarios experts from different domains have to collaborate. To assist the stakeholder in this process, we propose to integrate on the one hand semantics of simulation models and exchanged data and on the other hand domain knowledge in the planning, execution, and evaluation of interdisciplinary co-simulation based on ontologies. This approach aims to allow the high-level planning of simulation and the seamless integration of its information to simulation scenario specification, execution and evaluation. Thus, our approach intents to improve the usability of large-scale interdisciplinary co-simulation scenarios.

1 INTRODUCTION

The intended transition from fossil to renewable energies in the power system poses many new challenges. New technologies have to be developed to deal with fluctuating energy resources and available flexibilities. Additionally, the dependencies between different domains become more and more important and the power system can be considered neither detached from the ICT system nor ecological, economic, or sociotechnical systems. To handle this complexity in the development of new technologies simulation is an important approach. Especially, co-simulation is used to couple diverse simulation models, which is beneficial because in different domains usually specific software, programming languages, and paradigms are used. The coupling allows to reuse existing simulation models without the need for reimplementation and allows to use sophisticated models of the different domains.

Commonly, a simulation expert works together with the experts of the different simulation models in the planning of a co-simulation. This collaboration of simulation and domain experts can be a complex task, because they have to understand at least partly the other domains. For example, in the discussion the used terminology can be unclear, because the same terms may be used for different concepts. Therefore, it would be beneficial for the development of energy scenarios to directly integrate or reference external domain knowledge.

Co-simulation scenarios, which describe an executable co-simulation, are typically developed manually by the simulation expert. Central elements of this process are the parameters, dependencies, and data flows of simulation models. An increasing number of simulation models makes the planning more complex and error-prone, when done manually. Therefore, it is essential for the planning of complex co-simulation scenarios to get assistance in this process, e.g. in getting recommendations of suitable simulation models.

Often co-simulation is not used as standalone tool, but is integrated in energy scenarios adding even more complexity. Energy scenarios are used to describe possible future developments of the energy system (Grunwald et al., 2016). Typically, the future states are defined, tested with simulation and evaluated afterwards. For this, a clear definition of the parametrization, data flows, and results is crucial.

Our approach introduces ontological representations of domain knowledge in co-simulation of energy scenarios to address the described problems. Additionally, it uses Semantic Web technologies to structure the process of planning, execution, and evaluation of co-simulation. It has been developed in the project NEDS, which consists of an interdisciplinary

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consortium from the domains of business administration, computer science, economics, electrical engineering, and psychology. In the project a process for the integrated development of energy scenarios, their simulation, and the evaluation of their sustainability has been developed (Schwarz et al., 2019b) and executed for a future scenario for the German federal state Lower Saxony. In this context, our proposed ontology-based approach offers the following benefits:

Firstly, it enables the integration of knowledge from external ontologies. This allows to reuse existing ontologies from different domains and integrate definitions of used terms. Thus, the terminology used in a co-simulation project can be made clear and transparent.

Secondly, it allows to describe the semantics of data in several steps of co-simulation: The parametrization of simulation models, the exchange of data between simulation models, and the results of simulation. All of these different kinds of data can be semantically annotated to make the interpretation less error-prone.

Thirdly, Semantic Web technologies like RDF, OWL, and SPARQL offer a well-known and widespread structure for knowledge representation and querying. Their usage permits the utilization of manifold available tools and techniques. Especially, the querying based on the ontological description of dependencies and data flows assists the planning of simulation scenarios and enables the simulation expert on the one hand to check high-level scenarios for completeness and missing models or evaluation functions and on the other hand to verify simulation scenarios.

The remainder of this article is structured as follows: Section 2 gives an overview of the foundations and related work. Section 3 describes the proposed approach, gives some examples, and describes the evaluation of the approach in a field study. A conclusion is given in section 4.

2 FOUNDATIONS AND RELATED WORK

In this section, we will give an overview of related work using co-simulation and ontologies in the energy domain (see section 2.1) and introduce our previous work of a process for the planning and evaluation of energy scenarios with an information model and a catalog of components for co-simulation (see section 2.2).

