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***Abstract*—Heterogeneous software ecosystems and simulation tools' coupling complexities are significant challenges in the design and simulation of Multi-Energy-Systems (MES). In such multidisciplinary environments interoperability issues hinder effective collaboration, while data heterogeneity obstructs seamless integration and consistent interpretation. Moreover, as the number of simulated entities grows, the need for human intervention for configuring and coupling models for execution becomes increasingly necessary. Semantic web technologies offer powerful solutions to address these challenges by means of knowledge-driven strategies. In this context, this paper proposes an ontology-based methodology, that will support coherent simulation set-up design, easy integration of new tools and data into existing workflows and will ensure interoperability and reusability of simulation results, paving the way towards accurate and automated MES simulations. The proposed approach was validated through a multi-simulator co-simulation of a building energy system, confirming its effectiveness in ensuring semantic compatibility, dynamic configuration, and consistency of simulation outputs.**

***Index Terms*—Ontology, Knowledge Representation, Semantic web technologies, co-simulation**

I. Introduction

Multi-energy systems (MES) are complex infrastructures that integrate physical energy flows—such as thermal and electrical power—with digital communication networks and human interactions. A representative example of an MES is a district energy system that includes solar photovoltaic installations, heating systems, energy storage technologies, and smart metering infrastructure. These components collectively enable the optimization of energy generation, distribution, and consumption in urban contexts. A simple example topology of components capable of simulating a MES is illustrated in Fig. 1.

The example illustrates a simplified configuration comprising the main components of a real building and its context. All this components exchange data throughout the internet, enabling real-time interactions and coordinated operations . As the system scales to include multiple buildings, the number of variables scales significantly, introducing greater complexity and a higher likelihood of errors. Simulating these systems is of paramount importance for advancing the Sustainable Development Goals proposed by the United Nations [1]. However, due to their inherent complexity, monolithic simulation systems struggle to accurately capture MES behavior. Instead, MES exhibit a modular nature that aligns well with co-simulation, which enables more flexible and scalable analyses. Co-simulation, short for *"cooperative simulation"*, refers to the theories and techniques that enable the global simulation of a coupled system through the composition of independent simulators [2]. Simulators exchange messages in a synchronized manner, mirroring the interactions and dynamics of the overall system. This approach captures cross-domain interactions while avoiding the constraints of monolithic design; moreover, it enables reusability of components, scalability, and adaptability of models to new contexts [3]. Despite its advantages, co-simulation introduces other significant challenges: i) synchronizing tools' interactions to ensure accurate message exchanges, ii) managing coupling complexities, which grows with heterogeneity and system scale, iii) preparing and adapting data to meet the requirements of different simulation tools, posing a key challenge in automating simulation setup. The research community continues to advance knowledge to address this challenges.

Semantic web technologies have emerged as a solution to enhance machine interpretability, interoperability, and automation. Such technologies are grounded by the Resource Description Framework (RDF) [4]. In RDF, all information is represented as triples in the form *subject–predicate–object*, which together naturally form an RDF graph. These triples can be stored in a triplestore, a specialized database designed to efficiently store, retrieve, and query RDF data using the SPARQL (SPARQL Protocol and RDF Query Language) language [5], the de-facto standard to query and analyzing

This work is supported by COMET - Co-simulation of Multi-energy systems for Energy Transition, Italian National funded project under PNRR M4C2, Investimento 1.4 - Avviso n. 3138 del 16/12/2021 - CN00000013 National Centre for HPC, Big Data and Quantum Computing (HPC).

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linked data. Each element constituting the triple is identified by an IRI (International Resource Identifier), which provides a globally unique and unambiguous identifier for resources on the web. On top of RDF, vocabularies like RDFS (Resource Description Framework Schema) [6] and OWL (Ontology Web Language) [7] provide different levels of expressiveness that can be used to build ontologies, as defined in [8] *"An ontology of a domain is a document that is realized by a network of ontology versions about the domain"*. Ontologies encode concepts and relationships that both human and machines can use to interpret data. Thanks to standardized vocabularies and formal, shared knowledge representation, these technologies can complete and enhance co-simulation frameworks and standards by addressing their semantic limitations.

