Universidad de Salamanca

Doctoral Thesis

Ontologies for the Interoperability of Heterogeneous Multi-Agent Systems in the scope of Energy and Power Systems

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STATEMENT

Zita Maria Almeida do Vale, Full Professor at the School of Engineering of Polytechnic of Porto (ISEP-IPP), authorizes **Gabriel José Lopes dos Santos** to present his thesis using a collection of papers published during this Ph.D. thesis work (thesis by papers). The selected papers are published in international journals indexed at SCI and international conference proceedings as Springer book chapters.

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Salamanca, September 20, 2021

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Juan Manuel Corchado Rodríguez

STATEMENT

Tiago Manuel Campelos Ferreira Pinto, Researcher at the Research Group on Intelligent Engineering and Computing for Advanced Innovation and Development (GECAD) in the School of Engineering of Polytechnic of Porto (ISEP-IPP), authorizes Gabriel José Lopes dos Santos to present his thesis using a collection of papers published during this Ph.D. thesis work (thesis by papers). The selected papers are published in international journals indexed at SCI and international conference proceedings as Springer book chapters.

Porto, September 20, 2021

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"If you want to find the secrets of the universe, think in terms of energy, frequency and vibration."

Nikola Tesla

A ti e aos que partiram e nos protegem nas estrelas.

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Abstract

The electricity sector, traditionally run by monopolies and powerful utilities, has undergone significant changes in the last decades. The most notable advances are an increased penetration of renewable energy sources (RES) and distributed generation, which have led to the adoption of the smart grids (SGs) paradigm and to the introduction of competitive approaches in wholesale and some retail electricity markets (EMs). SGs rapidly emerged from a widely accepted concept to reality. The intermittency of RES and their large-scale integration poses new constraints and challenges, strongly affecting EMs' operations. The challenging environment of power and energy systems (PES) reinforces the need for studying, experimenting, and validating such competitive, dynamic, and complex operations and interactions. In this context, simulation, decision support, and intelligent management tools become essential to study different market mechanisms and the relationships among the involved stakeholders. To this end, the new generation of tools should be able to cope with the quick evolution of PES, providing participants with adequate means to adapt themselves, addressing new models and constraints, and their complex relationship with the technological and business developments.

Multi-agent-based platforms are particularly well suited for analyzing complex interactions in dynamic systems, such as PES, due to their distributed and independent nature. The decomposition of complex tasks into simple assignments and the easy inclusion of new data and business models, constraints, types of players and operators, and their interactions are some of the main advantages of agent-based approaches. In this domain, several modeling tools have emerged to simulate, study, and solve problems of specific PES subdomains. However, there is a generalized limitation referring to the significant lack of interoperability between heterogeneous systems, which prevents from addressing the problem globally, considering all the relevant existing interrelationships. This is essential to enable players taking full advantage of the evolving opportunities. Thus, to accomplish such a complete framework while taking advantage of existing tools that allow the study of specific parts of the global problem, interoperability between these systems is required.

Ontologies facilitate the interoperability between heterogeneous systems by giving semantic meaning to information exchanged between the various parties.

The advantage lies in the fact that all those involved in a particular domain know them, understand, and agree with the conceptualization defined therein. There are, in the literature, several proposals for the use of ontologies within PES, encouraging their reuse and extension. However, most 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 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.

These gaps motivate the development of the research work of this Ph.D., which emerges to provide a solution for heterogeneous systems interoperability within PES. The several contributions of this work result in a society of multi-agent systems (MAS) for the simulation, study, decision support, operation, and intelligent management of PES. This MAS society addresses PES from the wholesale EM to the SG and consumer energy efficiency, taking advantage of existing simulation and decision support tools, complemented by newly developed ones, ensuring interoperability between them. It uses ontologies for knowledge representation in a common vocabulary, easing interoperability between the various systems. Furthermore, using ontologies and semantic web technologies allows the development of model agnostic tools for a flexible adaptation to new rules and constraints, promoting semantic reasoning for context-aware systems.

The developed framework has been tested and validated against different contexts, considering both real-world operation and laboratory simulation environments, and under realistic scenarios using real and simulated data from heterogeneous sources acquired from databases or in real-time and represented in a common ground semantic model. The promising results achieved under realistic conditions support the thesis that ontologies contribute to increasing interoperability between heterogeneous tools directed to the study and management of PES, making it possible to address the problem globally.

Keywords: Decision-support; Intelligent Management; Multi-Agent Systems Society; Ontologies; Power and Energy Systems;

Reasoning; Semantic Interoperability; Semantic Web Technologies; Simulation.

Resumen

El sector eléctrico, tradicionalmente dirigido por monopolios y poderosas empresas de servicios públicos, ha experimentado cambios significativos en las últimas décadas. Los avances más notables son una mayor penetración de las fuentes de energía renovable (RES por sus siglas en inglés) y la generación distribuida, que han llevado a la adopción del paradigma de las redes inteligentes (SG por sus siglas en inglés) y a la introducción de enfoques competitivos en los mercados de electricidad (EMs por sus siglas en inglés) mayoristas y algunos minoristas. Las SG emergieron rápidamente de un concepto ampliamente aceptado en la realidad. La intermitencia de las fuentes de energía renovable y su integración a gran escala plantea nuevas limitaciones y desafíos que afectan en gran medida las operaciones de los EMs. El desafiante entorno de los sistemas de potencia y energía (PES por sus siglas en inglés) refuerza la necesidad de estudiar, experimentar y validar operaciones e interacciones competitivas, dinámicas y complejas. En este contexto, la simulación, el apoyo a la toma de decisiones, y las herramientas de gestión inteligente, se vuelven imprescindibles para estudiar los diferentes mecanismos del mercado y las relaciones entre los actores involucrados. Para ello, la nueva generación de herramientas debe ser capaz de hacer frente a la rápida evolución de los PES, proporcionando a los participantes los medios adecuados para adaptarse, abordando nuevos modelos y limitaciones, y su compleja relación con los desarrollos tecnológicos y de negocios.

Las plataformas basadas en múltiples agentes son particularmente adecuadas para analizar interacciones complejas en sistemas dinámicos, como PES, debido a su naturaleza distribuida e independiente. La descomposición de tareas complejas en asignaciones simples y la fácil inclusión de nuevos datos y modelos de negocio, restricciones, tipos de actores y operadores, y sus interacciones, son algunas de las principales ventajas de los enfoques basados en agentes. En este dominio, han surgido varias herramientas de modelado para simular, estudiar y resolver problemas de subdominios específicos de PES. Sin embargo, existe una limitación generalizada referida a la importante falta de interoperabilidad entre sistemas heterogéneos, que impide abordar el problema de manera global, considerando todas las interrelaciones relevantes existentes. Esto es esencial para que los jugadores puedan aprovechar al máximo las oportunidades en evolución. Por lo tanto, para lograr un marco tan completo

aprovechando las herramientas existentes que permiten el estudio de partes específicas del problema global, se requiere la interoperabilidad entre estos sistemas.

Las ontologías facilitan la interoperabilidad entre sistemas heterogéneos al dar un significado semántico a la información intercambiada entre las distintas partes. La ventaja radica en el hecho de que todos los involucrados en un dominio particular los conocen, comprenden y están de acuerdo con la conceptualización allí definida. Existen, en la literatura, varias propuestas para el uso de ontologías dentro de PES, fomentando su reutilización y extensión. Sin embargo, la mayoría de las ontologías se centran en un escenario de aplicación específico o en una abstracción de alto nivel de un subdominio de los PES. Además, existe una considerable heterogeneidad entre estos modelos, lo que complica su integración y adopción. Es fundamental desarrollar ontologías que representen distintas fuentes de conocimiento para facilitar las interacciones entre entidades de diferente naturaleza, promoviendo la interoperabilidad entre sistemas heterogéneos basados en agentes que permitan resolver problemas específicos de PES.

Estas brechas motivan el desarrollo del trabajo de investigación de este doctorado, que surge para brindar una solución a la interoperabilidad de sistemas heterogéneos dentro de los PES. Las diversas aportaciones de este trabajo dan como resultado una sociedad de sistemas multi-agente (MAS por sus siglas en inglés) para la simulación, estudio, soporte de decisiones, operación y gestión inteligente de PES. Esta sociedad de MAS aborda los PES desde el EM mayorista hasta el SG y la eficiencia energética del consumidor, aprovechando las herramientas de simulación y apoyo a la toma de decisiones existentes, complementadas con las desarrolladas recientemente, asegurando la interoperabilidad entre ellas. Utiliza ontologías para la representación del conocimiento en un vocabulario común, lo que facilita la interoperabilidad entre los distintos sistemas. Además, el uso de ontologías y tecnologías de web semántica permite el desarrollo de herramientas agnósticas de modelos para una adaptación flexible a nuevas reglas y restricciones, promoviendo el razonamiento semántico para sistemas sensibles al contexto.

El marco desarrollado ha sido probado y validado en diferentes contextos, considerando tanto entornos de simulación en laboratorio, así como operación en el mundo real, y bajo escenarios realistas utilizando datos reales y simulados de fuentes heterogéneas adquiridos de bases de datos o en tiempo real y representados en un terreno común de modelo semántico. Los prometedores resultados alcanzados en condiciones realistas apoyan la tesis de que las ontologías contribuyen a incrementar la interoperabilidad entre herramientas heterogéneas dirigidas al estudio y manejo de los PES, permitiendo abordar el problema de manera global.

Palabras clave: Apoyo a la Toma de Decisiones; Gestión Inteligente; Sociedad de Sistemas de Agentes Múltiples; Ontologías; Sistemas de Energía y Potencia; Razonamiento; Interoperabilidad Semántica; Tecnologías de Web Semántica; Simulación.

Resumo

O setor elétrico, tradicionalmente controlado por monopólios e grandes empresas de utilidade pública, tem sofrido mudanças significativas nas últimas décadas. Os avanços mais notáveis são uma maior penetração de fontes de energia renováveis (FER) e geração distribuída, que levaram à adoção de um novo paradigma, designado por redes elétricas inteligentes (REI) e à introdução de abordagens competitivas nos mercados grossistas e em alguns mercados retalhistas de eletricidade. As REI rapidamente evoluíram de um conceito académico para a aplicação em redes elétricas reais. A intermitência das FER e a sua integração em grande escala impõe novos desafios, afetando fortemente as operações dos mercados de eletricidade (ME). Este novo paradigma dos sistemas elétricos de energia (SEE) reforça a necessidade de estudar, experimentar e validar tanto a operação das redes como as interações entre as entidades envolvidas nos SEE. Estas interações são dinâmicas e complexas e, dependendo do contexto, as entidades podem adotar uma postura competitiva ou cooperativa. Neste contexto, ferramentas de simulação, apoio à decisão e gestão inteligente tornam-se essenciais para estudar os diferentes mecanismos de mercado e as relações entre as entidades envolvidas. Para tal, uma nova geração de ferramentas deverá emergir e ser capaz de fazer face à rápida evolução dos SEE, dotando as entidades de meios adequados para se adaptarem, abordando novos modelos e regras de negócio, e considerando a evolução tecnológica e empresarial.

As plataformas baseadas em sistemas multiagente (SMA) são particularmente adequadas para analisar interações complexas em sistemas dinâmicos, como os SEE, devido à sua natureza distribuída e independente. A decomposição de tarefas complexas em tarefas simples e a fácil inclusão de novos modelos de dados e de negócios, restrições, tipos de entidades e suas interações são algumas das principais vantagens de uma abordagem baseada em agentes. Neste domínio, várias ferramentas de modelação surgiram para simular, estudar e resolver problemas de áreas específicas dos SEE. No entanto, existe uma limitação generalizada referente à falta significativa de interoperabilidade entre sistemas heterogéneos, o que impede uma abordagem global do problema, considerando todas as inter-relações existentes. Esta abordagem global é essencial para permitir que os participantes aproveitem ao máximo as oportunidades emergentes. Deste modo, para realizar uma estrutura tão

completa e complexa e, ao mesmo tempo, tirar proveito das ferramentas existentes que permitem o estudo de partes específicas do problema global, é necessário assegurar um elevado grau de interoperabilidade entre estes sistemas.

O uso de ontologias facilita cabalmente a interoperabilidade entre sistemas heterogéneos, dando significado semântico às informações trocadas entre as várias entidades e/ou sistemas. A vantagem introduzida pelo uso das ontologias está no fato de que todos os envolvidos num determinado domínio conhecem, entendem e concordam com a conceptualização definida na ontologia. Existem, na literatura, diversas propostas para o uso de ontologias no âmbito dos SEE, incentivando a sua reutilização e extensão. No entanto, a maioria das ontologias conceptualiza um cenário de aplicação específico ou uma abstração de alto nível de uma área específica dos SEE. Além disso, há uma considerável heterogeneidade entre os vários modelos, dificultando sua integração e adoção. É essencial desenvolver ontologias que representem fontes de conhecimento distintas para facilitar as interações entre entidades de diferentes naturezas, promovendo a interoperabilidade entre sistemas baseados em agentes heterogéneos que possibilitem a resolução de problemas concretos dos SEE.

Estas lacunas motivaram o desenvolvimento do trabalho de investigação e desenvolvimento deste doutoramento, que surge para fornecer uma solução que garanta a interoperabilidade de sistemas heterogéneos no âmbito dos SEE. As diversas contribuições deste trabalho resultam numa sociedade de SMA para simulação, estudo, suporte à decisão, operação e gestão inteligente dos SEE. A sociedade de SMA aborda os SEE desde os ME grossistas, as REI e a eficiência energética do consumidor, tirando partido das ferramentas de simulação e de apoio à decisão existentes, complementadas por outras ferramentas recentemente desenvolvidas, garantindo a interoperabilidade entre elas. Para tal, utiliza ontologias para a representação do conhecimento num vocabulário comum, facilitando a interoperabilidade entre os diversos sistemas. Para além de facilitar a interoperabilidade, o uso de ontologias e tecnologias da web semântica permite o desenvolvimento de ferramentas agnósticas aos modelos de dados e de negócio para uma adaptação flexível a novas regras e restrições, promovendo a inferência semântica para sistemas sensíveis ao contexto.

A plataforma desenvolvida foi testada e validada em diferentes contextos, considerando tanto ambientes de operação no mundo real como de simulação laboratorial, em cenários realistas, usando dados reais e simulados de fontes

heterogéneas adquiridos em bases de dados ou em tempo real e representados num modelo semântico comum. Os resultados alcançados em condições realistas foram bastante promissores, corroborando a tese de que as ontologias contribuem para aumentar a interoperabilidade entre ferramentas heterogéneas voltadas ao estudo e gestão dos SEE, possibilitando abordar o problema de forma global.

Palavras-chave: Apoio à Decisão; Gestão Inteligente; Sociedade de Sistemas Multiagente; Ontologias; Sistemas Elétricos de Energia; Raciocínio; Interoperabilidade Semântica; Tecnologias da Web Semântica; Simulação.

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Acronyms

ACL	Agent Communication Language
AI	Artificial Intelligence
AiD-EM	Adaptive Decision Support for Electricity Market Negotiations
ALBidS	Adaptive Learning strategic Bidding System
AMQP	Advanced Message Queuing Protocol
ANN	Artificial Neural Network
BEMS	Building Energy Management System
BOT	Building Topology Ontology
BRICKS	Building's Reasoning for Intelligent Control Knowledge-based System
CFP	Call For Proposal ontology
CIM	Common Information Model
CSV	Comma-Separated Values
DAS	Data Access Service
DECON	Decision Support for Energy Contracts Negotiation
DER	Distributed Energy Resources
Dev-C	Device Connector Service
DF	Directory Facilitator
DG	Distributed Generation
DL	Description Logic
DR	Demand Response
EC	European Commission
EM	Electricity Market
EMO	Electricity Markets Ontology
EMR	Electricity Markets Results ontology
ERM	Energy Resources Management
ESS	Energy Storage Systems
EU	European Union
EV	Electric Vehicle
FCT	Fundação para a Ciência e a Tecnologia
FIPA	Foundation for Intelligent Physical Agents
GECAD	Research Group on Intelligent Engineering and Computing for Advanced Innovation and Development
GHG	Greenhouse Gas

HVAC	Heating, Ventilating, and Air Conditioning
HTTP	Hypertext Transfer Protocol
ICT	Information and Communication Technology
IDeS	Intelligent Decision Support Services
IDeSMAS	Intelligent Decision Support Multi-Agent System
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IES	Intelligent Energy Systems
IESO	Intelligent Energy Systems Ontology
IoT	Internet of Things
IRI	Internationalized Resource Identifier
ISS	Intelligent Systems Subcommittee
JCR	Journal Citation Reports
JSON	JavaScript Object Notation
JSON-LD	JavaScript Object Notation for Linked Data
KB	Knowledge Base
LDAP	Lightweight Directory Access Protocol
LMO	Local Market Ontology
MAS	Multi-Agent Systems
MARTINE	Multi-Agent based Real-Time INfrastructure for Energy
MASCEM	Multi-Agent Simulator of Competitive Electricity Markets
MASGriP	Multi-Agent Smart Grid simulation Platform
MQTT	Message Queuing Telemetry Transport
NM	Network Manager
ODS	Open Data Sets
OPC UA	Open Platform Communications Unified Architecture
OWL	Web Ontology Language
PCR	Price Coupling of Regions
PES	Power and Energy Systems
PLC	Programmable Logic Controller
PLCMAS	Programmable Logic Controller Multi-Agent System
QUDT	Quantity, Unit, Dimension, and Type
RBG	Renewable-Based Generation
RDF	Resource Description Framework
RES	Renewable Energy Sources
REST	Representational State Transfer

SAO	Software Agent Ontology
SAREF	Smart Appliances REFerence ontology
SCADA	Supervisory Control And Data Acquisition
SEAS	Smart Energy Aware Systems
SG	Smart Grid
SHIM	SCADA House Intelligent Management
SIDC	Single Intraday Coupling
SOF	Scheduling, Optimization, and Forecasting ontology
SPARQL	SPARQL Protocol and RDF Query Language
SSC	Semantic Services Catalog
SVM	Support Vector Machine
SWRL	Semantic Web Rule Language
TCP/IP	Transmission Control Protocol/Internet Protocol
TOOCC	Tools Control Center
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
W3C	World Wide Web Consortium
WADL	Web Application Description Language
WSDL	Web Services Description Language
XML	eXtensible Markup Language

Chapter 1

Introduction

1 Introduction

This chapter starts by disclosing the motivation that led to the development of the work of this Ph.D. thesis in section 1.1, droving to the research questions and objectives exposed in section 1.2. Section 1.3 highlights the main contributions of the thesis, the respective publications and related research projects. The final section, 1.4, outlines the document's structure and organization.

1.1 Motivation

Over the last decades, the electricity sector, traditionally run by monopolies and powerful utilities, has undergone significant transformations, including the liberalization of electricity markets (EMs), aiming to make them more transparent and competitive [1], [2]. The EU was, in fact, a pioneer and leader regarding climate change, environmental, and energy matters. The EU "20-20-20" targets set in 2007 played a relevant role, aiming to achieve, by 2020 in all EU, a reduction of 20% in greenhouse gas (GHG) emissions when compared to 1990, a 20% share energy renewable-based generation in EU, and an improvement of 20% in the energy efficiency [3]. Since then, the leaders of EU state members have been revising the previously defined targets and, currently, they aim to reduce GHG emissions by at least 40% from 1990 levels, increase the share of renewable energy consumption to at least 32%, and improve energy efficiency at least 32.5% by 2030 [4]. By 2050 the EU aims to be climate-neutral with an economy with net-zero GHG emissions [5], raising the bar to even more ambitious targets. Moreover, on 5 June 2019, the European Parliament and the Council of the EU launched the Directive (EU) 2019/9442 "on common rules for the internal market for electricity and amending Directive 2012/27/EU" [6], introducing significant changes to electricity markets and business models. This directive provides the final energy users with genuine alternatives, reinforcing their empowerment, creating new business opportunities while ensuring higher service standards, and contributing to the security of supply and sustainability [7].

The introduction of a competitive market approach aimed to promote public benefits and raise the sector's efficiency, providing end-users with reliable and quality service [8]. However, these changes are particularly challenging as the players that used to monopolize the sector want to take the lead, on the one hand, and, on the other, technical and economic factors are strongly correlated [9]. As the world evolves, there is an increase in electricity consumption. Civilizations are highly dependent on the use of electricity for secure, stable, and comfortable living. Thus, electricity demand is critical for economic development. Consequently, concerns about the environmental impact of the increase of electricity demand and the use of coil-based primary sources are taken very seriously by governments at the scientific, economic, and political levels [10]. Hence, this led to new energy policies and intensive research aiming to improve energy consumption efficiency and expand the generation of electricity based on renewable energy sources (RES).

EMs must adapt to society according to new policies and the needs of the various segments of power and energy systems (PES), namely the generation, transmission, distribution, and commercialization. The liberalization of these segments, previously nationally owned, promotes competitiveness [11], [12], bringing numerous benefits such as the improvement of quality of service, reduce the costs of electricity, and stimulate the creation of advanced market models, to name a few. Additionally, the high penetration of RES brought a new paradigm shift, and EMs' behavior became more unpredictable and complex due to the increasing number of business models, participating entities, and possible interactions among them [13].

The successes and failures of the EMs restructuring process lead to continuous models and rules updates [1], [2]. Nowadays, wholesale EMs are finally fulfilling most of their goals, mainly in the developed countries. The reforms implemented provided the means to form larger markets at the regional/international level, growing to the continental level by coupling existing EMs. A notable example of such is the Price Coupling of Regions (PCR), a project of the European Union's (EU) Power Exchanges to promote a single price coupling solution determining the day-ahead electricity prices across Europe, considering the network capacity, expecting to improve efficiency, liquidity, and social welfare [14]–[16]. The growth of RES generation capacity increased the importance of intraday markets in keeping the power systems balance between the day-ahead and the time of operation. Thus, the European Commission (EC) established the Single Intraday Coupling (SIDC) to create a pan-European cross-zone intraday market, aiming to increase the overall efficiency of intraday trading [17].

The common goal of decarbonizing the energy system creates new opportunities and poses new challenges for market participants. On the other hand, technological developments allow new forms of consumer participation and cross-border cooperation. In this way, this new directive adapts the Union's market rules to the current market reality.

In addition to responding to new challenges, this directive also aims to find solutions to overcome the remaining obstacles to the effective and efficient implementation of the internal electricity market, fostering new business models that are significantly different from those currently being used and supported by the existing regulatory framework. These policies and the incentives provided by the EU resulted in significant investments in RES equipment and renewable-based generation. However, the increased penetration of RES adds complexity to the power systems due to their intrinsic intermittency since most RES depend on natural sources such as the sun or wind. These constraints limit not only electricity generation but also its use. The unpredictability of renewable generation hardens the system balancing bringing new challenges to the sector [10], which brought the need to evolve PES, making them more flexible, intelligent, and sustainable [18]. Consequently, EMs are constantly adapting to new realities and new models and rules are continuously being developed to meet the new policies.

Additionally, the EU also incentivizes the formation of energy communities to trade electrical energy among them by using RES along with information and communication technology (ICT) [6]. In this context, the final customer can choose its electricity supplier at any moment and the type of energy (i.e., green versus brown) he/she is buying. Further, the end customer can become a prosumer, participate in the energy community trading, and use its generation for self-consumption selling its surplus in a seamless way. In addition to enabling small-scale players to trade electricity, community markets promote local balance, reduce the cost of electricity bills, incentivize investment in RES, and support a self-sustained energy community [19], [20]. At the same time, the distributed generation (DG) provided by these players plays a significant role in the power grids' energy management [21]. In this context, smart grids (SGs) quickly evolved from a widely accepted concept among the involved parties to an industrial reality [22]–[24]. An SG is an electrical distribution network with DG of RES using ICT to make the system more energy-efficient, economical, reliable, and sustainable. Although some pioneer countries provided their experience and guidance regarding the performance of the implemented models, it is still precocious to draw definitive conclusions [13], [25], [26].

The challenges brought by all these changes in PES reinforce the need to study, experiment, and validate the operations of such a complex, dynamic, and competitive environment, highlighting the importance of simulation and decision support tools. The need for understanding the sector's unpredictability and complexity, the mechanisms of new business models, the involved entities, how they interact, and how these synergies influence the results of these players stimulated the development and use of simulation and decision support tools [27], [28]. On one hand, regulators and operators must test and validate new and alternative rules and models to detect any fault or inefficiency before being deployed in practice while ensuring transparency and competitiveness. On the other, participating players are very interested in foreseeing and understand the market's behavior to act accordingly to maximize the outcomes of their participation by maximizing profits and minimizing costs [11], [29]. Thus, these tools must handle the constantly evolving reality of the PES sector, assuring the proper means and solutions for the actors to adapt themselves to the new challenges, gaining experience to operate in this shifting regulatory, economic, and financial environment. Such a volatile environment, where regulations and models renew so fast, demands simulation and decision support tools capable of keeping up with its fast-paced changes. Furthermore, these tools must be flexible enough to allow their users to test and simulate different options, such as new players that may emerge, new business models, or hybrid approaches from existing models and rules. Thus, regulators may test and validate them before implementing them in the real world.

The distributed and independent nature of multi-agent systems (MAS) makes them suitable for modeling complex and dynamic interactions between heterogeneous competing or collaborating actors, such as the PES entities, including their policies, regulations, mechanisms, business models, and constraints [30], [31]. Besides, MAS also ease the inclusion of new models, market mechanisms, types of participants, types of interactions, and the decomposition of complicated problems into simpler modules [32]–[34]. Thus, MAS can cope with the rapid evolution of PES, providing its stakeholders and players with adequate tools to prepare themselves for the continuous development of the sector. Several reference tools emerged for the simulation, emulation, and study of various PES areas, such as the wholesale and retail EMs [28], [30], [33], [35], microgrid and SG operation [36]–[38], demand response (DR) programs [39], [40], building energy management [41], [42], among others. Examples of tools developed by the author's research team are: the Multi-Agent Simulator of Competitive Electricity Markets (MASCEM) [30], [43] for the simulation of wholesale and retail electricity markets; the Multi-Agent Smart Grid simulation Platform (MASGriP) [36], [38] for the simulation of microgrids and SGs environments and their players' interactions; the Adaptive Decision Support for Electricity Market Negotiations (AiD-EM) [28], [44] to support EM participating players in their negotiations; and, more recently, the Multi-Agent based Real-Time INfrastructure for Energy (MARTINE) [45], [46] for the real-time simulation and emulation of loads, resources, and infrastructures, providing connection to physical resources. All these relevant tools validate the suitability and value of agent-based simulators and decision-support systems in the scope of PES.

Despite the meaningful advances made in PES simulation and decision support, most of the developed tools only focus and solve specific problems of an area or sub-area of the PES domain. Using them individually fails to capture the authenticity and accuracy required for the simulation and study of the energy sector since PES subdomains have a significant impact on each other, influencing the results [47]. One of the main challenges in this sector is the development of simulation, decision-support, operation, and management tools to address the problem as a whole. In this scope, existing systems could benefit from the integration of different models and platforms, sharing knowledge among each other and allowing agents from heterogeneous tools to participate in the same environment, learning from each other's experience. The lack of interoperability amongst heterogeneous MAS highlights a generalized limitation of agent-based tools in the scope of PES. Such interoperability strongly improves PES studies, from EM to the end consumer, considering all the relevant existing business models and stakeholders' interactions, providing a solution capable of addressing the PES complex and evolving reality globally. Thus, providing players with proper tools to adapt themselves to this dynamic reality and learn from experience. This is especially relevant considering the introduction of new players, operators, and regulations in the local EM paradigm in the frame of SGs. Such interoperable tools would improve PES studies and development by allowing joint and hybrid simulations of distinct models and more complex scenarios.

Interoperability between heterogeneous systems demands communication skills to understand and communicate effectively to cooperate or compete towards a common goal. Additionally, for the communications to be productive, these tools must share a common and previously agreed vocabulary and syntax. Otherwise, these systems will be communicating meaninglessly and getting nowhere. Regarding MAS interoperability, the Foundation for Intelligent Physical Agents (FIPA) [48], "*an IEEE Computer Society standards organization that promotes agent-based technology and the interoperability of its standards with other technologies*", defines a set of methods to promote inter-agent communication. These include a communication language [49], communicative acts [50], content languages [51], and message transport protocols [52], [53]. Using these standards, agents from different platforms can communicate. However, they will only be exchanging useful information if they use the same vocabulary. The FIPA's agent communication model assumes that interacting agents share a common ontology (vocabulary) and communication language (syntax) for the dialogue's domain, i.e., for the content of the messages. Additionally, agents should also be able to communicate using different ontologies translatable to each other. Further, FIPA leaves on the developer's side the decision of using explicit ontologies (made available to the agents' community) or implicit (encoded in the agent's implementation) [54]. Additional details about FIPA's ontology service specification are publicly available at [54].

