Intelligent Energy Systems Ontology to support markets and power systems co-simulation interoperability

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ABSTRACT

The significant changes the electricity sector has been suffering in the latest decades increased the complexity and unpredictability of power and energy systems (PES). To deal with such a volatile environment, different software tools are available to simulate, study, test, and support the decisions of the various entities involved in the sector. However, being developed for specific subdomains of PES, these tools lack interoperability with each other, hindering the possibility to achieve more complex and complete simulations, management, operation and decision support scenarios. This paper presents the Intelligent Energy Systems Ontology (IESO), which provides semantic interoperability within a society of multi-agent systems (MAS) in the frame of PES. It leverages the knowledge from existing and publicly available semantic models developed for specific domains to accomplish a shared vocabulary among the agents of the MAS society, overcoming the existing heterogeneity among the reused ontologies. Moreover, IESO provides agents with semantic reasoning, constraints validation, and data uniformization. The use of IESO is demonstrated through a case study that simulates the management of a distribution grid, considering the validation of the network's technical constraints. The results demonstrate the applicability of IESO for semantic interoperability, reasoning through constraints validation, and automatic units' conversion. IESO is publicly available and accomplishes the pre-established requirements for ontology sharing.

Keywords: Multi-Agent Systems Society; Ontology; Power and Energy Systems; Semantic Interoperability.

1. INTRODUCTION

The electricity sector has undergone significant changes in the last couple of years, aiming to avoid existing monopolies and to make the sector more competitive and fair [1], [2]. Financial and environmental concerns worldwide are promoting the integration of distributed generation (DG) based on renewable energy sources (RES) into distribution grids, aiming to reduce carbon emissions and improve the security and affordability of the power and energy systems (PES) [3]. The increasing use of RES and DG is completely revolutionizing the PES sector [4]. The intermittency and unpredictability of RES raise new challenges that need emergent solutions to accomplish a more intelligent and sustainable use of electricity [5], [6], such as: reduce the intrinsic risks of RES' intermittency and unpredictability, adapt the current physical infrastructures, lower the production and installation prices of renewable generation technology, implement new regulatory measures, to name a few. Electricity markets (EM) also had to conform to this new reality and develop new models, rules, and legislation to meet the new policies and challenges posed by the increasing RES penetration [7], [8].

The liberalized electricity sector is more competitive, with consumers becoming active players and new market, negotiation, and regulatory frameworks coming to play. However, it also became more complex and unpredictable, forcing its participants to rethink their strategies and behaviors to overcome the increasing decision-making challenge [9], [10]. Players must deal with such a dynamic and evolving environment with constantly changing rules and models to get the best possible outcomes of their participation in the markets. Hence, players and stakeholders must study and analyze the market's mechanisms and behaviors beforehand. Operators must assure transparency and competitiveness while players aim to maximize profits and minimize costs [11]. Thus, the use of simulation and decision support tools is now indispensable to deal with the new requirements by studying and experimeting different market mechanisms and the relationships among the various stakeholders [12], [13]. To this end, PES simulation and decision support tools must deal with the sector's emerging reality, warranting proper means for the several entities to learn skills to adjust to such evolving economic, financial, and regulatory environments.

Multi-agent systems (MAS) have already proven to be proper frameworks to model complex interactions between autonomous entities of cooperative, competitive, and dynamically evolving environments such as the PES [14]. The distributed and independent nature of software agents is suitable to model different entities, their interactions, business rules and constraints, negotiation mechanisms, to name a few [15], [16], addressing the model closer to reality while decomposing the problem into simpler blocks. On the other hand, MAS-based approaches facilitate the inclusion of new business models and mechanisms, types of players and operators, and their interactions [17], [18]. Several simulation and decision-support tools have emerged to study the different PES subdomains, such as EMs [19]–[21], smart grids (SG) [22]–[24], demand response (DR) [25], [26], to name a few. Despite their meaningful value, these tools only address specific concerns of the global problem, losing the required realism and precision. The PES subareas have a notable influence over each other, and studying them independently, has a significant impact on the results [27]. There is, however, a generalized lack of interoperability between heterogeneous tools in the scope of PES, creating barriers to address the problem globally.

A possible solution to solve interoperability issues between heterogeneous agent-based tools is using ontologies and semantic web technologies for semantic interoperability [28], [29]. Ontologies provide semantic meaning to the messages exchanged among the various parties. By sharing the same conceptualizations, systems interact seamlessly without misinterpretations [30], [31]. Besides communication purposes where different tools share the same vocabulary [32], ontologies also provide semantic reasoning, which allows for rules validation [33], [34] and infering new knowledge from the existing one, knowledge representation [35] for data uniformization in a common ground semantic model, among others. There are several proposals in the literature of ontologies developed in the scope of the PES. However, most ontologies in the literature are proprietary, only a few are publicly available, and each focuses on a specific application scenario or include an abstract high-level domain conceptualization. Some models are specific to a given subdomain, such as [36]–[38] for EMs, [28], [39], [40] for SGs, while others aim to be cross-domain models covering multiple fields [41]–[44]. Although developed for distinct areas of PES and purposes, these ontologies encourage their reuse and extension in developing semantic models describing different knowledge sources and specific PES sub-fields. Still, there is a high heterogeneity among the various semantic models in the literature that hardens the adoption of such semantically rich models and hinders the interoperability between ontology-based platforms using different semantic models [42]. Thus, it is essential to develop ontologies representing heterogeneous knowledge sources, aiming to ease interactions and meaningful messages exchange between MAS of different natures in the scope of PES. This work proposes the Intelligent Energy Systems Ontology (IESO), a semantic model developed to provide semantic interoperability, knowledge representation, and constraints validation within a society of MAS developed for the simulation, decision support, operation, management, and study of the PES. Such a framework overcomes the lack of interoperable tools within the PES, addressing the problem as a whole.

The following section (section 2) overviews relevant work regarding existing ontologies in the literature and the society of MAS for which IESO has been developed. Section 3 presents IESO, describing its purpose, requirements, development options, and the various modules and their main concepts. Section 4 demonstrates the use of IESO in an agent-based simulation of local grid management considering scenarios with technical limits violations. Finally, section 5 presents the final conclusions and future work.

2. RELATED WORK

This section starts by overviewing previous work related to the society of MAS that uses IESO for multiple purposes and concludes with a survey on the most relevant ontologies found in the literature developed for the PES domain.

2.1. Multi-Agent Systems (MAS) Society

PES are complex and dynamic environments characterized by their constantly evolving reality which require complex modeling, simulation, and decision support tools to capture and study their intricacies globally. To this end, the authors previously proposed a semantically interoperable MAS Society [45], [46], composed of existing and independently developed agent-based tools directed to the study of specific areas of PES, providing a modeling and simulation framework addressing the sector as a whole through the interaction of the involved agents. The MAS Society results from integrating previously developed agent-based tools, covering the entire energy system from wholesale EMs to the end-users, complemented with newly developed ones to assist their operation, while ensuring interoperability between them. To this end, heterogeneous MAS within the society use ontologies to share the same conceptualizations, giving semantic meaning to the messages exchanges, transforming data into knowledge.

The MAS Society allows the modeling of the PES as a whole by using all the available MAS, or partially, by selecting only the tools necessary for the case study in hands. It is also possible to execute a single system or service for a simple optimization or forecast. Therefore, it addresses the lack of interoperable platforms enabling the effective synergies between heterogeneous MAS and services in the scope of PES. Figure 1 illustrates the architecture of the proposed MAS Society.