In the energy domain, several ontology standards [9] [10] have gained increasing attention in the research community for their role in standardizing semantic representations in energy systems. However, a significant gap remains: *there is no framework that focus on mapping energy domain entities —such as Energy conversion systems or Heating systems— and their corresponding representations as co-simulation components*. By leveraging existing ontologies and co-simulation standards, prototyping complex simulations that comply also with well-established energy standards can benefit from rich semantic descriptions of simulation units, data, and services.

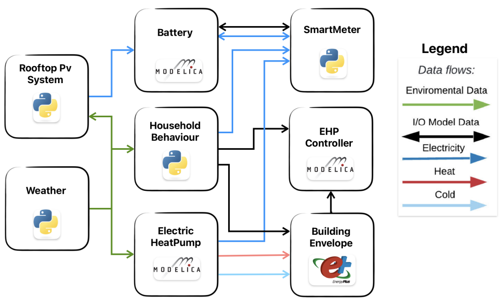

Fig. 1: Example of software components that can simulate the behavior of a MES

Integrating a semantic layer into the workflow is crucial to enable interoperability from data ingestion to the complete setup of complex energy co-simulations, and unlocks the possibility of automating the above mentioned processes, meanwhile enhancing interoperability of data and software. This approach can enable the exploration of decarbonization scenarios without requiring technical expert intervention, reducing time costs, errors, and data ambiguities in energy simulation setup. As the world moves toward mitigating the impact of climate change, assess the impact of MES is at the forefront of this transition. While the research on this topic is active in other domains, Literature highlights a gap in strategies for automating workflows and pipelines needed to setup a fully comprehensive energy simulation, starting from data preparation, passing through tools composition, execution, and results collection. In this context we propose a novel ontology-based methodology, having a basic Co-Simulation Ontology (CS-Ontology) as a core, that builds and extends on existing ontologies aiming at providing interoperability between different simulation models and simulators engines.

The remainder of this article is organized as follows. Section II presents literature solutions addressing aspects of the outlined problems. Section III details the proposed methodology. Section IV introduces the scenario used to validate the methodology, and Section V reports our concluding remarks.

II. Related work

During the last years, the problem of the composability of models to form complex cyber-physical system has been widely discussed. In particular, different approaches have been explored worldwide to exploit the potential of semantic web technologies for assistance in co-simulation scenarios prototyping. The power of ontology reasoning for assessing compatibility and similarity between systems, as well as identifying possible pitfalls in configurations, is one of the main applications of such technologies. Here, we revised the articles that have offered hints to develop the proposed methodology, even if they do not focus on the energy domain.

In [11], the authors propose a methodology to parametrize models using ontologies in order to automate their integration in the mobility domain. A crucial element in this regard is a domain ontology that covers all the aspects and parameters needed by the models used in the co-simulation. They argue that automated model integration can be obtained combining the standardization of terminologies by means of ontologies and the use of mappings between ontology concepts and models' meta-data. However, it is pointed out that a limit of this framework is the need of manually modifying the models in case of unserved inputs that are of paramount importance in the system's scope.

In [12] the authors present an ontology-based method for automatically connecting variables of different models in the maritime industry while complying with the Functional Mockup Interface [13] standard for co-simulation. The semantic description of model variables is mainly based on bond graph theory, which allows for describing energy exchange, but constrains models to follow the power-flow patterns, which is not always the case. Moreover, it is not clear how compatibility of signals outside the scope of bond theory should be modeled.

In the context of planning and evaluating energy co-simulation scenarios involving experts from diverse domains, [14] proposes to use a semantic media-wiki of components from where to retrieve simulation units starting from the definition of a co-simulation scenario in the form of a mind map. Moreover, external ontological knowledge is linked to the elements in the mind map, exploiting the meaning defined there for the entities of interest.

In [15] a semi-automated semantic engine is proposed to solve the problem of simulation model assembly in industrial plants. The methodology proposes to formalize plant and simulation knowledge so that having a formal description of the power plant topology, SPARQL based querying can be used to retrieve simulation models from a simulation models library for each entity of the power plant. The presented methodology is limited for single-output simulation blocks connected in series, but claimed to be extensible.