There are several solutions in the literature addressing interoperability between heterogeneous tools in the frame of PES. Some works propose and develop co-simulation tools [55]–[58] working as middleware translating data from a system's model to the next and managing the simulation timeline, the inputs, and outputs of each tool. This approach has the advantage of being able to interoperate with any software if the developer using the co-simulation tool is aware of the communication protocols and input and output models. On the downside, the workload is all on the developer's side as, for each simulation scenario, the co-simulation middleware must be (re)coded. The most common recommendation found in the literature is the use of well-known and well-established standard data models for data interchange between heterogeneous systems [42], [59], [60], implying that all developers must comply with the same PES standards. However, this solution faces several difficulties hardening its global acceptance and industrial deployment, such as i) most of these standards are not open access and must be paid (e.g., the International Electrotechnical

Commission (IEC) standards such as the Common Information Model (CIM) [61]); ii) private companies often prefer to keep interoperability closed within their tools; iii) there is a generalized difficulty of interpreting the standards due to overextended documentation, or lack of proper explanation, and multiple interpretations may occur; iv) most standards are designed by, and for, a specific group of technicians or domain experts which also hardens the correct interpretation of the data model and respective documentation by non-experts; v) the provided representation languages (or syntaxes) may also be an obstacle since translations between different syntaxes are not always straightforward, also leading to misinterpretations (e.g., when translating from the Extensible Markup Language (XML) to the JavaScript Object Notation (JSON), the elements' attributes are converted to JSON properties, and each developer must determine how to differentiate the XML attributes in the JSON representation to be possible to roll back the translation); to name a few.

Recently, an alternative solution is being explored and addressed to solve interoperability issues between heterogeneous tools and is gaining impact in the literature, proposing the use of ontologies for semantic interoperability [62]–[64]. The term ontology is borrowed from metaphysics, a branch of philosophy, and intends to describe things and beings in the world. In artificial intelligence (AI) and computer science, the most widely accepted definition is: "*An ontology is a formal, explicit specification of a shared conceptualization*" [65]. "*Formal*" implies the ontology is machine-readable, understandable, and processable, which excludes natural languages. "*Explicit*" means that ontology concepts, relations, and constraints are explicitly defined and interrelated. "*Shared*" denotes consensual knowledge accepted by a group of people and not by an individual only. "*Conceptualization*" refers to the abstract model of some domain or phenomenon, i.e., the relevant concepts and relations among them. In other words, ontologies provide semantic meaning to data, making them interpretable by both humans and machines. Their meaning is shared by the various actors that use the ontologies, thus contributing to knowledge sharing and reuse. Additionally, ontologies also provide computational inference by employing a reasoner, generating new knowledge from the existing information [66]. Although the promises of ontologies are broad and seem to fit MAS well, some drawbacks keep most agent-based developers away from using them. Ontologies have a life cycle, and their development is an iterative process requiring revision, maintenance, and evaluation throughout their whole life cycle [66], [67]. Thus, it implies a high development cost due to the necessary time and human expertise.

There is a clear need for more realistic and precise study and management tools in the scope of PES. To this end, such systems should interact with each other, making it possible to study more complex and complete study scenarios instead of using each tool separately. As the various PES subdomains significantly impact each other, the achieved results would be more reliable. Besides, it would be possible to address studies globally, addressing the problem as a whole. The lack of interoperable agent-based tools in the frame of PES must be tackled to improve studies and research in the field. The integration of different platforms sharing their models and knowledge considering all the relevant existing business models and stakeholders' interactions benefits regulators and players with adequate tools to adapt themselves and learn from experience. Concerning the dynamic and quick-evolving reality of the sector, these tools could also gain from being more flexible and adaptable to new paradigms, i.e., new models, regulations, business models, and involved entities. These systems should provide the means to simulate, study, and validate non-existent or hybrid approaches from the existing ones so that regulators and operators can test and certify they fit the sector's reality. This way, these platforms would keep up with the fast pace of PES. This is especially important regarding the new actors and regulations emerging in the scope of SGs and local EM communities. Such interoperable and adaptable agent-based platforms would improve not only studies but also the development of PES. Thereby, they would warrant proper solutions for the several entities to achieve experience to operate the challenges posed by the PES complex regulatory, economic, and financial environment.

1.2 Objectives

The limitations identified in the current state of the art point out the lack of adequate tools to study and manage the complexity of the PES with authenticity and accuracy, considering not only a specific problem but addressing the overall problem. Such a gap uncovers research challenges that bring out the need for interoperable platforms providing all interested parties with adequate tools to prepare themselves to address the complexity and evolving reality of PES. Taking advantage of the models and knowledge shared between these systems significantly improves the sector's development, validation, studies, and management, considering more complex and inclusive scenarios from which the various stakeholders and players could leverage. Thus, it is essential to provide interoperability between existing heterogeneous PES tools while keeping them open to interoperate with new platforms that may arise. The significant breakthroughs necessary to solve the interoperability gap among PES tools establish the main research question of this Ph.D. thesis:

Can ontologies effectively contribute to the increase of interoperability between heterogeneous agent-based models, directed to the study and management of power and energy systems and their components, thus making it possible to address the problem as a whole?

To answer this question requires dividing the problem into smaller and more specific topics, leading to the following focused research questions:

1. *How can heterogeneous data models from different sources be translated and represented in a common vocabulary?*
2. *How can ontologies facilitate interoperability between heterogeneous tools to take advantage of each system's capabilities and knowledge sharing?*
3. *How can a multi-agent systems society provide a flexible, intuitive, and complete framework for the study and management of power and energy systems?*
4. *Can the multi-agent systems society be tested and validated in realistic conditions, combining real-time and simulated data in both laboratory and real-world environments?*

The research work carried out within the scope of this Ph.D. work focuses on answering the aforementioned specific questions to confirm the thesis that ontologies can effectively contribute to increasing agent-based interoperability easing to address the PES problems globally. Thus, providing more realistic and reliable simulation, decision support, operation, and management platforms taking advantage of existing MAS' knowledge and models while paving the way to include new tools that may arise.

The main outcome expected of this Ph.D. work is a society of MAS aimed at the simulation, study, operation, and management of PES, taking advantage of existing simulation and decision support tools [30], [40], [68], and complementing it with new tools to be developed, ensuring interoperability between them. Additionally, it contemplates the (re)use and development of ontologies to accomplish interoperability between the various systems and for knowledge representation in a common vocabulary. The ontologies must describe the necessary and sufficient concepts, relations and constraints of the various involved fields from the electricity generation to transmission, EMs, electricity distribution, SGs, energy resources management, buildings' efficiency, involved actors, including the business and algorithms' data models. Furthermore, the ontologies must ease the inclusion of new metadata, as needed, for new research fields that may come into the MAS society with the incorporation of new tools in the future.

It considers the use of data acquired in real-time or from historical databases for studies as realistic as possible. The MAS can collect data from several online or onsite sources through physical infrastructures, such as websites, web services, smart devices, programmable logic controllers (PLCs), measurements campaigns, databases, input files, simulated data, etc. Moreover, data must be translated and standardized respecting a semantic base according to the vocabulary defined by the ontologies.

The new systems to develop include distributed decision support services for SG participants, providing previously developed scheduling and forecasting algorithms [69]–[71] for the management of energy resources of SGs and buildings. These will be integrated into this MAS society to facilitate access to these tools by agents of different natures. Besides the decision support services, it is also considered the development of a devices' control system, which should be flexible and configurable, allowing parallel simulations of different scenarios, considering connections to distinct controllers simultaneously. It must enable devices' data readings in real-time, including sensors' data and load consumption/generation, and act in the loads, namely in DR events [72].

Using the publicly available ontologies, external systems can participate in the simulations of the MAS society. The society of MAS must have the flexibility to communicate in different existing resource description framework[1] (RDF) languages. In this way, external systems can use the RDF language that best suits them. It is also considered the development of an agent-based tool for the control

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[1] RDF is a standard for data interchange used for representing highly interconnected data in expressions of the form subject–predicate–object, known as triples. The most used serializations of RDF include XML, JSON, JSON for Linked Data (JSON-LD), and Turtle syntaxes. https://www.w3.org/RDF/.

and simulation of the MAS society to ease the user's interaction with the system. This tool aims to facilitate the simulation of the various systems/algorithms independently, the joint simulation of some or all systems present in the agent society, and the automatic analysis/comparison of the results whenever it makes sense.

The results and conclusions of this Ph.D. work must be validated and supported by experimentation based on realistic scenarios deployed in both laboratory and real (pilot) environments. The laboratory allows verifying the correct functioning of the system in a controlled environment using real and simulated data. The pilot enables the validation of the solution in real-world settings using the facilities and physical infrastructures of the Research Group on Intelligent Engineering and Computing for Advanced Innovation and Development (GECAD), the hosting research group. In this way, the obtained results can be confirmed under realistic conditions, thus assuring the validation of the achieved solutions.

Considering the defined specifications, which guarantee the response to the introduced research questions, the following objectives are set, underlying the essential contributions:

1. **Electricity market and smart grid data models and sources**, regarding:
    a. The analysis of the main approaches in the design and development of simulation and decision support tools for electricity markets and smart grids considering the different models and data sources;
    b. The analysis of existing and publicly available ontologies for the semantic representation of the various models, identifying what can be reused and what must be included.
2. **Data acquisition and devices control including the incorporation of different data sources, through their semantic representation in a common vocabulary**, considering in particular:
    a. Online and on-site data sources;
    b. Data acquired in real-time or historical data (real/simulated) stored in databases, spreadsheets, comma-separated values (CSV) files, among others;
    c. Enable a flexible and configurable devices' control;

3. **Development of ontologies appropriate to the various models identified (business, actors, and algorithms) at the level of EMs, SGs, and consumer energy management, aiming at the interoperability between several heterogeneous systems;**
4. **Design and development of systems and services for agent support**, including:
    a. The development of new systems and services for the decision support of different SG players and the flexible and configurable active load control;
    b. The development of a semantic services catalog for the registration and search of web and agent based services;
5. **Design and development of a multi-agent society**, considering:
    a. The use of the ontologies developed for the semantic interoperability between different MAS, allowing:
        i. The integration and interoperability between existing MAS;
        ii. The agents' automatic adaption to different RDF languages;
    b. The use of real data, simulated and/or obtained in real-time, by the software agents;
    c. The design and development of a multi-agent tool for the control of the MAS society;
6. **Conception and experimentation of scenarios based on real and simulated data for the test and validation of the system in both laboratory and real environments.**

Each of these objectives will be explored in detail in chapter 2, identifying the published papers related to each contribution.

1.3 Outline and Main Contributions

The realization of the determined objectives and consequently the fulfillment of answers to the established research questions fully cover the aims defined in the Ph.D. scholarship (with reference SFRH/BD/118487/2016) in the scope of the "Ph.D. Studentships and Post-Doctoral Fellowships" program of Fundação para a Ciência e a Tecnologia (FCT - Foundation for Science and Technology). Moreover, the work developed in the frame of this thesis partially covers the objectives and results of various national and international R&D projects regarding business and data models, semantic interoperability, reasoning, and rule-based systems, with the participation or coordination of

GECAD, the hosting institution of this Ph.D. work and thesis development. The participation in such breakthrough projects provided innovative viewpoints which enriched the developed work. The respective projects are:

- PRECISE – Power and Energy Cyber-Physical Solutions with Explainable Semantic Learning, reference no. PTDC/EEI-EEE/6277/ 2020;
- TradeRES – New Markets Design & Models for 100% Renewable Power Systems. Funded by the European Union's Horizon 2020 research and innovation program under grant agreement 864276;
- MAS-Society - Multi-Agent Systems SemantiC Interoperability for simulation and dEcision supporT in complex energY systems, reference no. PTDC/EEI-EEE/28954/2017;
- CONTEST - Innovative CONsumer aggregation to improve demand response and Tariff design for Energy and Services Transactions, reference no. SAICT-POL/23575/2016;
- DOMINOES – Smart Distribution Grid: A Market Driven Approach for the Next Generation of Advanced Operation Models and Services, under the H2020 grant agreement no. 771066;
- DREAM-GO – Enabling Demand Response for short and real-time Efficient And Market Based smart Grid Operation – An intelligent and real-time simulation approach. Funded by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no. 641794;
- SIMOCE – Sistema Inteligente e seguro para a Monitorização e Otimização do Consumo Energético (Smart and Safe System for Monitoring and Optimizing Energy Consumption), reference no. NORTE-01-0247-FEDER-017690;
- GREEDi – Plataforma Inteligente e Segura para Gestão de Recursos Energéticos em Edifícios de Grande Dimensão (Smart and Secure Platform for Energy Resource Management in Large Buildings), reference no. P2020-33/SI/2015-17822;
- AVIGAE – Assistente Virtual Inteligente para a Gestão Ativa da Energia em Edifícios (Intelligent Virtual Assistant for Active Energy Management in Buildings), reference no. UID/EEA/00760/2013;

- M2MGrids – Smart M2M Grids – M2M Internet for dynamic M2M Information Business ecosystem, project no. 13011, funded by European Union's EUREKA – ITEA2;
- FUSE-IT – Future Unified System for Energy and Information Technology, project no. 13023, funded by European Union's EUREKA – ITEA2;
- SEAS – Smart Energy Aware Systems, project no. 12004, funded by European Union's EUREKA – ITEA2.

The work and the findings accomplished during the development of this Ph.D. thesis resulted in the publication of a total of nineteen scientific papers. From these, ten papers were presented and published in the proceedings of top-level conferences in the fields of MAS, PES, and AI; one book chapter was published in a book dedicated to the related areas; and eight articles were published in JCR[2]-indexed journals with high impact factors. Four of these journal articles and three papers from conference proceedings published as book chapters cover the objectives proposed, which answer the research questions, composing the core of this Ph.D. work. The core publications are available in Appendix A. Core Publications, and chapter 2 discusses the main contributions towards fulfilling the objectives settled for this thesis. The seven core publications are the following:

I. Gabriel Santos, Zita Vale, Pedro Faria, Luis Gomes, "BRICKS: Building's reasoning for intelligent control knowledge-based system", Sustainable Cities and Society, vol. 52, no. 101832, pp. 1-15, January 2020, DOI: 10.1016/j.scs.2019.101832. (2020 Impact Factor: **7.587**) [73];
II. Brígida Teixeira, Gabriel Santos, Tiago Pinto, Zita Vale, Juan M. Corchado, "Application Ontology for Multi-Agent and Web-Services' Co-Simulation in Power and Energy Systems", IEEE Access, vol. 8, pp. 81129-81141, April 2020, DOI: 10.1109/ACCESS.2020.2991010. (2020 Impact Factor: **3.367**) [74];
III. Gabriel Santos, Pedro Faria, Zita Vale, Tiago Pinto, Juan M. Corchado, "Constrained Generation Bids in Local Electricity

[2] Journal Citation Reports (JCR): https://jcr.clarivate.com.

Markets: A Semantic Approach", Energies, vol. 13(15), no. 3990, pp. 1-27, August 2020, DOI: 10.3390/en13153990. (2020 Impact Factor: **3.004**) [75];

IV. Gabriel Santos, Tiago Pinto, Zita Vale, Rui Carvalho, Brígida Teixeira, Carlos Ramos, "Upgrading BRICKS – The Context-Aware Semantic Rule-Based System for Intelligent Building Energy and Security Management", Energies, vol.14(15), no. 4541, pp. 1-14, July 2021, DOI: 10.3390/EN14154541. (2020 Impact Factor: **3.004**) [76];

V. Gabriel Santos, Tiago Pinto, Zita Vale, "Multi-agent Systems Society for Power and Energy Systems Simulation", in Davidsson P., Verhagen H. (eds) Multi-Agent-Based Simulation XIX. MABS 2018. Lecture Notes in Computer Science, 2019, vol 11463, pp. 126-137. Springer, Cham. DOI: 10.1007/978-3-030-22270-3_10. [77];

VI. Gabriel Santos, Alda Canito, Rui Carvalho, Tiago Pinto, Zita Vale, Goreti Marreiros, Juan M. Corchado, "Semantic Services Catalog for Multiagent Systems Society", in Frank Dignum, Juan Manuel Corchado, and Fernando De la Prieta (eds.) Advances in Practical Applications of Agents, Multi-Agent Systems, and Social Good. The PAAMS Collection, 2021, vol. 12946. Springer Cham. DOI: 10.1007/978-3-030-85739-4_19. [78];

VII. Gabriel Santos, Tiago Pinto, Zita Vale, Juan M. Corchado, "Semantic Interoperability for Multiagent Simulation and Decision Support in Power Systems", in Fernando De la Prieta, Alia El Bolock, Dalila Durães, João Carneiro, Fernando Lopes, and Vicente Julián (eds.) Highlights in Practical Applications of Agents, Multi-Agent Systems, and Social Good. The PAAMS Collection, 2021, vol. 12946. Springer Cham. DOI: 10.1007/978-3-030-85710-3_18. [79].

Additionally, there are two articles submitted to international journals for publication with publicly available preprints, complementing and reinforcing the accomplishment of the proposed objectives. These papers are made available in Appendix B. Preprint Publications. The two preprint publications are:

I. Gabriel Santos, Luis Gomes, Tiago Pinto, Pedro Faria, Zita Vale, "MARTINE's real-time local market simulation with a semantically interoperable society of multi-agent systems", Research Gate, Preprint, August 2021, [Accessed: 26-Aug-2021], DOI: 10.13140/RG.2.2.22220.33921/1. [80];

II. Gabriel Santos, Hugo Morais, Tiago Pinto, Zita Vale, "Intelligent Energy Systems Ontology to support markets and power systems co-simulation interoperability", Research Gate, Preprint, September 2021, [Accessed: 24-Sep-2021], DOI: 10.13140/RG.2.2.20472.16644. [81].

The combined contributions provided by the work developed in the scope of this Ph.D. thesis presently result in an enhanced MAS society. The MAS Society is introduced in paper V [77] and presented as a whole in paper VII [79], preprint I [80], and preprint II [81], being also addressed in article VI [78]. It integrates heterogeneous agent-based tools with web-based services to provide a simulation, decision support, operation, and intelligent management framework in the scope of the PES for validation, test, and study of the various areas of this sector. The interoperability between the several agent-based tools is realized through ontologies for semantic communications and knowledge representation in a common vocabulary (confirmed by all publications, being given special focus in preprint II [81]). Furthermore, using ontologies and semantic web technologies enables developing systems agnostic to the data models and business rules, as demonstrated in the published articles I [73], III [75], and in preprints I [80] and II [81]. Another feature of the MAS Society is the possibility to embed real-time data and historical data in the same simulation environment. Depending on the user configuration, tools can collect data from databases or directly from devices through the infrastructure installed in the host institution building. At the same time, systems can also control smart appliances or devices connected to a PLC. Publications I [73], IV [76], V [77], VII [79], and preprint I [80] demonstrate such features

Finally, an agent-based tool was developed to ease the user's interaction with the configuration and control of the simulations of the MAS Society (Core publication II [74], and extra papers [82], [83]). Additionally, a catalog of semantically described services has been developed (see articles VI [78], VII [79], preprint I [80], and extra paper [84]) to alleviate the agents' configuration burden at each simulation. Agents from heterogeneous platforms can only communicate with each other if properly configured. This web-based service also provides a centralized platform where agents can search for a specific service provider (such as an agent or web service) and get the necessary information for an automatic connection to the selected service. Figure 1.1 illustrates the architecture of the resultant MAS Society framework.

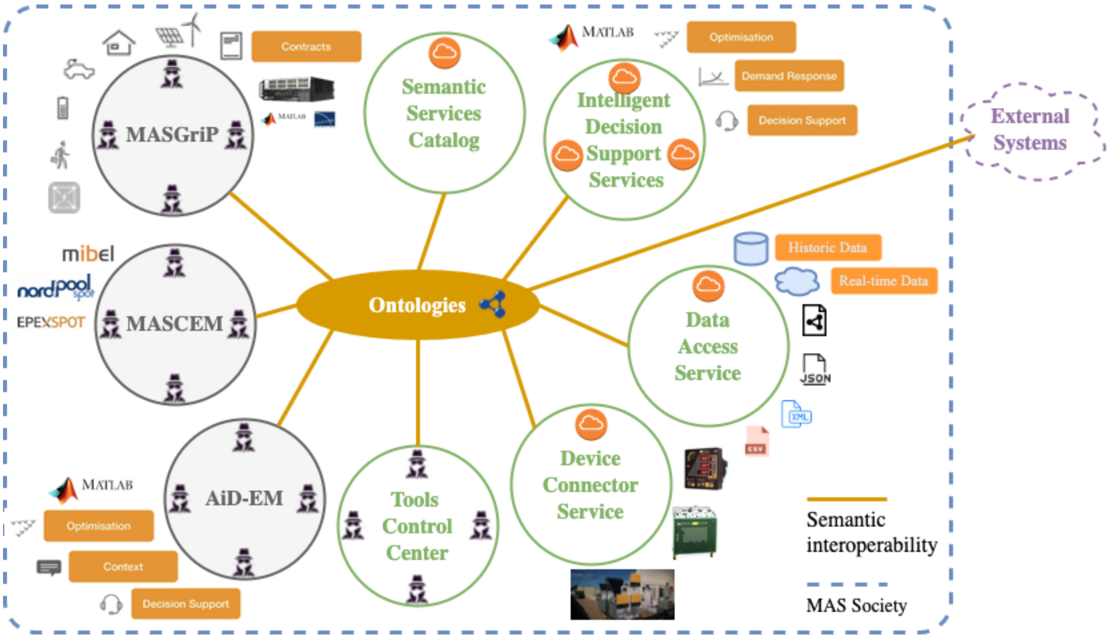

Figure 1.1. MAS Society framework architecture [79].

Represented in grey on the left side of Figure 1.1 are heterogeneous MAS previously developed in the author's research institution (mentioned in section 1.1). Each tool has been developed for the simulation and decision support of a specific area of the PES. MASCEM [26], [39] is a modeling and simulation tool for the study of the competitive EMs. It allows the simulation models of three European day-ahead EMs, namely EPEX [85], MIBEL [86], and Nord Pool [87], and the intraday market of MIBEL [88], considering the constraints and complex conditions of each of these wholesale markets. It also enables bilateral contracts negotiations, including ancillary services, forward contracts, and futures. MASCEM agents represent the main entities of the sector, from the market and system operators to the buyer and seller agents.

To support EM players' negotiations arises AiD-EM [28], [44], a MAS providing decision support to MASCEM players. AiD-EM itself can be seen as a society of MAS as it is composed of a couple of MAS for different types of negotiations, namely the Adaptive Learning strategic Bidding System (ALBidS) [31] for auction-based biddings and the Decision Support for Energy Contracts Negotiation (DECON) [89] for bilateral negotiations. Each system makes use of different AI methodologies to provide players adaptation in the planning and negotiation phases. MASGriP [36], [38] models and simulates relevant entities as software agents at the level of microgrid and SG, considering different types of aggregators, energy resources, consumers, producers, prosumers, to name a few.

Agents can be fully simulated or connected to physical resources for automatic control, providing complex alternatives in realistic settings.

In turn, the newly developed systems are represented in green. The Semantic Services Catalog (SSC) (see papers VI [78], [84], and subsection 2.4.2) provides a common ground for services registration and search. Registered services may be web or agent-based services. It aims to overcome the complexity of manual configurations of heterogeneous agent platforms to communicate with each other and with web services. Using SSC, service providers (agent or web-based) can register their services, describing their capabilities and how to reach them. And client agents can search for a specific service or type of service, receiving all the necessary data for an automatic connection configuration. This way, if any required service is not available, the user is notified instead of occurring a system crash.

The Intelligent Decision Support (IDeS) services (see paper VII [79], preprint I [80], and subsection 2.4.1) are configurable and distributed web services providing intelligent and decision-support algorithms to the MAS Society. These services are registered on SSC to be searched and used by the participating agents. The Data Access Service (DAS), in turn, provides historical and real-time data to the MAS society (see paper VII [79], preprint I [80], and subsection 2.2.1). Data is made available according to the ontologies of the MAS society and following the linked data best practices[3]. Alternatively, the JSON format is also available for non-semantic tools. The Device Connector Service (Dev-C) supplies agents with connections to physical devices (see papers I [73], IV [76], V [77], VII [79], preprint I [80], and subsection 2.2.2). It enables raw data readings from real hardware and their control to test real-world scenarios and apply the results to devices accordingly.

Finally, the Tools Control Center (TOOCC) is the interface between the user and the MAS Society (see papers II [74], V [77], VII [79], and subsection 2.4.4). TOOCC uses SSC to identify the available tools for simulation at each moment. The user may decide which systems to use in the simulation, the execution order of composite services defining the mappings between the output of the former service and the input of the next, to simulate different scenarios simultaneously,

[3] W3C Best Practices for Publishing Linked Data: https://www.w3.org/TR/ld-bp/.

and automatically analyze and compare the results. Realistic simulation scenarios have been used to test and validate the MAS Society at different levels (see core papers I [73], II [74], III [75], IV [76], V [77], VI [78], preprints I [80], II [81], and section 2.5). External systems can also participate in MAS Society simulation using the publicly available ontologies to communicate with the different MAS and SSC to discover the accessible services and respective tools.

1.4 Document Structure

This thesis document consists of three chapters. This introductory chapter exposed the motivation for developing this Ph.D. thesis and a background overview of the most relevant topics related to this work, the research questions and the respective objectives, and the outline and a summary of the main contributions.

Chapter 2 details the most relevant contributions of this thesis, describing the research questions and discussing how each core paper addresses these questions fulfilling the determined objectives. The chapter is organized by the key contributions of this Ph.D. work, where each subsection addresses a specific topic related to a research question.

Finally, chapter 3, presents the most relevant conclusions and findings achieved from the developed work. Additionally, this chapter reveals perspectives of future research paths to be explored.

Chapter 2

Contributions

2 Contributions

This chapter presents the main contributions of the work developed within this Ph.D. thesis discussing how each core paper addresses the respective research questions. It also describes the realization of the objectives delineated as result of the several key contributions.

2.1 Introduction

There are several agent-based tools developed in the scope of PES directed to solve specific problems of the field. Although being very important contributions, these tools by themselves are still limited and unable to surpass the lack of management and decision-support solutions in the PES field. To this end, systems' interoperability is mandatory to take advantage of existing and well-established tools in their particular domains to accomplish more complex tasks in an efficient and secure way. The current literature gap regarding interoperability among heterogeneous tools in the scope of PES has led to the research questions presented in section 1.2 and, consequently, have determined the objectives of this Ph.D. work.

The development of ontologies for semantic interoperability to achieve an interoperable society of MAS, as a result of this Ph.D. thesis, provides a significant breakthrough to overcome existing limitations of current PES solutions, while taking advantage of existing simulation, decision support, and operation platforms. Moreover, using the proposed and publicly available ontologies to (semantically) communicate within the MAS Society, external systems or newcomer tools that may arise can be included with minor effort. Additionally, the conducted research work proposes a novel approach to develop software that uses ontologies for knowledge representation given the volatility of a domain's information, such as the PES domain. The findings realized in the development of this Ph.D. thesis answer the research questions identified as prominent to the progress of the current state of the art, contributing to its advance.

Table 2.1 presents the relation between the key contributions, the related objectives and research questions, and each paper that has resulted from this Ph.D. work. The publications I to VII are the core papers previously introduced in section 1.3. The "Other" column refers to additional scientific articles published in the scope of this Ph.D. thesis that provide additional details regarding the developed work, complementing the core publications. Likewise, the "Preprint" column concerns relevant papers supporting this Ph.D. thesis submitted to JCR journals (also introduced in section 1.3).

Table 2.1. Ph.D. thesis main contributions, related objectives, research questions, and publications.

Main Contribution	Related Objective	Research Question	Publication								Preprint	
			I	II	III	IV	V	VI	VII	Other	I	II
Data acquisition from heterogeneous sources and representation in a common vocabulary	1 & 2	1	X			X			X	[90], [91]	X	
Configurable devices control	1 & 2	1	X			X	X		X	[82], [83], [90], [92]	X	
Ontologies for semantic interoperability	1 & 3	2	X	X	X	X	X	X	X	[82]–[84], [91]–[94]	X	X
Interoperable services for agents' support	1 & 4	3	X	X		X	X	X	X	[82], [83], [90], [92], [94]	X	
Catalog of semantically described services	1 & 4	3						X	X	[84], [95]	X	
Semantic reasoning for the validation of business constraints towards agnostic systems	1 & 5	3	X	X	X	X		X	X		X	X
Tool for the simulation and control of the MAS society	1 & 5	3		X			X		X	[82], [83], [91], [92], [94]	X	
MAS Society	1 & 5	3		X			X	X	X	[91]–[94]	X	X
Experimentation and validation	6	4	X	X	X	X	X	X	X	[92], [93], [95]–[97]	X	X

Analyzing Table 2.1, one can see that the core publications address multiple main contributions. Additionally, other publications and preprints that have resulted from this Ph.D. work, addressing specific topics on the related subject, complement and detail the information in the core publications. Each research question is related to one or more key contributions, and each of these contributions completely or partially fulfills an objective of the Ph.D. work.

The following sections describe each research question, its importance to the work developed, and detail how the produced papers address the Ph.D. work contributions that give answers to the research questions.

2.2 Data Acquisition and Devices Control

How can heterogeneous data models from different sources be translated and represented in a common vocabulary?

ICT has been used within PES for a long time by big producers, operators, and utilities. Supervisory Control and Data Acquisition (SCADA) systems and PLCs are some examples of systems and equipment that produce large amounts of data that need to be dealt with [98]. With the advent of the SGs, the introduction of RES, DG, smart meters, smart appliances, sensors, building energy management systems (BEMSs), DR, local EMs, new players, business models, and regulations, the amount of data produced within the sector is enormously increased. The more the data, the more information is available, and with it should come relevant knowledge. However, to take full advantage of this knowledge, it is essential that it can be usable by software tools, so that it can be processed automatically [99]. Unfortunately, data from different sources come under distinct representations and formats depending on the companies that have developed the hardware and software, which hardens their reuse by heterogeneous systems. Moreover, most knowledge comes implicit in data and should be explicit in order to be helpful and usable by management, study, and decision-making platforms.