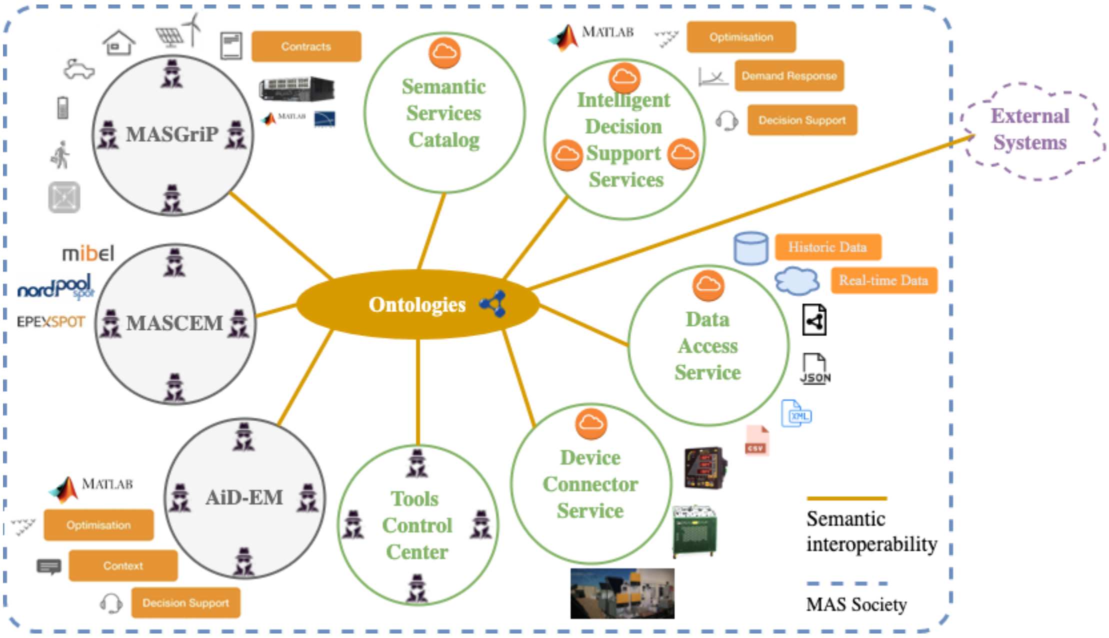

Figure 1. MAS Society architecture (adapted from [47]).

The simulation and modeling of EMs are performed by the Multi-Agent Simulator of Competitive Electricity Markets (MASCEM) [15], [17]. It supports the simulation of a diversity of market models, such as day-ahead and intraday auction-based pools; bilateral contracting; and forward markets; to name a few, allowing the combination of different market models for hybrid simulation scenarios. MASCEM's multi-agent model represents the most relevant operators and participating players of EMs. The Adaptive Decision Support for Electricity Markets Negotiations (AiD-EM) [12], [19] provides decision support to EM participating players. Its agents perform different tasks from portfolio optimization to auction-based and bilateral negotiation decision-support using several artificial intelligence (AI) methods, considering context-awareness and an efficiency/effectiveness mechanism to balance between the quality of results and the execution time. The modeling and simulation of SG and microgrid environments, including all relevant stakeholders as software agents, is provided by the Multi-Agent Smart Grid simulation Platform (MASGriP) [22], [23]. It enables agents' connection to physical infrastructures for automated management and control of resources in real-time, thus allowing the test and validation of complex alternative approaches in realistic settings. MASGriP models include local EMs, energy resources management (ERM), DR, and negotiation procedures.

The Intelligent Decision Support (IDeS) services, formerly IDeSMAS [45], [46], assist different agents of the MAS Society with AI-based algorithms, such as forecast, optimization, and scheduling algorithms, DR programs, ERM, among others. The Data Access Service (DAS), as the name expresses, provides access to real-time and historical data from the database, as well as simulated data. It collects data from heterogeneous sources, from input files to physical devices and infrastructures, to make it available to the several agents and services of the MAS Society. By default, IDeS and DAS respond to requests using JSON syntax. However, agents can request data in a resource description framework (RDF) syntax, respecting the shared vocabulary, by setting it in the "Content-Type" header. The device connector (Dev-C), previously Programmable Logic Controller (PLC) MAS [45], [46], is the service supplying software agents with the control of physical devices with simples REST requests, abstracting MAS from the devices' communication protocols (e.g., Modbus[1], MQTT[2], AMQP[3]). This service allows testing scenarios in realistic conditions applying the results to physical devices in real-time, making them act accordingly.

To overcome the burden and error-prone manual configuration of distributed MAS arises the Semantic Services' Catalog (SSC) [48]. SSC provides a common place for the registration and discovery of services within the MAS Society. Services may be web-based or agent-based. When software agents search for a determined service or type of service, SSC responds with the service description, location, the list of requests available, and the respective input and output models. This way, agents autonomously interact with the web or agent-based service using the response data to connect and communicate properly with the system. Finally, the tools control centre (TOOCC) [31], [49] is a MAS designed and developed for the user interaction and control of the MAS Society. It allows the definition of multiple scenarios to run simultaneously, ranging from the co-simulation of all available tools to selecting only a few or simply running a service or algorithm independently. TOOCC takes advantage of SSC to know which services and MAS are available for use at each moment. The user may request an automatic analysis and comparison of results whenever it makes sense. TOOCC facilitates the configuration, realization, and analysis of complex scenarios and dynamics between the heterogeneous tools.

The proposed MAS Society eases the modeling, study, simulation, and validation of the PES globally; partially, by using part of the available tools; or the execution of a specific system individually, allowing to configure, customize, execute, and analyze complex scenarios, exploring the dynamics between the main involved entities represented as software agents.

2.2. Ontologies for PES MAS Interoperability

Most agent-based tools in the PES domain use their proprietary ontologies, conceptualizing heterogeneously concepts and relations commonly present among these MAS. These systems could benefit from interacting and sharing knowledge, taking full advantage of each other's capabilities. To this end, ontologies provide the means for accomplishing semantic interoperability between heterogeneous tools, as demonstrated by the MAS Society [45], [46]. Moreover, combining ontologies with semantic web technologies and reasoners makes it possible to develop semantic rule-based systems, infer knowledge from the existing one, validate constraints, among others.

To reuse publicly available and well-established ontologies instead of reinventing the wheel is a common best practice. In this sense, the first steps taken towards the MAS Society reused and extended existing semantic models from the literature, namely the Electricity Markets Ontology (EMO) [32], the Smart Energy Aware Systems (SEAS) [41] ontology, and the Smart Appliances REFerence (SAREF) [30] ontology (version 2.1.1). EMO [32] describes abstract concepts and axioms in the EMs domain. It aims to be an inclusive model to be extended and reused by market-specific ontologies independently of their features and constraints. EMO has been developed to

[1] Homepage: https://modbus.org/.
[2] Homepage: https://mqtt.org/.
[3] Homepage: https://www.amqp.org/.

provide MASCEM semantic interoperability with external agent-based systems. Thus, EMO has been extended to develop the MIBEL [50], EPEX [51], and Nord Pool [52] ontology modules, as well as the call for proposal (CFP) and electricity markets results (EMR) [36] modules for the agents' messages exchange. Finally, being AiD-EM a MAS providing decision support to agent-based EM players, its ontology [53] also extends EMO.

SEAS [41] has been developed to describe the knowledge model of the SEAS project[4] as the basis for semantic interoperability between heterogeneous IoT (Internet of Things) services and smart devices within the project's ecosystem, ensuring stability and efficiency of the future power grids. SEAS is a modular ontology designed to meet the best practices in terms of quality, metadata, and publication, reusing and aligning existing standards to cover the project's use cases (UC) expressivity while being extensible to other UCs. SEAS ontology and architecture enable the exposure, sharing, reasoning, and querying of knowledge semantically. SAREF [30] semantic model, in turn, aims to facilitate the matching between existing assets in the smart appliances domain by gathering the semantics and data from buildings and households IoT devices. Its design offers building blocks that allow the combination or separation of the various parts of the ontology to accomplish the specific needs. The "Device" class is SAREF's main concept from which a set of basic device functions can be defined. Combining these basic functions allows producing more complex ones. It is also possible to describe devices' states and the services they provide. Energy/Power profiles are also considered to enable the enhancement of facilities' energy efficiency. It eases the combination of data from distinct vendors, fitting into the machine-to-machine (M2M) architecture of the European Telecommunications Standard Institute (ETSI).