In [16] a methodology for the joint use of Functional Mockup Interface standard, semantic web technologies, and Building Information Modeling for modular building performance simulation is presented. The overall building model is decomposed into sub-systems, whose variables are enhanced by semantics meta-information that is both human and machine-readable. To achieve this, an ontology called FMUOnt has been developed together with an annotation tool. However, semantics elements are represented by individuals rather than ontology classes, which reduces the expressive power of the representation and limits the potential for reasoning, generalization, and alignment with other ontologies.

In [17] a military combat application scenario is used to show the approach of using an ontology-based method to address challenges in simulation model integration. The methodology presented in [17] uses a so called Community Of Interest ontology to align multiple domain ontologies with ontologies of simulation tools, enabling ontological reasoning to find mismatches in the composition of models.

In [18] the concept of ports and a related ontology to represent them is discussed. Ports are defined as 'the locations of interaction at the boundaries of components or sub-systems' and are characterized by geometric, functional, and behavioral attributes. As a proof of concept, an ontology useful for assembling LEGO ports is presented. Moreover, the authors argue the necessity to describe not only the single ports by which two models are interfaced, but also the way they interact.

[19] presents a methodology for reducing the manual effort in retrieving and coupling models from different sources by exploiting an agent-based assistance system for digitally simulating and analyzing the life-cycle of industrial plants. Even if no ontologies are involved, the methodology explains a mechanism that starting from a topology of the power plant expressed in the AutomationML language models can be automatically selected and configured without the intervention of the user.

While previous works in the energy domain have applied semantic web technologies to either model annotation or simulation workflows, this work introduces a novel integration of co-simulation logic with domain-specific semantics in an executable configuration pipeline. The key novelty lies in the use of a unified semantic layer to decouple data sources, simulation models, and the co-simulation engine, allowing machine-readable descriptions to drive the automated discovery, semantic matching, and composition of simulation units. Unlike prior approaches, which often require manual intervention or focus narrowly on one aspect of the simulation process, our framework supports the end-to-end generation of interoperable co-simulation setups from semantically enriched data and model catalogs.

III. METHODOLOGY

COESI (Co-simulation and Optimization for Energy Systems Integration) [20] represents a foundational piece of previous work that can serve as the basis for building a semantic layer. Its structure, concepts, and integration approach offer a valuable starting point for modeling and connecting energy systems, services, and data within an ontology-driven framework. COESI is a hybrid multi-model co-simulation infrastructure that bridges heterogeneous software simulators and real-time hardware (DRTS) within a distributed, synchronized framework. It is designed to simplify setup and overcome integration, scalability, and automation challenges commonly encountered in smart grid analysis through the use of a dedicated co-simulation configuration file. Leveraging a modular and automated tool for Urban Energy System Modelling [21], COESI can integrate diverse data sources and fill information gaps using statistical estimations and domain-specific assumptions. The urban energy model is provided in the CityJSON [22] format, a compact and structured representation of city objects and their properties. Data about buildings from the CityJSON serves characterization parameters for various simulation tools, offering rich information such as census data, estimated energy demands, and spatial relationships. However, COESI configuration file is compiled manually, posing a significant obstacle towards scaling the deployment of energy co-simulations. The following sections summarize fundamental aspects for the proposed ontology-driven approach, the layer must satisfy the following requirements:

R1: Semantic Representation of Simulation Modules The ontology must semantically represent simulation modules, including inputs, outputs, and parameters, by attaching semantic tags that enable black-box representation while ensuring interpretability.

R2: Modularity and reusability The ontology used to represent simulation units should be domain-agnostic and adaptable to various application fields, with the possibility to allow integration with domain-specific ontologies.

In order to satisfy the need of retrieving, configuring and composing simulation units for co-simulation, the ontology should be able to answer several competency questions. In particular, all the information required by the COESI platform described in the introduction must be made available:

CQ1: Which simulation units are suitable to simulate a specific technology (e.g. see Rooftop PV System in Fig. 1)?