2.1 Co-simulation and Ontologies in Energy Domain

As stated in the introduction, the power system becomes more and more complex, because multiple domains have to be considered. An approach for handling this issue is co-simulation, which is defined as *"an approach for the joint simulation of models developed with different tools (tool coupling) where each tool treats one part of a modular coupled problem"* (Bastian et al., 2011, p.1).

In energy domain, many different smart grid co-simulation frameworks exist, which are developed for different use cases. For example, the usage of real-time and co-simulators for the development of power system monitoring control and protection applications (Rehtanz and Guillaud, 2016), the coupling with power flow simulators (Lehnhoff et al., 2015), the integration of power system and communication networks (Mets et al., 2014), or a holistic view on the power system (Schwarz et al., 2019b). Schlögl et al. (2015) suggest a typification for the available co-simulation frameworks and Vogt et al. (2018) compare many of them. However, Palensky et al. (2017) state that challenges in co-simulation are still massive, which is caused among other things by often missing software interoperability in the modeling.

Although ontologies would offer many benefits for interoperability, the utilization in co-simulation approaches is not common with two exceptions: Teixeira et al. (2018) describe an approach for co-simulation with integration of ontologies for the interoperability between different electricity market multi-agent simulation platforms, which is called TOOCC (Tools Configuration Center). But the focus of this approach seems to be mainly on energy markets and building energy management and the data structure of messages between simulation models. Another approach is CODES (Composable Discrete-Event scalable Simulation), described by Teo and Szabo (2008). It contains the COSMO ontology, which supports the classification of components to allow component discovery and reuse with a model repository, but it is limited to discrete-event simulation. As our focus is more on the high-level scenario planning, the integration of external domain knowledge, and the usability, our approach aims to be integrated in the established open-source co-simulation framework mosaik[1] (Steinbrink et al., 2019). It is focused on providing high usability and flexibility to enable interdisciplinary teams to develop co-simulation scenarios. For the coupling of simulation models mosaik provides an API, which is

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[1] https://mosaik.offis.de

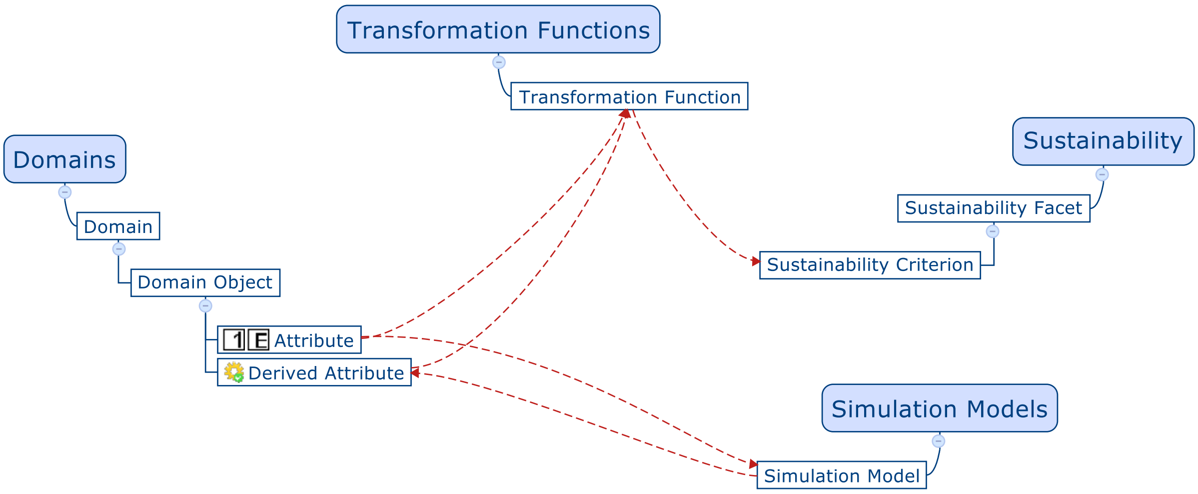

Figure 1: Structure of the SEP information model (Schwarz et al., 2019b).

available in several programming languages and can also be accessed via network packages.