More recently, new ontology models arose in the scope of the PES domain, and a new version of the SAREF semantic model [54] following SEAS best practices [55] came into play. It led to their study and analysis to verify how these models could contribute to the MAS Society, taking advantage of the most recent developments of the literature. SAREF is currently an ETSI standard, reusing knowledge from more than 20 existing models and aligning with the oneM2M [56] and Semantic Sensor Network (SSN) [57] ontologies. The latest version provides extensions covering several domains from the energy (SAREF4ENER) [44] to the building (SAREF4BLDN) [58], smart cities (SAREF4CITY) [59], industry and manufacturing (SAREF4INMA) [60], to name a few. SAREF4ENER, for instance, had the collaboration of EEBus[5] and Energy@Home[6] associations, promoting interoperability and reuse between smart appliances implementing these standards and energy management systems (EMS). The Ontology for Energy Management Applications (OEMA) [61] is a modular ontology unifying existing ontologies representing different domains, levels of detail, and terminologies within city energy management solutions, describing heterogeneous energy-related data. To this end, it reuses existing ontologies to define unique terms for concepts differently represented among the various semantic models. The Domain Analysis-Based Global Energy Ontology (DABGEO) [42], by the same authors, upgrades OEMA by presenting a layered structure to balance the ontology reusability and usability. It provides a common ground representation of existing energy semantic models for energy management applications to reuse in developing the respective application-specific ontologies.

[4] Homepage: https://itea3.org/project/seas.html.
[5] Homepage: https://www.eebus.org/.
[6] Homepage: http://www.energy-home.it/.

DABGEO layers separate the top-level domain knowledge from variant domain knowledge to reduce its reuse effort.

The Open Energy Ontology (OEO) [43] is a cross-domain ontology for the energy systems analysis domain, providing semantic annotation of data. Thus, making data semantically searchable, exchangeable, reusable, and interoperable while easing computational model coupling. Its main goal is to mitigate data heterogeneity within research data, promoting scientific knowledge exchange and transparency. OEO extends the Basic Formal Ontology (BFO) [62] upper ontology, aligning with the Open Biological and Biomedical Ontology (OBO) Foundry principles[7], to promote its reusability. The OpenADR Ontology [63], in turn, semantically enriches the OpenADR standard[8] for bi-directional information exchange for automated DR. Therefore, it provides semantic interoperability between DR stakeholders and systems, reasoning, and validation while facilitating its reuse and alignment with existing ontologies. The DELTA Ontology [64], on the other hand, reuses the OpenADR Ontology to accomplish semantic interoperability between currently available DR schemas applying the smart grid architecture model (SGAM) [65] framework to evaluate and quantify the semantic interoperability in the context of DR schemes. In addition to DR, it models knowledge related to energy markets, SGs by reusing and extending other publicly available ontologies, such as SAREF. The Building Topology Ontology (BOT) [66] is a minimalistic ontology to be reused and extended to describe buildings' core topology concepts and axioms. It intends to be the core ontology for the buildings industry domain, offering several alignments with existing semantic models defining building topology. The simplicity and transparency of BOT make it suitable to model buildings within the PES since the buildings' energy efficiency and management are being increasingly studied within the SGs domain.

In summary, although several proposals for the use of ontologies within PES can be found in the literature, most of these ontologies focus on a specific application scenario or a high-level abstraction of a PES subdomain. Moreover, there is considerable heterogeneity among these models, hardening their integration and adoption. It is, thereby, essential to develop ontologies representing distinct knowledge sources to facilitate the interactions between entities of different natures, promoting interoperability between heterogeneous agent-based systems that enable solving specific PES problems.

3. INTELLIGENT ENERGY SYSTEMS ONTOLOGY

This section introduces the Intelligent Energy Systems Ontology (IESO)[9] developed to provide semantic interoperability with and within the MAS Society. IESO is also reused and extended in developing the various MAS application-level ontologies and knowledge bases while providing data uniformization, knowledge extraction, reasoning, and validation. It results from the previous experience in developing the preliminary MAS Society ontologies considering all the pros and cons faced and from studying contemporary state-of-the-art semantic models and best practices, leveraging from the knowledge representation of the previously developed ontologies

[7] OBO Foundry principles: http://obofoundry.org/principles/fp-000-summary.html.
[8] Homepage: https://www.openadr.org/.
[9] Publicly available at: https://www.gecad.isep.ipp.pt/ieso/v1.0.0/.

and publicly available and well-established vocabularies. IESO design options take into account the interests of the various platforms of the MAS Society, establishing the following requirements:

- IESO must be a modular semantic model, where each module represents a domain of interest for the MAS Society;
- IESO must be publicly available to support interoperability among agent-based tools of the MAS Society and between external systems and the agents of the MAS Society;
- IESO must evolve according to the needs of different tools of the MAS Society and the evolution of the PES;
- IESO must be clear and avoid redundancy as much as possible since some specifications may be transversal to various modules;
- IESO must be versioned to provide the chance to use a conceptualization of a specific version;
- All IESO modules must use the same ontology prefix (i.e., ieso:) to facilitate their use.

IESO gathers the domain knowledge required to ensure semantic interoperability within the agents' community, including markets, contracts, infrastructures, assets, measures and units, and actor roles models, to be reused and extended, as needed, by the applicational ontology modules of each MAS. There are several ontology development methodologies available in the literature [67]. Each specifies the principles, methods, and best practices to follow along the engineering process, which supports the ontology specification, conceptualization, formalization, implementation, and maintenance, resulting in the ontology life cycle. The simplicity and straightforward perspective of the 101 (one-on-one) development methodology [68] led to its use in developing each module's semantic model. The 101 development methodology is an iterative process that continuously refines the ontology to the developers' requisites. It admits that several distinct conceptualizations can represent a domain. However, to this end, ontology engineers must clearly define concepts and relations among them by specifying the subjects and predicates.

A common practice to reuse existing semantic models is to import the ontologies into our model and extend them. It promotes interoperability between models by using a shared conceptualization while avoiding reinventing the wheel [68]. However, it also creates a high dependency on the imported models as ontologies evolve over time, and the specifications made may no longer make sense [69]. Plus, publicly available models may also become unavailable, making our model obsolete. Furthermore, importing ontologies from cross domains may cause inconsistencies due to heterogeneous definitions of the same concepts, different granularities, among others. These considerations led to determining additional requirements:

- IESO must be self-sufficient and do not depend on existing publicly available ontologies;
- Instead of importing ontologies directly, IESO references the concepts and properties extended from external semantic models;
- IESO modules should provide mapping files with external ontologies describing the equivalent knowledge.

Agreeing with SEAS ontology best practices [41], IESO consists of a core module importing the several domain modules. The modules' design considers the MAS Society systems to optimize their use by the different tools. Each module is a versioned ontology file using the IESO namespace for concepts and properties definition. It avoids using a prefix per module, which can lead to errors, facilitating its use. The IESO namespace includes the version to ensure the use of a class of a particular version. In addition, whenever a module's version upgrades, the IESO namespace version must be updated accordingly. Following the World Wide Web Consortium (W3C) [70] recommendations, IESO is a web ontology language (OWL) 2 description logic (DL) ontology written in the RDF 1.1 Turtle[10] syntax, ensuring that reasoning and rules conclusions are computable in a finite time. The OWL 2 DL language provides maximum expressiveness, computational completeness, and decidability. Figure 2 presents IESO's domain modules.

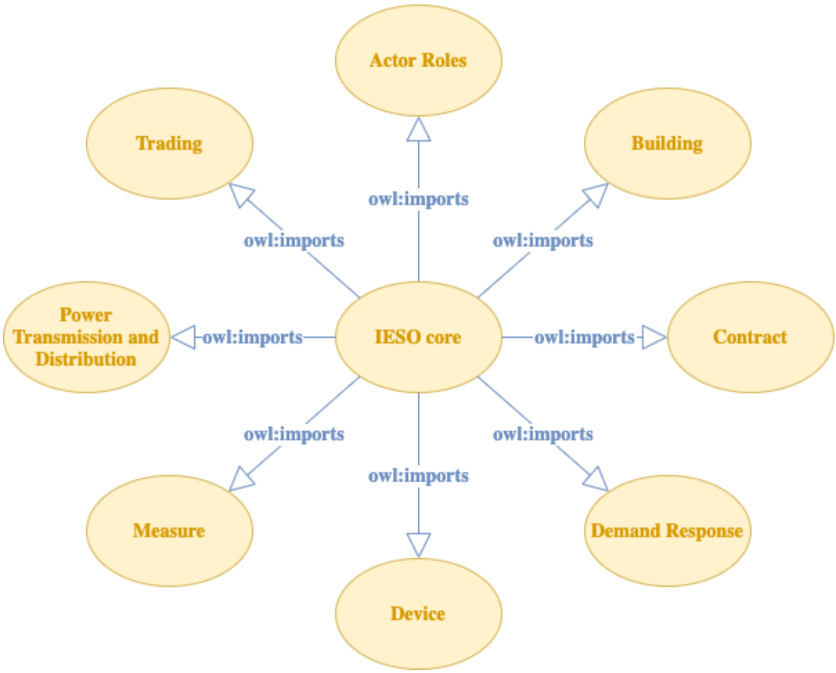

Figure 2. IESO's domain modules.