Nowadays, buildings are key elements of SGs and have huge potential to deliver flexibility through the use of various DR schemes [100], [101]. BEMSs should provide an automated response to DR events to improve the building's energy efficiency [102], [103]. The industry made available various solutions for energy management in buildings [72], [104] with different technologies, protocols, and standards. However, these solutions usually focus on one particular aspect of energy efficiency, such as heating, ventilating, and air conditioning (HVAC) systems, lighting, smart appliances, to name a few. With different solutions to address different energy aspects of the building, there is a great variety of data from heterogeneous sources differently represented and dispersed. The fact that these systems cannot interact in a seamless way hardens the building's energy efficiency management. This highlights the need for a system capable of aggregating data from different sources, taking advantage of the gathered knowledge to control several assets intelligently, automatically respond to DR events and notify the user about unexpected events while considering the current context and the user's comfort and preferences.

2.2.1 Data acquisition from heterogeneous sources and representation in a common vocabulary

The use of real data is of utmost importance for the development of adequate models and software tools for the study, decision support, operation, and management of PES. Both real-time and historical data enable knowledge extraction, the definition of realistic scenarios and the consequent achievement of relevant results. On the other hand, simulated data also plays a significant role in testing and validating implemented models. Such relevant PES-related data is made available from numerous sources in many forms and formats.

In the scope of this work, data must be gathered and represented homogeneously independently of its origin, so that it may be valuable for the interoperability of the agent-based tools, i.e., data must be meaningful, which leads to the need for turning raw data into knowledge [91]. Moreover, homogenizing data using the same vocabulary eases its interpretation and knowledge extraction. A diversity of data sources is considered in this work, namely the use of databases, stylesheets, structured text files (such as CSV, XML, or JSON), web repositories, and real-time readings from smart devices and PLCs, available at GECAD's living lab building infrastructure.

Paper I [73] proposes a context-aware semantic rule-based system for the intelligent management of buildings' energy and security named BRICKS (Building's Reasoning for Intelligent Control Knowledge-based System). It uses ontologies and semantic web technologies to convert the raw data from PLCs, devices, and structured data from web services or databases into a uniform semantic model to perform building monitoring and apply rules to trigger alarms, notifications, and automated control. It can also integrate SCADA systems and smart appliances using Modbus TCP/IP[4] and HTTP REST[5] protocols. Additionally, BRICKS uses external web services for different purposes, namely, to get weather data, the context-based profiles (introduced in [90]) of each asset in each moment, among others, converting these data to ontology instances. Figure 2.1 illustrates the translation of raw data into the semantic model.

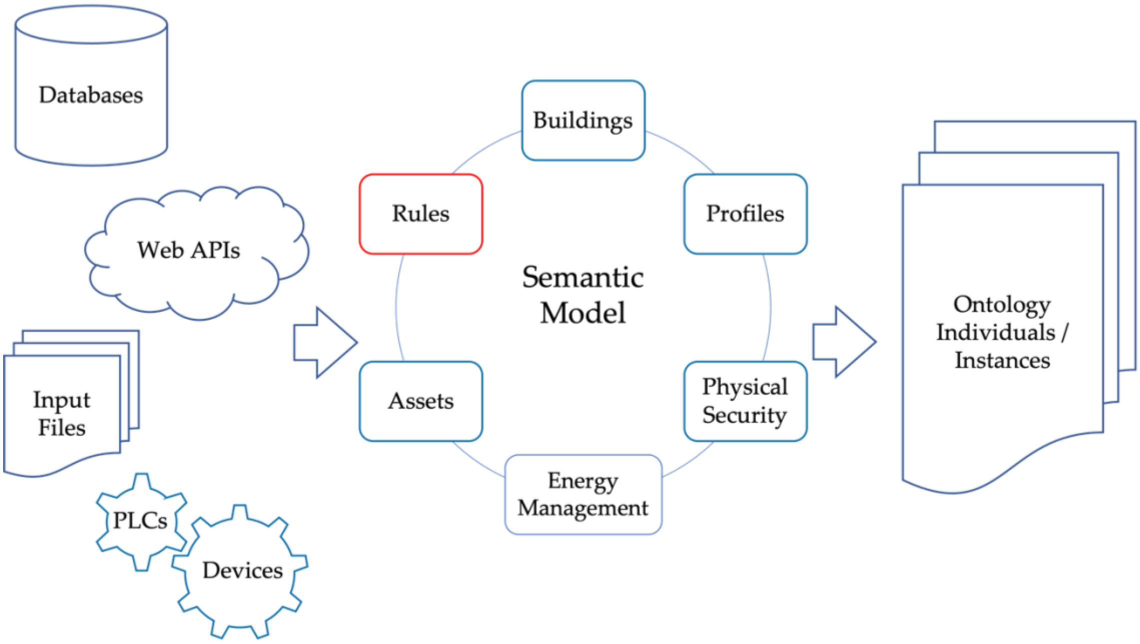

Figure 2.1. BRICKS data translation to the semantic model [73].

BRICKS is a flexible and configurable system agnostic to the ontologies and semantic rules used to avoid reprogramming the system every time a new device is installed in a building. Focusing on the measurements and data conversion to the semantic model, the used ontologies represent all the necessary knowledge to connect to each device using its Modbus or REST configuration and to assert the measurement of each reading. Using this information, BRICKS queries its knowledge base (KB) to get each device's configuration and collects measurements at a user-defined timestep. After, BRICKS uses a SPARQL Protocol and RDF Query Language (SPARQL)[6] Construct template to replace the tags of the template with the values of the readings accordingly. To this end,

[4] http://www.modbus.org/.
[5] https://www.w3.org/TR/2004/NOTE-ws-arch-20040211/#relwwwrest.
[6] SPARQL is a recursive acronym of a set of specifications to query and manipulate RDF graphs. https://www.w3.org/TR/sparql11-overview/.

BRICKS uses a JSON configuration with the mappings between each tag and the respective device's measurement. Paper IV [76] upgrades BRICKS by adding new modules and services for DR contracts, aggregation, and execution; autonomous interaction between BRICKS instances of aggregators and clients; facilitated semantic configuration of the building and assets; improved monitoring and control web interface; among others.

Based on the work developed in regard to BRICKS, the next step was to design and develop a service to make data available to the various agent-based systems of the MAS society. Paper VII [79] introduces and preprint I [80] further describes the Data Access Service (DAS), a service providing (near) real-time and historical data to the MAS society. It gathers data from heterogeneous sources to provide data in a common vocabulary, represented according to the developed ontologies (described in section 2.3). Data sources include databases, real-time readings from devices through the infrastructure installed at GECAD's research lab and from smart appliances, web dataset repositories, stylesheets, and CSV, XML, JSON, and RDF files. DAS gathers the collected data in local databases developed for different purposes. The system's administrator must configure the mappings between the models of each data source and the database. The real-time readings occur at a predefined time step, while data from the remaining sources are collected by demand. Gathering data in databases eases the conversion process from raw to semantic data.

Using the same approach as in BRICKS, a SPARQL Construct template and a JSON file with the mappings between the database queries results and the tags of the SPARQL template allow generating and providing semantic data to the agents of the MAS Society on demand. Thus, using simple REST requests, agents get semantically represented data respecting the linked data principles according to the ontologies of the MAS society. This way, agents can use meaningful data directly without the need to translate it to RDF. However, by default, the DAS supplies data in JSON for the algorithms made available as REST web services or other platforms without the ability to interpret semantic data. To get data semantically represented, agents of the MAS Society use the "Content-Type" parameter of HTTP requests to define the RDF language to receive the linked data. If DAS does not recognize the specified content type, it retrieves data in JSON format.

The main resulting contribution is DAS, a web-based service to provide agents of the MAS Society with real-time and historical data semantically represented in a common vocabulary, i.e., the ontologies used within the MAS community. Data can be retrieved in both RDF, using linked data principles, or in JSON for the input of algorithms. This contribution fulfills objectives 2.a and 2.b, answering the research question considered in this section.

2.2.2 Configurable devices control

The agents' connection to physical resources is another relevant aspect to consider for the study and management of DR events, building's energy efficiency and security, users' comfort, among many other relevant aspects. Thus, this work has provided agents of the MAS Society with a flexible and configurable tool to take the maximum advantage of the available infrastructures and installed devices. The first step taken in this direction was developing the Programmable Logic Controller Multi-Agent System (PLCMAS) introduced in paper V [77] (see also [82], [83], [92]). PLCMAS serves external agents with connections to PLCs using Modbus protocol, thus, providing agents the real-time measurements and control over the physical devices (e.g., lights, sockets, HVAC) connected to the PLCs.

PLCMAS is a semantically interoperable MAS. Its client agents use PLCMAS' publicly available ontology[7] to request its Main Agent for a PLC Agent. The Main Agent responds with success if it can create the PLC Agent or with a failure message otherwise. When created successfully, the PLC Agent requests the client agent for the PLC configuration. After receiving it, the PLC agent connects to the PLC, and if successful, it starts a thread to read the PLC registers at every user-defined timestep. From this point, client agents may request for a specific reading or all readings at once. Similarly, at the client's request, the PLC Agent controls a given device by writing the value sent by its client to the respective PLC register. Finally, in order to free up resources, client agents must send a shutdown request to the PLC Agent when it is no longer needed.

The main advantages of PLCMAS are the possibility to test and study scenarios using real infrastructures and to manage and apply results in the

[7] PLC Ontology: http://www.gecad.isep.ipp.pt/ontologies/ies/demos/plc.owl.

physical devices in real-time, making them act accordingly. Additionally, since each client agent is attributed a PLC Agent, PLCMAS allows the flexibility of several PLC Agents being connected to the same PLC using distinct registers to simulate multiple facilities with different resources in the same study. The main disadvantage is that it requires devices to be connected to a PLC using the Modbus protocol. Furthermore, having multiple agents communicating with the same PLC may cause concurrency problems that can disconnect them, leading to errors. Nowadays, there are more and more solutions available on the market and industry based on the Internet of Things (IoT) communicating using web-based protocols such as the Message Queuing Telemetry Transport (MQTT)[8], the Advanced Message Queuing Protocol (AMQP)[9], and the Open Platform Communications Unified Architecture (OPC UA) [105]. These solutions are better dealing with concurrency and security, freeing the developer from these concerns, hence they are also considered in the scope of the MAS Society.

Both MQTT and AMQP are protocols for asynchronous message queuing. The main difference between them is that MQTT uses a publish/subscribe model in a client/broker architecture and AMQP allows the use of a request/response model in addition to the previous, enabling more flexibility. Nevertheless, MQTT has the advantage of working on devices with limited bandwidth. BRICKS takes a step forward in this direction (see papers I [73] and IV [76]), where besides the Modbus protocol, it is also able to communicate using the REST protocol to read measurements, control smart appliances, and interact with external web services. The model implemented in BRICKS follows the client/server architecture using the request/response approach of AMQP. OPC UA, in turn, is pointed out as the most promising protocol to standardize communications in scopes such as Industry 4.0, IoT, or SGs [105]–[107]. It works as middleware on top of universal and established transport protocols, like Modbus [107]. However, its specification is not straightforward, resulting in incomplete implementations, hardening its use. The inclusion of OPC UA in BRICKS requires implementing an OPC UA server layer over Modbus TCP, an OPC UA client, and a semantic converter like the one developed for the Modbus protocol.

[8] MQTT Homepage: https://mqtt.org/.
[9] AMQP Homepage: https://www.amqp.org/.

Taking into account the advantages of PLCMAS and BRICKS, the different IoT communication protocols, and the benefits of having a service available for both software agents and services led to the development of a more flexible and configurable web-based solution for the control of physical resources within the MAS Society. The Device Connector Service (Dev-C) (see paper VII [79] and preprint I [80]) is the resultant service. It is responsible for providing connection and real-time control over physical devices to the MAS Society agents. Dev-C enables data readings in real-time or at a given timestep, depending on the configuration provided by the agent's request. Currently, Dev-C can connect to physical assets using Modbus protocol and REST-based requests such as AMQP and MQTT. However, it is open to implementing other protocols, e.g., others that may be considered interesting to be experimented at GECAD's laboratory building. This way, Dev-C connects to any smart appliance or dummy device connected to a PLC, enabling the test, study, and management of real-world environment scenarios, applying the results on the physical resources to make them act accordingly.

Dev-C is the main contribution of this segment of the Ph.D. work, providing the MAS Society agents with connection to physical devices for real-time energy management and simulation of realistic scenarios while keeping the agents apart from the devices' communication protocols. In this way, agent developers only need to focus on the command requests of each device so that they act accordingly. This contribution fulfills objective 2.c and partially accomplishes objective 4.a.

2.3 Ontologies for Semantic Interoperability

How can ontologies facilitate interoperability between heterogeneous tools to take advantage of each system's capabilities and knowledge sharing?

Considering the advantages and disadvantages of the main proposals found in the literature to address interoperability between heterogeneous systems, the solution proposed and developed in this Ph.D. work follows the last approach discussed in section 1.1, i.e., using ontologies for semantic interoperability. Ontologies ease heterogeneous MAS' interoperability by providing a common shared vocabulary for the correct interpretation of the exchanged messages, enabling effective communication without misunderstandings. The selection of this approach is not only based on accomplishing semantic interoperability but also on exploring the use of ontologies for knowledge representation and semantic reasoning towards achieving more intelligent and flexible tools, agnostic to the data model and business rules. The volatility and fast-paced evolution of PES require tools able to keep up with it. Therefore, systems must be able to update the different data and business models smoothly, avoiding as much as possible recoding (see subsection 2.4.3).

This Ph.D. work gathers and extends existing ontologies for the EM and SG domains to develop a shared semantic model for PES simulation, study, operation, and management. Nowadays, the literature offers various ontologies developed in the scope of PES, such as the ontologies addressed in [62], [108], [109] for the EM's domain, in [64], [110], [111] for the SG domain, and in [112]–[115] which aim to be cross-domain ontologies for the energy domain. Although developed for distinct subdomains, these semantic models encourage their reuse and extension in developing ontologies describing different PES fields and knowledge sources to achieve interoperability between heterogeneous agent-based tools in the PES domain. Considering the multiple systems involved in the MAS Society and the possibility of including new ones, the ontologies must evolve accordingly. Thus, this work aims to accomplish a multi-level modular ontology (see papers V [77], VII [79], preprints I [80], II [81], and auxiliary publications [83], [92], [94]), where top-level modules describe general domain concepts, attributes, and properties, which are transversal to some or several low-level modules. Low-level modules, in turn, import, extend and reuse concepts and relations of top-level modules to represent the application-level semantics of each agent-based tool. The domain ontology modules (see preprint II [81]) are publicly available and provide semantic interoperability within the MAS Society. The application ontology modules provide each semantic tool with knowledge representation, business constraints, and validation and inference rules to draw conclusions and extract new knowledge.

Paper V [77] (see also [82], [93]) proposes a set of ontologies for the interoperability between independent agent-based tools in the scope of EMs, SGs, and residential energy management. It presents the Electricity Markets Ontology (EMO)[10] [62] developed to provide MASCEM with semantic interoperability as

[10] Publicly available at: http://www.mascem.gecad.isep.ipp.pt/ontologies/.

well as the modules used and extended from the Smart Energy Aware Systems (SEAS)[11] [112] ontology to describe actors, infrastructures, and power systems. EMO is a modular ontology where the main module describes abstract concepts and hypotheses from the EM domain. The remaining modules extend EMO to specify the communications between the market operator and player agents, conceptualize the MIBEL, EPEX, and NordPool EM domains, and provide MASCEM players interoperability with AiD-EM. SEAS is also a modular ontology designed for semantic interoperability in PES, developed within the SEAS project ecosystem. The SEAS ecosystem involves IoT services and smart devices to guarantee power grid stability and efficiency. Besides interoperability, the ontology modules enable the knowledge representation in a common vocabulary, regardless of the data source.

Later, paper VII [79], preprint I [80], and the auxiliary publication [92] introduce the inclusion of the Smart Appliances Reference (SAREF)[12] [116] ontology for the smart appliances domain and the Intelligent Energy Systems (IES) ontologies[13] describing various optimization, scheduling, and forecasting algorithms available within the MAS Society, including also the PLC ontology.

SAREF ontology aims to facilitate the match of smart appliances assets by enabling interoperability among different IoT sectors and between solutions of heterogeneous providers, contributing to the advance of global digital markets. It gathers smart device semantics, including their functionalities and their sensing and control capabilities. Additionally, SAREF provides extensions for several domains, such as Energy, Building, Smart Cities, Industry and Manufacturing, and Agriculture, to name a few. IES ontologies, in turn, provide the means for semantically communicating with PLCMAS (see subsection 2.2.2) and with the Intelligent Decision Support Multi-Agent System (IDeSMAS) (see subsection 2.4.1).

The work developed in papers I [73] and IV [76] includes four application ontologies. The GREEDi ontology[14] references concepts from the SEAS, SAREF

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[11] Publicly available at: https://w3id.org/seas/.
[12] Version 2.1.1. Publicly available at: https://w3id.org/saref.
[13] Publicly available at: http://www.gecad.isep.ipp.pt/ontologies/ies/.
[14] Publicly available at: http://www.gecad.isep.ipp.pt/ieso/greedi.ttl.

(FIEMSER[15] module), and OWL Time[16] ontologies to describe buildings, devices, measurements, instants, and time intervals. BRICKS reuses the PLC ontology[17] for the knowledge representation of PLCs, including the connection configuration and the registers related to each building resource. The WebService ontology[18] describes knowledge related to the smart appliances' REST requests for measurement readings and devices control. Finally, the Context-based Rules Matching Profile ontology[19] defines abstract rules matching models based on contexts and respective profiles. It imports OWL Time ontology to represent the temporal concepts and relations. Developers must extend this ontology to define contexts and profiles properly for each rule. The context-based rules can be written in the Semantic Web Rule Language (SWRL)[20] or SPARQL, as proposed in paper I [73].

Paper II [74], on the other hand, presents TOOCC's application ontology. It aims to support the definition of the simulation scenarios, the results comparison, and ease the interoperability with external tools (see subsection 2.4.4). TOOCC's ontology describes the simulations' configuration model, including the input and output models of the systems to run. It allows reusing the output model of a tool to get the needed knowledge to feed the next platform, system, or algorithm to be executed. The automatic comparison of results is configured using the output models of different systems. Finally, TOOCC's ontology is agnostic to the data models of other tools since these can be both semantic (e.g., agent-based systems) or syntactic (e.g., web services). Paper III [75], in turn, introduces the Local Market Ontology (LMO)[21]. It describes the knowledge model of an ontology-based library for auction-based local EMs considering constrained bids, from the data to the business constraints. LMO extends the Call For Proposal (CFP)[22] and

[15] Homepage: https://sites.google.com/site/smartappliancesproject/ontologies/fiemser-ontology.
[16] Publicly available at: https://www.w3.org/TR/owl-time/.
[17] Publicly available at: http://www.gecad.isep.ipp.pt/ieso/plc.ttl.
[18] Publicly available at: http://www.gecad.isep.ipp.pt/ieso/ws.ttl.
[19] Publicly available at: http://www.gecad.isep.ipp.pt/ieso/crmp.ttl.
[20] https://www.w3.org/Submission/SWRL/.
[21] Publicly available at: http://www.gecad.isep.ipp.pt/mdpi/energies/845690/files/onto/local-market.ttl.
[22] Publicly available at: http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl.

Electricity Markets Results (EMR)[23] modules [117] of EMO to include concepts and rules related to the local EM. Preprint I [80] reuses LMO and the local market library proposed in paper III [75].

Paper VI [78] presents a semantic catalog, namely SSC, for the registration, search, composition, and invocation of web and agent-based services. SSC is the materialization of the architecture proposed in [84]. SSC is presented in detail in subsection 2.4.2 . The semantic layer added to describe services provides richer machine-readable descriptions, supporting interaction between agent-based tools and web services by explicitly exposing a service's capabilities, input, and output models, accepted syntaxes, and how to communicate with it. To this end, SSC uses OWL-S[24] [118] as the basis for the semantic description of services and two additional extensions proposed in [84] to detail services provided by software agents and REST services. The last extension is the RESTful Grounding ontology[25] introduced in [119], and the former is the Software Agent Ontology (SAO)[26] purposely developed by the author for SSC [84]. Contrarily to web services, for which there are standardized formats, such as Web Services Description Language (WSDL)[27] or Web Application Description Language (WADL)[28], there is no standardized format for software agents to expose their services. Although agent gateways are an option to publish an agent's service on the web, these might result in a bottleneck, being a potential point of failure [120]. Besides, agent gateways do not allow agents to move between machines if necessary and must be defined programmatically beforehand [121]. SAO is an abstract software agent ontology disclosing the required information to facilitate the automatic interaction with an agent-based service.

The recent advances in the literature regarding the development of ontologies related to PES, e.g., [113], [114], [122]–[124], and the needs found in

[23] Publicly available at: http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl.
[24] Publicly available at: https://www.w3.org/Submission/OWL-S/.
[25] Publicly available at: https://otaviofff.github.io/restful-grounding/.
[26] Publicly available at: http://www.gecad.isep.ipp.pt/epia/19/services/forecast/software-agent.ttl.
[27] W3C Recommendation: https://www.w3.org/TR/wsdl/.
[28] W3C Submission: https://www.w3.org/Submission/wadl/.

applying the developed ontologies to the MAS Society, led to the identification of some requirements for improvement as follows:

- The new version of the ontology must be modular and multi-level, having the domain modules at the top level and the application modules at the lower level;
- The domain modules must be publicly available, supporting the interoperability among agent-based tools of the MAS Society and between external systems and the agents of the MAS Society;
- The ontology must evolve according to the evolution of the PES and the needs of the MAS Society tools;
- The ontology must be transparent and clear, avoiding redundancy as much as possible, since some terminologies may be transversal to several modules;
- Ontology versioning must be assured to guarantee the possibility of using definitions of a specific version;
- The domain modules of the ontology must use the same ontology prefix to ease their use.

The best practices for ontology development encourage the reuse of ontologies to avoid reinventing the wheel and promote interoperability by sharing a common conceptualization [67]. To this end, the common practice is to import the semantic models to reuse to our ontology as a start point and extend it from there. However, this can reveal unpractical in some cases as it creates a high dependency between the developed ontology and the ones that are imported [125]. On the one hand, ontologies may change over time, and the extensions and relationships made may no longer make sense. Publicly available ontologies may also become unavailable without notice. Besides, when importing various ontologies from transversal domains, multiple definitions of the same concepts may occur and cause inconsistencies. Additionally, ontology reasoning with extensive models may cause the systems to crash due to out-of-memory issues. Thus, the consideration of these issues determined additional requirements:

- The ontology must be self-sufficient and do not depend on existing publicly available ontologies;

- Instead of importing ontologies directly, the ontology must reference the concepts and properties extended from external semantic models;
- The ontology should provide modules with mappings to external ontologies whenever it makes sense.

The Intelligent Energy Systems Ontology (IESO) (see preprint II [81]) describes domain concepts and relations, including business, market, infrastructure, and actor models. IESO aims to provide the means for semantic communications between heterogeneous agent-based systems, ease a homogeneous knowledge representation, and enable reasoning to validate constraints and business rules and extract new knowledge from the one already existing within the MAS Society. It gathers the domain knowledge required for semantic interoperability within the agents' community, leveraging from the knowledge representation of the previously developed ontologies and other publicly available and well-established vocabularies. IESO is extended, as needed, by the application ontology modules. Its development follows the 101 ontology development methodology [67]. This methodology is an iterative process where the ontology is continuously refined to the users' needs, fitting well the demands of the PES and MAS Society. After defining the domain and scope of each module, there was a detailed analysis of the previously developed ontologies and relevant publicly available ontologies in the literature to assess their potential for reuse or align for the semantic representation of the various models. IESO modules organization optimizes their use considering the current tools that are part of the MAS Society. It is publicly available[29] to ease their reuse and extension to interoperate with the agent-based platforms.

Following the SEAS ontology best practices example [112], IESO's core module imports the various domain modules. Each domain module has its version. The Internationalized Resource Identifiers (IRIs) of all modules use the same namespace, i.e., the IESO namespace, and the complete IESO ontology is accessible from its namespace IRI[30]. IESO is a Web Ontology Language (OWL) 2 Description Logic (DL) ontology as recommended by the World Wide Web

[29] Latest version publicly available at: https://www.gecad.isep.ipp.pt/ieso/.
[30] IESO's namespace IRI: https://www.gecad.isep.ipp.pt/ieso/v1.0.0/.

Consortium (W3C) [126]. The OWL 2 DL language provides maximum expressiveness, computational completeness, and decidability. So, all reasoning and constraints validation conclusions are computable in a finite time. Figure 2.2 illustrates IESO's domain modules.

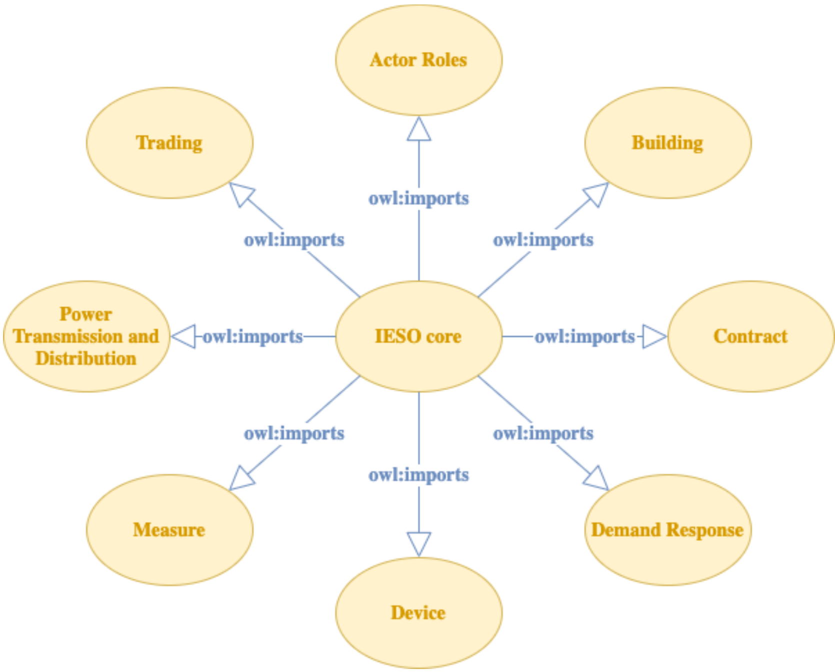

Figure 2.2. IESO's domain modules [81].

Currently, IESO is composed of eight core domain modules, namely the Actor Roles, Building, Contract, Demand Response, Device, Measure, Power Transmission and Distribution, and Trading. The Actor Roles module describes the main entities involved in the PES, modeling the main involved actors, their roles, and behaviors. The Building module defines terminology related to building topologies as required in the scope of the MAS Society, reusing knowledge from the Building Topology Ontology (BOT) and SAREF's extension for buildings. The Contract module describes contract concepts, relations, and properties in the scope of PES, such as aggregation contracts for DR, forward contracts, futures contracts, wholesale bilateral contracts, among others. The Demand Response module describes DR concepts, relations, and properties related to DR programs, events, and results, reusing concepts from the Actor Roles, the Contract, and the Measure modules.

The Device module, strongly inspired by the SAREF, describes devices and their respective functions, commands, and states. The Measure module describes measurements, types of measures, measurement values, and units of measure, receiving input from the Quantity, Unit, Dimension, and Type (QUDT) [31] ontology and SAREF. The Power Transmission and Distribution module describes the power transmission and distribution grids from power generation to distribution and consumption, merging knowledge from existing standards, such as the CIM, and data models, such as the pandapower tool[32] data structure. Finally, the Trading module describes EMs from wholesale to regional and local markets, including market types such as auction-based (day-ahead, intraday) and bilateral negotiation markets (e.g., ancillary services, future, forward), reusing concepts from EMO, LMO, OWL Time, and the modules Actor Roles, Contract, and Measure.

Following the general ontologies' need for iterative update and management, IESO needs continuous improvement. There are already advances to include three new domain modules, i.e., a module to represent different contexts to provide decision support based on ontology reasoning, a module to describe different types of profiles according to a given context, and another integrating knowledge from various decision support tools, namely the AiD-EM's ontology[33], the Scheduling, Optimization, and Forecasting (SOF) ontology[34], the Energy Resources Management (ERM) service ontology[35], and the SCADA House Intelligent Management (SHIM) service ontology[36]. Additionally, different modules will provide alignment files in their web pages whenever it makes sense.

The main contribution in this section of the Ph.D. work is IESO, providing the agents of the MAS Society with a common ground vocabulary for knowledge representation, semantic interoperability, and reasoning. IESO also contributes to the data and business models description and validation within the agents' society while aligning with concepts of different ontologies. Using the publicly available IESO, external systems can participate in the studies of the MAS Society and exchange data and knowledge meaningfully. Additionally, the use of ontologies and semantic web technologies enables the development of more

[31] Publicly available at: http://qudt.org/.
[32] Homepage: http://www.pandapower.org/.
[33] Publicly available at: http://www.mascem.gecad.isep.ipp.pt/ontologies/aid-em.owl.
[34] Publicly available at: http://www.gecad.isep.ipp.pt/ontologies/ies/demos/sof.owl.
[35] Publicly available at: http://www.gecad.isep.ipp.pt/ontologies/ies/demos/erm.owl.
[36] Publicly available at: http://www.gecad.isep.ipp.pt/ontologies/ies/demos/shim.owl.

flexible tools, agnostic to the data and business models, as is demonstrated in subsection 2.4.3. This contribution fulfills objective 3 and answers the research question addressed by this section.