2.2 Process for Assisted Simulation Planning for Co-simulation

In previous work we have introduced the Sustainability Evaluation Process (SEP) and an information model for the high-level planning of co-simulation in the context of energy scenarios (Schwarz et al., 2019b). The SEP describes an integrated process for the sustainability evaluation of future scenarios based on literature review and co-simulation. The first step of the SEP is the development of qualitative future scenarios, which describe thinkable future states of the power system – the energy scenarios. Afterwards, these qualitative assumptions are quantified and used as input for simulation. The last step is the evaluation of the simulation results based on multi-criteria decision making. The evaluation function for the SEP is sustainability, but also other evaluation functions could be defined in the information model. The information model links future scenarios and simulation scenarios to the sustainability evaluation as shown in figure 1. On the left-hand side the domains of interest are modeled and described by attributes, which can be defined based on either future scenarios or simulation. On the right-hand side sustainability is defined as evaluation function and subdivided in facets and criteria. The connection between the two sides is established through transformation functions from attributes to the sustainability criteria. The information model aims to support the information exchange in the SEP. It describes a structure for modeling scenarios and assists the users in the process.

Based on the information model, a process for the planning of co-simulation was developed, which is shown in figure 2 (Schwarz et al., 2019a). In this planning of a co-simulation, simulation models have to be found, which can provide the results defined in the information model. For this, a catalog of co-simulation components was developed to give an overview of the available components. The interfaces of the simulation models are described in the catalog based on the Functional Mockup Interface (FMI) standard, which has been developed to allow the coupling of different simulation models in industrial and scientific projects (Blochwitz et al., 2009). A substantial part of FMI is the definition of variables, which define the inputs and outputs of simulation models (Modelica Association Project FMI, 2013). Each variable can be described by seven attributes in FMI. For example, the attribute causality can have values like *input*, *output*, *parameter*, or *calculatedParameter* or the attribute variability characterizes time instants when a variable can change its value and can have values like *constant*, *fixed*, *discrete*, or *continuous*.

3 APPROACH

Our approach for the ontological integration of domain knowledge in co-simulation is based on the information model and component catalog summarized in the previous section. In previous papers, first ideas of this approach were described (Schwarz and Lehnhoff, 2018; Schwarz et al., 2019a,b), which will be detailed in the following regarding the ontological integration.

The information model of the SEP aims to assists the collaboration of a simulation expert and domain experts, which provide the simulation models. It can

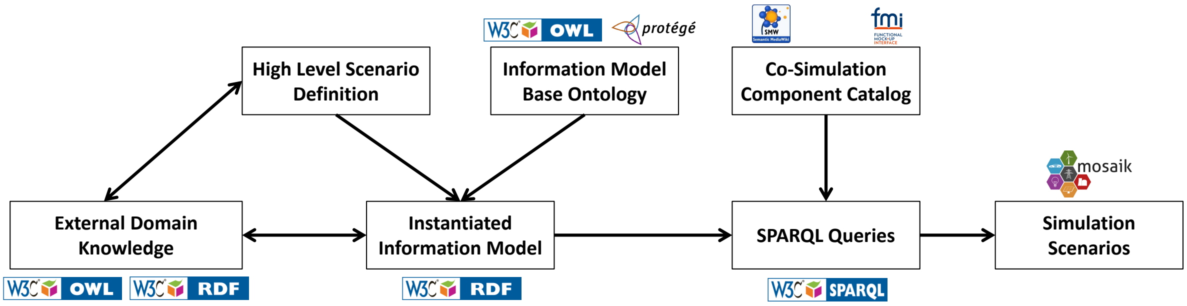

Figure 2: Overview of the approach for ontological integration of domain knowledge in energy scenario simulation (Schwarz et al., 2019a).