Eight domain modules compose the first release of IESO, namely the Actor Roles, Building, Contract, Demand Response, Device, Measure, Power Transmission and Distribution, and Trading modules. The following subsections present each module in detail. IESO is a work in progress to continuously improve and follow up with PES advances and new tools that may arise within the MAS Society. Ongoing developments include new domain modules describing contexts and related profiles for context-based decision support as well as a module gathering and abstraction knowledge relevant to the application ontologies of the decision support tools and services.

3.1. Actor Roles

The IESO's Actor Roles module abstracts actors, the roles they can assume, and respective behaviors to describe the main players, operators, and stakeholders present within the PES, which are modeled as software agents within the MAS Society. To this end, it models the three core abstract concepts **Actor**, **Role**, and **Behaviour**. Figure 3 illustrates the root concepts of the Actor Roles ontology module.

[10] https://www.w3.org/TR/turtle/.

Figure 3. Actor Roles module main concepts.

An **Actor** represents a PES entity and assumes at least one **Role**. A **Role** performs at least one **Behaviour**. This module aims to describe abstract roles and behaviors a software agent can take in a simulation environment, being extended by the applicational ontology modules to specify the several entities of a MAS. By extending this module, application-level ontologies define the roles and behaviors an agent can represent, providing the means to set each agent's roles and behaviors at runtime according to the user's configuration. Besides, it eases the creation of hybrid approaches by setting existing behaviors in a new role or existing roles in a new actor. The **Role** class provides extensions representing the most common roles within the MAS Society, outlining several types of existing players and operators of the PES. The **Behaviour** class, in turn, must be extended by each application ontology to define the behaviors of each agent's role. Using this module eases the development of semantically configurable agents. E.g., an aggregator role can include a demand flexibility behavior for DR events and, additionally, the local market behavior for auction-based EMs. This way, easing the agent's configuration and the update of models.

3.2. Building

The IESO's Building module, mainly inspired by the BOT ontology, and receiving input from the SEAS Building Ontology module and the SAREF extension for buildings (SAREF4BLDN), describes building topologies in the scope of MAS Society. It does not present itself as an alternative to any existing building ontology. It aims to represent only the necessary and sufficient conditions in the frame of the tools available in the society of MAS. Figure 4 presents the core concepts of the Building ontology module.

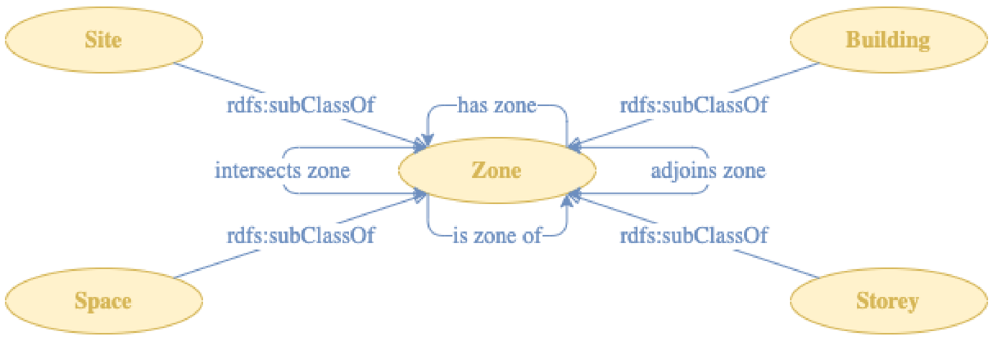

Figure 4. Building module core concepts.

Using the BOT's concepts as a base, the root concept of the Building module is **Zone**, from which the **Building**, **Site**, **Space**, and **Storey** concepts extend. A zone may be composed of several zones ('*has zone*' property) or be part of a zone ('*is zone of*' property). Likewise, a zone may intersect ('*intersects zone*' property) or be adjacent ('*adjoins zone*' property) to other zones. These core classes are directly mapped to the respective BOT classes using the OWL property *owl:sameAs*. Furthermore, BOT ontology already provides alignment modules with the most used ontologies defining building-related terminology, which can be reused to map this module with those models. The **Building** and **Space** concepts were extended to provide classes of the most commonly modeled building and space types within the MAS Society tools. Sub-properties of the '*has zone*' and '*is zone of*' properties were also developed for each subclass of **Zone**. Again, application ontologies reuse and extend this domain module as needed.

3.3. Contract

The IESO's Contract module describes contract concepts, relations, and properties in the scope of PES, such as aggregation contracts for demand response, forward contracts, futures contracts, wholesale bilateral contracts, among others. Figure 5 represents the Contract module main concepts and properties.

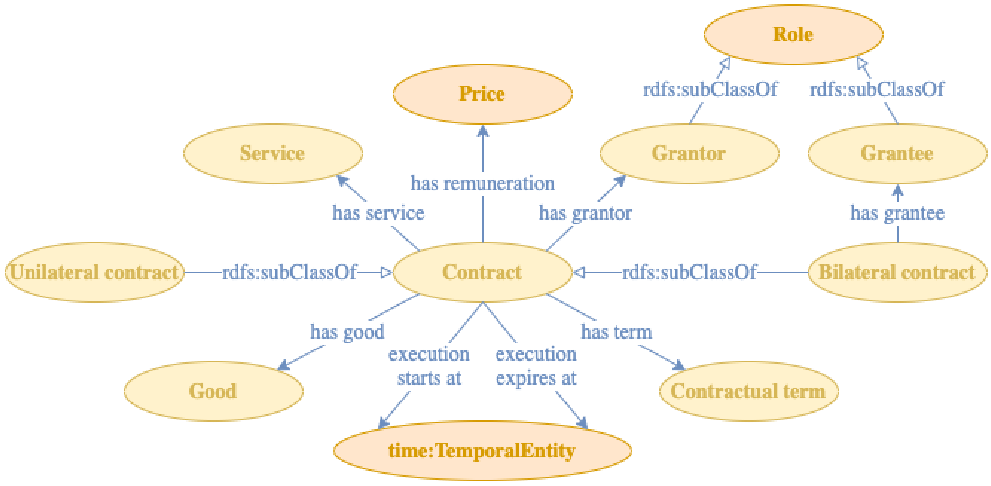

Figure 5. Contract module main concepts.

The **Contract** class is the superclass of **Bilateral contract** and **Unilateral contract**. The **Bilateral contract** is the superclass of more specific types of contracts, such as **Aggregation contract**, **Demand response contract**, **Forward contract**, **Futures contract**, among others. Its definition includes a **Grantor** and a **Grantee**, the **Good**(s) or **Service**(s) to trade, the remuneration (**Price**), a set of **Contractual terms**, a start, and an end of its execution whereas, the **Unilateral contract** does not include a **Grantee**. The **Grantor** and **Grantee** classes extend the **Role** class of the Actor Roles module (subsection 3.1). The **Price** class is from the Measure module (see subsection 3.6), and the start and end of the contract's execution reuse the **Temporal Entity** class of OWL Time[11]. The **Contractual term**, in turn, identifies the term's **Grantor** and **Grantee**, a set of **Conditions**, a set of **Penalty**(ies), and a set of **Promises**. Application ontologies extend this module as needed to describe their knowledge further.

3.4. Demand Response

The IESO's Demand Response module describes concepts, relations, and properties related to DR programs, events, and results. It reuses and extends concepts from the Actor Roles, Contract, and Measure modules. This module also reuses OWL Time **Interval** and **Temporal Entity** concepts (see footnote 11). Figure 6 shows the Demand Response module central concepts.

[11] Publicly available at: https://www.w3.org/TR/owl-time/.