2.4 Multi-Agent Systems Society for PES

How can a multi-agent systems society provide a flexible, intuitive, and complete framework for the study and management of power and energy systems?

Interoperability is the key to accomplish a society of heterogeneous MAS. To achieve interoperability among agent-based systems, communications must be meaningful. To this end, agents must share the same conceptualization about the information they share. The work developed in this Ph.D. thesis uses ontologies for knowledge representation and semantic communications among agents from heterogeneous tools. The use of ontologies in environments with such a fast evolution as the PES can reveal laborious. Ontologies must reflect a domain's knowledge and evolve accordingly, at the same pace as the systems using these semantic models. Traditionally, this translates into a need to recode the tools. However, this thesis proposes a solution to avoid recoding a tool every time its data model or business rules are updated by using ontologies and semantic web technologies.

Another important subject to complement the society of MAS is the need to provide interoperable services to support the agents in different matters, such as decision support algorithms and the connection to physical devices. Such services also enable users to plug and play services to test distinct approaches, at different timings, without having to code the agents. Finally, the necessary means to enable the management and execution of the MAS Society to be intuitive and to abstract the user from the configuration complexity and burden are also developed by this work.

2.4.1 Interoperable services for agents' support

The use of decision support models and methods based on AI approaches improves the outcomes of players' participation in EM negotiations and DR events [69], [71]. It also helps increasing buildings' energy efficiency or providing security [127]. Thus, in the scope of this Ph.D. work, software agents and systems take advantage of previously developed AI approaches, such as forecast [128], clustering [72], scheduling [70], portfolio optimization [68], and context-aware

[90] algorithms to make better decisions and improve their results. The first step taken to enable agents using such algorithms was the development of the Intelligent Decision Support Multi-Agent System (IDeSMAS) presented in paper V [77] and [82], [83], [92], [94]. IDeSMAS accommodates different decision support algorithms based on clustering, machine learning, data mining, pattern analysis, and game theory approaches, making them available to the community of MAS.

IDeSMAS is a semantically interoperable MAS providing services to heterogeneous systems in the MAS Society. The provided services include forecast algorithms based on different techniques (e.g., artificial neural networks - ANN, support vector machines - SVM, and fuzzy inference systems) to predict energy consumption and generation, market prices and other relevant factors in the PES domain, scheduling algorithms for energy resources management at the SG and building levels, and DR program algorithms, among others. To interact with IDeSMAS, agents use the IES ontologies (see footnote 13). Similarly to PLCMAS, a client agent must interact with IDeSMAS Main Agent using the SOF ontology (footnote 34) to request support, specifying the algorithm to run. The Main Agent generates an auxiliary agent to execute the specific algorithm, sending the client's data so he can interact directly with the client. The auxiliary agent requests the input to its client and runs the algorithm. After sending the results to its client, the agent shuts down to free resources, informing the Main Agent accordingly.

IDeSMAS is used as the basis for the development of a distributed web platform where an algorithm can be published simply by uploading it, configuring the request(s), and providing some documentation about the algorithm. Making these algorithms available as web services is beneficial not only to the MAS Society, but also to researchers and other tools (such as in paper I [73] and paper IV [76]). Consequently, Paper VII [79] and preprint I [80] introduce the Intelligent Decision Support (IDeS) framework, a configurable and distributed platform where the intelligence and decision support algorithms coexist across the MAS Society network. Keeping services distributed instead of located in the same server brings several advantages, such as improved performance, stability, and automation.

The IDeS framework consists of a containerized tool that must be configured for each algorithm. To add a new algorithm, a new container is started and configured for the first time. The user must upload the script file(s) of the algorithm, input and output schemas for each possible request, provide a human-readable description and the documentation for the service's webpage, and set the service's semantic description to register the service on SSC (see subsection 2.4.2). Optionally, the user may also upload an input example for the system to automatically generate a demonstration test page. IDeS accepts SWI Prolog[37], Python[38], and R[39] scripts since these are the main development languages used within GECAD and it is able to import packages automatically for the different development languages. IDeS algorithms accept JSON as input, providing the output in the same syntax. Input and output schemas for each request are also available on a service's documentation webpage.

Currently, IDeS provides energy forecasting algorithms using ANN and SVM (see paper IV [76] and publication [92]), a deterministic optimization algorithm to minimize energy costs, several ERM algorithms for SG and microgrid (see paper VI [78] and publications [82], [83], [92], [94]), algorithms that execute and simulate DR programs (see paper II [74] and paper IV [76]), clustering algorithms for contextual decision support (see papers I [73] e IV [76]) and players' aggregation (see paper II [74]), algorithms for contextual profiling (see paper I [73], paper IV [76] and publication [90]), among others. When configuring the service for the first time, the user can set a list of managers (as long as they have a user account at GECAD) to update the service's configuration at any time, including uploading a new version of the script. IDeS framework also allows making different versions of the algorithm available, distinguishing them by adding the version string to the request's Uniform Resource Locator (URL).

IDeS is the main contribution of this part of the Ph.D. work, providing decision support and intelligence algorithms as web services to the society of MAS. Besides being valuable services to the agents within the MAS Society, the IDeS framework provides a web-based interface for researchers to use the available algorithms, being also available through the TOOCC's user interface (see subsection 2.4.4). Using TOOCC, users can manually define the composition

[37] Homepage: https://www.swi-prolog.org/.
[38] Homepage: https://www.python.org/.
[39] Homepage: https://www.r-project.org/.

of services, making them run sequentially (see paper II [74]). Additionally, BRICKS also takes advantage of some services provided by IDeS, namely the Forecast, the Context-Profiles, and the Demand Flexibility services (see paper IV [76]) for building energy management. This contribution and the contribution described in subsection 2.2.2 completely fulfill objective 4.a.

2.4.2 Catalog of semantically described services

Solving complex tasks is frequently accomplished by composing multiple atomic services. Yet, the design and development of such workflows are very time-consuming since one must find the right services, learn how to interact with them regarding communication protocols, inputs and outputs, and program the workflow and data transformations between services to solve the task. Software agents and MAS able to solve specific tasks to accomplish a given goal can be seen as service providers, as is the case of agent-based decision support systems [31], [44], [82]. Moreover, agents often execute tasks that depend on the outputs of web-based services (see paper II [74]) or of services provided by other MAS [83], [94]. One possible solution to expose agents as web services is to implement agent gateways. However, these are static, hindering the agents' mobility capability [121] and reducing the service's performance since it may result in a bottleneck [120]. On the other hand, service providers may shift to different locations without notice, which results in systems' failures, requiring the reconfiguration of the tools using those services.

When dealing with the interoperability between multiple MAS, one must ensure that independently developed agent-based platforms are able to communicate. However, depending on the chosen development framework, this may not always be possible. For this reason, agents within the MAS Society must be FIPA compliant, assuring the exchange of messages between heterogeneous systems independently of their development platform. Being FIPA-compliant allows an agent from a MAS to register in the Directory Facilitator (DF) agent [121] of another agent-based platform. Still, this registration is traditionally hardcoded beforehand programmatically or using configuration or property files. Besides, depending on the way agents are programmed, it may also oblige to start the different MAS in a specific order for the simulation to run smoothly. Such may easily lead to errors in addition to the burden of reconfiguring each system for each simulation.

In order to overcome these issues, the Semantic Services Catalog (SSC), a web service for agent-based and web-based services' registration, search, and invocation has been developed and is presented in paper VI [78] (see also paper VII [79] and preprint I [80]). SSC provides the means for searching a specific service or MAS returning all the required data for an automatic connection configuration, thus enabling autonomous interactions between agents and services within the MAS Society. It is a catalog of semantically described services since ontologies and semantic web technologies enrich the services' descriptions, supplying them in a machine-readable form. The semantic layer gives meaning to syntactic data, allowing agents to achieve service matching and composition through reasoning processes. This way, the discovery and selection processes become easier for intelligent agents [129] while facilitating the interactions between heterogeneous web services and MAS, making the co-simulation configuration of systems more straightforward and less error-prone while also potentiating its automation.

SSC materializes the architecture proposed in [84], making use of OWL-S (see footnote 24) and the extensions proposed in [84] to provide REST (footnote 25) and agent-based (footnote 26) services semantic descriptions (see section 2.3). Figure 2.3 illustrates the application-level architecture, identifying SSC at the bottom, the service providers on the top left, and the clients on the top right side.

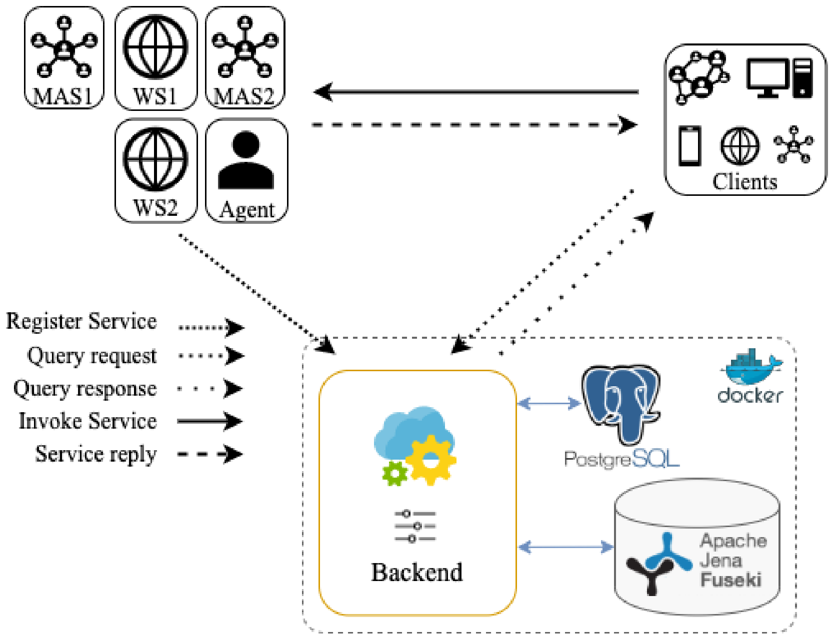

Figure 2.3. Application-level architecture (paper VI [78]).

To register a service in SSC, the service providers (on the top left corner of Figure 2.3) must provide the service's semantic description, the language (syntax) used in the semantic description, and a Uniform Resource Identifier (URI) to identify the RDF graph in the triple store (see folder ***POST register*** of [95]). The semantic specification must include the service's name, a description of the service's processes, how to reach and communicate with the service, the available requests, and the respective input and output models. On the other hand, to search for a service in SSC, client tools (on the top-right corner of Figure 2.3) can use simple searches using keywords (see folder ***POST search*** of [95]) or advanced searches using SPARQL queries which allow adding constraints as fit. As a response, SSC returns the URI graph that stores the service, the service's individual, its name, the description, the input and output models individuals, and the triple store endpoint to get the complete semantic description of the service. With it, agents can reason and interpret the data models to autonomously interact with the respective services.

Finally, SSC is a containerized, distributed, and configurable tool that connects various systems for different purposes. I.e., a triple store for the semantic description of services, a relational database to store the system's configurations, a Lightweight Directory Access Protocol (LDAP) server for the administrators' login, and an external service to validate SPARQL queries and templates (see paper VI [78]). The SPARQL queries and templates are configurable, allowing SSC to be agnostic to the semantic models used to describe the services. SPARQL templates are helpful to replace specific tags for search keywords. Figure 2.4 presents the system's architecture.

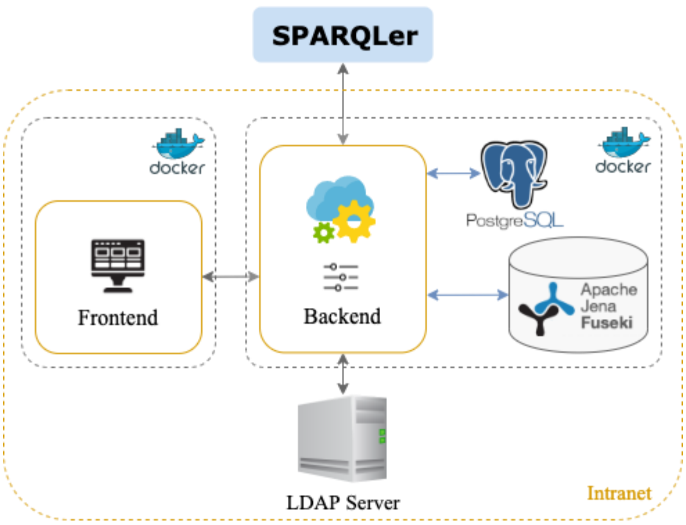

Figure 2.4. SSC's architecture (paper VI [78]).

SSC overcomes the complex and error-prone manual configurations of distributed MAS to communicate with each other and web services by providing the means for searching a specific service or MAS returning all the required data for an automatic connection configuration. This way, there is no need to reconfigure the tools at each simulation. SSC is a web platform gathering and making different services available to the agents' community, allowing them to find and request a service execution without the user's interaction. It is the main contribution of this portion of the Ph.D. work, fulfilling objective 4.b. This contribution completes the fulfillment of objective 4.

2.4.3 Semantic reasoning for the validation of business constraints towards agnostic systems

During the early-stage development of this Ph.D. thesis work, one of the main issues that needed to be dealt with was the necessity of reprogramming tools every time the ontologies or data models needed to be updated. The fast-paced evolution of PES and the will to test different hypotheses are some of the reasons that trigger such circumstances. On the other hand, working with ontologies can be very time-consuming and it is often arduous to achieve consensus between the involved parties, which usually leads to dropping the use of semantic models. Such issues led to the need for rethinking how to improve this process to ease the developers' effort while making it less time-consuming.

Given that ontologies and data models evolve frequently, MAS must be flexible in order to update and use the semantic models accordingly. Additionally, by updating a data model, one must recode the business model and rules programmed in accordance, or the system will not compile. Thus, the idea of keeping the systems decoupled as much as possible from the data model, the business model and rules arose. Ontologies and semantic web technologies allow keeping agents agnostic to the used ontologies. Moreover, if the semantic model also includes the business model, it is possible to develop tools where the business rules are configurable and not coded. In this way it is possible to achieve a system that is agnostic to the used ontologies and applied rules, where the user configures the ontologies and the business rules to apply, without needing to reprogram the system if a constraint or the semantic model change.

Paper I [73] (see also paper IV [76]) introduces the first step taken in this direction with the development of BRICKS. BRICKS provides intelligent, integrated, efficient, and optimized building management control. It is at a higher level than a SCADA system, so it can integrate knowledge from different SCADA systems and smart appliances and apply rules upon it for building energy efficiency and security. BRICKS is reusable, with a simple configuration, in any building or building area with PLCs or IoT devices, by keeping it agnostic to the ontologies, business model, and rules.

BRICKS is configured once before its first use. Its configuration starts with defining the ontologies to use, which must describe the necessary knowledge for the building's energy efficiency, security, contexts, devices, measurements, etc., to create the respective instances (ontology individuals). Afterward, the mappings between the raw data readings and the semantic model are defined, as well as the alarm, notification, and automatic control rules. Rules can be written in SWRL or SPARQL. Finally, the monitoring and triggered rules queries to the knowledge base are set. Figure 2.5 illustrates BRICKS' reasoning process.

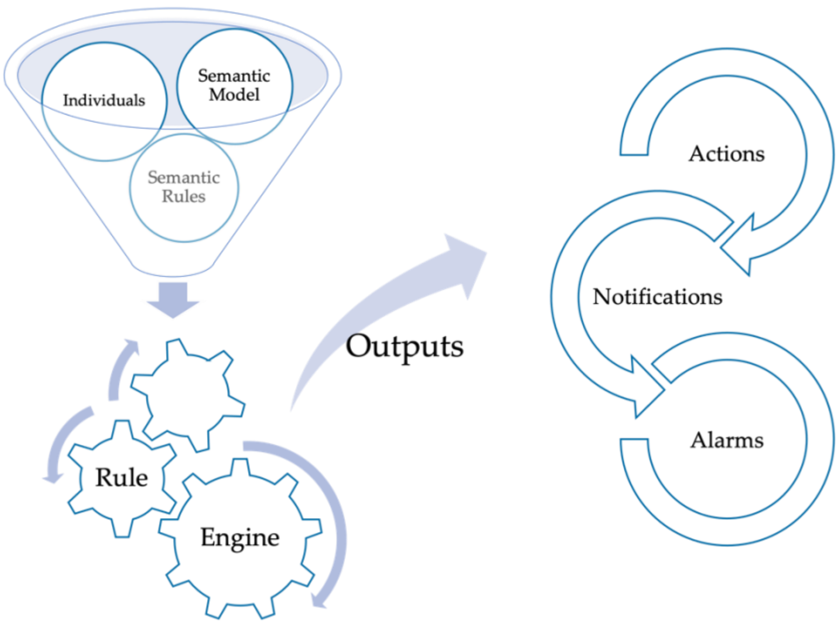

Figure 2.5. BRICKS rule engine (paper I [73]).

At each time step, BRICKS reads the devices' measurements and their profiles for the current context (provided by the external service [90]), gathering them in a temporary graph and matching them against the previously defined semantic rules. BRICKS starts by executing the SWRL rules so that the SPARQL rules can take advantage of the knowledge inferred by the semantic reasoner. Using a SPARQL query over the temporary knowledge graph, BRICKS gets all the alarms, notifications, or control (Actions) to take.

Leveraging from the knowledge and experience acquired with BRICKS development, paper III [75] proposes a software library for auction-based EM with constrained bids taking advantage of ontologies and semantic web technologies. It demonstrates how to develop such libraries in a way to be flexible, configurable, and agnostic to the ontology and constraints, revealing to be useful to tools in the scope of constantly evolving areas such as PES. Moreover, ontologies give contextual meaning to data, enabling applying semantic reasoning for knowledge validation and extraction, besides the business rules implementation. The article explains step by step how to develop such configurable and flexible libraries. Again, the semantic model must conceptualize all the knowledge required by the tool, as demonstrated by the presented study.

The work presented in paper III [75] compels the use of SPARQL for the constraints definition for two main reasons: i) the first is because SPARQL is more flexible than SWRL (e.g., SWRL cannot assert a new individual, only makes assertions about existing individuals – see footnote 20); ii) the second is related with computational resources. SWRL rules are matched by reasoners that try to infer new knowledge at each execution, asserting triples to the knowledge base. It means that, at each iteration, the process will be slower since the reasoner has more triples to analyze and deal with. SPARQL, instead, uses only the available knowledge to answer the query or update the triple store. However, the library runs the reasoner before executing each EM session over the base graph to ensure the library validates and infers (implicit) knowledge before running the constraints. Additionally, this paper proposes a set of bid constraints for local EM, an application ontology, and the respective SPARQL templates according to the ontology, representing the defined bid constraints, explaining them step by step. Finally, the case study demonstrates the simplicity of updating or adding a constraint, making the system act accordingly, without recoding and recompiling it. All the library KB and configuration files are publicly available[40].

The previously presented SSC service (see subsection 2.4.2 and paper VI [78]) is also decoupled from the ontologies used to describe the registered services and is agnostic to the SPARQL queries and templates required to

[40] Auxiliary data: http://www.gecad.isep.ipp.pt/mdpi/energies/845690/.

provide the data to its clients. This way, the semantic model can be updated and the SPARQL templates be reconfigured accordingly, while the tool continues working without being reprogramed nor compiled. Ontology reasoning also leverages TOOCC (see subsection 2.4.4 and paper II [74]) for knowledge validation and automatic results comparison. The semantic layer of DAS (see subsection 2.2.1) is also agnostic to the ontologies by using SPARQL templates to translate data from the databases to linked data. Finally, the works published in paper VII [79], preprint I [80], and preprint II[81] include agents developed using this approach decoupled from the model and business rules. Preprint II [81] goes a step further by demonstrating agent semantic reasoning and data units' uniformization using the proposed ontology model (presented in section 2.3).

The main contribution of this portion of the Ph.D. work is the leveraging of ontologies, semantic web technologies, and reasoning to accomplish more intelligent and flexible tools by keeping the systems agnostic to the semantic models and by using semantic reasoners and rules instead of coded business rules. This approach avoids recoding the software every time a rule updates or the data models changes. On the other hand, it is always necessary to have some level of persistency to abstract the software from the semantic model and rules. This software may need recoding if the level of abstraction is not enough to represent the changes made to the model or business rules. This contribution provides a step further on the proposed objectives, resulting in advances in the work related to objectives 2, 3, 4, 5, and 6.

2.4.4 Tool for the simulation and control of the MAS society

The integration of multiple MAS and services demands a significant effort and time to configure each tool properly, which is aggravated when considering studies that bring together multiple tools. One must ensure the correct inputs to guarantee that the systems represent and act according to the intended scenario and study. SSC already contributes towards the connections' configurations for the MAS to communicate among them and with web services, the publication of the services available, the data models expected for input and output, parameterizations, etc., enabling an automatic connection instead of a static one. However, the user still has the tasks of initializing each MAS and providing tools the necessary data and knowledge for the agents to operate under the stipulated scenario. Platforms with the flexibility of simulating and studying completely new models or combinations between new and existing models have an added configuration complexity, often leading to human errors.

The success of a tool within a community of users is strongly related to the user's experience [130], [131], i.e., the easiness of use, the effort to accomplish the goals, how comfortable and attractive the user feels when using the tool, among others. When dealing with multiple interoperable and flexible systems, their configuration complexity may become the biggest obstacle. Besides, depending on the outputs of each platform, the interpretation of the results can also become a burden. This Ph.D. work proposes and develops a MAS for the scenarios' definition, simulation, and control of the MAS Society, contributing to overcome and avoid the user's effort and error-prone situations.

Paper II [74] (see also paper VII [79] and preprint I [80]) presents an enhanced version of the Tools Control Center (TOOCC), previously introduced in [82], [83] (see also paper V [77] and publications [91], [92], [94]). TOOCC is a MAS developed to enable the setup, control, and analysis of the MAS Society. It provides a centralized user interface for configuring and managing the distributed community of MAS and services. TOOCC allows the co-simulation of some or all the heterogeneous systems within the society, as well as running each tool independently. It acts as a facilitator between the various platforms, allowing them to share knowledge and interact in complex scenarios resulting from joining the individual features of each system or service.

The interoperability amongst the various MAS and services is accomplished using ontologies and semantic communications. TOOCC can also be seen as a decision support tool, as it facilitates the analysis of complex problems within the PES domain. It enables the study of EMs, SGs operation, buildings' energy and resources management, DR programs, to name a few. TOOCC's multi-agent architecture allows to perform multiple simulations simultaneously for results comparison or to reduce the execution time compared with running each simulation at a time. Figure 2.6 presents TOOCC's multi-agent model.

TOOCC API Agent is responsible for providing and managing the user (web) interface, serving as a facilitator between the user and TOOCC Main Agent. TOOCC Main Agent is the coordinator of the simulations, creating Scenario Agents for each configured scenario. The Scenario Agent controls a specific scenario, coordinating the various phases by creating a Step Agent for each.

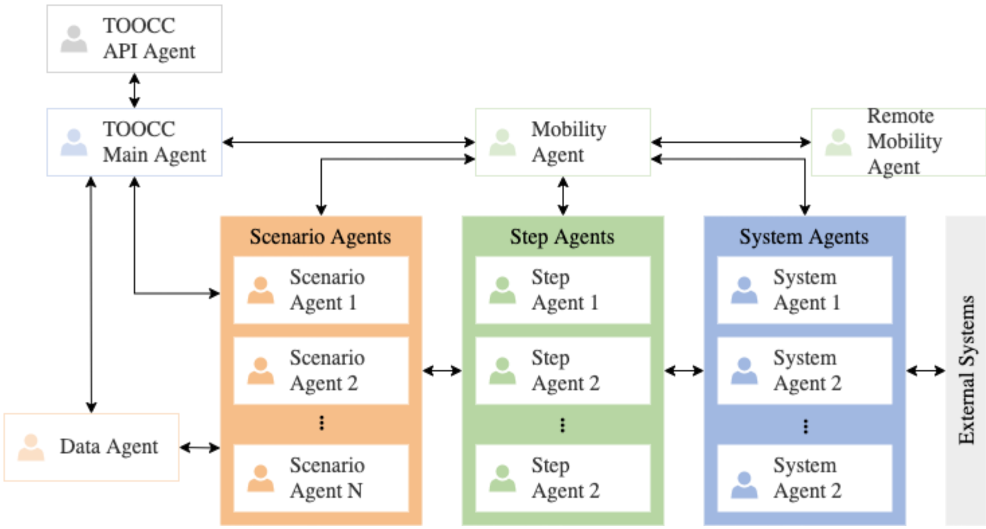

Figure 2.6. TOOCC's multi-agent model (adapted from paper II [74]).

The Step Agent manages the interactions with external systems that run in parallel. To this end, it starts a System Agent for each system within the execution phase. On one hand, it allows agility in obtaining results. On the other, it assures that the next step will only start after all necessary results are available (as these are input to the next phase). The Mobility Agent and the Remote Mobility Agent provide the means for the automatic distribution of agents amongst the available machines. The Remote Mobility Agents are initialized in the computers available for use in the network and inform the Mobility Agent about its characteristics, including the operating system and installed software. With the available information, the Mobility agent determines the agents to move to the respective machine. Finally, the Data Agent is the agent responsible for managing the simulation data. On one side, it guarantees the results are stored correctly. On the other, it provides the TOOCC API Agent the data for automatically filling the inputs of tools selected by the user.

TOOCC's application ontology describes its configuration model, supporting the definition and control of the simulation scenarios. At startup, TOOCC queries SSC to get a list of MAS and services available to present to the user. The user starts by selecting the tools to use for the study. Choosing a tool assumes other tasks, which may or may not be mandatory. Depending on the platform, the user may need to set the configuration parameters and the input data. To ease this process, the user may import data from the database (using the DAS service - see subsection 2.2.1) or input files and modify the values at will. When a scenario includes more than a tool, the user must determine their execution order, defining which tools run sequentially or simultaneously.

Systems running simultaneously are executed in the same step (or phase). When configuring sequential platforms, the user may have to define the mappings between the output models of tools running in a previous step and the input models of the systems running afterwards. There may be cases that the input of a platform depends on the outputs of multiple tools. Finally, the user can set up automatic comparisons between results obtained in different simulations, scenarios, or systems. TOOCC is then ready to start the simulation(s), presenting the results at the end.

To add a new system into TOOCC is as simple as add a new configuration. If the new tool communicates semantically, mappings can be made between the domain ontologies of the MAS Society and the semantic model of the system to add. However, if the new platform communicates using a structured language (e.g., XML or JSON), it is possible to configure TOOCC to translate between the syntactic model and the semantic model using SPARQL. TOOCC acts as a facilitator middleware between heterogeneous systems unable to interact with each other, using ontologies to translate their data models. However, tools such as MASCEM, AiD-EM, and MASGriP, which already interacted using the EMO ontology modules, do not need TOOCC's aid in the communication and translation processes, thus continuing to interact autonomously.

TOOCC is the main contribution of this part of the Ph.D. thesis. It is an innovative agent-based system designed and developed for the simulation and control of the MAS-Society. It enables the co-simulation of the complete energy chain, which cannot be accomplished by using the different tools independently and in a non-integrated way. TOOCC grants the definition of a wide variety of scenarios, providing diversified models and allowing the study of the impact of these models. Ontologies provide the means for the scenarios' definition, data models' translation, semantic communications, and results' comparison. Finally, TOOCC uses SSC to know, at each time, which systems are available for simulation and DAS for the automatic filling of the input data of different tools. Using TOOCC, complex dynamics between heterogeneous MAS and services are realized, customized, configured, and analyzed. This contribution partially fulfills objective 5, completing objective 5.c, and partly fulfilling objectives 5.a.i and 5.b.

2.4.5 MAS Society

The ultimate outcome from this Ph.D. work is an interoperable MAS Society for the study, simulation, decision support, operation, and management in the scope of PES, using ontologies and semantic web technologies to achieve interoperability between heterogeneous agent-based tools and services. Besides supporting the meaningful communications between the various systems, ontologies also allow applying semantic reasoners to extract new knowledge, validate data models, and use semantic rules.

The MAS Society provides effective solutions to enable the widespread of Distributed Energy Resources (DER), such as Renewable-Based Generation (RBG), DR, Energy Storage Systems (ESS), and Electric Vehicles (EVs). Thus, enabling them to reach their full potential to increase the overall energy efficiency and economic and energetic sustainability. Providing the joint simulation and management of multiple problems focused on specific areas of the PES allows studying the domain globally in a realistic way.

Paper V [77] (see also publications [93], [94]) introduces the early version of the MAS Society, proposing a set of ontologies for providing interoperability between heterogeneous agent-based tools regarding EMs, SG, and residential energy management. It presents a solution for integrating existing MAS directed to distinct areas of the PES, taking advantage of the individual capabilities of each platform to achieve an inclusive PES simulation environment, proposing an architecture composed of multiple MAS covering the whole energy system.