CQ2: Given a specific simulation module with annotated inputs/outputs, what other modules are compatible for connection based on semantic relationships (e.g. in Fig. 1, only the Smart Meter should able to accept electrical power coming from the Rooftop PV System)

CQ3: What are the model and simulation parameters of a given simulation unit? (e.g. which is the simulation time step of the Rooftop PV System? What contextual information does the model require? the slope of the building rooftop on which the PV system is deployed is an example of such contextual information)

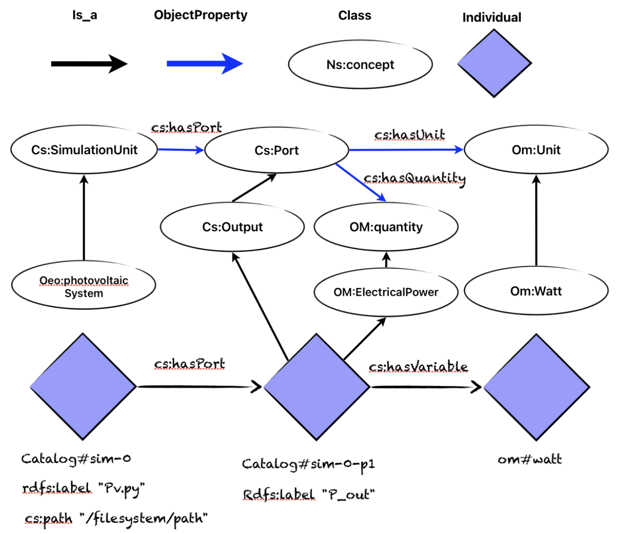

Fig. 2: Example of annotated simulation unit. For simplicity, only one variable is shown

CQ4: What are the execution commands and arguments required to run a specific simulation unit? (e.g. the Rooftop PV System is a python class that can be run with the command "python" and as such requires as an argument the name of the script to be executed, in this case "pv_sim_v1.02.py").

The ontology needed to store all this information is designed following a systematic and iterative process as proposed in [23] and is under continuous refinement. Protégé [24] has been chosen as the design tool, where core concepts such as SimulationUnit, Port and Parameter were modeled with formal relationships and properties. Existing ontologies like OM (Ontology of Units of Measurement) [25] and OEO (Open Energy Ontology) [26] are used as starting point and extended, as described in the following paragraph. The basic idea of the proposed approach is to represent the simulation unit structure in a black-box fashion, adding semantic tags and linking them to existing concepts in the semantic web to provide interpretable meaning, as shown in Fig. 2. This approach ensures compatibility and extensibility in diverse application scenarios.

The resulting CS-Ontology is agnostic to the specific domain of the co-simulation, making it adaptable to various fields and satisfying requirement **R2**. Domain-specific details can be incorporated by integrating existing ontologies: the Open Energy Ontology (OEO) has been selected as an ontology for the energy domain since it covers the majority of concepts used in the validation scenarios; a full list of ontologies for the energy domain can be found in [27]. An extended ontology of measurement units, incorporating the quantities addressed in the case studies, was used to represent the model variables. By leveraging these existing ontologies, the framework can enrich its semantic representation with specialized domain knowledge, enhancing the interpretability of simulation units. Fig. 2 presents an example of how ontologies have be integrated to semantically describe a simulation unit and its communication interface. In this case, a photovoltaic system (`Catalogsim-0`) is modeled as an instance of `Cs:SimulationUnit` and is linked to a specific script and file path. The unit exposes an output port (`Catalogsim-0-p1`) defined as a `Cs:Output` via the `cs:hasPort` property. This port represents an output variable (`Catalogsim-o-p1`), semantically annotated through the `OM:quantity` and `OM:unit` properties from the Ontology of Units of Measurements, indicating that the output is electrical power measured in watts (`OM:Watt`). The concept of the system itself is linked to the OEO ontology (`Oeo:photovoltaicSystem`). This integrated model demonstrates how the CS-Ontology, the OM (Units of Measure), and OEO— can work together to support machine-readable, interoperable descriptions of simulation components in the energy domain, in order to form a semantically-enriched model catalog.