be assumed that the simulation expert is a software expert familiar with the co-simulation framework and several programming languages and simulation tools, but has only limited knowledge about all domains included in simulation. The domain experts may also be software experts, especially, if they provide simulation models. But they could also have no background in computer science or software development. Therefore, an important requirement for our approach is to facilitate the participation of domain experts in the modeling without previous knowledge of Semantic Web technologies. Thus, a semantic diagram in form of a mind map is used for modeling the SEP information model (see *high level scenario definition* in figure 2). This allows to start the planning of scenarios with brainstorming in the project team and bringing the information step by step in the correct structure. Objects in the mind map can also be annotated directly with additional information. For example, references to external ontologies (see section 3.1), or the context of the future scenarios can be annotated.

The map has to comply to the structure of the information model shown in figure 1 in the end. Other methods for knowledge modeling with the graph-based structure of concept maps also exist, as Simon-Cuevas et al. (2009) describe it for example. We argue that a tree-based mind map is sufficient for the described use case and the superior flexibility of a graph-based concept map would distract the users.

For the ontological representation of the modeled information, a base ontology representing the information model structure has been developed (see section 3.2). The mind map tool XMind[2] was used and extended with a plug-in to instantiate the information model ontology. Therefore, the scenario can be modeled inside the mind map and be transformed to RDF (see *instantiated information model* in figure 2).

To build an executable co-simulation based on this, a co-simulation component catalog was implemented (Schwarz et al., 2019a). For this, a Semantic MediaWiki (SMW) (Krötzsch et al., 2007) was used to collect available simulation models. It is used to facilitate the participation of users without experiences in Semantic Web technologies. With the page forms extension[3] it offers intuitive usable forms to add new models to the catalog. The SMW allows to import vocabularies from external ontologies and to export the content to RDF or to use directly a triplet store as database. Thus, the catalog can directly be integrated in the instantiated ontology of the information model and the user can be assisted in finding the suitable simulation models for his purpose. Some example queries showing this assistance are shown in section 3.3. For the integration of the approach in co-simulation a prototype for the framework mosaik has been developed. It allows to use the information from the information model and the component catalog to assist the simulation expert in the development and validation of executable simulation scenarios. Finally, the integration in data management is shortly described in section 3.4 and the evaluation of the approach in section 3.5.

3.1 Referencing External Ontologies

The ontological modeling allows to reference existing external ontologies in different manners. Exemplary ontologies for the following relevant use cases are described in this section. On the one hand, the objects of interest for the simulation (*domain objects*) and objects of evaluation (*sustainability criteria*) in the information model can be mapped to external ontologies to define their meaning. On the other hand, external ontologies can be used for the definition of units of measurement for different kinds of attributes in the information model.

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[2] https://www.xmind.net/

[3] https://www.mediawiki.org/wiki/Extension:Page_Forms

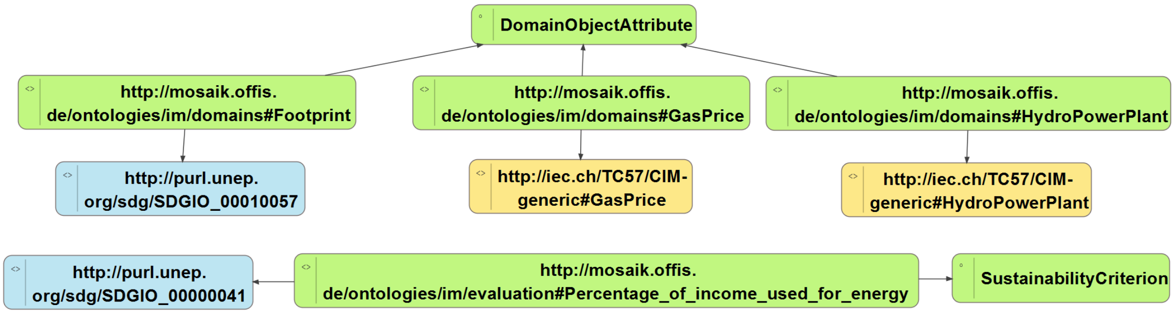

Figure 3: Mapping of individuals of the instantiated information model from project NEDS to external ontologies.