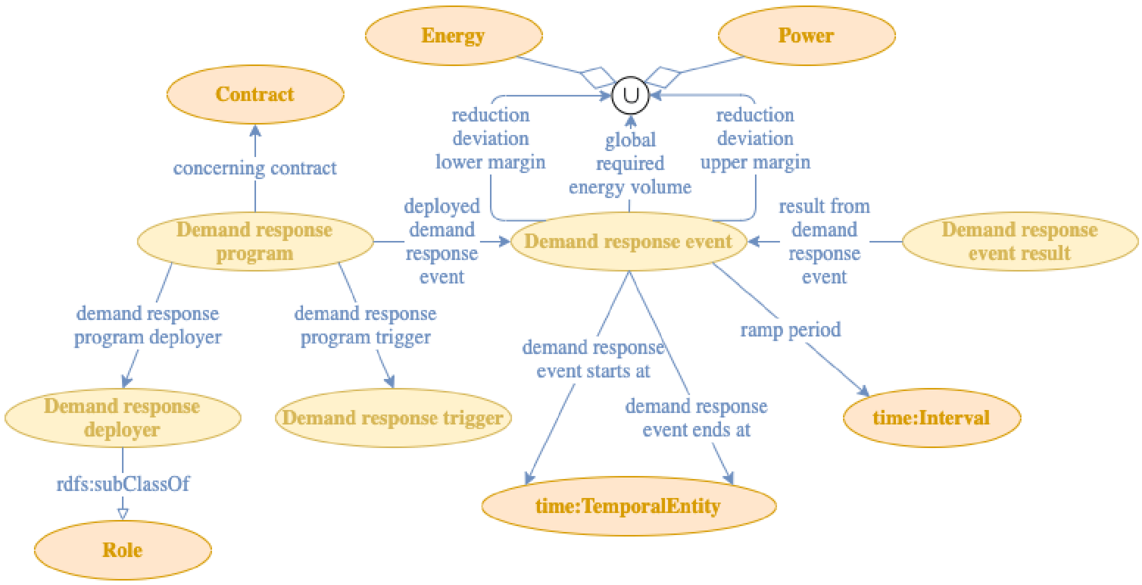

Figure 6. Demand Response module central concepts.

The central classes of IESO's Demand Response module are **Demand response event**, **Demand response event result**, **Demand response program**, and **Demand response trigger**. A **Demand response event** (at the center) is characterized by a start and an end **Temporal Entity** (at the bottom), a global required **Energy** or **Power** volume (at the top center), a ramp period **Interval** (at the bottom right), and the lower and upper margins of **Energy** or **Power** volume deviation (at the top). The **Power** and **Energy** concepts are from the Measure module (see subsection 3.6). The **Demand response event result** (on the right side) provides the outcomes of a **Demand response event**. This class has been extended further to distinguish the results of aggregators from the participating players. A **Demand response program** (on the left side) identifies the respective **Contract** (from the Contract module – see subsection 3.3), the **Demand response deployer** (which is a subclass of **Role** – see subsection 3.1) the **Demand response trigger**, and the **Demand response event** deployed. The Demand Response module is reused and extended as needed by lower-level applicational ontology modules.

3.5. Device

The IESO's Device module is strongly inspired by the SAREF core ontology, describing devices and respective functions, commands, and states. However, unlike the Building module, which mimics BOT base concepts, the Device module only borrows from SAREF core concepts and relations that fit the platforms and services of the MAS Society. Thus, the core concepts of this module are **Device**, **Command**, **Function**, and **State**. Figure 7 demonstrates the Device module base concepts.

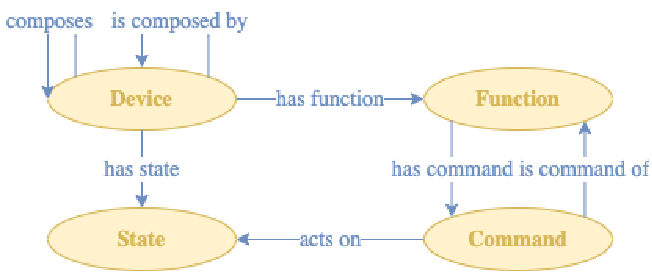

Figure 7. Device module base concepts.

A **Device** is defined by having some **Function** and **State**, and it can be composed by some devices or be part of another device. The **Function** class is described by having at least one **Command**, which, in turn, acts on some device's **State**. This module presents extensions to each of the base concepts to specify different kinds of devices, functions, commands, and states. The devices' measurements and units of measure, in turn, are covered by the Measure module (see subsection 3.6). Similar to the Building module, the base classes of the Device module are directly mapped to the analogous concepts of SAREF using the OWL property *owl:sameAs*. The application-level ontologies needing to detail devices knowledge reuse and extend this module to represent their data and business models.

3.6. Measure

The IESO's Measure module describes measurements, measurement values, types of measures, and units of measure. This module received input from the Quantity, Unit, Dimension, and Type (QUDT)[12] ontology and SAREF core. Figure 8 illustrates the Measure module core concepts.

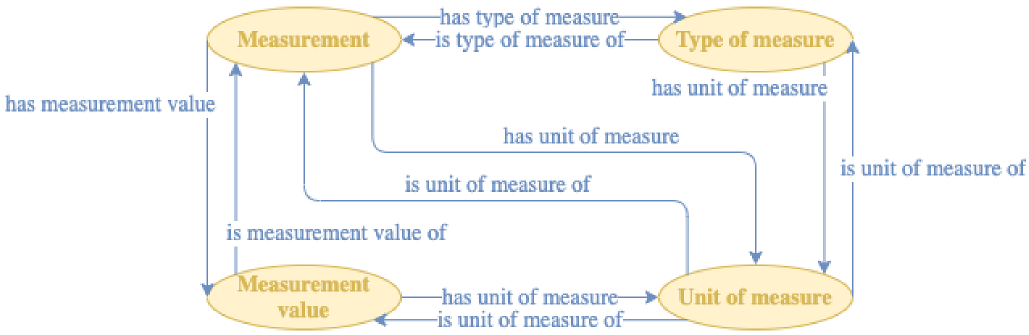

Figure 8. Measure module core concepts.

A **Measurement** is composed of a **Type of measure**, at least a **Measurement value**, and the respective **Unit of measure**. Thus, this module allows associating different values to a measure where each measurement value holds a different unit. When dealing with dimensional units, a **Measurement** can be related to several measurement values with different units; if they derive from the same SI unit, e.g., a power measurement can have a value of 2000W and another of 2kW, representing the same value in different magnitudes. If using a dimensionless unit, it is also possible to define multiple values with different units. An example of such is the conversion between currency units, such as Euro and US Dollar. A **Type of measure** is also related to a **Unit of measure**, allowing data validation. The **Measurement value**, in turn, is defined by exactly one literal value and the respective **Unit of measure**. The **Type of measure** and **Unit of measure** classes include several extensions with the most common units and related types. Additionally, this ontology defines a **Unit converter template** class to provide conversion templates for automatic values conversion. This class is defined by a string template with the conversion query or rule and its syntax, which can be one of "SPARQL", "SWRL", or "SQWRL". This module conceptualizes knowledge transversal to the various IESO and applicational ontology modules, being reused and extended as needed.

[12] Publicly available at: http://qudt.org/.

3.7. Power Transmission and Distribution

The IESO's Power Transmission and Distribution module describes the power transmission and distribution grids from power generation to consumption. This model merges knowledge from existing standards, such as the Common Information Model (CIM) [71], and data models, such as the data structure of the pandapower tool[13], the most used library for power flow algorithms and services available within the MAS Society. Moreover, the Power Transmission and Distribution module has been designed striving to describe such knowledge in a conceptualization understandable by people outside the domain. Figure 9 displays the main concepts of the Power Transmission and Distribution module.

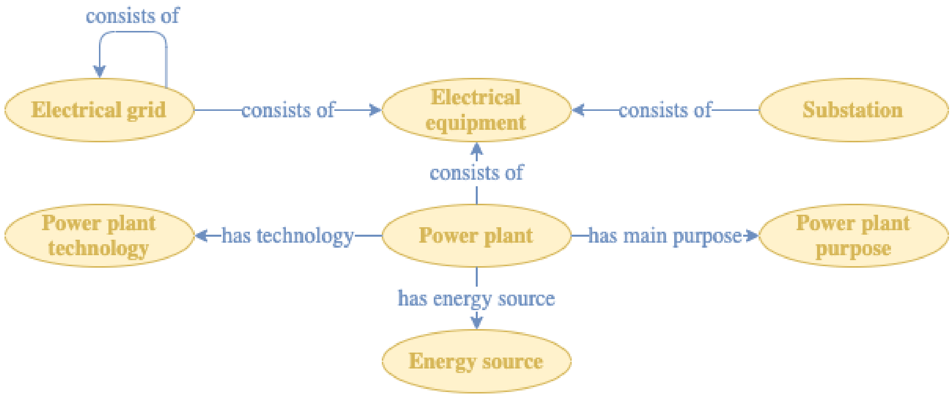

Figure 9. Power Transmission and Distribution module main concepts.