The MAS included MASCEM, AiD-EM, MASGriP, IDeSMAS, PLCMAS and TOOCC. The joint simulation benefits these tools with knowledge and model sharing, allowing agents to learn from the experience gained from interacting with each other. This ability enhances the PES study, providing players and stakeholders with proper tools to adapt to such dynamic reality. It also allows operators to appropriately test and validate new models before implementing them in the real world. To this end, the proposed MAS Society models and represents the most relevant players, operators, and stakeholders as software agents taking advantage of their distributed and individual nature to make them cooperate or compete to achieve their goals.

The conception and development of a public ontology-based knowledge model to represent domain concepts, considering the various business, market, and players models of the agent-based tools, provide a common ground vocabulary for meaningful knowledge exchange between heterogeneous systems (see preprint II [81] and publication [92]). However, it is also relevant to consider the syntax in which the platforms exchange the information. If two platforms use different syntaxes to describe the same concepts, the agents may not communicate effectively. Combining the use of ontologies and semantic web technologies eases the translation between ontology serializations. Thus, all agents of the MAS Society can interpret any RDF syntax (see publication [91]), being able to communicate with external agents by answering using any RDF syntax they acknowledge. To this end, external agents must adopt the FIPA's Agent Communication Language (ACL) message structure [49] to describe the message's content. I.e., use the "ontology" field to identify the URI of the semantic model used to describe the message's content and fill the "language" field with the respective RDF syntax. The "encoding" field is optional. By default, agents expect to receive messages encoded in UTF-8[41]. Some agents of the MAS Society also accept JSON as content language, ignoring in these cases the "ontology" field. It only occurs in communications among agents of the same MAS since most the agent-based tools have been developed before the emergence of the MAS Society.

By using a shared conceptualization and flexible serialization, platforms interact without misinterpretations. In addition, reusing and extending domain knowledge to describe the applicational models eases the validation of data and business models (see paper II [74]). Moreover, taking advantage of reasoning and semantic web technologies enables developing more intelligent and configurable tools, adaptable to new models and constraints, avoiding the need for recoding and recompiling whenever these update (as paper I [73], paper III [75], preprint II [81], and subsection 2.4.3 demonstrate). This approach allowed the improvement and development of more flexible and versatile tools to keep up with the constantly evolving reality of the PES while guaranteeing interoperability within the society of MAS and with the support services. Paper II [74] and paper VI [78] present two platforms (see subsections 2.4.2 and 2.4.4)

[41] http://www.unicode.org/versions/latest/.

that, alongside, provide the means for external and non-semantic systems to interoperate within the MAS Society.

Paper VII [79] and preprints I [80] and II [81] present the latest version of the MAS Society. Preprint I [80] demonstrates an example of the interaction of the MAS Society platforms with the external agent-based tool MARTINE using ontologies for semantic interoperability, leveraging from the previous work presented in paper III [75]. Besides, it shows the communications between MARTINE and different tools of the MAS Society, making them publicly available (see publication [96]). In this work, a MARTINE Prosumer agent interacts with a Local Market Operator agent from MASCEM to participate in a community auction-based EM. To this end, the Prosumer agent requests DAS service (see subsection 2.2.1) for historical data to forecast the amount of energy to bid in the local EM. The forecast is provided by an ANN-based forecast algorithm [128] made available by the IDeS service (see subsection 2.4.1). At the end of the local EM session, the Prosumer agent of MARTINE realizes the need to use the Dev-C service (see subsection 2.2.2) to shift some consumption to another periods when it was not possible to sell its surplus energy.

Paper VII [79] and preprint II [81], in turn, overview the cooperation between the agent-based tools and services that compose the society of MAS for PES simulation, study, decision support, operation, and management as a solution to address the lack of interoperability between existing PES tools. Besides interoperability, preprint II [81] also demonstrates the use of ontologies and semantic web technologies for agent reasoning, constraints validation, and the conversion of units of measure in the simulation of a local network operation considering technical limits violation and real-time local market participation. In this work, a Network Manager (NM) agent uses a power flow service [132] to validate the grid constraints at a given time step. When any violation of the network's technical limits occurs, the NM requests flexibility to its players to solve the grid's congestion. To this end, the NM uses a single-sided auction-based algorithm to run a local flexibility EM [132] in order to acquire the needed consumption reduction. Preprint II [81] also shows how to accomplish data and business model agnostic agent-based tools, being more flexible to updates while avoiding recode and recompilation.

The MAS Society is the main contribution of this section of the Ph.D. work, being achieved by implementing a comprehensive simulation infrastructure that combines several distinct MAS and services directed to studying specific problems in PES. Ontologies and semantic web technologies play a relevant role in providing interoperability between such heterogeneous tools. Understanding the same language allows these tools to communicate and interact with each other. Taking advantage of existing simulation and decision support tools, and complementing them with new ones, allows achieving more complex and inclusive studies. Thus, allowing to assess the impact of different business, market, and player models in the scope of EMs and SGs, and analyzing the outcome from alternative decision support approaches. This contribution fulfills objective 5, benefiting from the fulfillment of the previous objectives, and answers the research question contemplated in this section.

2.5 Experimentation and Validation

Can the multi-agent systems society be tested and validated in realistic conditions, combining real-time and simulated data in both laboratory and real-world environments?

The conception, development, and implementation of the proposed MAS Society needs to be tested and validated under realistic conditions and scenarios. Experimentation and validation under real or near-real conditions are crucial to confirm its adequacy and accuracy in representing real-world PES models and actors and to realize the potential advantages of its applicability in the study, simulation, decision support, operation, and management within PES. A lack of proper study and simulation of new models could result in a disastrous application in the real world that could jeopardize the operation and management of PES and prejudice operators, players, and stakeholders.

Therefore, the developed framework requires test and validation under laboratory and realistic conditions, using real-time, historical, and simulated data, to assure the proper integration, functioning, workflow, and, consequently, results. The laboratory environment is characterized by two controllable rooms where exhaustive testing can be performed. The real-world environment regards GECAD's office facilities. Table 2.2 compiles the main characteristics used as the basis for the conception and creation of the case study scenarios for the experimentation and validation of the MAS Society in realistic conditions.

Table 2.2. Summary of the case studies' characteristics.

Characteristic		Core Publication							Other					Preprint	
		I	II	III	IV	V	VI	VII	[92]	[93]	[95]	[96]	[97]	I	II
Wholesale EM						X	X		X	X	X				
Local EM				X								X	X	X	X
SG			X	X	X		X	X	X	X	X	X	X	X	X
DG			X	X	X		X			X	X	X		X	
DR			X		X		X		X	X	X				
Aggregation Contracts					X										
Building Energy Management		X			X				X			X		X	
Automated Devices Control		X			X		X		X	X	X	X		X	
Real Data	Real-Time	X			X		X			X	X	X		X	
	Historic		X	X	X		X		X	X	X	X	X	X	X
Simulated Data				X		X		X	X			X	X	X	X
Real-World Environment		X			X							X		X	
Laboratory Environment			X	X		X	X	X	X	X	X		X		X

Table 2.2 offers a clear picture of the analyzed PES areas, the type of used data and its environment. The SG, DG, and DR are the most common scenarios. Some of these studies consider the wholesale EMs and a few the local EMs. Building Energy Management, in turn, always applies Automated Devices Control taking advantage from GECAD's building infrastructure. However, the latter sometimes occurs associated with DR. Only one publication regards the Aggregation Contracts since it was one of the last accomplishments. Nevertheless, it is a relevant subject from the end-users' perspective to continue researching, exploring, and developing to study and learn which possibilities are the best for each case. Concerning the use of data, one can see that Real-Time and Historical data have been preferred over Simulated data. This was only possible due to the infrastructures available, and the conditions provided by the GECAD research group. Finally, the Laboratory Environment was the most used due to GECAD's infrastructures and equipment. On the other hand, the Real-World Environment often involves disturbing the colleagues working at the offices.

Different tools enable the use of real data within the MAS Society. Regarding MASCEM and AiD-EM, which deal with diverse EMs' models, such as auction-based markets and bilateral negotiations, an automatic extraction tool presented in [133] gathers EMs results as soon as they are available on the power exchange operators' websites. It collects anonymous data about the bid prices and amount of energy, the accepted bids and market price per trading period, the execution of bilateral contracts, etc. Besides, MASCEM can also use RealScen [134], a scenario generator to create simulation scenarios representing an EM of a given region at a smaller scale or considering different configurations to deal with the same players under different scenarios. To this end, RealScen uses the publicly available data gathered by the extraction tool. In addition, the physical infrastructures installed at GECAD's laboratory collect the building's data in real-time [45] and store them every 10 seconds to a database accessible via DAS service. The last measurements available are stored as (near) real-time data and the remaining are stored as historical data. It is also possible to request DAS for electric energy data with different granularities and units, as presented in preprint I [80]. The database also gathers data collected in measurement campaigns in the various departments of the university campus, in some volunteers' residences and businesses, and open data from the Institute of Electrical and Electronics Engineers (IEEE) Intelligent Systems Subcommittee (ISS) Open Data Sets (ODS)[42]. The data made available by these tools are used to test and validate the MAS Society and the ontologies developed in the scope of this Ph.D. thesis.

Paper I [73] illustrates BRICKS configuration and management in GECAD's facilities, deploying a BRICKS instance for each building area using data measured in real-time. Results demonstrate how ontologies and semantic web technologies provide machine intelligence to a rule-based system while overcoming interoperability issues among heterogeneous BEMSs and devices, collecting their data for alarms, notifications, and automated control. Paper IV [76], in turn, presents the latest BRICKS version performance in a multi-level DR event using real-time measured data and historical data stored in its database, focusing on the autonomous interactions among BRICKS systems. The scenario considers dummy players modeled using previously measured data. The results confirm the tool's autonomy to handle DR events considering the user's comfort and priorities.

The case study of Paper V [77] confirms the value of using EMO to support heterogeneous players' participation in MASCEM. It uses simulated data generated by RealScen using real data collected by the extraction tool to represent

[42] https://site.ieee.org/pes-iss/data-sets/.

the European EMs reality with a summarized group of players. Paper II [74] uses real consumption and generation historical data to evaluate and validate the use of TOOCC's ontology in the definition and execution of a DR scenario using three web services available at IDeS. It demonstrates the fulfillment of TOOCC's application ontology requirements and how TOOCC accomplishes interoperability by mapping a service's output to the following input.

Paper III [75] presents a constrained local EM scenario combining measured data with simulated prices respecting the bounds of the Portuguese national generation and consumption tariffs. It shows how players can use constraints as part of their negotiation strategies and how simple it is to change, add, or remove a constraint without the need to recode and recompile the tool. It demonstrates the advantages of using ontologies and semantic web technologies to develop systems agnostic to data and business rules. In turn, preprint I [80] makes use of the work introduced in paper III [75] to demonstrate the use of ontologies and semantic web technologies to enable the participation of MARTINE in the MAS Society. It focuses on the interactions of MARTINE with the different tools of the MAS Society in the simulation of a local community EM (see publicly available data [96]). Like in the previous work, this case study scenario combines real-measured data and simulated prices.

To show the advantages of SSC in facilitating autonomous interaction between agent-based tools and web services, Paper VI [78] presents a co-simulation using MASCEM, MASGriP, and AiD-EM tools and decision support services registered in SSC. The case study focuses on the agents' interactions with SSC, and SSC's responses to agents' requests are publicly available [95]. The scenario uses real data sets made available by the DAS service. The previous publication [93] uses the same data sets in a similar scenario. However, the SSC, IDeS, and the DAS services were not yet developed. Still, the results reveal the agents' effective interactions using ontologies, providing the means for interoperable MAS and services.

Paper VII [79] presents a basic energy balance scenario using simulated data to demonstrate how using ontologies and semantic web technologies allows knowledge representation, interoperability and the validation of data and application of business rules. This enables providing flexible and interoperable tools for an inclusive simulation and study environment. Publication [92] focuses on showing the applicability of ontologies for semantic interoperability within the MAS Society. It uses historical data for consumption and generation forecasts, AiD-EM's bid prices definition, and the dummy players' bids. Additionally, the case study describes two approaches for load control, namely, using BRICKS and PLCMAS. Results validate the use of ontologies for providing the MAS Society a solid platform to experiment and study the implications of PES.

Finally, preprint II [81] demonstrates the use of IESO in the simulation of the management of a rural distribution grid. The study concerns the violation of the network's technical limits and consequent execution of a local demand flexibility market. It shows how IESO provides interoperability between heterogeneous agents and services, semantic reasoning and constraints validation, and units conversion. The scenario considers simulated and historical data. The results confirm the accomplishment of IESO requirements and the benefit of applying ontologies and semantic web technologies in developing interoperable and ontology-agnostic agent-based tools with semantic reasoning. Such tools avoid recoding and recompiling each time the model or business rules update, saving time in the tools development phase while facilitating employing completely new and hybrid approaches.

The realization of ontologies for an interoperable society of MAS and services is confirmed by the test and validation of the MAS Society under realistic scenarios and data, thus accomplishing objective 6 of this Ph.D. work. The various case study scenarios produce encouraging results strengthening the adequacy of the MAS Society for the study, operation, and decision support in the scope of PES. Additionally, the studies performed, and the evaluation of their results answer the research question considered in this section.

2.6 Summary

The core contribution of this Ph.D. thesis is the answer to the main research question of this work, i.e.: *Can ontologies effectively contribute to the increase of interoperability between heterogeneous agent-based models, directed to the study and management of power and energy systems and their components, thus making it possible to address the problem as a whole?*

The work developed in the scope of this Ph.D. thesis in pursuit of the answers to the various specific research questions resulted in the development of the MAS Society framework. It answers the main research question by demonstrating how ontologies can contribute to the interoperability between agent-based tools and support services developed for the study, simulation, decision support, operation, and management of distinct areas of PES. The success of the framework produced during this Ph.D. work is assessed throughout its test, analysis, and validation using realistic scenarios. The obtained results support the thesis that ontologies can contribute to increasing interoperability among MAS developed in the scope of PES, thus providing the means to address the problem globally.

Ontologies provide the common ground vocabulary for supporting heterogeneous systems interoperability. By sharing the same conceptualization, tools communicate meaningfully and effectively, ensuring the correct interpretation of the exchanged knowledge. To this end, this work conceived a modular domain ontology to be reused, extended, or mapped by the application-level ontologies of each participating or external platform. In the scope of this Ph.D. work, this domain ontology represents all the domain knowledge necessary for the message exchanges among the various systems of the MAS Society. Its modular architecture aims to promote concepts' reusability while segregating knowledge in multiple interest areas of the PES that can be used independently of each other. The application-level ontologies, in turn, reuse and extend concepts from the domain ontology to describe the tools' applicational knowledge. It is also possible to map application-level concepts with domain concepts. This feature is valuable for external systems to map their proprietary ontologies with IESO, allowing their participation in the MAS Society studies and simulations, reinforcing the potentialities of the developed framework.

Using ontologies for semantic interoperability enables taking advantage of existing tools and their knowledge while leaving the door open for the easy inclusion of new systems to be developed to complement this interoperable society of MAS. Moreover, the use of ontologies in combination with reasoning and semantic web technologies leverages this Ph.D. work providing the means to accomplish systems loosely coupled concerning their data and business models. This feature eases the update of models while keeping the tools flexible and configurable, avoiding reprogramming and recompiling a system each time a model or rule needs to be updated. In addition to the ontologies, this Ph.D. work contributes with a central control platform to ease users' interactions with the MAS Society. Moreover, additional tools developed to complement existing agents-based systems by supporting their operations are proposed.

DAS service gathers heterogeneous data sources to provide historical and real-time data to the agents' community in both JSON and RDF syntaxes. Dev-C service, formerly PLCMAS, enables the control of smart appliances and devices connected via IoT and Modbus protocols. IDeS service (formerly IDeSMAS), in turn, makes decision support algorithms available to the various player and operator agents of the society. SSC service facilitates registration and search of agent- and web-based services to provide platforms with an autonomous connection and interaction. TOOCC MAS is the user's control interface where, besides easing interoperability between the various services and MAS, allows the definition of multiple scenarios, the results' comparison at the end of execution whenever it makes sense, and to distribute the agents across the available machines in the network according to their capabilities. Such a framework contributes to improving the studies of the PES globally, providing regulators, operators, and players with proper tools to test, validate and learn in such a dynamic and constantly evolving environment by supporting hybrid simulations of more complex scenarios.

The contributions of the work developed within the scope of this doctoral thesis provide the answers to the specific research questions, which together answer the main research question. The research work that led to obtaining the answers to the research questions also fulfills all the objectives defined for this Ph.D. work.

Chapter 4

Conclusions and Future Work

3 Conclusions and Future Work

This chapter concludes the thesis manuscript by highlighting the most relevant contributions and conclusions derived from the development of this Ph.D. and finalizing with directions of potential future work.

3.1 Main Conclusions and Contributions

The worldwide electricity sector has undergone major changes over the last decades [1], [2]. The most significant changes are the increase of RES and DG penetration [10] which led to the adoption of the SG paradigm and the introduction of a competitive approach in the electricity wholesale market, and more recently in some aspects of retail markets [13]. SG quickly evolved from a concept widely accepted by the involved parties to an industrial reality. In Europe, the goals of the EU have played an important role in these changes, with the "20-20-20" targets [3] and the constant revisions to these targets currently aiming for the EU to be climate-neutral with an economy with net-zero GHG emissions by 2050 [5], [6]. The restructuring of EM has been another major concern of the EU, particularly with the formation of pan-European EMs, namely for the day-ahead market with the PCR project [14]–[16] and for the intraday market with the SIDC [17].

In this context, simulation and decision support tools are essential for studying the different market mechanisms and the relationships among their stakeholders. MAS-based tools are particularly well suited for analyzing complex interactions in dynamic systems, such as the PES, due to the facilitated inclusion of new models, market mechanisms, types of participants and different types of interactions. However, these platforms focus on solving specific problems from specific areas or subdomains of PES. One of the main challenges in this area is the development of simulation and decision support tools to address the problem globally.

Despite the significant advances already made, using these tools individually fails to capture the authenticity and accuracy required for the simulation and study of the energy domain, since subdomains have a meaningful impact on each other, influencing the outcomes. There is a clear need for more realistic and precise study and management tools in the scope of PES. It is fundamental to provide interoperability between the different systems that study specific parts of the PES to overcome the accuracy, authenticity, and reliability issues. The interaction of heterogenous systems promotes the sharing of models and knowledge, enabling to study more complex and complete scenarios closer to the real world and benefiting regulators, operators, and players with proper tools to learn from experience and adapt themselves to the PES reality. This gap led to the specification of the various research questions, which were the basis for defining the objectives of this Ph.D. work.

This thesis conceives a society of MAS for the study, simulation, decision support, operation, and management of PES, conceptualizing an ontology-based knowledge model to represent the domain concepts and provide the means for supporting meaningful communications and knowledge sharing between the several considered systems, applications, and services. The MAS Society integrates existing MAS developed to operate distinct subdomains of the PES with newly developed tools and services, overcoming the identified issues that compose the main topic addressed in this Ph.D. work.

MASCEM and AiD-EM address, respectively, the EM simulation and decision support. MASGriP, in turn, models and simulates the SG and microgrid environments and respective participating entities. The newly developed tools aim to take advantage of these tools' capabilities while opening the way for including new systems that may arise. To this end, SSC provides a registration and search platform to ease the process of finding available services and support interactions between the different tools and services in an autonomous way. IDeS makes available several decision-support algorithms for different types of SG operators and players by registering those services at SSC. DAS, in turn, contributes with real-time and historical data ranging from the building to the SG and EMs. Dev-C allows agents and services to control physical devices abstracting them from the used communication protocols. Finally, TOOCC provides users with a centralized interface to control, configure, simulate, and study the PES globally or just a specific part, as desired.

The developed ontologies facilitate the interoperability between heterogeneous systems giving semantic meaning to information exchanged between the various parties. The advantage lies in the fact that all the members of the MAS Society know them, understand, and agree with the concepts defined therein. Moreover, combining ontology reasoning and semantic web technologies made it possible to develop more flexible and adaptable systems capable of following up with the dynamic and quick-evolving reality of the sector by keeping the tools agnostic to the semantic model and business rules that are applied. Besides, it also eases the implementation and validation of new models, including model combinations, which is a relevant feature for regulators and operators to test and certify that they fit the sector's reality and for players to learn and adapt to new realities.

The work developed has been subject to validation under laboratory and real-world environments, using historical, real-time, and simulated data to ensure the adequate integration and functioning of the diverse MAS and services in realistic conditions and scenarios. The achieved results show the achievement of the determined objectives to answer the defined research questions, contributing to significant advances in the state of the art of interoperable platforms overall, and in specific for those developed for the study, simulation, decision support, operation, and management in the scope of PES. The nineteen scientific papers published as result from this Ph.D. work and the contribution of the developed work in accomplishing the goals of various national and international projects are clear indicators of the relevance of the achieved findings.

3.2 Perspectives of Future Work

The development and results achieved in the realization of this Ph.D. work provide the foundation for future research and development for continuously evolving the proposed framework and knowledge model, following alongside with the PES evolution and the needs of the involved entities. Among the many ideas for future research paths that this thesis promotes, the most relevant ones are listed as follows:

- The IESO domain ontology must be continuously upgraded and maintained while ensuring the established requirements. There are already three new modules in development for context-based decision support and profiles, namely: the Context module, which describes different contexts relevant for ontology reasoning-based decision support; the Profile module, representing diverse types of profiles according to a given context; and a module integrating knowledge from the various AI-based algorithms available to the agents' community;

- Different modules of IESO will soon provide mappings with existing and well-established domain ontologies that represent and describe related knowledge that can be aligned with those modules. The mapping files will be available on the webpages of the respective modules;

- Another relevant step forward is to upgrade the application-level ontologies. In PES, several entities can assume multiple roles in the SG and EM domains. Describing those roles in application-level ontologies (extending IESO's Actor module) allows developing a semantically configurable software agent that can assume multiple roles and related behaviors at execution time. This approach allows to experiment and test different options by combining different roles, also contributing to avoiding recoding by taking advantage of ontologies and semantic web technologies;

- IESO will be the basis of the semantic model of the PRECISE project, which combines explainable AI with semantic reasoning and learning for the intelligent management and control of PES cyber-physical solutions, thus further extension on the semantic model is proposed to enable capturing the expressiveness required by explanations;

- Often, to perform a complex task, the composition of multiple microservices is required. To this end, one of the following steps is to upgrade SSC to provide automatic service composition by breaking down a search request into several queries to verify if a given composition makes sense to generate the desired outcome. If the suggestion fits the client's needs, it will be stored as a composite service for future use. This task will employ multiple techniques of service discovery and composition;

- With the upgrade of the MAS Society, by adding new systems or physical infrastructures, the DAS and Dev-C services will be updated accordingly to accommodate the new data models and communication protocols that may arise;

- The IDeS framework will offer the possibility of choosing RDF serialization in the services' requests and responses, applying the linked data principles. This way, agents will be able to use the algorithms output data directly without translating it from JSON to RDF and vice versa. To this end, the request will identify the accepted response format(s) using the "Content-Type" header;

- Although TOOCC already provides the comparison of results at the end of simulations, the mappings between output models are currently configured manually by the user (unless the user is comparing results of the same tool with different input data). An interesting approach would be making TOOCC suggest the user for results comparison whenever it makes sense. It is possible to make automatic suggestions to the user by taking advantage of the common ground domain vocabulary and exploring the reasoning capabilities of the system;

- Continuously evolve the MAS Society framework by adding new tools, services, and models to improve the studies and results of realistic or alternative approaches, from the EMs to the SGs and final consumers energy management, providing users with a complete simulation, decision support, operation, and intelligent management platform for the PES.

Most of the perspectives of future research work are relevant, not only as future development work of this Ph.D. thesis but also to some ongoing national and international projects, which ensure the continuation of the research undertaken in this Ph.D. work, namely:

- TIoCPS – Trustworthy and Smart Communities of Cyber-Physical Systems, project no. 18008, funded by European Union's EUREKA – ITEA 3;

- TradeRES – New Markets Design & Models for 100% Renewable Power Systems. Funded by the European Union's Horizon 2020 research and innovation program under grant agreement 864276;

- PRECISE – Power and Energy Cyber-Physical Solutions with Explainable Semantic Learning, reference no. PTDC/EEI-EEE/6277/2020;

- MAS-Society – Multi-Agent Systems SemantiC Interoperability for simulation and dEcision supporT in complex energY systems, reference no. PTDC/EEI-EEE/28954/2017

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Appendix

Appendix A. Core Publications

Core Publication I

Gabriel Santos, Zita Vale, Pedro Faria, Luis Gomes, "BRICKS: Building's reasoning for intelligent control knowledge-based system", Sustainable Cities and Society, vol. 52, no. 101832, pp. 1-15, January 2020, DOI: 10.1016/j.scs.2019.101832. (2020 Impact Factor: **7.587**).

Resumen

Los sistemas de gestión energética de edificios se han implementado en gran medida, centrándose en dominios específicos. Cuando se instalan juntos, carecen de interoperabilidad para que funcionen correctamente y para lograr una interfaz de usuario centralizada. El razonamiento del edificio para el sistema basado en el conocimiento de control inteligente (BRICKS por sus siglas en inglés) supera estos problemas mediante el desarrollo de un sistema de gestión de edificios interoperable capaz de agregar diferentes dominios de interés. Es un sistema basado en reglas semánticas y consciente del contexto para la gestión inteligente de la energía y la seguridad de los edificios. Su salida puede ser un conjunto de alarmas, notificaciones o acciones de control a realizar. BRICKS en sí, y sus características son la contribución innovadora del presente artículo. Es muy importante para la gestión energética de los edificios, concretamente en el ámbito de los programas de respuesta a la demanda. En este trabajo se muestra cómo se utiliza la semántica para permitir el intercambio de conocimiento entre diferentes dispositivos, algoritmos y modelos, sin necesidad de reprogramar el sistema. Un escenario es desplegado en un edificio real para demostración.

Core Publication II

Brígida Teixeira, Gabriel Santos, Tiago Pinto, Zita Vale, Juan M. Corchado, "Application Ontology for Multi-Agent and Web-Services' Co-Simulation in Power and Energy Systems", IEEE Access, vol. 8, pp. 81129-81141, April 2020, DOI: 10.1109/ACCESS.2020.2991010. (2020 Impact Factor: **3.367**).

Resumen

Los sistemas de potencia y energía son muy complejos y hay varias herramientas disponibles para ayudar a los operadores en su planificación y operación. Sin embargo, estas herramientas no permiten un análisis sensible del impacto de la interacción entre los diferentes subdominios y, en consecuencia, en la obtención de resultados más realistas y fiables. Uno de los desafíos clave en esta área es el desarrollo de herramientas de apoyo a la toma de decisiones para abordar el problema como un todo. El Centro de Control de Herramientas – TOOCC por sus siglas en inglés - propuesto y desarrollado por los autores, permite la co-simulación de sistemas heterogéneos para estudiar los mercados eléctricos, el funcionamiento de las redes inteligentes y la gestión energética del consumidor final, entre otras cosas. Para ello, utiliza una ontología de aplicación que soporta la definición de escenarios y comparación de resultados, mientras que facilita la interoperabilidad entre los distintos sistemas. Este artículo presenta la ontología de la aplicación desarrollada. El trabajo aborda la metodología utilizada para su desarrollo, su propósito y requerimientos, y sus conceptos, relaciones, facetas e instancias. La aplicación de la ontología se ilustra a través de un estudio de caso, donde se prueban y demuestran diferentes requisitos. Se concluye que la ontología de aplicación propuesta cumple sus objetivos, ya que es adecuada para representar el conocimiento requerido para apoyar la interoperabilidad entre los diferentes sistemas considerados.

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Application Ontology for Multi-Agent and Web-Services' Co-Simulation in Power and Energy Systems

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ABSTRACT Power and energy systems are very complex, and several tools are available to assist operators in their planning and operation. However, these tools do not allow a sensitive analysis of the impact of the interaction between the different sub-domains and, consequently, in obtaining more realistic and reliable results. One of the key challenges in this area is the development of decision support tools to address the problem as a whole. Tools Control Center – TOOCC – proposed and developed by the authors, enables the co-simulation of heterogeneous systems to study the electricity markets, the operation of the smart grids, and the energy management of the final consumer, among others. To this end, it uses an application ontology that supports the definition of scenarios and results comparison, while easing the interoperability among the several systems. This paper presents the application ontology developed. The paper addresses the methodology used for its development, its purpose and requirements, and its concepts, relations, facets and instances. The ontology application is illustrated through a case study, where different requirements are tested and demonstrated. It is concluded that the proposed application ontology accomplishes its goals, as it is suitable to represent the required knowledge to support the interoperability among the different considered systems.

INDEX TERMS Application Ontology, Co-simulation, Multi-Agent Systems, Power and Energy Systems, Semantic Interoperability, Web-Services

I. INTRODUCTION

CONSIDERING the climatic urgency that society is facing in recent years, the European Commission (EC) has defined a set of targets to be achieved by 2020, known as 20-20-20 targets [1], [2]. These targets are: i) a 20% reduction in CO_2 emissions compared to 1990 levels; ii) a 20% increase in energy efficiency; and iii) increase the use of Renewable Energy Sources (RES) to represent 20% of energy production in the European Union. As a result, the EC intends to achieve a significant change in the energy sector, by implementing new legislation to increase the inclusion of RES and make their use more intelligent and sustainable. The evolution of Power and Energy Systems (PES) to support the intermittent nature of RES raises new challenges [3], [4]. It is crucial to reduce the inherent risk in the intermittency and unpredictability of the use of RES, to lower prices for production and installation of renewable generation technology, to adapt the existing physical infrastructure, and to adopt new regulatory measures, among others. Electricity Markets (EM) have also to be adapted to the different segments of PES (e.g. generation, transmission, distribution, and commercialization), to the new policies and needs of RES penetration, by conceiving and implementing new market models, changing the market operation rules, and creating new legislation [5], [6].