3.1.1 Definition of Terms

In the energy domain the Common Information Model (CIM) is widespread to facilitate interoperability in the power system. It contains a data model in form of a domain ontology, various interface specifications, and mappings between technologies. Thus, it enables automated communication between components of smart grids. For our approach mainly the first use case for CIM described by Uslar et al. (2012) is of interest, which is CIM as a large domain ontology providing a vocabulary. This vocabulary can be used to map objects to definitions in the CIM. The CIM is defined as an UML model, but the complete model or subsets (so-called profiles) can be transformed to Web Ontology Language (OWL) with the CIMTool[4].

As in the SEP sustainability is evaluated, it is examined here as example as well. The United Nations defined Sustainable Development Goals (SDGs), which should be fulfilled until the year 2030 (UN General Assembly, 2015). To reference these goals and their indicators the SDG Interface Ontology[5] (SDGIO) based on the Environment Ontology (ENVO) (Buttigieg et al., 2016) is under development. It contains definitions of indicators for the measurement of the SDGs defined by the United Nations.

The mapping to external ontologies allows integrating definitions of terms to make clear their meaning in an interdisciplinary simulation or to relate internal evaluation criteria to external criteria. Examples of mapping to the external ontologies CIM and SDGIO are described as follows (see also figure 3). The CIM ontology contains definitions for objects of the power system like *CIM-generic#EnergyMarket*, *CIM-generic#HydroPowerPlant*, and *CIM-generic#GasPrice*, which are mapped to domain objects and attributes of the information model in the project NEDS. Additionally, the domain object attribute *footprint* in NEDS is mapped to the class *material footprint* (*sdg/SDGIO_00010057*) and its definition in the SDGIO. Another example is the sustainability criterion *Percentage of income used for energy* in NEDS, which addresses the SDG 7: "*Ensure access to affordable, reliable, sustainable and modern energy for all*" (UN General Assembly, 2015, p. 21), which is represented by the individual *sdg/SDGIO_00000041* in the SDGIO.

3.1.2 Units of Measure

The Ontology of units of Measure (OM) is an OWL ontology of the domain of quantities and units of measure described by Rijgersberg et al. (2013). It aims to *"support making quantitative research data more explicit, so that the data can be integrated, verified and reproduced"* (Rijgersberg et al., 2013, p. 1). In the OM every measure is defined by a unit of measure, which can have a prefix. These units of measure are defined by a quantity and each quantity has a dimension. For example, the measure "3 meters" would be defined by the unit "meter", which could be defined by the quantity "length" or "height", which both are in the "length dimension". Additionally, a java library for conversion of units based on the ontology is available[6].

Units play an important role in the attributes, transformation functions, and sustainability criteria in the information model as well as in simulation models and co-simulation. All connections have to be validated in consideration of their unit to ensure the functionality. Therefore, the OM is used to add references to the units of attributes and criteria annotated in the information model. Additionally, the OM is used to assist the user in annotating directly in the mind map, comparable to the assistance with an Excel add-in described by Rijgersberg et al. (2013). With this information the OM allows to validate the connections. In the case of problems, a conversion can be added or the user be warned. The information can also be used

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[4] http://wiki.cimtool.org

[5] https://github.com/SDG-InterfaceOntology/sdgio

[6] https://github.com/dieudonne-willems/om-java-libs

within the co-simulation scenarios to check for correctness of connections between simulation models.