The core concepts of this module are the **Electrical grid**, **Power plant**, **Substation**, and **Electrical grid**. An **Electrical grid** (top left corner) can be a composition of some **Electrical grid**s and consists of some **Electrical equipment** (top center). A **Substation** also consists of some **Electrical equipment**. On the other hand, a **Power plant** (in the center), besides consisting of **Electrical equipment**, its definition also includes the **Energy source**(s), **Power plant technology**, and **Power plant purpose**. Regarding the **Energy source** concept, it can be a **Clean energy source**, a **Renewable energy source**, or a **Non-renewable energy source**, extending each of these classes with the respective types of sources. The **Power plant technology**, in turn, can be **Hydro technology**, **Photovoltaic technology**, **Thermal technology**, or **Wind technology**. The most common **Power plant purpose**s are the **Base load**, **Load following**, and **Peaking** [72]. Finally, the **Electrical equipment** concept is the most comprehensive, being extended to represent from the **Bus** to the **Electric line**, **Generator**, **Load**, or **Transformer**, to name a few. Applicational ontologies reuse and extend this module as needed for the knowledge representation and reasoning on transmission and distribution grids of the respective platforms.

3.8. Trading

The IESO's Trading module describes electricity markets from the wholesale to the regional and local markets, including different types of markets, such as auction-based (symmetric and asymmetric) and bilateral negotiations (ancillary services, future, forward). This module reuses and improves knowledge from EMO ontology and its modules to conceptualize trading in the scope of PES. Additionally, it reuses concepts from the OWL Time ontology (footnote 11) and the

[13] Homepage: http://www.pandapower.org/.

IESO modules Actor Roles (subsection 3.1), Contract (subsection 3.3), and Measure (subsection 3.6). Figure 10 presents the most relevant concepts of the Trading module.

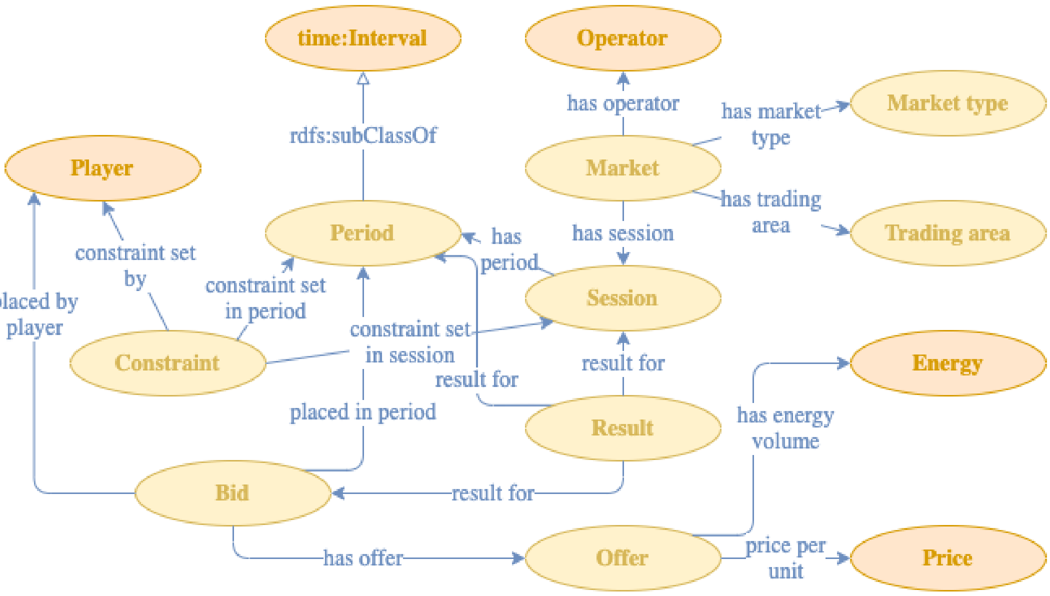

Figure 10. Trading module most relevant concepts.

The main concepts of the Trading module are the **Market** (on top), **Trading area** (top right corner), **Market type** (top right corner), **Session** (at the center), **Period** (at the center), **Bid** (bottom left corner), **Offer** (at the bottom), **Constraint** (at the left), and **Result** (at the middle bottom). The **Market** is the central class of the Trading module. It is composed of one or more **Market type**s, one or more **Session**s, one or more **Operator**s, and at least one **Trading area**. Examples of subclasses of **Market** are the **Day-ahead market**, **Intraday market**, **Balancing market**, to name a few. As subclasses of the **Market type** concept, it includes the **Auction-based market** and the **Continuous market**. The Trading module definitions of **Market** and **Market type** differ from the EMO's definitions. In EMO, the **emo:Market** class refers to the energy service company providing the marketplace, and the **emo:MarketType** concept represents the equivalent to the **Market** class from the Trading module. The **Operator** concept, in turn, is reused from the Actor Roles module (see subsection 3.1). The **Trading area** concept identifies areas of a **Market** that, under certain circumstances, can be kept isolated. An example of it is when the amount of energy traded in the market surpasses the transmission lines limits. In these cases, the market is split into trading areas and executed separately for each area. Depending on the market, the minimum and maximum bid prices may differ among the trading areas. The **Session** class is described by a set of trading **Period**s, which extend the **time:Interval** class from the OWL Time ontology (see footnote 11), and a **Bid** is defined by a set of **Offer**s, a transaction type ("buy" or "sell"), and the respective **Player** (also reused from the Actor Roles module). An **Offer** is composed of an **Energy** and **Price** pair (from the Measure module). The **Constraint** class abstracts different restriction types that players may pose as strategies for their benefit, participating only if their conditions are met. Finally, the **Result** class abstracts different kinds of results, such as **Player result**, **Session result**, and **Period result**, to name a few. These are useful for operators and players. As the above modules, the Trading module is reused and extended as needed for the trading-related knowledge representation of different tools, namely MASCEM and some aggregator agents of MASGriP.

4. CASE STUDY / ONTOLOGY EVALUATION

The present case study aims to demonstrate de use of IESO in an agent-based simulation of local grid management considering the violation of technical limits. It shows how IESO, and semantic web technologies, provide semantic interoperability between the involved software agents and services and the application of semantic rules for the network constraints' validation. The case study scenario has been configured using TOOCC and includes MASGriP, AiD-EM, two services from IDeS, and SSC. The services are the Power Flow Service[14] (PFS) and the Electricity Market Service[15] (EMS) [73]. The PFS provides power flow algorithms for the technical validation of transmission and distribution grids. The EMS, in turn, supplies day-ahead and intraday EM algorithms, including the double auction (symmetric) and single-sided auction (asymmetric) market types. TOOCC uses SSC to get the available tools for simulation, their location for the agents' interactions with each other and with services, and their input and output models.

Our scenario considers a local network manager (NM) agent and 14 player agents from MASGriP in the simulation of the technical limits' validation of a rural distribution grid. If any technical limit violation occurs, the NM runs demand flexibility asymmetric-based market to reduce the necessary amount to respect the network technical limitations. In the asymmetric market type, buyers only submit the required amount of energy, while sellers propose prices per unit of energy supplied. Finally, some players use AiD-EM to request strategic bid price definitions. To ease the readers' follow along, and since most interactions have been presented and explained in previous works (e.g., [48], [53], [74], [75]), this case study focuses on the NM reasoning and interactions with its player agents and with the PFS and EMS services. The relevant data regarding the NM interactions, services inputs and outputs, semantic queries, and business rules are made available at [76].

The simulation scenario considers the low voltage (LV) network from [77], a representative synthetic grid for voltage control analysis, including 12 household loads (loads 0-11) and 2 special loads (loads 12 and 13). Figure 11 illustrates the considered rural network.

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[14] Publicly available at https://pf.gecad.isep.ipp.pt.
[15] Publicly available at: https://em.gecad.isep.ipp.pt/.