In this context, the use of simulation tools developed to analyze and study the PES domain is indispensable, since they allow the participating entities to deal with its unpredictability and complexity [7], [8]. Simulators based on multi-agent technology have particularities that make them suitable tools for the study of PES, mainly due to their distributed nature [9], [10]. These tools make it easier to model the various

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systems and entities, as well as their constraints, making the model closer to reality, while decomposing the problem into less complex modules. Although there are several tools in the literature for the study of PES, most of them only solve problems of a specific PES sub-domain. Therefore, by using those tools individually, it is not possible to simulate and study the energy sector with realism and precision, as the sub-domains have a great interdependence that strongly impacts the results [11].

One possible solution to take advantage of existing and well-established PES simulation tools, is to make them interoperable through middleware that enables the co-simulation of heterogeneous tools [12]–[16]. A set of interoperable tools provides results with higher reliability and realism, besides of a better understanding of wider implications, restrictions and influences [17]. It is possible to find in the literature a few solutions for the cooperation of simulation tools in PES, namely the Electric Power and Communication Synchronizing Simulator (EPOCHS) [12], the Global Event-driven Co-simulation (GECO) [13], Mosaik [14], and Tools Control Center (TOOCC) [15], [16], conceived and developed by the authors of the current paper.

These tools use different approaches to achieve interoperability between heterogeneous systems. From these, TOOCC is the only tool that takes advantage of semantic web technologies for the interoperability with external systems. Ontologies give semantic meaning to the data exchanged between heterogeneous parties, promoting their interoperability [18]. The motivation for the development of ontologies as a means to provide interoperability between heterogeneous Multi-Agent Systems (MAS) in the scope of PES is addressed in [19], where the inclusion of external systems that may arise in the future is also considered.

This paper presents TOOCC's application ontology for MAS and web-services co-simulation in PES. TOOCC's semantic model describes the scenarios' configuration while easing the interoperability between the different simulation tools and enables the subsequent comparison of results, thereby overcoming the identified limitations in the field.

The following section gives a background on the different co-simulation tools found in literature, describing their limitations, and explaining how TOOCC overcomes those limitations. Section III presents an overview of TOOCC, detailing its architecture, the multi-agent model, and explaining why semantic interoperability has been chosen. Section IV introduces TOOCC's ontology, describing its concepts, properties, and purposes. Section V demonstrates the usefulness of TOOCC's semantic model through a case study where the ontology evaluation is also carried out. Finally, section VI presents the conclusions of this work.

II. BACKGROUND

Few relevant tools have emerged in the literature to provide interoperability among already existing PES well-established simulators. Examples of such tools are EPOCHS [12], GECO [13], Mosaik [14], and TOOCC [15], [16].

EPOCHS [12] is a multi-agent platform created to simulate PES components together with the communication network, to study the grid with the aim to prevent blackouts. It essentially combines three simulators: i) the Power Systems Computer-Aided Design/Electromagnetic Transients including Direct Current (PSCAD/EMTDC) [20]; ii) the Positive Sequence Load Flow (PSLF) [21]; and iii) the Network Simulator 2 (NS2) [22]. An entity called Runtime Infrastructure (RTI) performs the interface between all components, ensuring the synchronization in the messages' exchange. To interconnect these simulators, EPOCHS uses an application programming interface (API) encapsulated by the RTI.

GECO [13] has similar characteristics to EPOCHS, as it also integrates NS2 and PSLF simulators. Its purpose is to validate monitoring schemes, control, and grid protection. The communication between GECO and the simulation tools NS2 and PSLF is made through both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). The messages exchanged include information about power data and control commands.

Mosaik [14] provides interoperability among heterogeneous applications through two components: the simulation interface (SIM API) and the Master Control Program (MCP). The SIM API enables the communication between Mosaik and external simulation tools, while the MCP manages the scenarios' composition and the tools' execution. To integrate a new tool with Mosaik, it is necessary to proceed with the implementation of a default interface to guarantee the proper model configuration and the scheduling of the tasks' execution.

Although these three solutions allow interoperability with external tools, only Mosaik provides a way to integrate any tool, while EPOCHS and GECO are restricted to the simulators they use. Furthermore, whenever it is intended to run a different scenario, their configuration, data preparation, and execution's schedule definition, are complex tasks since there is a need to write code. Ideally, the execution of alternative scenarios should be possible with a simple system reconfiguration, without the need of reprogramming it. It is possible to realize that these tools were not designed having in mind a smooth scenarios' definition, nor a simplified results analysis.

On the other hand, semantic-based approaches are particularly suitable for solving interoperability issues [23]. Semantic models establish a common vocabulary so that applications can interact and communicate, regardless of the communication mechanisms [24]. Furthermore, it is possible to compose more sophisticated solutions by reusing already existing robust applications and merging different domains, without interfering with their capabilities [25]. Besides, these models combined with semantic reasoners allow to perform more intelligent tasks such as complex queries, the application of rules, and to infer new knowledge.

TOOCC [15], [16] has been conceived to overcome the previously identified limitations in the co-simulation domain. TOOCC has been proposed by the authors as a multi-agent

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tool capable of creating, simulating, and analyzing scenarios covering different PES domains through the interoperability between heterogeneous simulation tools developed in the GECAD research center. TOOCC takes advantage of ontologies to be able to interoperate with different systems. On one side, domain ontologies are used to describe the knowledge exchanged between the external systems. On the other, the formalization of the scenarios and respective simulations' configuration is achieved by TOOCC's application ontology that enables the definition of the external tools to be used, their input and output models, their input data, order of execution, and how the results shall be analyzed. The following section overviews the TOOCC tool, describes its architecture and multi-agent model, as well as the options made on semantic interoperability.

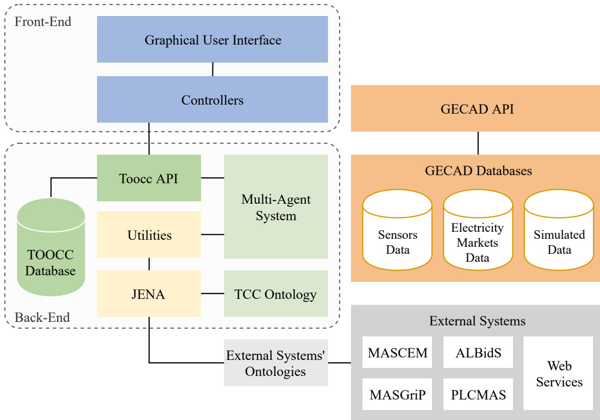

FIGURE 1. TOOCC's architecture.

III. TOOCC OVERVIEW

Tools Control Center (TOOCC) [15], [16] is a co-simulation solution that acts as a facilitator between heterogeneous tools, enabling them to share vocabularies and concepts, and thus collaborate in the simulation of PES scenarios. It allows us to simulate complex scenarios that result from merging the individual capabilities of each embedded tool, considering different PES domains in the same scenario, making the simulation more realistic and precise.

TOOCC can be seen as a decision support system, as it provides the user with the means to analyze different problems with different particularities. It can be adopted to study PES from the perspective of various entities, such as system operators, market operators, grid operators, aggregators, prosumers, producers, consumers, among others. There are several domains where TOOCC is being used, namely: electricity markets, to study the impact of the inclusion of RES, buildings energy management, demand response (DR), tariffs application, among others. The simulation for specific time horizons (e.g.: real-time, hour-ahead, day-ahead) is also considered, as well as the analysis and results comparison of alternative scenarios. TOOCC has been designed having in mind the reduction of the complexity in the definition of simulation scenarios.

A. ARCHITECTURE

The need to establish interoperability between heterogeneous systems is one of TOOCC's key goals. TOOCC's architecture enables the communication with external systems regardless of the programming languages they have been developed. It also supports scalability and distribution of agent-based systems, considering the processing capacity of the machines available for the simulation. Figure 1 illustrates the core modules of TOOCC's architecture.

Analyzing Figure 1, it is visible that TOOCC's architecture is based on two main modules: the *Front-End*, for the user's interaction, and the *Back-End*, where the processing occurs. The interaction between the *Front-End* and the *Back-End* is established through the communication between the *Controllers* and the *Toocc API* sub-modules. The *Multi-Agent System* sub-module is responsible for managing the interoperability with the external systems, as well as for scheduling simulation scenarios defined by the user. Additionally, TOOCC uses auxiliary libraries to communicate, interpret, and transform the knowledge exchanged among the various integrated systems.

B. MULTI-AGENT MODEL

TOOCC is developed in Java using the Java Agent DEvelopment framework (JADE) [26], [27], which is compliant with the Foundation for Intelligent Physical Agents (FIPA) [28] standards.

FIPA promotes the *Agent Communication Language* (ACL) as the standard for communication between agent-based systems. It is also possible to add meaning to the messages exchanged through the use of ontologies, which allow the definition of syntax and semantics to their content. Consequently, agents are able to communicate meaningfully since they can interpret each message correctly.

Figure 2 presents TOOCC's multi-agent model.

This model considers six types of agents that provide a conceptual perspective on the execution of a scenario, namely:

- *TOOCC API Agent* (ApiA): is the agent responsible for bridging the *Toocc API* with the *Multi-Agent System* sub-module. It asks the main agent to run the simulation and waits for the results.
- *TOOCC Main Agent* (TMA): is the agent responsible for initiating and coordinating the entire simulation at a high level. When the simulation starts, it triggers the creation of a *Scenario Agent* for each configured scenario. It also concludes the simulation after the execution of all *Scenario Agent*s.
- *Scenario Agent* (ScenA): is responsible for coordinating the execution of a specific scenario. The execution phases are managed by creating *Step Agent*s and ensuring that the scenario runs entirely.
- *Step Agent* (StepA): its function is to manage communications with external systems in parallel. That is, it

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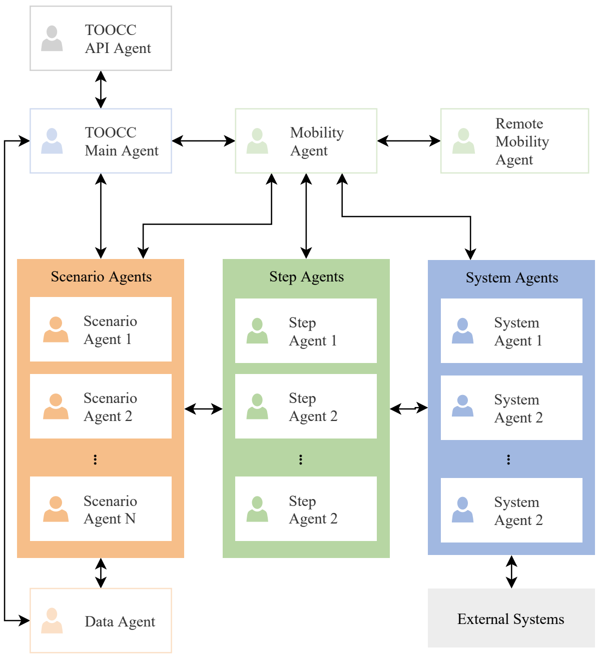

FIGURE 2. TOOCC's multi-agent model.

will create *System Agent*s that will simultaneously communicate with their respective external systems, within the same execution phase, allowing agility in obtaining results.

- *Service Agent* (ServA): establishes direct communication with external systems, being aware of the semantics used in the communication. As soon as it receives the results, it notifies its creator (*Step Agent*).
- *Mobility Agent* (MobiA): has the responsibility to distribute the several agents to the available machines. The decision is made according to the operating system and software installed on each machine.
- *Remote Mobility Agent* (RMobA): it is hosted on the available domain machines to which the agents can be moved and communicates with the *Mobility Agent* sending the information it needs to decide where to move the simulation agents.
- *Data Agent* (DataA): performs centralized management of simulation data, ensuring that the results are stored correctly, and that the status of each simulation point is updated, ensuring complete system's execution.

In addition to the agents presented, there are also others native to JADE. These are the *Directory Facilitator* agent as a yellow page directory for service delivery, the *Agent Management System* agent for the management and control of agents and platform, and the *Remote Agent Management* which provides a graphical interface for managing and viewing agent status and communications.

C. SEMANTIC INTEROPERABILITY

Establishing interoperability between heterogeneous systems is a complex task. It is not just the exchange of data messages between systems, but the exchange of knowledge. This knowledge can be about the domain, about data, or about features that can be made available and shared.

In computer science, ontologies describe vocabularies that can model domains shared between heterogeneous entities [29]. The inclusion of semantics in the messages exchanged allows an unambiguous conceptualization about the knowledge shared by both parties, making the communication more effective by removing misunderstandings. Additionally, other advantages result from the use of semantic models, such as computational inference and knowledge reuse [30]. They can be used to develop systems decoupled from the data model, with a high level of abstraction and flexibility that eases the evolution of the system, such as in [31]; as well as to validate the system's knowledge or apply rules by using, for example, the Semantic Web Rule Language (SWRL) [32].

Using these techniques, it is possible to strategically use the individual capabilities of each external tool integrated with TOOCC, allowing the study of scenarios addressing several PES sub-domains. At the same time, it allowed to develop TOOCC with the ability of integrating any external tool without the need to be reprogrammed, nor to extend any of TOOCC's class, nor to implement any interface in the system to be integrated.

TOOCC's semantic model is described in Section IV, where the engineering process is detailed, namely its purpose, goals, requirements, implementation, evaluation, and evolution.

IV. TOOCC'S APPLICATION ONTOLOGY

TOOCC makes use of semantics to ensure the co-simulation between heterogeneous simulation tools. These simulation tools may be MAS or web services available in the authors' research center laboratory. Each system that interoperates with TOOCC has its knowledge model, which can be semantic or syntactic, and must be considered to ensure the systems' co-simulation. This section presents TOOCC's application ontology (TCC), the methodology used in the engineering process, and the options made to fulfill our requirements. There are several methodologies for the development of ontologies that specify the methods, principles, and rules to follow during the engineering process [33]. These processes support the specification, conceptualization, formalization, implementation, and maintenance of an ontology, which result in its life cycle. TCC was developed based on the 101 development methodology [34]. This approach is characterized by its simplified view regarding the ontology development. It is based on the premise that the development of an ontology is an iterative process, where the ontology is continuously refined to the needs of its users. This method considers that there are several possible approaches for the representation of a domain, where the concepts and their

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relations must be clearly stated through the specification of subjects and predicates.

The 101 methodology is based on the following steps:

- Scope and domain identification;
- Reuse of ontologies;
- Enumeration of important terms;
- Classes definition;
- Properties definition;
- Properties facets definition;
- Creation of instances.

TCC was written using the open-source application Protégé [35]. It has Ontology Web Language with Logic Description (OWL-DL) [36] syntax, being represented in the Resource Description Framework (RDF) Turtle language [37]. Being an application ontology, TCC is embedded in the TOOCC's application as a resource file. The following subsections specify TCC's development process.

A. DOMAIN AND SCOPE

TCC's purpose is to configure TOOCC's simulations, facilitate the process of interoperability between external tools ran by TOOCC, and enable the results' comparison, when applicable, at the end of the simulation. To this end, TCC must be able to: i) describe TOOCC's configuration model (i.e., the model that describes the simulations); ii) include the input and output data models of external systems (semantic or syntactic); iii) reuse the output model of a system (or part of it) to get the necessary data for the input of the next system to execute; and iv) to take advantage of the output models to perform the automatic results' comparison, whenever it makes sense.

Since the input and output models of the systems to be integrated can be semantic or syntactic, TCC must be agnostic regarding other data models. TCC must be able to use other ontologies whenever required, but it does not need to import them. However, these models must be publicly available or shared by the external tools.

Thus, the following functional requirements have been defined to fulfill all the above-mentioned objectives:

- The model must allow the configuration of a set of simulations to be run simultaneously;
- The model should allow configuring different scenarios in each simulation (to be executed simultaneously too, where, after execution, the results can be compared);
- A scenario consists of one or more steps;
- A step can include one or more external systems that provide services (the step ensures that all services in it are performed before proceeding to the next step. Services in the next step are waiting for the results of the previous step);
- Each service (provided by a given system) includes input and output data models, as well as the input data source;
- The input data source can be a local file, a web resource, or a database;
- The model must allow the automatic results' comparison at different levels, namely: simulation level, scenario level, or service level.

Regarding the non-functional requirements, the following have been determined:

- Accuracy - determines if the knowledge asserted in the ontology is according with the domain expert's knowledge;
- Clarity - validates if the ontology communicates effectively the intended meaning of the defined terms;
- Cohesion - refers to the ontology's relatedness of elements, i.e., if the defined classes are strongly related;
- Completeness - checks if the ontology can answer all the questions;
- Computational efficiency - relates to how fast tools (like reasoners) can work with the ontology;
- Conciseness - reflects if the ontology defines irrelevant or redundant elements regarding the domain;
- Consistency - ensures that the ontology does not include nor allow contradictions;
- Coverage - how well the ontology represents the domain model.

The functional and non-functional requirements help to efficiently identify the knowledge that the ontology must define. Additionally, they also offer a baseline for the validation and verification of the developed model.

B. REUSING ONTOLOGIES

One of the first phases to be considered in the ontology development process concerns the reuse of other existing ontologies. Although there are several ontologies publicly available in [38] specifying concepts that could be useful to the configuration of TOOCC's simulations, these semantic models were designed for different purposes in different domains and contexts. Thus, they include decontextualized vocabulary regarding TOOCC's configuration purpose. For this reason, TCC does not import any ontology. On the other hand, importing those inappropriate models could lead to inconsistencies or ambiguity, since a concept may have distinct meanings depending on the context or domain.

However, it is important to keep in mind that TCC must be able to work with the data models (semantic or syntactic) of the external systems with which it operates. Regarding the semantic models of external systems, one option could be to import them into TCC. However, it implies that whenever a system is included in TOOCC, TCC ontology also has to be redesigned to ensure there are no inconsistencies nor ambiguity, which is very time costly.

Instead, it is intended that TCC establishes a relationship with the input/output models of external services, being desegregated from the domain concepts of each system, unnecessary to the configuration of simulations in TOOCC. As a result of this approach, TOOCC's semantic model will only know the necessary vocabulary to perform its tasks. In this way, well established PES ontologies such as SEAS [39], SAREF [40], EMO [41], DABGEO [42], among others, can be used by tools that interoperate within TOOCC, without the need to be imported by TCC.

C. ENUMERATION OF IMPORTANT TERMS

Another important step in the development of an ontology is the enumeration of important terms that must be represented as concepts. These concepts are introduced in the ontology as a class hierarchy.

Considering TCC's domain and scope, these are the terms that describe the sufficient and necessary conditions to meet the above-mentioned requirements:

- **Simulation Set** - it is the root element of the configuration, where several simulations can be configured to run simultaneously;
- **Simulation** - this term describes a user defined simulation;
- **Scenario** - to define a simulation scenario, since a user may want to run simultaneously different scenarios and compare their results at the end;
- **Step** - identifies the execution phase of a scenario, helping the system to realize which services can run concurrently;
- **Service** - describes an external service (agent-based or web service) used at a phase of a scenario;
- **Input Model** - defines the input model (semantic or syntactic) of a service;
- **Output Model** - defines the output model (semantic or syntactic) of a service;
- **Input Data Source** - identifies the service's data source, which can be a local file or web-based;
- **File Data Source** - describes a service's file data source;
- **Web Data Source** - describes a service's web-based data source;
- **Comparable** - identifies classes that can be compared between instances of themselves.

The following subsection details the definitions of classes and their sub-classes, as well as their properties, facets, and instances.

D. CLASSES, PROPERTIES, FACETS AND INSTANCES

TCC's concepts were created using the middle-out approach, which starts from the most fundamental terms in the domain before moving on to more abstract and more specific terms. According to [43], it makes it easier to relate terms more precisely while it is also likely to reduce rework.

In the previous subsection, a list of terms and respective descriptions were defined to assist in the development of the classes and properties of the ontology. Figure 3 introduces TCC's class hierarchy and the relations between them. Each class (in italic) is then described, including the relationships (in blue) between them.

The $Comparable$ class allows the abstraction of classes that are intended to be comparable between instances of themselves, namely the $Simulation$, the $Scenario$, and the $Service$ classes. It is an abstract class that is not supposed to be instantiated by itself. Instead, one must instantiate its sub-classes, ensuring that they are only comparable to other instances of the same class.

The $SimulationSet$ class is the root concept in TCC's model. It gathers the various simulations configured by the user, resulting in a set of $Simulation$ instances. Each $Simulation$ instance is related to this class by using the $hasSimulation$ object property.

The $Simulation$ class describes a user-defined simulation. It is a subclass of $Comparable$ and collects a set of $Scenario$s, by using the $hasScenario$ object property, as well as a set of comparable $Simulation$s settle by the $hasComparable$ object property, ensuring that only instances of itself are accepted.

In turn, the $Scenario$ class describes the user-defined scenario. It is also a subclass of $Comparable$, meaning that a set of comparable $Scenario$s can be included by using the $hasComparable$ object property, allowing only instances of the $Scenario$ class. This class reunites a set of $Step$s established through the object property $hasStep$.

The $Step$ class describes the execution phase of a scenario. The execution phase allows the system to understand which services will run concurrently. A $Step$ has configured one or more $Service$s through the $hasService$ relationship. Each $Step$ is related to the next by the $hasNext$ object property, and to the previous by the $hasPrevious$ object property. It must be stressed that the first $Step$ of each $Scenario$ only has the $hasNext$ object property, while the last $Step$ only considers the $hasPrevious$ object property.

The $Service$ class defines a service provided by a MAS or a web-service. It is a subclass of $Comparable$, allowing only to add $Service$s instances with the object property $hasComparable$. Similarly to the $Step$ class, a $Service$ is also related to the previous or next service to be executed by using the $hasPrevious$ and $hasNext$ object properties. However, both its precedents and the following belong to different implementation phases, i.e., $Step$s. These properties serve to create a precedence in which the result of a service will serve as input to the next one. In addition, a $Service$ is characterized by an $InputModel$ and respective $InputDataSource$, an $OutputModel$, and the actual result. The object properties $hasInputModel$, $hasInputDataSource$, and $hasOutputModel$ relate the class $Service$ to the classes $InputModel$, $InputDataSource$, and $OutputModel$ respectively. In turn, the $hasResult$ object property relates to the superclass $owl:Thing$. This way, the result of a $Service$ can be related to instances of the service's output model.

The $InputModel$ and $OutputModel$ classes characterize the $Service$'s input and output models, respectively. These are abstract classes that enable a recursive definition of $InputModel$s and $OutputModel$s, by using the $hasInputModel$ and $hasOutputModel$ object properties respectively. This way, a complex model can be composed of simpler ones recursively. On the other hand, it is also allowed

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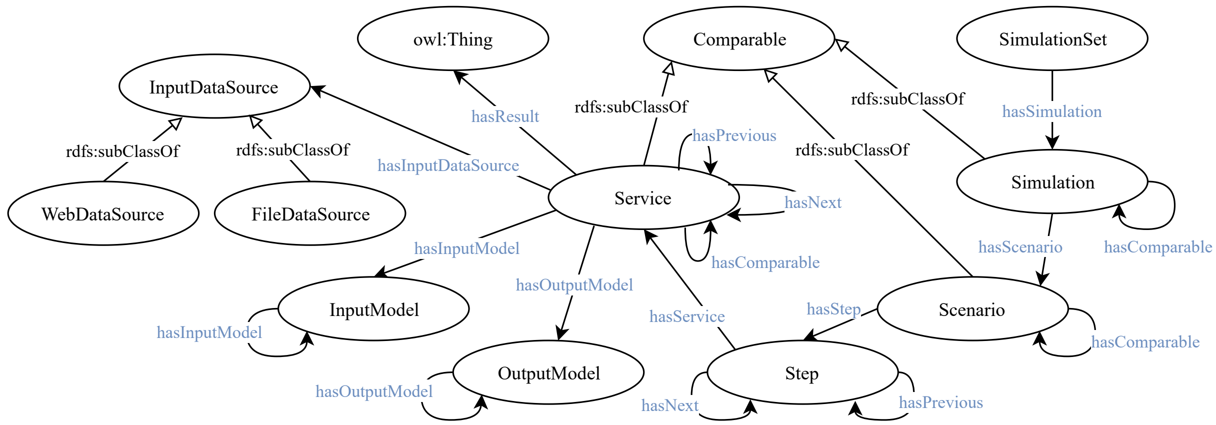

FIGURE 3. TCC's classes and relations.

to define an existing input model (from other ontology) as a subclass of $InputModel$, as well as an existing output model as a subclass of $OutputModel$. Thus, the reuse of semantic data models from external systems is assured. Regarding syntactic data models, their use is guaranteed through their (XML[1] or JSON[2]) schemes, made available by the tools integrated in TOOCC. These are identified by Uniform Resource Identifiers (URIs) that can be included in the ontology as subclasses of $InputModel$ and $OutputModel$, since classes are identified as URIs in RDF languages [37]. TOOCC is then able to interpret those schemes to operate with the integrated systems.

Finally, the $InputDataSource$ class defines the data source responsible for providing data to the input model. It is an abstract class that is not supposed to be instantiated. Instead, one must use its sub-classes, namely the $FileDataSource$ and the $WebDataSource$ classes. The former describes files as input data sources, while the latter declares APIs end-points as data sources.

So far, we have seen the class hierarchy and relations (object properties) among them. The next step is to present the classes' attributes (datatype properties), their value types, and the properties' cardinality. The value type is the most relevant facet in the development of an ontology, as it defines the type of each property used in the classification process [44].

Table 1 presents TCC's classes, their properties, and respective facets, where TCC's object properties are written in blue, and the datatype properties are in green.

Observing Table 1, it can be seen that both the $Comparable$ and $InputDataSource$ classes have no properties defined. As already explained, these are abstract classes that are not supposed to be instantiated.

In the $SimulationSet$ class, the $hasSimulation$ object property must have at least one $Simulation$ class associated. In turn, the object properties $hasInputModel$ and $hasOutputModel$, of $InputModel$ and $OutputModel$ respectively, have no cardinality restrictions.

The $Simulation$ class is defined by an unsigned integer id, a string $name$, a string $description$, and a $created$ and a $modified$ date-time. The $hasComparable$ and the $hasScenario$ object properties must have at least one $Simulation$ or $Scenario$ classes respectively.

The $Scenario$ class is also defined by an unsigned integer id, a string $name$, a string $description$, and a $created$ and a $modified$ date-time. Additionally, it is also described by an unsigned integer $numberOfSteps$, with the number of $Step$ classes set with the object property $hasStep$. The $hasStep$ object properties must have at least one $Step$ class, while the $hasComparable$ object property can have one or more $Scenario$ class.

The $Step$ class, in turn, is defined by one unsigned integer $step$ describing the number of the execution phase (i.e., the $Step$ number), and one boolean flag ($isCompleted$) to indicate if the $Step$ has finished its execution. The $hasService$ object property must have at least one $Service$ set, while the $hasPrevious$ and $hasNext$ object properties can only have at most one $Step$ each.

The $Service$ class is not defined by any datatype property. Similarly to $Simulation$ and $Scenario$, the $hasComparable$ object property, if set, must have at least one $Service$ class defined. In the same way, the $hasPrevious$ and $hasNext$ object properties can only relate to one $Service$ at most. Finally, the $hasInputModel$, the $hasInputDataModel$, the $hasOutputModel$, and the $hasResult$ object properties, can only be related to one $InputModel$, one $InputDataModel$, one $OutputModel$, and one $owl:Thing$ respectively.

In turn, the $FileDataSource$ and the $WebDataSource$ classes are not defined by any object property. The $FileDataSource$ object is defined by exactly one URI $filePath$ datatype property describing the local file path, at most one string $fileFormat$ datatype property with the file format, and one URI $parseFileTo$ datatype property

[1] https://www.w3.org/XML/Schema
[2] https://json-schema.org/

TABLE 1. TCC's classes, properties and facets.

Class	Properties	Facets
Comparable		
Simulation-Set	*hasSimulation*	≥ 1 *Simulation*
Simulation		*Comparable*
	id	1 *unsignedInt*
	name	1 *string*
	description	1 *string*
	created	1 *dateTime*
	modified	1 *dateTime*
	hasComparable	≥ 1 *Simulation*
	hasScenario	≥ 1 *Scenario*
Scenario		*Comparable*
	id	1 *unsignedInt*
	name	1 *string*
	description	1 *string*
	created	1 *dateTime*
	modified	1 *dateTime*
	numberOfSteps	1 *unsignedInt*
	hasComparable	≥ 1 *Scenario*
	hasStep	≥ 1 *Step*
Step	*step*	1 *unsignedInt*
	isCompleted	1 *boolean*
	hasService	≥ 1 *Service*
	hasPrevious	≤ 1 *Step*
	hasNext	≤ 1 *Step*
Service		*Comparable*
	hasComparable	≥ 1 *Service*
	hasPrevious	*Service*
	hasNext	*Service*
	hasInputModel	≤ 1 *InputModel*
	hasInputDataSource	≤ 1 *InputDataSource*
	hasOutputModel	≤ 1 *OutputModel*
	hasResult	≤ 1 *Thing*
Input-Model	*hasInputModel*	*InputModel*
Output-Model	*hasOutputModel*	*OutputModel*
Input-Data-Source		
FileData-Source		*InputDataSource*
	filePath	1 *anyURI*
	fileFormat	≤ 1 *string*
	parseFileTo	≤ 1 *anyURI*
Web-Data-Source		*InputDataSource*
	requestURL	1 *anyURI*
	requestMethod	1 *string*
	requestHeader	*string*
	requestBody	≤ 1 *string*
	requestBodyContentType	≤ 1 *string*
	responseContentType	≤ 1 *string*
	responsePath	≤ 1 *string*

defining the semantic model to which the file content should be translated to.