3.2 Ontological Representation

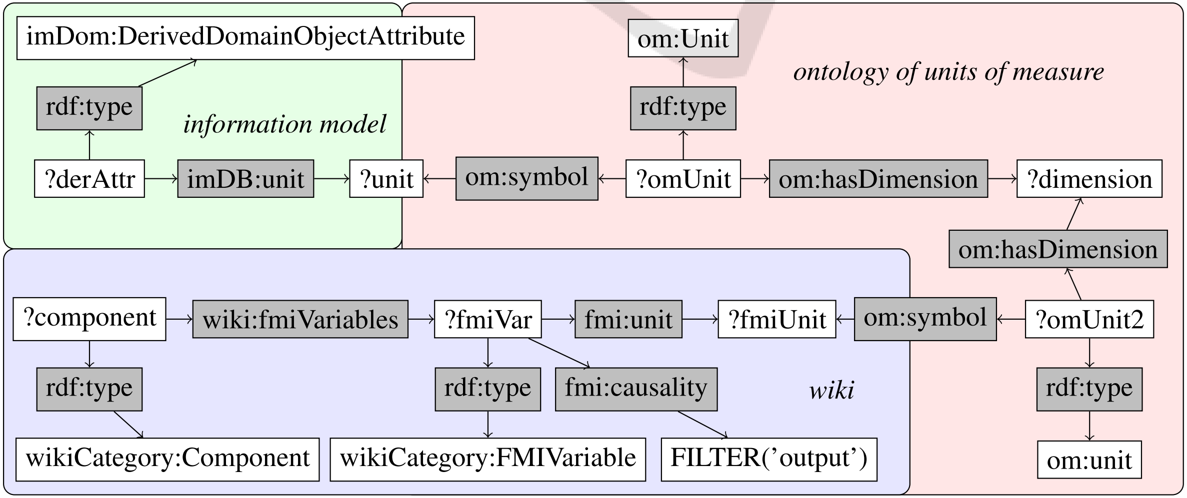
Three base ontologies have been developed and are imported in an additional ontology for integration. This modularity enables the reuse of the ontologies. The first ontology represents the structure of the information model for the high-level scenario planning. The second ontology represents the structure of the component catalog and the FMI-based specification of variables. The third ontology represents the structure of a simulation scenario modeled in mosaik. Such a scenario consists of multiple simulation component with their parametrization and the connections between simulation component and the exchanged attributes between them. Based on these three ontologies the available data is described and can be used for queries.

3.3 Example Queries

The usage of ontologies provides a structure for querying the data of the planning in the information model, the component catalog, and the mosaik scenario with SPARQL to assist the development of simulation scenarios. In the following, two examples are given, which show the opportunities of the ontological representation in the planning of executable co-simulation scenarios. For both examples the SPARQL code and a visualization of the query are shown. The following prefixes are used: The prefixes *wiki* and *fmi* are referencing the component catalog in the SMW. The prefixes *imDB, imDom*, and *im* are referencing the information model base ontology. The prefix *om* is referencing the OM. In the visualization (see figures 4(b), and 5(b)) the data source is indicated by the background color and label.

```
SELECT DISTINCT ?derAttr ?unit ?omUnit ?dimension ?component ?fmiVar
    ?fmiUnit
  WHERE {
    ?derAttr rdf:type imDom:DerivedDomainObjectAttribute; imDB:unit ?unit
    ?omUnit rdf:type om:Unit; om:symbol ?symbol
    FILTER( ?symbol = ?unit )
    ?omUnit om:hasDimension ?dimension
    ?component rdf:type wikiCategory:Component; wiki:fmiVariables ?fmiVar
    ?fmiVar rdf:type wikiCategory:FMIVariable
    ?fmiVar fmi:unit ?fmiUnit; fmi:causality ?fmiCausality
    FILTER( ?fmiCausality = ’output’ )
    ?omUnit2 rdf:type om:Unit; om:symbol ?symbol2
    FILTER( ?symbol2 = ?fmiUnit )
    ?omUnit2 om:hasDimension ?dimension }
```

(a) SPARQL code



(b) Visualization

Figure 4: Query 1 – Simulation models from wiki providing output for derived attributes of information model.

3.3.1 Query 1

This query (see figure 4) assist the user in common use cases for the development of a co-simulation scenario. If the simulation models are not predefined, the simulation expert has to find simulation models matching the goal of the simulation. This can be a complex task, because there can be a vast amount of available simulation models, which were usually not developed by the simulation expert. Therefore, the simulation expert does not know all details about the simulation models and is assisted by querying the information model and the specification of the simulation models in the component catalog.