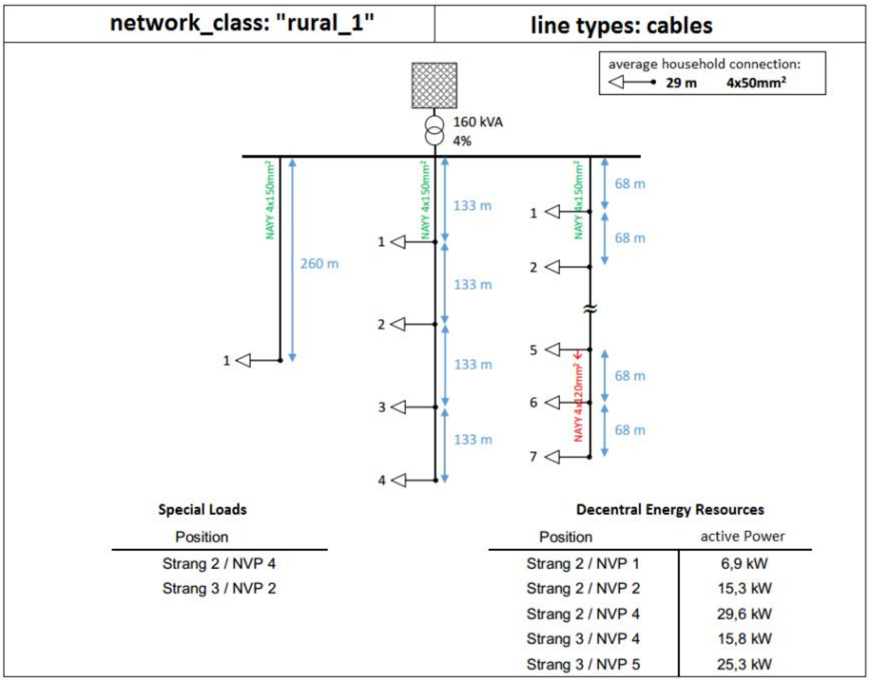

Figure 11. Synthetic voltage control LV rural network [77].

The rural distribution network of Figure 11 is connected to an external grid using a transformer of 0.16 MVA 20/0.4 kV. The grid includes three feeders, 25 buses, 24 lines, 14 loads, and five static generators. The NM performs power flow checks continuously to ensure the security and supply within the grid. To this end, at each time step, the NM agent queries his knowledge base (KB) (file 1; folder "kb" [76]) to get the input of the PFS. Using the PFS, it is only required to provide the complete configuration of the network if it does not exist yet in the service's database. Being this network previously configured, the NM only queries the loads' data (file 2; folder "sparql/query"), which vary according to the players' consumption. The query over the KB returns a JSON string (file 3; folder "pfs") respecting the PFS input schema. Table 1 presents the buses and consumption of each load.

Table 1. Loads input data for PFS.

Load	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Bus	3	8	9	10	11	19	20
kW	19.635	19.635	19.635	19.635	19.635	19.635	19.635
Load	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Bus	21	22	23	24	25	7	13
kW	19.635	19.635	19.635	19.635	19.635	30.415	30.415

After executing the PFS, the NM agent must convert the JSON output (file 4; folder "pfs") to RDF to save it on his KB. To this end, the agent uses SPARQL Update[16] template files (folder "sparql/template"), JSON Path[17] to query the JSON data, and a mappings file (file 5) to map the JSON data with the respective template. The "sparql/template" folder includes a template file for

[16] Homepage: https://www.w3.org/TR/sparql11-update/. SPARQL is a recursive acronym for SPARQL Protocol And RDF Query Language.
[17] JSONPath – XPath for JSON: https://goessner.net/articles/JsonPath/.

the overall power flow result (file 6.1) and for each type of element of the network (files 6.2 to 6.7). The mappings file provides a mapping list for each template file, where each mapping includes the "tag" to be replaced, the JSON "path" query string, and the "type" of response the JSON Path query returns. The "type" of response determines how to replace the tags with the respective values. E.g., if the "type" is "simple", it means that it is a direct replacement; if the "type" is a list of objects ("list object"), it means the agent must replace and execute the SPARQL Update for each element of the list. An example of each update file after replacing the tags with the respective values is available in the folder "sparql/update" (files 6.1 to 6.7).

Having the output data available in the KB, the NM agent runs validation queries (folder "sparql/validation") to check the results. These queries use the ASK query form, which returns a Boolean indicating if the query pattern matches or not. First, the NM checks if the tripe "*:Validation :isValid true*" exists in the KB (file 7.1.1). As the query returns *false*, the agent queries the KB to get the motives for the non-convergence of the power flow (file 7.1.2). The response indicates voltages below 0.95 per unit (pu) in buses 17, 18, 24, and 25 (file 7.1.3). Since the description provided by the PFS for the non-convergence reason is only human-readable, the agent must verify the output data to understand why it did not converge. To this end, the NM agent starts by validating if the Buses' voltage magnitudes are within the acceptable limits (file 7.2.1), which must be between 0.95 and 1.05 pu. Equation 1 presents the mathematical formulation of the rule.

$$0.95\ V_N \leq V_{BUS} \leq 1.05\ V_N \quad (1)$$

where:

- V_N – Nominal Voltage;
- V_{BUS} – Bus Voltage.

As the query returns false, the agent queries the KB (file 7.2.2) to get the buses and voltage values outside the boundaries. Table 2 presents the response (file 7.2.3) values from the agent's query. Figure 12 illustrates the nominal voltage limits and the voltages of each bus.

Table 2. Buses off limits voltages.

Bus	17	18	24	25
Voltage Magnitude (p.u.)	0.9478	0.9458	0.9454	0.9434

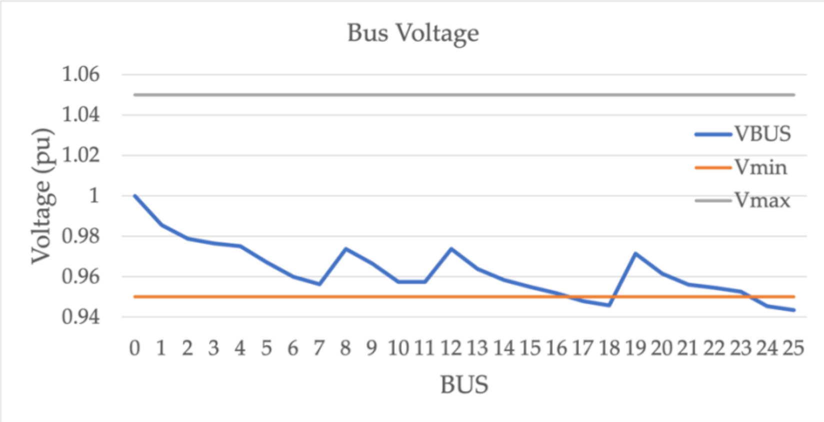

Figure 12. Buses' voltages and nominal voltage limits.

As Table 2 demonstrates, all values are below the 0.95 p.u. limit. As presented in Figure 12, the voltage of buses 17, 18, 24 and 25 is lower than the minimum voltage allowed in the system (0.95 pu). This happens in the consumers connected at the end of the feeders due to the high demand in the system.

The following constraint to verify is the lines' maximum current between buses. The current of a line cannot exceed the maximum current supported. Otherwise, performance issues may occur, a protected shutdown, or a component failure. Equation 2 introduces the mathematical formulation of this constraint.

$$I_{Line} \leq I_{LineMax} \quad (2)$$

where:

- I_{Line} – Current in line "Line";
- $I_{LineMax}$ – Maximum Current in Line (Line Thermal limit).

In this case, the ASK query (file 7.3.1) conducted by the NM agent returns false. It means that all lines are within their current limits. Otherwise, the NM would query (file 7.3.2) the KB to get the lines where the current exceeded.

Finally, the last condition to confirm is the transformer's power flow at the high voltage (HV) side. The transformer's nominal power is 160 kVA and surpassing this value may damage this component and provoke a system's failure. Thus, the NM agent must ensure this value is below or equal to 160 kVA. Equation 3 shows the mathematical formulation of this condition.

$$S_{Transf} \leq S_{TransfNom} \quad (3)$$

where:

- S_{Transf} – Transformer's Apparent Power;
- $S_{TransfNom}$ – Transformer's Nominal Power.