The *WebDataSource* class is defined by exactly one URI (*resquestURL*) and a *requestMethod* string with the HTTP request method. A *requestHeader* string may also be defined with the request header information. Optionally, at most one *requestBody* string may be defined with the message body, whenever it makes sense; as well as a *requestBodyContentType* string. Similarly, at most one *responseContentType* string may be set, and in case the response is a JSON or XML structure, the user may also set the *responsePath* string to get the intended value.

As already stated, TCC is written in OWL-DL syntax. OWL-DL provides the maximum expressiveness possible, maintaining computational completeness, decidability, and the availability of reasoning algorithms [45]. TCC's expressiveness is *ALCQ(D)*, i.e., it allows: to demonstrate attributive language (*AL*), which includes atomic negation, conceptual intersection, universal constraints, and limited existential quantification; complex conceptual negation (*C*); qualified cardinality constraints (*Q*); and the use of data type properties and values *(D)*.

Finally, instances (or individuals) are the objects of the classes that can be classified and validated by the ontology. The following section presents a case study where the use of TCC is demonstrated. It features the ontology instantiation, including its evaluation in which the previously defined requirements are validated.

V. ONTOLOGY EVALUATION

The following case study was developed to evaluate and test the requirements established for TCC in subsection IV-A. To this end, it is considered a scenario where a DR event is applied to reduce the operating costs of the network while returning a fair compensation of the resources involved. The modeled scenario considers historical data for August 2018, with a granularity of 15 minutes. It includes consumption data from 144 consumers with varying profiles (domestic and industrial), generation data from 43 renewable energy sources (solar and wind), and data from 1 regular supplier and 5 backup suppliers to be used whenever the regular supplier is not able to fully satisfy the grid needs. In terms of scalability, this scenario is based on a large amount of data.

Conceptually, the aggregator shall perform the energy scheduling of the network, taking into account all restrictions of its users. After scheduling, the users who reduce their consumption according to what is established by the aggregator are rewarded. Thus, it is necessary to determine what will be the fair remuneration value for each individual. For this are made clusters based on the amount of power cut. Finally, to remunerate the end-user, the maximum rate of each group will be determined. The consumption reduction is made in certain consumers' devices, detailed in their DR contracts. These devices can be air conditioners, sockets, refrigerators, washing machines, among others. To ensure that a sensitive device is not affected, it is possible to assign each device a degree of priority where the highest priority level means that it should be cut only as a last resort, while those with lower priority can be considered more often.

To be able to simulate the described scenario, three web services were selected. The first service will be the scheduling optimization, which will be followed by the aggregation (clustering) service and after by the service that determines the remuneration applicable to each group. Services should run sequentially, where part of the output from the first tool is used by the second, and so on. Figure 4 illustrates which services run in each phase and their dependencies.

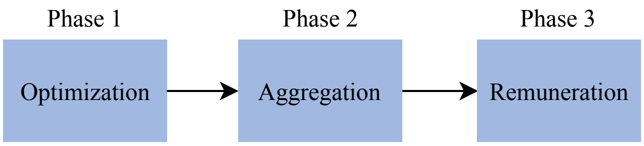

FIGURE 4. Case study execution phases.

After the scenario configuration, and the `Start` button is pressed, TOOCC's knowledge base (KB) is filled with the simulation data. The KB is then queried by `TMA` to initialize all necessary agents with the knowledge they need to proceed. A simplified representation of this process is illustrated in Figure 5.

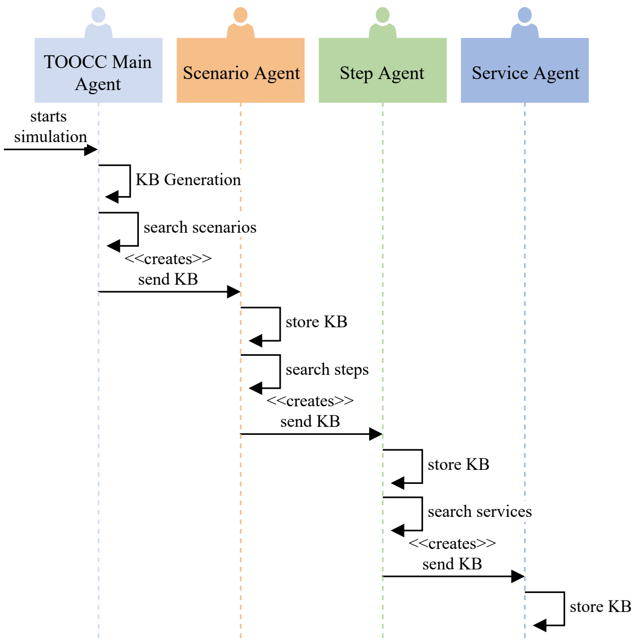

FIGURE 5. Sequence Diagram for multi-agent communications.

After initializing the `ScenA`, `TMA` sends it the KB data about `:scenario-1`. Listing 1 presents a snippet of `:scenario-1` definition in Turtle.

Listing 1. General scenario configuration

```
1  :simulation-set rdf:type tcc:SimulationSet ,
       owl:NamedIndividual ;
2    tcc:hasSimulation :simulation-1 .
3
4  :simulation-1 rdf:type owl:NamedIndividual ,
       tcc:Simulation ;
5    tcc:hasScenario :scenario-1 ;
6    tcc:id "simulation-1" ;
7    tcc:name "Service to Service (S2S) Simulation
         " ^^xsd:string ;
8    tcc:descrition "The simulation demonstrates
         the Service to Service integration where
         the output of a Service is mapped to be
         the input of the next one."^^xsd:string ;
9    tcc:created "2019-07-25T16:26:24"^^xsd:
         dateTime ;
10   tcc:modified "2019-07-25T16:26:24"^^xsd:
         dateTime .
11
12 :scenario-1 rdf:type owl:NamedIndividual , tcc:
       Scenario ;
13   tcc:hasStep :step-1-scen-1 , :step-2-scen-1 ,
          :step-3-scen-1 ;
14   tcc:numberOfSteps "3"^^xsd:unsignedInt ;
15   tcc:id "scenario-1" ;
16   tcc:name "Service to Service (S2S) Scenario"
         ^^xsd:string ;
17   tcc:descrition "The scenario demonstrates the
          Service to Service integration where the
          output of a Service is mapped to be the
         input of the next one."^^xsd:string ;
18   tcc:created "2019-07-25T16:26:24"^^xsd:
         dateTime ;
19   tcc:modified "2019-07-25T16:26:24"^^xsd:
         dateTime .
```

In line 1, it is possible to observe the definition of an individual (`:simulation-set`) of type `tcc:SimulationSet`. In line 2 the object property `tcc:hasSimulation` indicates that there is only one simulation defined for this case study (i.e., `:simulation-1`). If multiple simulations where defined, this object property would have more individuals, separated by commas (as defined in the first requirement). In the same way, if more scenarios were defined for this case study, the object property `tcc:hasScenarios` (line 5) would have more individuals (as determined in the second requirement). The `:scenario-1` individual has three steps configured (lines 12 to 13) fulfilling the third requirement. For each step, a *StepA* agent is initialized, and the knowledge about each particular step is sent to the respective agent for its execution. As it is possible to verify, the first three requirements defined in the subsection IV-A are present in Listing 1. Listing 2 shows the `:step-1-scen-1` instantiation, as well as the definition of the `:service-optimization-algorithm`.

Listing 2. First phase configurations

```
1  :step-1-scen-1 rdf:type owl:NamedIndividual ,
       tcc:Step ;
2    tcc:hasService :service-optimization-
         algorithm ;
3    tcc:hasNext :step-2-scen-1 ;
4    tcc:step "1"^^xsd:unsignedInt .
5
6  :service-optimization-algorithm rdf:type owl:
       NamedIndividual , tcc:Service ;
7    tcc:hasNext :service-aggregation-algorithm ;
8    tcc:hasInputModel :InputOptimizationAlgorithm
          ;
9    tcc:hasInputDataSource :input-file-opti-algo
          ;
10   tcc:hasOutputModel :
         OutputOptimizationAlgorithm .
```

The link between the optimization service running at this stage and the aggregation service running at the next stage is achieved through the `tcc:hasNext` relationship (line 7). The same happens with the `tcc:Step`, where the execution order is also established through the same relationship (line 3), together with the `tcc:step`

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property (line 4), which indicates the order in which the phase will execute. For each service defined in the `tcc:hasService` object property (line 2), the *StepA* agent creates a *ServA* agent, being the service information transmitted to the latter. If the `tcc:hasService` object property would have two services defined, then these would run concurrently. This property fulfills the fourth requirement set in subsection IV-A. Additionally, for the `:service-optimization-algorithm` individual, the relationships are constructed for the input data model `:InputOptimizationAlgorithm` (line 8) and the output data model `:OutputOptimizationAlgorithm` (line 10) to be able to communicate with the external services. Here is also demonstrated the fifth requirement defined in subsection IV-A.

Listing 3 demonstrates how the semantic input data model is built for the scheduling service `:service-optimization-algorithm`.

Listing 3. Excerpt of input model of the first execution phase

```
1  :InputOptimizationAlgorithm rdf:type owl:Class
       ;
2    rdfs:subClassOf tcc:InputModel , [
3      rdf:type owl:Restriction ;
4      owl:onProperty tcc:hasInputModel ;
5      owl:cardinality "1"^^xsd:nonNegativeInteger
           ;
6      owl:onClass :CutLimitIn
7    ] ,
8    [ rdf:type owl:Restriction ;
9      owl:onProperty tcc:hasInputModel ;
10     owl:cardinality "1"^^xsd:nonNegativeInteger
           ;
11     owl:onClass :ConsumptionIn
12   ] ,
13   [ rdf:type owl:Restriction ;
14     owl:onProperty tcc:hasInputModel ;
15     owl:cardinality "1"^^xsd:nonNegativeInteger
           ;
16     owl:onClass :ProductionIn
17   ] , [ ... ] .
```

In this model, it is possible to view some of the fields required for execution, such as: `:CutLimitIn` (line 6), `:ConsumptionIn` (line 11), and `:ProductionIn` (line 16). These fields inform the algorithm of the characteristics of the network players, so that it can perform a more efficient scheduling based on consumption and production profiles.

Listing 4 shows a small excerpt of the data instantiated with the `:CutLimitIn` model.

Listing 4. Excerpt of input data of the first execution phase

```
:iPmaxidr a csi:CutLimitIn ;
  mat:item :iArray39iPmaxidr , (...) .

:iArray39iPmaxidr a mat:Array ;
  mat:item :iItem2316iArray39iPmaxidr , (...) .

:iItem2316iArray39iPmaxidr a mat:Item ;
  mat:pos "2316"^^xsd:unsignedInt ;
  mat:val "0.0037"^^xsd:double .
```

On the other hand, Listing 5 gives an overview of the scenario configuration for running the aggregation algorithm `:service-aggregation-algorithm` (line 8).

Listing 5. Configuration of the second phase of execution

```
1  :step-2-scen-1
2    rdf:type owl:NamedIndividual , tcc:Step ;
3    tcc:hasService :service-aggregation-algorithm
         ;
4    tcc:hasPrevious :step-1-scen-1 ;
5    tcc:hasNext :step-3-scen-1 ;
6    tcc:step "2"^^xsd:unsignedInt .
7
8  :service-aggregation-algorithm
9    rdf:type owl:NamedIndividual , tcc:Service ;
10   tcc:hasPrevious :service-optimization-
         algorithm ;
11   tcc:hasNext :service-remuneration-algorithm ;
12   tcc:hasInputModel :InputAggregationAlgorithm
         ;
13   tcc:hasOutputModel :
         OutputAggregationAlgorithm .
```

The second step (`:step-2-scen-1`) is the execution of the aggregation algorithm, which will create clusters of consumers to help determine the most appropriate remuneration rate. However, for this service to run, it needs to populate its input data model `:InputAggregationAlgorithm` with some of the values that compose the previous phase output data model. The use of concepts between the output model of a service and the input model of the next one is done by using the same class. An example of this process is illustrated in Listing 6.

Listing 6. Reuse of concepts between different data models

```
1  :OutputOptimizationAlgorithm rdf:type owl:Class
       ;
2    rdfs:subClassOf tcc:OutputModel ,
3    [ rdf:type owl:Restriction ;
4      owl:onProperty tcc:hasOutputModel ;
5      owl:cardinality "1"^^xsd:nonNegativeInteger
           ;
6      owl:onClass :DGResOut ] ,
7    [ ... ] ,
8    [ rdf:type owl:Restriction ;
9      owl:onProperty tcc:hasOutputModel ;
10     owl:cardinality "1"^^xsd:nonNegativeInteger
           ;
11     owl:onClass :ReduceAmountResOut ] .
12
13 :InputAggregationAlgorithm rdf:type owl:Class ;
14   rdfs:subClassOf tcc:InputModel ,
15   [ rdf:type owl:Restriction ;
16     owl:onProperty tcc:hasInputModel ;
17     owl:cardinality "1"^^xsd:nonNegativeInteger
           ;
18     owl:onClass :OptimizationSolutionIn ] ,
19   [ ... ] .
20
21 :OptimizationSolutionIn rdf:type owl:Class ;
22   rdfs:subClassOf tcc:InputModel ,
23   [ rdf:type owl:Restriction ;
24     owl:onProperty tcc:hasInputModel ;
25     owl:cardinality "1"^^xsd:nonNegativeInteger
           ;
26     owl:onClass :ReduceAmountResOut ] ,
27   [ rdf:type owl:Restriction ;
28     owl:onProperty tcc:hasInputModel ;
29     owl:cardinality "1"^^xsd:nonNegativeInteger
           ;
30     owl:onClass :DGResOut ] .
```

The code shows that the input data model for the aggregation algorithm `:InputAggregationAlgorithm` (lines

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13 to 19) contains the class `:OptimizationSolution-In` (line 18). This class is composed by `:DGResOut` (line 30) and `:ReduceAmountResOut` (line 26) that result from `:OutputOptimizationAlgorithm` (lines 6 and 11 respectively) of the previous step, demonstrating that the output model of a service can be used as part of the output model of another service, or completely.

Besides the input model already presented in Listing 6, a representation of the output data model `:Output-AggregationAlgorithm` is shown in Listing 7.

Listing 7. Output model of the second phase of execution

```
:OutputAggregationAlgorithm
  rdf:type owl:Class ;
  rdfs:subClassOf tcc:OutputModel , [
    rdf:type owl:Restriction ;
    owl:onProperty tcc:hasOutputModel ;
    owl:cardinality "1"^^xsd:nonNegativeInteger
        ;
    owl:onClass :BestKOut ] ,
  [ rdf:type owl:Restriction ;
    owl:onProperty tcc:hasOutputModel ;
    owl:someValuesFrom :AggregationListItem ] .
```

The next service to be performed is the remuneration service. It will assign a remuneration rate to each entity, according to the group in which it was classified in the aggregation phase. The configuration of phase three is shown in Listing 8.

Listing 8. Configuration of the third phase of execution

```
:step-3-scen-1
  rdf:type owl:NamedIndividual , tcc:Step ;
  tcc:hasService :service-remuneration-
      algorithm ;
  tcc:hasPrevious :step-2-scen-1 ;
  tcc:step "3"^^xsd:unsignedInt .

:service-remuneration-algorithm
  rdf:type owl:NamedIndividual , tcc:Service ;
  tcc:hasPrevious :service-aggregation-
      algorithm ;
  tcc:hasInputModel :InputRemunerationAlgorithm
      ;
  tcc:hasOutputModel :
      OutputRemunerationAlgorithm .
```

As can be seen in Listing 8, unlike the previous phases, this service does not have the `tcc:hasNext` relationship, since it is the last phase that will be executed. The input data model `:InputRemunerationModel` of the third phase is represented in Listing 9.

Listing 9. Input model of the third phase of execution

```
:InputRemunerationAlgorithm rdf:type owl:Class
    ;
  rdfs:subClassOf tcc:InputModel ,
  [
    rdf:type owl:Restriction ;
    owl:onProperty tcc:hasInputModel ;
    owl:cardinality "1"^^xsd:nonNegativeInteger
        ;
    owl:onClass :AggregationSolutionIn ] ,
  [ rdf:type owl:Restriction ;
    owl:onProperty tcc:hasInputModel ;
    owl:cardinality "1"^^xsd:nonNegativeInteger
        ;
```

```
11      owl:onClass :CostIn ] ,
12    [ ... ] .
```

Listing 10 presents the algorithm output data model for obtaining remuneration.

Listing 10. Output model of the third phase of execution

```
:OutputRemunerationAlgorithm rdf:type owl:Class
    ;
  rdfs:subClassOf tcc:OutputModel , [
    rdf:type owl:Restriction ;
    owl:onProperty tcc:hasOutputModel ;
    owl:someValuesFrom :RemunerationListItem ]
        .
```

At the end of the execution the results are made available to the user so that he can analyze and draw conclusions about them. These include the results of each intermediate phase, as well as the final results extracted from the last execution phase.

With the present case study, it is possible to verify the fulfillment of several TCC's requirements identified in Section IV-A. It shows the possibility of creating a scenario with several steps that will execute sequentially, and where each step can consider one or more services simultaneously, to improve the simulation performance. The interoperability of those services is achieved through the knowledge exchanged between the input and output data models.

In the simulation process, it was possible to verify that TCC effectively achieves its purpose. Moreover, the simplicity of TCC design enables a good performance, and it was proven that the system can execute scenarios with a large amount of data.

TCC has the flexibility to model different problems in the scope of PES, taking into account different perspectives, roles, and objectives, as can be seen by this case study and by others already published [15], [16]. This article is distinct from previously published works, as it presents the application ontology defined for the TOOCC tool and uses a case study to illustrate its use. At the same time, this case study not only evaluated TCC, but also demonstrated the execution of a complex simulation scenario in which three web services are integrated to simulate a DR program in a local community.

VI. CONCLUSION

The large-scale implementation of distributed energy sources, as well as the targets imposed worldwide to face the new climate paradigm, are causing severe changes in the sector, which are continually adapting to meet the new challenges. The development of decision support tools to address the problem as a whole is one of the key challenges in PES.

TOOCC contributes to increase interoperability between heterogeneous systems that study, experiment, and test the PES domain. This work introduces TOOCC's application ontology. TCC supports the scenarios' definition and results comparison while easing the interoperability among the several systems. It has been developed considering a level of abstraction and flexibility that allows its evolution. At the same time, TCC can include the semantic or syntactic models of the various integrated tools, as long as these models are publicly available or shared by the external tools.

The case study presents a DR program in which the consumer's remuneration (per power unit) depends on the cluster to which he is assigned. In turn, this cluster depends on the amount of energy that the consumer can make available to the network. The main purpose of the case study is to evaluate the presented application ontology, while demonstrating how a simulation is configured and how the interoperability is achieved by mapping the output of a service to the input of the next one. During the case study, it was possible to demonstrate several requirements defined for TCC.

As future work, the next step intends to show the benefits of using this ontology for the results (models) comparison, by exploring the reasoning capabilities of the system. For this purpose, two different scenarios will be considered: i) using different simulation tools aimed at the study of similar problems; and ii) using the same system with different inputs. This way, it will also be possible to demonstrate the simultaneous execution of distinct simulations and scenarios.

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Core Publication III

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Resumen

La inversión mundial en fuentes de energía renovable está conduciendo a la formación de comunidades energéticas locales en las que los usuarios pueden comerciar energía eléctrica localmente. Actualmente se están diseñando las regulaciones y los habilitadores necesarios para transacciones efectivas en este nuevo contexto. Por lo tanto, el desarrollo de herramientas de software para respaldar las transacciones locales aún se encuentra en una etapa temprana y enfrenta el desafío de las actualizaciones constantes de los modelos de datos y las reglas de negocios. El presente articulo propone un enfoque novedoso para el desarrollo de herramientas de software para resolver los mercados eléctricos locales basados en subastas, considerando las necesidades especiales de las comunidades energéticas locales. El enfoque propuesto considera ofertas restringidas que pueden aumentar la efectividad del uso de generación distribuida. El método propuesto aprovecha las tecnologías de la web semántica, con el fin de proporcionar modelos con el dinamismo requerido para superar los problemas relacionados con los constantes cambios en los datos y modelos de negocio. El uso de estas técnicas permite que el sistema sea agnóstico del modelo de datos y las reglas de negocios. La solución propuesta incluye las restricciones propuestas, la aplicación de ontologías y las plantillas de reglas semánticas. El articulo incluye un estudio de caso basado en datos reales que ilustra las ventajas de utilizar la solución propuesta en una comunidad con 27 consumidores.

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Constrained Generation Bids in Local Electricity Markets: A Semantic Approach

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Abstract: The worldwide investment in renewable energy sources is leading to the formation of local energy communities in which users can trade electric energy locally. Regulations and the required enablers for effective transactions in this new context are currently being designed. Hence, the development of software tools to support local transactions is still at an early stage and faces the challenge of constant updates to the data models and business rules. The present paper proposes a novel approach for the development of software tools to solve auction-based local electricity markets, considering the special needs of local energy communities. The proposed approach considers constrained bids that can increase the effectiveness of distributed generation use. The proposed method takes advantage of semantic web technologies, in order to provide models with the required dynamism to overcome the issues related to the constant changes in data and business models. Using such techniques allows the system to be agnostic to the data model and business rules. The proposed solution includes the proposed constraints, application ontology, and semantic rule templates. The paper includes a case study based on real data that illustrates the advantages of using the proposed solution in a community with 27 consumers.

Keywords: constrained bid; local electricity market; semantic rules; semantic web technologies

1. Introduction

On 5 June 2019, the European Parliament launched the Directive (EU) 2019/9442 "*on common rules for the internal market for electricity and amending Directive 2012/27/EU*" [1]. This new directive introduces significant changes in the business models and electricity markets, intending to provide a real choice to all of the Union's final consumers, creating new business opportunities, offering competitive prices, showing signs of effective investments and ensuring higher service standards, as well as contributing to the security of supply and sustainability [2]. The common goal of decarbonizing the energy system creates new opportunities and poses new challenges to market participants [3]. Technological developments allow new forms of consumer participation and cross-border cooperation [4]. In this way, this new directive adjusts the Union's market rules to a new market reality. In addition to responding to new challenges, this Directive also aims to find solutions to overcome the remaining obstacles to the effective and efficient implementation of the internal electricity market [5]. Thus, this directive incentivizes the development of new business models, which are significantly different from those that are currently possible.

Across the globe, financial and environmental concerns are leading to a reduction in carbon emissions and to the improvement of system security and affordability of power and energy systems by promoting the integration of distributed generation (DG) into the power system [6]. To this end, governments are encouraging the use of renewable energy sources (RES) [7] along with information and communication technology (ICT) [8] devices to form so-called energy communities where end users can trade energy [9,10]. These communities are already a reality in some pilot microgrid and smart grid (SG) projects [9–13]. SGs take advantage of ICT to enable the bi-directional flow of energy while providing the fully automated monitoring, control, and protection of the grid [14], fulfilling the supply of sustainable, secure, and economical energy and considering the participation of active end users.

End consumers, who can both generate and consume energy, are called prosumers. Prosumers can curtail, trade, store, or send their surplus energy to the power grid. These players are mainly motivated by financial incentives, environmental concerns, and low levels of trust in energy suppliers [15,16]. Local electricity markets enable small-scale players to trade within their communities, promoting the local grid balance, reducing the cost of electricity bills, incentivizing the investment in RES, and supporting a self-sustained SG community [17,18]. Several works present solutions to solve local electricity markets for various purposes, such as peer-to-peer [10,15,16], blockchain [11,19], bidding [20–23], bilateral negotiation [24,25] and constrained markets [26], among others.

The application of constrained bids in competitive markets has been explored in the literature, mostly through theoretical analyses of the impact of this type of bid on the market equilibrium and players' results [27–29]. However, the literature lacks works that address the application of constrained bids in local electricity market environments. Different types of restrictions may be applied in this context, namely constraints intrinsic to the distribution network, as well as constraints on the users' aggregation contracts [30,31]. Additionally, when considering auction-based transactions, players should also be able to determine constraints making the local market more competitive and attractive to its participants. In fact, not only are adequate models to support players' actions in local electricity markets lacking, but the development of software to solve local electricity market transactions is also at an early stage. Accommodating the novel and constantly changing business rules may become a burden due to their volatile nature. Any update to the system requires it to be reprogrammed and recompiled. Ideally, the system should be abstracted from the data model and the business rules and receive them as inputs. In this way, the system would only need to be reprogrammed when the business model changes significantly.

In the present paper, a novel approach is proposed to develop tools to solve auction-based local electricity market transactions, considering constrained bids. The proposed approach overcomes programming issues, making the system more flexible and adaptable to the evolution of local market rules. To this end, we take advantage of ontologies and semantic web technologies to keep the system agnostic to the data model and business rules. The use of ontologies and semantic web technologies provides the means to develop systems decoupled from the data models and business rules. These techniques enable the development of systems with a higher flexibility, avoiding the need for reprogramming whenever the data models or business rules need to be updated. Additionally, when using these technologies, systems are able to perform reasoning upon data since semantic models provide context and information about data. The proposed constrained bids are developed specifically for local market transactions, in order to enable players to improve the potential outcomes from market participation by providing them with the means to incorporate strategic information into their—otherwise straightforward—bids. In this way, the players are able to specify the conditions of their offers regarding distributed generation, which can sometimes be difficult to model, as the modeled constraints can be conflicting in the search for optimal solutions. The proposed model offers a different product for local markets that considers constraints that will ease players' participation in local markets. Therefore, it allows for the incentivization of increased consumer participation, by offering options that allow local trading to be performed according to players' interests, objectives, strategic needs and preferences. Each player is able to select the constraints that are more relevant and easier to use, according to their reality and preferences.

The following section provides the background on auction-based electricity market types, local market bid constraints, and the advantages of using ontologies and semantic web technologies instead of coding data models and business rules. Section 3 presents the proposed solution to solve constrained transactions in local electricity markets while keeping the system flexible to test different alternatives. It will detail the defined constraints, the ontology designed and used to describe the data and business models, and the semantic rules developed for each specified constraint. The case study presented in Section 4 illustrates the operation of the developed software tool, focusing on the use of the semantic rules. The conclusions about the developed work are presented in Section 5.

2. Background

Local electricity markets are the future in the decentralization of power and energy systems, focusing on consumers, energy efficiency, and distributed micro generation [1,2,4,5]. In recent years, a growing interest in the study and development of local electricity markets has emerged, namely in peer-to-peer [10,15,16], blockchains [11,19], transactive energy [9,21,32], and demand response (DR) [33,34], among others. This section provides the background of the different domains brought together to compose the proposed solution. These domains are auction-based local electricity market types, local market bid constraints, and ontologies and semantic web technologies. Section 2.1 gives an overview of the auction-based local market types proposed in the literature, while Section 2.2 presents the ontologies and semantic web technologies, explaining why their use is considered in the proposed approach.

2.1. Auction-Based Local Electricity Market Types

Auction-based local electricity markets are addressed in the literature [20–23]. The most common trading designs are the double auction [20,21] (symmetric), and the single-sided auction [22,23] (asymmetric). In symmetric market pools [35,36], both buyers and sellers compete by submitting their bids. In electricity markets, a bid is a pair made up of the amount of energy to trade and the price per unit. Bids from buyers are ordered by price in descending order, while seller bids are ordered ascendingly. These bids form the demand and supply step curves. The point where both curves intersect (Figure 1a) determines the amount of energy to trade, while the market price is set by the last seller to sell. Buyer bids offering prices higher than the market price and seller bids offering prices lower than the market price trade in the market pool. In the end, each buyer must pay the market price per each accepted supply unit.

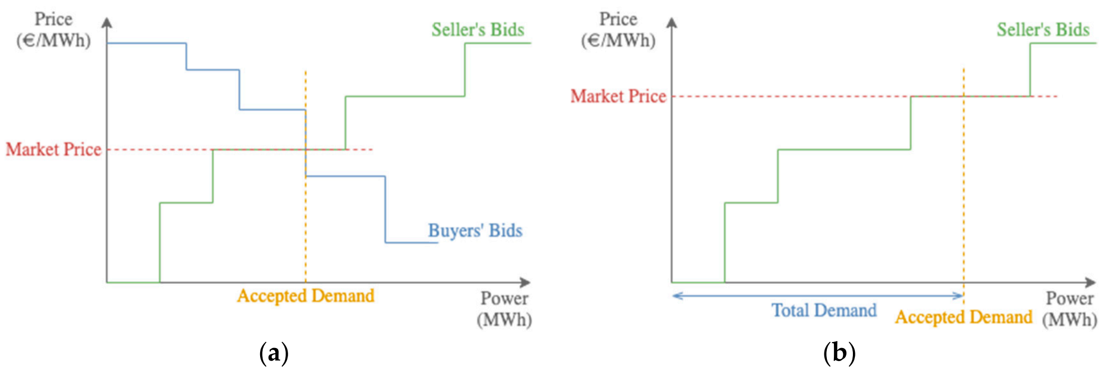

Figure 1. Common designs in auction-based electricity markets: (**a**) double auction or symmetric market pool; (**b**) single-sided auction or asymmetric market pool.