The objective of the system is to identify a valid topology of co-simulation units that represents the energy scenario provided as input. To better define the problem, the mathematical model is presented in the following: i) let $M = \{m_1, m_2, \ldots, m_n\}$ be the set of available simulation modules; ii) let $V = \{v_1, v_2, \ldots, v_k\}$ be the set of variables; iii) let $P = \{p_1, p_2, \ldots, p_r\}$ be the set of ports. Each port is defined as a tuple:

$$p = (m, v, c, u)$$

where $m \in M$ is the simulation module exposing the port, $v \in V$ is the associated semantic variable, $c \in \{\text{Input}, \text{Output}\}$ denotes the causality, and u is the unit of measurement (from the OM ontology).

We define a semantic compatibility function between two ports p_i and p_j as:

$$\text{compatible}(p_i, p_j) = \begin{cases} 1 & \text{if } v_i \equiv v_j \land c_i \neq c_j \\ & \quad \land \text{unit\_match}(u_i, u_j) = \text{true} \\ 0 & \text{otherwise} \end{cases}$$

where $v_i \equiv v_j$ means that the variables are semantically equivalent, $c_i \neq c_j$ ensures opposite causality (input vs. output), and $\text{unit\_match}(u_i, u_j)$ verifies that the units are compatible or convertible. A valid co-simulation configuration is then defined as a directed graph $G = (N, E)$, where $N \subseteq M$ is the set of selected modules, and $E = \{(p_i, p_j) \mid \text{compatible}(p_i, p_j) = 1\}$ defines the set of valid semantic connections between module ports.

Thanks to such machine interpretability, given an analysis target, the user will be assisted in future during the selection and coupling of models from the catalog, and their contextualization into a geographic area. To test the proposed methodology, two versions of the MES topology described in Fig. 1 have been made available as potential targets analysis for the user. A SPARQL-based agent explores the knowledge base to identify the set of simulation modules that can setup the analysis. Regarding connection between the identified model, the agent looks for candidate variables with opposite causality, matching data type, equivalent semantic type (e.g., Temperature), and dimensionally compatible units of measurement, ensuring semantic and numerical interoperability.

While models are described semantically as summarized in Fig. 2, cityJSON data are processed to perform simple mapping of its keys to ontological IRIs. The cityJSON file serves two purposes: first, it acts as the input format for the co-simulation composer, providing detailed descriptions of the test buildings, such as their location, geometry, and energy-related attributes; second, CityJSON is a well-established standard that is utilized to render 3D city models, which will be an important visualization aspect on the frontend interface in future, enabling users to visualize and interact with the simulation setup in a spatial context.

When a CityJSON file containing building data for a specific area is served—along with a reference topology that is linked to specific analysis, like the one shown in Fig. 1 — the unique IDs of buildings are used to replicate and associate simulation units with each individual building. Information about the required simulation units is then retrieved from the catalog and added to the co-simulation configuration file. At this stage, the file specifies which model instances will be deployed, how many of each are needed, the commands required to run them, where their binaries are located, and the input parameters they require.

For example, the Electric Heat Pump model in Fig. 1 requires the `net_leased_area` parameter, which has been defined as a subclass of the *om:Area*, and is in turn a key for the same property of building objects in the CityJSON file. Each model instance is initialized and linked to its corresponding building in the cityJSON via the unique ID. This ID also enables model aggregation —for instance, connecting the Rooftop PV System model and the Smart Meter model to the same building. Using these IDs, structured rules for aggregating and connecting simulation components can be established.

Exploiting information encoded in the model catalog, the system service is able to complete the configuration file with information about model instances interaction, finalizing it for execution.

IV. METHODOLOGY APPLICATION

The method was applied to a case study on a single building [28] to verify the electrical load of heaters, with focus being placed on its correlation with in-house photovoltaic generation and storage systems.

Co-simulation units used include eight independent simulators (as shown in Fig. 1), ensuring consistent contextual conditions across all simulations.