This ASK query (file 7.4.1), in turn, returns *true*, indicating that the apparent power flow of the transformer at HV is above 160 kVA. Hence, the agent queries his KB (file 7.4.2) to get the power flow of the transformer at HV and the amount of energy that should be reduced/curtailed to decrease the load in the power transformer to the nominal values (160 kVA). Table 3 presents the query results (file 7.4.3).

Table 3. Transformer's power flow at HV and surplus to reduce.

Nominal Power (MVA)	HV Active Power (MVA)	Reduction (MVA)	Reduction (kVA)
0.16	0.21219	0.05219	52.1896

As shown in Table 3, the transformer's data (first three columns) is in MVA. However, using the Measure module of IESO, the NM agent can obtain converted values (last column) from different magnitudes of the same SI unit (see file 7.4.1), facilitating units' uniformization while preparing the EMS service input.

Holding the required total consumption to reduce, the NM agent sends a call for proposal (file 8.1; folder "ems") to all its players, requesting energy consumption reduction. In that case, we are assuming that reducing active power in the same amount of apparent power, we will solve the constraints at the power transformer. In practice, assuming the normal load factor the reduction of apparent power will be higher. The call for proposal identifies the market, market type, session, and period (single period from 17:00 to 18:00). According to the call for proposal, each player prepares a bid proposal (e.g., file 8.2; folder "ems") to reply to the NM. To determine the prices strategically, players interact with AiD-EM decision support MAS as exemplified in [53]. Table 4 presents the proposals of each player.

Table 4. Players bids for local flexibility market.

Player	**0**	**1**	**2**	**3**	**4**	**5**	**6**
kWh	3.6856	3.9072	4.0044	1.7122	1.1206	1.0967	5.2004
€/kWh	0.1324	0.1494	0.1619	0.0930	0.0739	0.1852	0.1312
Player	**7**	**8**	**9**	**10**	**11**	**12**	**13**
kWh	5.5666	4.3339	0.6038	0.6670	7.2409	9.8465	6.4711
€/kWh	0.0576	0.0361	0.0385	0.1129	0.0658	0.0955	0.1019

To execute the local flexibility market, the NM agent uses the EMS service. The NM is the only buyer, while the players sell consumption flexibility. To prepare the EMS input, the NM uses a SPARQL template (file 9; folder "sparql/template") to generate the query (file 9; folder "sparql/query") that gets the JSON input for the EMS asymmetric algorithm (file 10; folder "ems").

Receiving the demand flexibility market results (file 11; folder "ems") from EMS, the NM agent translates the JSON data into the semantic model using SPARQL Update template files (files 12.1 and 12.2; folder "sparql/template"), JSON Path, and the respective mappings (file 5.0). An example of each update file is also available in the folder "sparql/update" (files 12.1 and 12.2). Figure 13 illustrates the player results in the demand flexibility market.

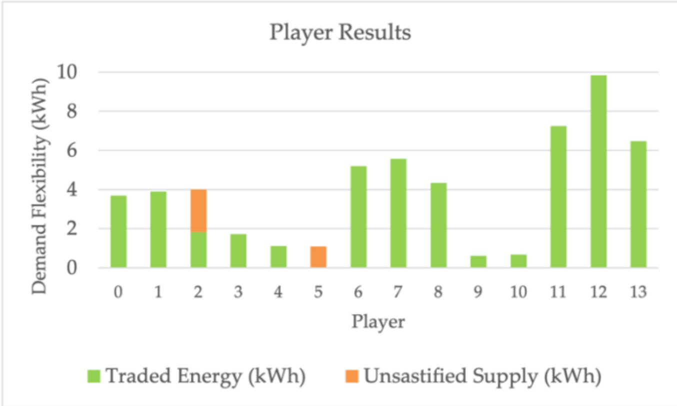

Figure 13. Players results.

Observing the chart of Figure 13, player 5 was the only player not selling any demand flexibility in the market. Player 2, in turn, only sold near half the presented proposal, setting the market price per kWh. The overall market results are shown in Table 5.

Table 5. Overall market results.

Total Demand (kWh)	Total Supply (kWh)	Total Satisfied (kWh)	Market Price (€/kWh)
52.18964	55.4569	52.18964	0.1619

As Table 5 demonstrates, the NM agent was able to buy the required consumption flexibility from its players. Having the results in its KB, the next step is to execute the PFS considering the effectively reduced amount. To this end, at the start of the negotiation period, the NM agent repeats the previously explained process to query his KB to get the PFS input with the updated loads' consumption (file 13; folder "pfs"). The service's output (file 14) is then saved in the agent's KB The agent converts the service's output to the semantic model and validates the results using the ASK queries. The results show that the power flow converged, and there are no technical limits violations both in the power transformer and in the bus voltages. The buses' voltages are within limits, as the lines' current and the transformer's active power on the HV side. The voltage in each bus of the LV network is presented in Figure 14, allowing the comparison between the initial voltage and the voltage after the activation of the market flexibilities (VBUS_NEW).

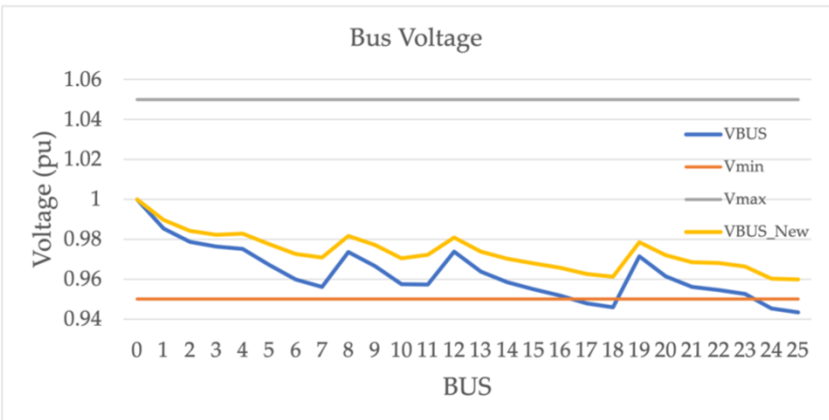

Figure 14. Buses' voltages comparison before and after demand flexibility market.

Using IESO, the NM was able to interact with the different services and players. IESO semantic models also allowed the validation of network constraints and the automatic conversion of units of measure. As demonstrated in [34], the SPARQL queries and SPARQL Update template files are configuration inputs to keep the NM agent agnostic to the semantic model and business rules. This way, the ontology may change without the need to recode and recompile the agent. It only requires the update of the SPARQL files accordingly.

5. CONCLUSIONS

This work introduces the IESO ontology, a modular semantic model to provide semantic interoperability, data uniformization, knowledge extraction, reasoning, and validation within a society of MAS and services. Each module represents a domain of interest in the frame of the MASs that are part of the agents' community. IESO leverages the experience and best practices of existing and well-established ontologies. It overcomes the heterogeneity of existing ontologies developed for distinct purposes, bringing together cross-domain knowledge relevant to the study, simulation, and validation of the PES. IESO is publicly available (footnote 9) to enable the participation of external agent-based tools and services in the simulations of the MAS Society. Ultimately, IESO provides a base model to overcome interoperability issues between heterogeneous tools developed in the scope of PES.

The case study demonstrates the use of IESO in the simulation of a distribution grid technical validation. The simulation involves various tools from the MAS Society, focusing on the NM agent. It aims to demonstrate how IESO provides semantic interoperability among agents and services, constraints validation, and data uniformization. To this end, the NM agent runs the PFS to verify the network technical constraints. After, the NM applies constraints' validation over the PFS output. Given the violations of the buses' tensions limits and the transformer's active power on the HV side, the NM requests for demand flexibility to lower the network power flow, running an asymmetric-based auction. The flexibility acquired in the market allowed to balance network congestion. Additionally, the case study also shows how using ontologies and semantic web technologies enables the development of data and business model agnostic tools, avoiding recoding and recompiling.

IESO is a continuously evolving ontology to follow along with the evolution of the MAS and services of the MAS Society. As future work, the development of new modules is already in progress to support contextualized profiling and to gather common knowledge from the various decision-support tools. IESO's webpage will be upgraded to provide usage examples for each module considering the reuse of complementary modules. Additionally, different modules' webpages will provide alignment files with existing and publicly available ontologies whenever it makes sense.

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