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Towards a Data-Centric Distributed Simulation Framework for the Energy Domain

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Abstract: Existing simulation tools from the energy domain are often limited to specific problems in the energy sector. Co-simulation frameworks enable the combination of these models and, thus, a more realistic simulation of the energy domain. This paper analyzes some co-simulation frameworks from the energy domain by evaluating them according to specific criteria. Since none of the presented frameworks fulfills all the criteria, we then present a data-centric distributed simulation framework and how we extend it for the energy domain.

Keywords: Co-Simulation, Data-Centric Distributed Simulation, Energy System Modeling

1 Introduction

The importance of analyzing, simulating, and optimizing energy systems to manage the energy transition increases. Since energy domain research is interdisciplinary, modeling energy systems is a complex task [1]. Existing analysis tools for energy and power systems often focus on specific aspects within those systems. When used by themselves, these tools do not provide a realistic simulation of the entire energy sector, as the different domains are highly interconnected and influence each other [2]. A promising solution to this problem is to make existing tools interoperable by connecting them via middleware. This allows the co-simulation of different heterogeneous models and provides more reliable and realistic results [2].

During co-simulation, different models are executed and solved. Therefore, synchronization and orchestration are significant challenges of co-simulation [3]. There are already various approaches to co-simulating energy simulators in the literature. In the following, we provide an overview of several co-simulation frameworks from the energy domain and show which criteria for co-simulation they fulfill. Afterward, we describe the data-centric distributed simulation framework (DaceDS) [4] and how we plan to extend it to the energy domain.

2 Overview of Co-Simulation Frameworks

Table 1 gives an overview of co-simulation frameworks used in the energy domain. We review the frameworks according to the following criteria:

- Are they extendable,
- do they couple multiple domains,
- do they use loose coupling,
- do they enable distributed simulation,
- do they have a graphical user interface, and
- are they open source?

A co-simulation framework should be extendable as new simulation tools are constantly developed and existing tools are constantly improved. Extendability refers to how easily the framework can be customized by adding new features, modules, or interfaces to meet specific requirements or use cases. Extendable co-simulation frameworks, like mosaik [5] and FNCS [6], allow developers to integrate additional components, models or algorithms without redeveloping the entire system [7].

The way simulators are coupled can vary. Some simulators, like GECOS [8] and EPOCHS [9], are directly or strongly coupled, meaning that the coupled simulators can exchange specific functions and data directly. MESCOS [10], on the other hand, uses a loose coupling of the simulators. Loose coupling means that the simulators work independently of each other and communicate via an interface or middleware without having to intervene deeply in the internal processes of the other simulator [11]. Simulators can run in parallel and communicate with each other as required [12]. Loosely coupled simulators are flexible and can easily be replaced or updated with new simulators without affecting the other simulators.

Since the energy domain interoperates with other domains, a co-simulation framework should allow coupling with simulators from other domains. Simulators from different domains often use different models and data formats. Converting and harmonizing these models to connect them can be difficult. The TOOCC [2] uses ontologies to promote interoperability between heterogeneous systems by providing a joint vocabulary base for information exchange [2]. Simulators can have different time steps and temporal resolutions depending on what they are simulating. Synchronizing these simulators to enable a coherent simulation is a big challenge in co-simulation [3].

Some frameworks, like the VILLASframework [13], offer the possibility to perform parallel simulations in addition to co-simulation. During a parallel simulation, the execution of a single simulation is split across several processors. The aim is to shorten the execution time of a simulation [14]. [15] summarizes these types of simulation under the generic term distributed simulation.

The last two criteria in the table are graphical user interface and open source. These criteria are important for a co-simulation framework as they determine the accessibility and user-friendliness of the framework.

Table 1 shows that no framework satisfies all the criteria simultaneously. We need a framework that meets all criteria to provide a simulation service. Therefore, in the next section, we present DaceDS [4].

Table 1. Overview of Co-Simulation Frameworks from the Energy Domain

Criteria/ Framework	Extendable	Connencting multiple domains	Loose Coupling	Distributed Simulation	Graphical User Interface	Open Source
DACCOSIM [16]	X			X	X	X
EPOCHS [9]		X		X		
FNCS [6]	X	X	X	X		X
GECO [8]		X				
GridIQ [17]	X					X
GridSpice [18]			X	X	X	X
HELICS [19]	X	X				X
INSPIRE [20]	X	X	X			
MACSimJX [21]						X
MECSYCO [22]	X	X	X	X		X
MESCOS [10]	X		X	X		
mosaik [5]	X	X				X
PowerNet [23]	X	X				
Ptolemy II [24]	X		X	X	X	X
SGsim [25]	X	X				X
SMB [26]	X	X	X	X		
TOOCC [2]	X	X			X	
VILLASframework [13]	X	X		X	X	X
VirGIL [27]	X	X				
VPNET [28]		X			X	
DaceDS [4]	X	X	X	X	X	X

3 A Data-Centric Distributed Simulation Framework

DaceDS provides a coupling method for distributed simulations based on a data-centric concept. It does not store data within the individual subcomponents of a simulation but in a shared data pool. The framework uses a middleware-based approach, with the topic-based publish/subscribe message streaming system Kafka [4]. Using a structured, rule-based procedure, the framework couples components by exchanging predefined data tuples. The components are described using a domain layer taxonomy, which achieves a trade-off between the structured coupling of components and addressing components [29]. Hence, the framework uses loose coupling and is extendable. It offers the possibility to carry out parallel and distributed simulations. Via a graphical user interface, users can compose models or components, trigger the simulation of scenarios, and evaluate results from the simulation [4].

The framework can link the MATSim [30], PTV Visum [31], SUMO [32], Carla [33], and OMNeT++ [34] simulators. It was initially developed for the mobility sector but is not conceptually limited to this domain. To extend the framework with simulators from the energy domain, we have to perform the following steps:

- Write a wrapper for each new simulator,
- write translators for the communication between simulators with different levels of abstraction and
- write projectors for the communication with simulators from other domains.

We already started integrating the energy simulator Python for Power System Analysis (PyPSA) [35] into the framework. Therefore, we have written a wrapper that allows one or more instances of the simulator to be called by the framework, which allows the parallel simulation of power systems with PyPSA. In addition, the wrapper allows the individual instances of PyPSA to exchange messages via Kafka.

4 Conclusion

Co-simulation of different models is necessary for the complete and realistic simulation of energy systems. There are many co-simulation frameworks in the literature. In Table 1, we summarized different co-simulation frameworks from the energy domain and evaluated them using different criteria. The table shows that none of the existing frameworks from the energy domain meet all of the criteria. As shown in the previous section, DaceDS fulfills all the criteria, but we still need to extend it to include simulators from the energy domain. We are already working on adding the PyPSA simulator and plan to add further simulators from the energy domain. Furthermore, we want to simplify coupling multiple domains with the help of ontologies to make writing additional translators or projectors no longer necessary.

Data availability statement

Not applicable.

Underlying and related material

Not applicable.

Author contributions

Conceptualization: C.S., M.N.; Data curation: C.S.; Funding acquisition: R.G.; Investigation: C.S.; Methodology: C.S.; Project administration: M.N.; Supervision: R.G.; Validation: C.S.; Visualization: C.S.; Writing – original draft: C.S.; Writing – review & editing: C.S., M.N., R.G;

Competing interests

The authors declare that they have no competing interests.

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