The validation focused on three main aspects: (i) the correctness of the semantic configuration process, (ii) the reliability of data flow between modules, and (iii) the consistency of simulation results. Furthermore, the ontology was evaluated against the above mentioned competency questions (CQs). Querying the ontology effectively answered all four competency questions: it enabled the identification of simulation units suitable for specific technologies (CQ1), supported semantic matching of module interfaces to ensure compatibility (CQ2), provided access to both model and contextual parameters required for initialization (CQ3), and described commands and runtime arguments for simulation units (CQ4).

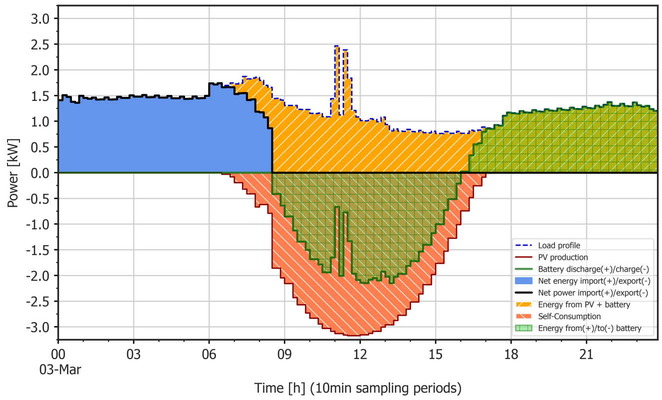

Fig. 3: Energy performance indicators of the examined house over a typical day with a 10-minute resolution, generated using the COESI platform.

The following modules were utilized as building blocks for the co-simulation scenarios, each one of them equipped with a standardized cosimulation interface.

Weather data and **Temperature Schedules**: two independent simulators in Python designed to process and manage CSV data related to weather conditions and temperature schedules, ensuring accurate input data to the simulation.

Rooftop PV System, Household behaviour and **Smart Meter**: three independent simulators in Python to simulate the photovoltaic system, the occupancy of people at home and the smart meter monitoring system, respectively.

Building Envelope: an EnergyPlus [29] instance to simulate the detailed thermal behaviour of buildings under dynamic conditions.

Electric Heat Pump, Battery and **EHP controller**: three independent simulators implemented in modelica simulating the operational characteristics of a heat pump (including efficiency curves and dynamic response to thermal demands), electric energy storage and the heating system control strategies, respectively.

The automatic retrieval and mapping of parameters from the cityJSON and ontology-based triple store were verified through manual cross-checking with expected values for the simulation results. The successful execution of the co-simulations using both EnergyPlus, Python and Modelica-based simulation units demonstrated the correct initialization and interoperability of all components. Moreover, the simulation outputs, including time-series data of heating energy demand and system operation, were consistent with expected patterns, as shown in Fig. 3 that shows the balance of power among PV production, battery storage, and load demand. The dashed line displays the load profile, and colored zones signify the flows of energy. Positive values describe net imports, and negative values refer to exports. The PV production is self-consumed or stored by the battery or exported. The battery stores energy during excess PV and discharges as required to provide the load. With the results reflecting the expected system's operation, the proper setup of all the components and their proper functioning are verified. These outcomes confirm that the framework is capable of dynamically configuring complex simulation networks with minimal manual intervention, supporting its scalability and robustness for scenario-based analysis in MES.

V. Conclusion

This work explores how semantic web technologies can improve integration and interoperability in co-simulation environments. By leveraging domain-specific ontologies, the proposed approach simplifies the configuration of simulation modules, ensures compatibility, and supports extensibility. The architecture enables reusable setups, efficient module coupling via semantic queries, and lays the groundwork for advanced analyses like dependency tracking and model calibration.

Planned improvements include automatic unit handling and enriched semantic tagging of outputs to support cross-domain comparison. Despite its benefits, the method depends on high-quality ontologies and expert knowledge, and faces challenges such as managing abstraction levels and avoiding execution conflicts. These will be addressed in future work to enhance reliability and usability across domains.

The approach holds promise for integration into real-world energy planning workflows, enabling modular platforms that offer customizable simulation capabilities. This supports the development of smart, adaptive tools that can serve a wide range of users and advance the vision of sustainable, intelligent urban systems.

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