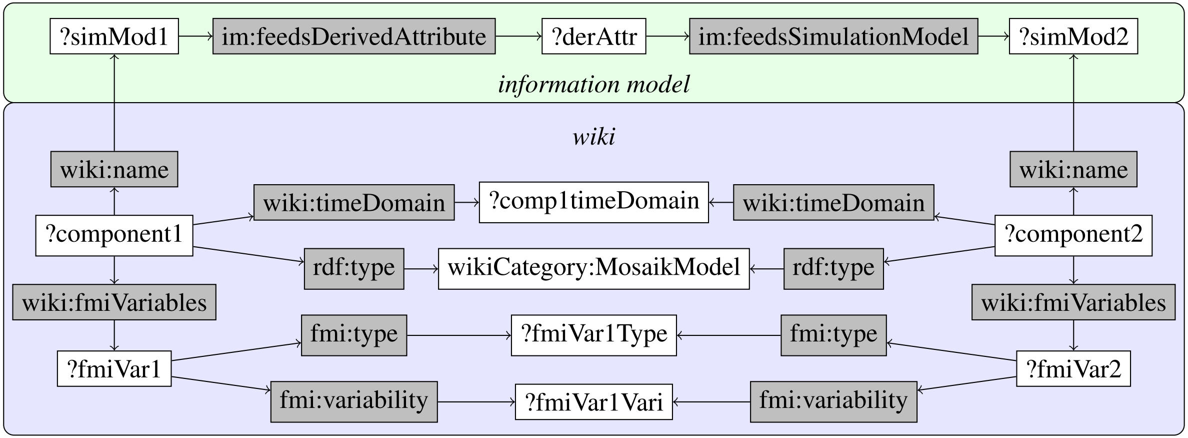
Query 1 shows simulation models, whose output can be used in the information model. These derived attributes in the information model are by definition the output of a simulation. In the query the derived attributes (*?derAttr*) in the information model are mapped to the variables (*?fmiVar*) of simulation models (*?component*) in the component catalog. The variables are filtered by their *fmi:causality*, which has to be *output*. To find suitable combinations of derived attributes and variables the units annotated in the mind map are used. In this query the units are not compared directly, but the OM is used to reference the dimension (*?dimension*) of the unit, e.g., the unit "meter" is in the length dimension. Hence, differences in unit prefixes or the system of measurement (imperial or metric system) are of no importance for mapping.

3.3.2 Query 2

This query searches for simulation models that use the output of another simulation model as input(see figure 5). In the information model such kind of connection is modeled via a derived attribute, but it is usually realized by a direct coupling of the two simulation models in co-simulation. For these cases, the query checks the technical interfaces and characteristics of the simulation models for compatibility based on the component catalog. In the query, the first simulation model (*?simMod1*) is mapped to the derived attributes (*?derAttr*) and the second simulation model (*?simMod2*). If two simulation models in the information model are modeled this way, the technical characteristics of the

```
SELECT DISTINCT ?simMod1 ?fmiVar1 ?fmiUnit1 ?derAttr ?fmiVar2 ?fmiUnit2
    ?simMod2
  WHERE {
    ?simMod1 im:feedsDerivedAttribute ?derAttr
    ?derAttr im:feedsSimulationModel ?simMod2
    ?component1 rdf:type wikiCategory:MosaikModel
    ?component1 wiki:name ?simMod1; wiki:fmiVariables ?fmiVar1
    ?fmiVar1 rdf:type wikiCategory:FMIVariable
    ?component2 rdf:type wikiCategory:MosaikModel
    ?component2 wiki:name ?simMod2; wiki:fmiVariables ?fmiVar2
    ?fmiVar2 rdf:type wikiCategory:FMIVariable
    ?fmiVar1 fmi:type ?fmiVar1Type; fmi:variability ?fmiVar1Vari
    ?fmiVar2 fmi:type ?fmiVar1Type; fmi:variability ?fmiVar1Vari
    ?component1 wiki:timeDomain ?comp1timeDomain
    ?component2 wiki:timeDomain ?comp1timeDomain
```

(a) SPARQL code



(b) Visualization

Figure 5: Query 2 – Finding suitable simulation models for coupling with another simulation model.

simulation models can be checked for compatibility based on the component catalog.

In the example, the characteristics *fmi:variability* and *fmi:type* of the FMI variables (*?fmiVar1* and *?fmiVar2*) are compared. Additionally, the characteristics *wiki:timeDomain* of the simulation models (*?component1* and *?component2*) are compared. This characteristic can have values like “discrete”, “continuous”, or “stationary” and addresses the common problem of different timing in simulation models. This query can also be adapted to find suitable simulation models based on these characteristics, if one of them is missing in the information model.

3.4 Data Management

In the SEP, values from future scenarios, simulation scenario parametrization, and simulation results have to be managed and are directly integrated in the information model. The information model provides one central storage for the semantics of all relevant data in the complete process. Thus, also the data management is integrated with the information model.

As briefly mentioned in Schwarz et al. (2019b) the information model was used to generate the schema for a data store, which was implemented in a relational database (RDB) in the NEDS project. To facilitate the collaboration of different domain experts, different views were defined on the schema. To integrate the data from a relational database again Ontology-based Data Access (OBDA) could be used. It is based on a three-level architecture containing an ontology, data sources, and a mapping between them Daraio et al. (2016). Thus, OBDA faces the challenge of data heterogeneity by replacing a global scheme in data management with the ontology describing the domains. It allows also to integrate data from other sources like CSV, XML, and XLSX directly in SPARQL queries, which can be helpful in the interdisciplinary environment of co-simulation.

To reduce the complexity the direct usage of a triple store would be preferable compared to a RDB with ODBA, but is not always possible. However, the usage of a triple store or OBDA would allow to access data based on the information model ontology and to integrate the data store directly in SPARQL queries.

3.5 Evaluation

The proposed approach aims to support users in the modeling and management of information in the development of co-simulation scenarios. For its evaluation, the process was used in a field study in the interdisciplinary project team of the project NEDS. Altogether, 28 scientific researchers participated and used the information model to model a simulation scenario, which integrated several simulation models from different domains and to evaluate the results of simulation. The members of the project team came from the domains energy, computer science, business administration, economics, electrical engineering, and psychology. 29 domain objects, 231 attributes, and 19 sustainability criteria where modeled with their dependencies and data flows in the information model and transformed to RDF automatically for further usage. Based on the RDF representation of the information model SPARQL queries where used to check for completeness and correctness of the modeled information. As the project partners were mostly not from computer science, we defined the SPARQL queries to get the needed information. The implementation of a GUI to enable the users to do this themselves would be interesting future work.

The field study showed that the process was helpful to include domain experts in the design of simulation scenarios. The use of the information model allowed easy participation and offered a central model. Also, the semantic diagram was supportive as tool for discussion in the project team. The field study showed that not all participating domains have ontologies which could be referenced for definition of terms. However, the modeling of the information model improved the processes in the interdisciplinary project team during the development of energy scenarios and helped significantly making clear the terminology.

4 CONCLUSION

In this paper, we described an approach for the ontological integration of semantics and domain knowledge in the process of planning, execution, and evaluation of interdisciplinary co-simulation of the energy system. Our approach incorporates the SEP and its information model representing the process and providing the ontological structures for the modeling of energy scenarios using co-simulation. It can be instantiated in collaboration of interdisciplinary domain experts and allows to integrate external ontologies for definition of terms and referencing external works. The modeling of the scenarios in the information model allows also the integration in data management of scenario parametrization and results.

Also, a catalog of simulation components in a SMW was integrated to assist the simulation expert finding suitable simulation model during the planning of co-simulation. The integration of the approach in the co-simulation framework mosaik has been implemented prototypical. This prototype uses the information model and simulation model specification from the SMW to validate simulation scenarios. Based on this validation, also wrong connections of simulation components should be found in the future. These could be corrected by automatically added conversions.

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