On the other hand, in asymmetric market pools, only sellers submit energy/price bids, while buyers only submit their demand. The seller bids are ordered by price ascendingly. The sum of the buyers' required energy sets the total demand. The seller bids are accepted until the total demand is satisfied. The last seller to trade sets the market price that buyers must pay per each energy unit traded (Figure 1b).

The most common types of local market constraints found in the literature are related to network limitations, such as the capacity of the distribution lines, congestion management, voltage deviations and thermal limits, among others [26,30,31]. The work presented in the present paper goes forward in exploring the bid constraints that local market players can submit, in order to have their preferences respected, so buyers can easily say how much and when they want to buy, and sellers can easily say how much and when they want to sell. In this way, the players are able to specify the conditions of their offers regarding distributed generation. As a result, the authors decided to design, develop, and propose constraints that make sense, are interesting, and attractive for local market participants so they participate more, and with a greater amount of energy. Section 3.1 details these constraints.

2.2. Ontologies and Semantic Web Technologies

In computer science, ontologies conceptualize meaningful descriptions of the domains' abstract and rational models, describing their concepts, properties, and the relations between them. Their formal and explicit representation enables both humans and machines to comprehend them and reason upon them [37,38]. They allow knowledge sharing, reuse, and common understanding across heterogeneous entities. Moreover, they provide computational inference, through inference engines, on conceptual models and stored data, enabling the automatic generation of new knowledge [39].

"The W3C Web Ontology Language (OWL) is a Semantic Web language designed to represent rich and complex knowledge about things, groups of things, and relations between things" [40]. In other words, OWL is designed to represent ontologies on the world wide web (WWW). It eases the machine readability and the interpretation of information content while providing a means for knowledge inference. OWL 2 [41] is the latest version published and it is usually written in Resource Description Framework (RDF). RDF [42] is a language designed to represent data about web resources. It uses Uniform Resource Identifiers (URI) to describe resources and relationships between them, setting triples in the form of "<subject> <predicate> <object>". This structure creates directed, labeled graphs providing a consistent and standard way to describe and query resources on the web. The graph view is the easiest mental model for easy-to-understand explanations. The RDF allows information to be exchanged between applications without losing its meaning. Its vocabulary is defined by RDF Schema (https://www.w3.org/TR/rdf-schema/), which describes the RDF's abstract syntax and basic concepts, its formal semantics, and serialization syntaxes. There are different serialization formats available to write RDF graphs, such as RDF/Extensible Markup Language (XML, https://www.w3.org/TR/rdf-syntax-grammar/), JavaScript Object Notation for Linked Data (JSON-LD) (https://www.w3.org/TR/json-ld11/) and Turtle (https://www.w3.org/TR/turtle/), among others.

Triple stores, or RDF stores, are databases designed for the storage and retrieval of data triples through semantic queries [43]. Semantic queries process structured data, such as triples, named graphs, and linked data. The WWW Consortium (W3C) recommends the SPARQL Protocol and RDF Query Language [44] (SPARQL) as an RDF query language. SPARQL 1.1 is considered one of the key technologies of the semantic web as it provides protocols to query and manipulate RDF graphs. SPARQL query results are retrieved in one of the following well-known formats: (i) Extensible Markup Language (XML); (ii) JavaScript Object Notation (JSON); (iii) Comma Separated Values (CSV); (iv) Tab-Separated Values (TSV).

In summary, semantic web technologies provide a common framework to: (1) define data models and represent data through them, understandable by both humans and machines; (2) ease interoperability between software tools by sharing both the data and the models; (3) store, query, and manipulate these structured data and models. Other advantages of using the semantic web framework are the possibility of keeping the data model decoupled from the software and the use of SPARQL to implement the business rules, as exemplified in [45]. In this way, developed systems can be more flexible and configurable, avoiding the need to reprogram them when the data model or a rule is updated as much as possible. The following section will demonstrate how this is achieved.

3. Proposed Semantic-Based Constrained Bid Model

The proposed semantic-based constrained bid model for local electricity markets aims to be used to manage auction-based local electricity markets and for studying and testing them in the scope of simulation systems. The model is written as a code library so it can be reused by different systems and tools, including agent-based systems, desktop applications, and web services. Keeping in mind the need to develop a flexible and configurable system able to address different alternatives to solve auction-based transactions, considering constrained bids in local electricity markets, the following requirements where defined:

- the system must take advantage of semantic web technologies;
- the semantic model(s) must describe all the required knowledge;
- the system must be agnostic to the semantic model(s) used;
- the connection to the triple store must be configurable;
- SPARQL must be used to query/update the knowledge base (KB);
- the system must be agnostic to the bid's constraints;
- the bids' constraints must be written in SPARQL;
- the bids' constraints must be configurable.

In the present work, the proposed solution is applied and driven to a smart grid aggregator aimed at local communities with around 100 players. For this community size, the proposed methodology takes around five minutes to run a complete market session. The aggregator is modelled as a software agent of an agent-based smart grid simulation platform developed with the Java Agent Development framework (JADE) [46]. Therefore, this library was developed in Java [47] programming language, and uses Apache Jena Fuseki [48] as the triple store. Figure 2 illustrates the architecture of the library designed and developed.

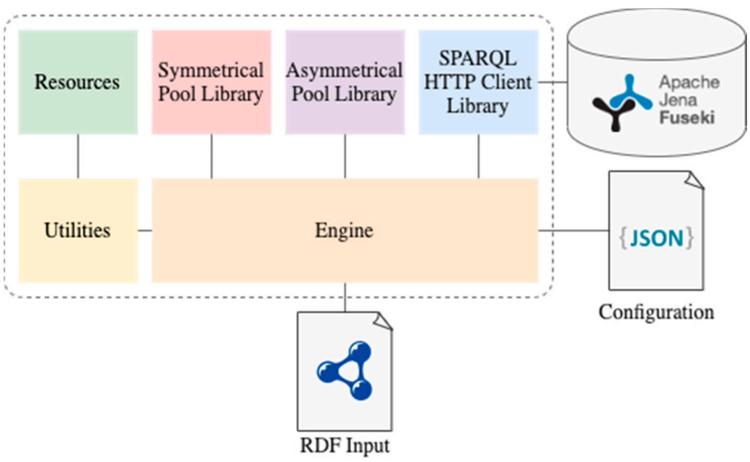

Figure 2. Proposed library's architecture.

The local market library receives, as an input, an RDF KB file, as well as a configuration JSON file. The RDF KB file has the input data necessary to run the local auction-based market algorithm, detailing the type of market pool to run (symmetric, by default, or asymmetric), the session and respective periods, and the players' bids and constraints. The configuration JSON file detains information about the KB file path and its RDF language (such as Turtle, RDF/XML, JSON-LD, etc.), Fuseki server configuration, and the local market constraint templates for each possible bid constraint. The configuration file makes the use of remote KB files, as well as the different SPARQL triple stores available, and also the addition, updating, or removal of constraint templates much easier, without the need to reprogram the system.

The library itself is composed of three packages, namely the Engine, the Resources, and Utilities, and imports three libraries developed during the present work: the Symmetrical Pool Library, the Asymmetrical Pool Library, and the SPARQL HTTP Client Library. The first two libraries are to execute each of the auction-based market pool algorithms: the double auction and the single-sided auction, respectively. The third library provides a SPARQL over an HTTP (SOH) client to communicate with any triple store compliant with SPARQL 1.1. The Utilities package provides general useful methods, as well as access to the Resources files necessary to manage data from the triple store. These resource files include configuration JSON schemas to validate both the input configuration file and the results output, as well as SPARQL queries and updates to manage the KB data during the system's execution.

The Engine is the core package that, using all the abovementioned features, makes the library run smoothly. To keep the system agnostic to the data model, the Engine uses JSON objects instead of Java classes. The resource SPARQL query files used to obtain the data from the KB return JSON strings that respect predetermined JSON schemas used by the Engine. Thus, the ontology may change without the need to reprogram the system, as long as it is possible to get the same JSON strings from the accordingly updated SPARQL queries.

The following subsections detail the defined bid constraints (Section 3.1), the application ontology (Section 3.2), and each constraint's SPARQL template (Section 3.3).

3.1. Bid Constraints for Auction-Based Local Electricity Market

In order to overcome the gap in the literature regarding bid constraints for auction-based local electricity markets, this work proposes new constrained bid models for this type of exchange. The authors consider different types of constraints, namely session and period constraints. Additionally, some constraints are directed to buyers and others to suppliers. The proposed constraints for each session (typically composed of a set of four periods) are Minimum Income, Maximum Cost, Minimum Matched Energy, and Maximum Matched Energy. For each period, the proposed constraints are Minimum Matched Energy, and Maximum Matched Energy. These proposed bid constraints were designed for the symmetric pool. However, if desired, some may be applied to the asymmetric market, namely the ones related to the suppliers.

The motivation for the definition and use of such constraints include the following aspects:

- allowing a single, small-size player to bound its participation, and probably increase the number of players actively participating as they can be surer that bidding actions will not be disadvantageous for them;
- as consequence, this allows an increase in the competitiveness of the local market as more players are participating;
- some players can be motivated by profit, while other can be motivated, for example, by the amount of negotiated energy, so adequate modeling of both types of motivations should be accommodated;
- the risk or unpredictability of a bid to be accepted is sometimes not easy to handle by a local player of a small size. With the implemented constraints, the player can make more risky bids in terms of price in specific periods, at the same time ensuring that a certain amount of remuneration must be respected in the session;
- some players may want to always have an accepted bid, while other players may disregard the single-period results and bind their objectives regarding the session;
- the possibility of different players selecting different constraints they want to use makes it possible to keep simple models for each player;

- in this way, it is important to find a way in which some players can choose certain constraints, then disregard the remaining constraints, while other players can choose other constraints that are more relevant for them.

It should be highlighted that adding these constraints to the local market model make it more complex, and it is hard for players to understand how the price was formed. However, the way in which the increased participation of players in the local market can be obtained is an advantage, putting the complexity burden on the retailer side.

The Minimum Income for a session is a constraint that sets a minimum acceptable value for the player's total income, as presented in Equation (1). Suppliers submitting this constraint do not want to participate in the market session unless the total income A is reached.

$$\sum_{t=1}^{T}\left[E_{(t)} \times Price.M_{(t)}\right] \geq A \tag{1}$$

where:

- $E_{(t)}$—energy transacted in period t;
- $Price.M_{(t)}$—market price of period t;
- A—the minimum income set by the player;
- T—the session's total number of periods.

Additionally, the Minimum Income also sets a lower bound of the session's average price per kWh and must be higher or equal to the value B submitted in Equation (2).

$$\frac{\sum_{t=1}^{T}\left[E_{(t)} \times Price.M_{(t)}\right]}{\sum_{t=1}^{T}\left[E_{(t)}\right]} \geq B \tag{2}$$

where:

- $E_{(t)}$—energy transacted in period t;
- $Price.M_{(t)}$—market price of period t;
- B—the minimum average price per kWh set by the player;
- T—the session's total number of periods.

The Maximum Cost session constraint is the opposite of the Minimum Income. It sets a maximum acceptable value for the player to pay at the end of the session. Buyers submitting this restriction do not want to participate in the session if their costs are higher than the total cost value C set in this rule, as presented in Equation (3).

$$\sum_{t=1}^{T}\left[E_{(t)} \times Price.M_{(t)}\right] \leq C \tag{3}$$

where:

- $E_{(t)}$—energy transacted in period t;
- $Price.M_{(t)}$—market price of period t;
- C—the maximum cost set by the player;
- T—the session's total number of periods.

Likewise, the *Maximum Cost* additionally sets a maximum price to pay per kWh. Buyers submitting this restriction do not want to participate in the session if the average price paid per kWh is higher than value D, as presented in Equation (4).

$$\frac{\sum_{t=1}^{T}\left[E_{(t)} \times Price.M_{(t)}\right]}{\sum_{t=1}^{T}\left[E_{(t)}\right]} \leq D \tag{4}$$

where:

- $E_{(t)}$—energy transacted in period t;
- $Price.M_{(t)}$—market price of period t;
- D—the maximum average price per kWh set by the player;
- T—the session's total number of periods.

The Minimum Matched Energy session constraint sets a minimum energy amount to trade in the market session. Players submitting this constraint do not want to participate in the market session unless their total transacted energy is higher or equal to the minimum amount F set, as presented in Equation (5).

$$\sum_{t=1}^{T} E_{(t)} \geq F \tag{5}$$

where:

- $E_{(t)}$—energy transacted in period t;
- F—the minimum amount of energy to trade set by the player;
- T—the session's total number of periods.

The Maximum Matched Energy session constraint, in opposition to the above Minimum Matched Energy, determines a maximum energy amount to trade in the market session. Players setting this restriction only want to participate in the market session if their total transacted energy is lower than or equal to the maximum amount submitted G, as presented in Equation (6).

$$\sum_{t=1}^{T} E_{(t)} \leq G \tag{6}$$

where:

- $E_{(t)}$—energy transacted in period t;
- G—the maximum amount of energy to trade set by the player;
- T—the session's total number of periods.

Regarding period constraints, the Minimum Matched Energy period constraint is similar to the Minimum Matched Energy session constraint but applied in a specific period. Players applying this constraint do not want to participate in the period's pool unless their traded energy is higher or equal to the predetermined amount H, as presented in Equation (7).

$$Bin_{(t)} \times E_{(t)} \geq H, \quad \forall t \in [1:T] \tag{7}$$

where:

- $Bin_{(t)}$—Decision variable regarding the participation in period t;
- $E_{(t)}$—energy transacted in period p;
- H—the minimum amount of energy to trade set by the player;

- T—the session's total number of periods.

The Maximum Matched Energy period constraint is the opposite of the Minimum Matched Energy period constraint as it sets a maximum trade amount for the given period. Players using this restriction only want to participate in the period's pool if the traded energy is lower than or equal to the amount defined I, as presented in Equation (8).

$$Bin_{(t)} \times E_{(t)} \leq I, \;\; \forall t \in [1:T] \quad (8)$$

where:

- $Bin_{(t)}$—Decision variable regarding the participation in period t;
- $E_{(t)}$—energy transacted in period t;
- X—the maximum amount of energy to trade set by the player;
- T—the session's total number of periods.

These restrictions are a good starting point to test and study the impact of constrained bids in local electricity markets. It should be noted that the order in which these constraints are triggered determines the market's outcomes. However, the constraints' priorities must be previously defined by proper legislation and also exposed to the players in their contracts to make the market fair and clear to every participant, so they can take full advantage of participating. The developed system enables the configuration of each constraint's priority within the semantic model, avoiding the need to reprogram the system every time a user wants to try a different configuration. The constraints' priorities do not change during the system's execution.

3.2. Application Ontology

The application ontology represents all of the system's required knowledge, from the data model to the business rules. Since the system must be agnostic to the semantic model used, an application ontology has been specifically developed for test and proof purposes. However, the developed library enables the user to use another ontology, as long as the resource files, configuration files, and SPARQL rules are updated accordingly. This section briefly presents the Local Market Ontology (LMO), introducing the required concepts for the system to work properly. Not being the main result of this work, the development process of LMO will not be described in great detail. The LMO application ontology has been developed using the 101 development methodology [49]. Its domain and scope are the local auction-based electricity markets with constrained bids. LMO is publicly available (http://www.gecad.isep.ipp.pt/mdpi/energies/845690/files/onto/local-market.ttl).

Reusing existing ontologies is one of the first steps in the development process as it is good practice [49]. Publicly available ontologies facilitate interoperability between heterogeneous systems, as well as knowledge reuse and extension. Thus, the Electricity Market Ontology [50] (EMO) was reused and extended to include the necessary concepts and relations for local market execution. It is publicly available a modular ontology (http://www.mascem.gecad.isep.ipp.pt/ontologies/), developed to provide semantic interoperability with the Multi-Agent Simulator of Competitive Electricity Markets (MASCEM) [51]. Its modular design eases the extension and reuse of the necessary concepts and relations. The LMO application ontology imports and extends the Call for Proposal (CfP) ontology and the Electricity Market Results (EMR) ontology [52], which already import EMO's high-level module. Table 1 presents LMO's classes, as well as their properties and facets. The object properties, properties that relate concepts with each other, are written in blue. The datatype properties, properties that relate concepts with their values, are in green.

Table 1. Local Market Ontology (LMO)'s classes, properties, and facets.

Class	Properties	Facets
Constraint	*priority*	1 *unsignedInt*
HourAhead		*emo:MarketType*
HourAheadSession		*emo:Session*
LocalMarket		*emo:Market*
MaximumCost	 *hasTotalCost* *pricePerkWh*	*Constraint* 1 *emo:Price* 1 *emo:Price*
MaximumMatchedEnergy	*emo:hasPower emo:placedInPeriod*	*Constraint* 1 *emo:Power* *emo:Period*
MinimumIncome	 *hasTotalIncome* *pricePerkWh*	*Constraint* 1 *emo:Price* 1 *emo:Price*
MinimumMatchedEnergy	*emo:hasPower emo:placedInPeriod*	*Constraint* 1 *emo:Power* *emo:Period*
cfp:Proposal	*instant* *emr:fromPlayer*	1 *unsignedLong* 1 *emo:Player*
emr:BidResult	*wasTraded*	1 *boolean*
emo:Player	*setPeriodConstraint* *setPeriodsConstraint* *setSessionConstraint* *totalBoughtEnergy* *totalCost* *totalIncome* *totalSoldEnergy* *totalTransactedEnegy*	*Constraint* *Constraint* *Constraint* 1 *emr:TradedPower* 1 *emo:Price* 1 *emo:Price* 1 *emr:TradedPower* 1 *emr:TradedPower*

Constraint is the top-level class for the bid constraints. Any bid constraints defined for the local auction-based market must be subclasses of this class. This class is defined by one unsigned integer priority datatype property, which sets the order in which the bid constraints must be checked.

The HourAhead, HourAheadSession, and LocalMarket classes are subclasses of the EMO's classes emo:MarketType, emo:Session, and emo:Market, respectively. Although these classes do not declare any new properties, they inherit their super-classes' properties (available at [50]).

The MaximumCost is a subclass of Constraint. It describes the constraint defined in Equations (3) and (4). As well as the inherited priority datatype property, it is also defined by the hasTotalCost and the pricePerkWh object properties. The hasTotalCost object property defines the maximum cost that the player will pay, using one instance of EMO's emo:Price class. Similarly, the pricePerkWh object property defines the maximum accepted price per kWh to be paid.

The MaximumMatchedEnergy is also a subclass of Constraint, describing the constraints defined in Equations (6) and (8). This constraint was designed to be used in both equations since the parameter is the same. By extending Constraint, it inherits the priority datatype property. It is also defined by the EMO's emo:hasPower object property that relates to an instance of EMO's emo:Power class, determining the maximum amount of matched energy. Finally, when using this class as a period constraint, the emo:placedInPeriod object property must be used to determine the period in which this rule applies. This property relates to EMO's emo:Period classes, enabling us to assign the same value to different periods.

MinimumIncome is another subclass of Constraint. It describes the constraint of Equations (1) and (2). Its definition is similar to the MaximumCost class, being the difference in the use of the hasTotalIncome object property instead of hasTotalCost.

The MinimumMatchedEnergy is, again, a subclass of Constraint and describes the constraints defined in Equations (5) and (7). Similarly, this class was designed to be used in both Session and Period equations. It is defined exactly as the MaximumMatchedEnergy class. However, the name of the class informs the system which SPARQL rule applies.

The CfP's cfp:Proposal was extended to add two important details for the aggregator's KB. One is the instant the aggregator receives the player's proposal as an unsigned long timestamp in milliseconds. The second is the information about the player presenting the proposal, using the EMR's emr:fromPlayer object property.

The EMR's emr:BidResult class was also extended with a new datatype property, wasTraded. It sets whether a player's bid was traded or not, after a pool execution.

The EMO's emo:Player class was redefined by adding eight new object properties. The setPeriodConstraint, setPeriodsConstraint, and setSessionConstraint object properties relate to the Constraint class. They enable the definition of period and session constraints for a given player. The setPeriodsConstraint object property is used with constraints for multiple periods, while setPeriodConstraint is used with single period constraints. The totalBoughtEnergy, totalSoldEnergy, and totalTransactedEnegy object properties associate with one instance of EMR's emr:TradedPower class. The first two properties are for players who buy/sell in the session, respectively. The last is useful for players who both buy and sell in different periods of the same session. The totalCost and the totalIncome object properties reflect a player's total cost and income, depending on their bought and sold energy, respectively.

Additionally, three datatype properties were added, namely the algorithms startInstant and endInstant. The first determines which algorithm to use, accepting only one of the following literal values: "symmetric" or "asymmetric". The next are sub-properties of the instants and describe the start and end instants of classes such as emo:Period and emo:Session. These datatype properties are agnostic to any class and vice versa, leaving the decision to use them and where to use them to the ontology engineer. Finally, the details about the remaining classes, object and datatype properties used from EMO, CfP, and EMR are available in [50,52].

It must be kept in mind that the developed solution is not held to any semantic model. The reason for briefly presenting this ontology is to clarify to the reader how the semantic model and SPARQL rules are strongly coupled. With a different semantic model, the constraints' SPARQL templates, presented in the following subsection, must be updated accordingly.

3.3. SPARQL Templates

After deciding on the ontology to use, the next step is to write the SPARQL templates for the bids' constraints. The following templates consider the use of the LMO ontology exposed in Section 3.2. These SPARQL strings are templates because of the use of tags that the developed system uses to replace them with the correct values. Listing 1 presents the SPARQL template for the Minimum Income constraint defined by Equations (1) and (2).

Listing 1. Minimum Income SPARQL template.

```
1 PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
2 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
3 PREFIX emo: <http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#>
4 PREFIX lmo: <http://www.gecad.isep.ipp.pt/ieso/local-market/>
5
6 DELETE {
7   GRAPH ?g {
8     ?power emo:value ?powerVal.
9   }
10 }
11 INSERT {
12   GRAPH ?g {
13     ?power emo:value "0"^^xsd:double .
14   }
15   GRAPH <http://temp/graph/session> {
16     <http://temp/session> <http://temp/updated> true .
17   }
18 }
19 WHERE
20   { <[PLAYER]>
21                   lmo:setSessionConstraint    ?constraint .
22     ?constraint   rdf:type                    lmo:MinimumIncome ;
23                   lmo:hasTotalIncome          ?totalIncome ;
24                   lmo:pricePerkWh             ?pricePerkWh .
25     ?totalIncome  emo:value                   ?totalIncomeVal .
26     ?pricePerkWh  emo:value                   ?pricePerkWhVal
27     GRAPH <http://temp/graph/session>
28     { <[PLAYER]>
29                   lmo:totalIncome             ?ti ;
30                   lmo:totalSoldEnergy         ?tse .
31       ?ti         emo:value                   ?tiVal .
32       ?tse        emo:value                   ?tseVal
33       FILTER ( ?tseVal > 0 )
34       BIND(( ?tiVal / ?tseVal ) AS ?ekWh)
35     }
36     FILTER ( ( ?tiVal < ?totalIncomeVal ) || ( ?ekWh < ?pricePerkWhVal ) )
37     GRAPH ?g
38     { <[PLAYER]>
39                   emo:placesBid               ?bid .
40       ?bid        emo:hasOffer                ?offer ;
41                   emo:transactionType         "sell" .
42       ?offer      emo:hasPower                ?power .
43       ?power      emo:value                   ?powerVal
44     }
45   }
```

Looking at Listing 1, it starts with the tuples' prefixes from line 1 to line 4. Their use eases the writing and reading of the SPARQL string. Otherwise, complete URIs must be used. The rule consists of three parts: the DELETE clause (lines 6 to 10), the INSERT clause (lines 11 to 18), and the WHERE clause (lines 19 to 45). A graph variable (?g) is visible in lines 7, 12, and 37. This variable refers to the periods' temporary graphs that the system adds to manage the session execution without losing the initial data submitted by the players. In this specific case, this variable is useful to refer specifically to periods where the player is selling (line 40) and to keep the query as simple as possible. The DELETE clause defines the triples to delete from the temporary graphs if the WHERE clause is valid. The INSERT clause updates triples in more than one graph. The power is set to zero in the periods' temporary graphs to remove the player from the session. The triple to inform the system that the current session must be rerun is inserted in the session's temporary graph (line 15). This triple is removed before the session reruns. The WHERE clause is composed of three parts. The first part (lines 20 to 26) gets the constraint's values for the minimum income and price per kWh. The second part (lines 27 to 35) gets the player's total income in the session, and the price per kWh received. The FILTER on line 33 ensures that the player has traded in the current session, while the FILTER on line 36 checks if one of the total income or the price per kWh is lower than what is desired. Finally, the third part (lines 37 to 44) of the WHERE clause causes the triple to be updated (line 43) in case the rule is triggered, ensuring that it only considers periods in which the player sold energy. Finally, to validate the constraints, the system replaces the [PLAYER] tag with the respective player's URI.

Listing 2 shows the SPARQL template for the Maximum Cost constraint defined by Equations (3) and (4).

Listing 2. Maximum Cost SPARQL template.

```
1 PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
2 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
3 PREFIX emo: <http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#>
4 PREFIX lmo: <http://www.gecad.isep.ipp.pt/ieso/local-market/>
5
6 DELETE {
7    GRAPH ?g {
8     ?power emo:value ?powerVal .
9    }
10 }
11 INSERT {
12    GRAPH ?g {
13     ?power emo:value "0"^^xsd:double .
14    }
15    GRAPH <http://temp/graph/session> {
16     <http://temp/session> <http://temp/updated> true .
17    }
18 }
19 WHERE
20    { <[PLAYER]>
21                lmo:setSessionConstraint   ?constraint .
22       ?constraint rdf:type          lmo:MaximumCost ;
23                lmo:hasTotalCost        ?totalCost ;
24                lmo:pricePerkWh         ?pricePerkWh .
25       ?totalCost  emo:value           ?totalCostVal .
26       ?pricePerkWh    emo:value         ?pricePerkWhVal
27       GRAPH <http://temp/graph/session>
28         { <[PLAYER]>
29                   lmo:totalCost             ?tc ;
30                   lmo:totalBoughtEnergy    ?tbe .
31            ?tc        emo:value              ?tcVal .
32            ?tbe       emo:value              ?tbeVal
33            FILTER ( ?tbeVal > 0 )
34            BIND(( ?tcVal / ?tbeVal ) AS ?ekWh)
35         }
36       FILTER ( ( ?tcVal > ?totalCostVal ) || ( ?ekWh > ?pricePerkWhVal ) )
37       GRAPH ?g
38         { <[PLAYER]>
39                   emo:placesBid            ?bid .
40            ?bid       emo:hasOffer             ?offer ;
41                   emo:transactionType    "buy" .
42            ?offer     emo:hasPower             ?power .
43            ?power     emo:value                ?powerVal
44         }
45    }
```

The Maximum Cost rule is very similar to the Minimum Income shown in Listing 1. The differences are in lines 22, 23, 29, 30, 36, and 41. Line 22 searches for the lmo:MaximumCost constraint and line 23 uses the lmo:hasTotalCost property instead of the lmo:hasTotalIncome to get the constraint's value. Line 29 gets the total cost and line 30 the total bought energy of the session. The FILTER on line 36 has the opposite sign (> instead of <), and line 41 causes the triples to be updated only for periods where the player buys energy.

Listing 3 shows the SPARQL template for the session's Minimum Matched Energy constraint defined in Equation (5).

Listing 3. Session's Minimum Matched Energy SPARQL template

```
1 PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
2 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
3 PREFIX emo: <http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#>
4 PREFIX lmo: <http://www.gecad.isep.ipp.pt/ieso/local-market/>
5
6 DELETE {
7   GRAPH ?g {
8     ?power emo:value ?powerVal .
9   }
10 }
11 INSERT {
12   GRAPH ?g {
13     ?power emo:value "0"^^xsd:double .
14   }
15   GRAPH <http://temp/graph/session> {
16     <http://temp/session> <http://temp/updated> true .
17   }
18 }
19 WHERE
20   { <[PLAYER]>
21               lmo:setSessionConstraint   ?constraint .
22     ?constraint rdf:type               lmo:MinimumMatchedEnergy ;
23               emo:hasPower              ?constPower .
24     ?constPower   emo:value             ?cVal
25     GRAPH <http://temp/graph/session>
26       { <[PLAYER]>
27               lmo:totalTransactedEnergy    ?tte .
28         ?tte         emo:value              ?tEnergy
29         FILTER ( ?tEnergy > 0 )
30       }
31     FILTER ( ?tEnergy < ?cVal )
32     GRAPH ?g
33       { <[PLAYER]>
34               emo:placesBid   ?bid .
35         ?bid         emo:hasOffer    ?offer .
36         ?offer       emo:hasPower    ?power .
37         ?power       emo:value       ?powerVal
38       }
39   }
```

This rule has a similar structure to those previously presented. The difference is in the WHERE clause. The first part of the WHERE clause (lines 20 to 24) searches for the lmo:MinimumMatchedEnergy constraint instance and its value. The second (lines 25 to 30) validates the total transacted energy value against the constraint's value in the FILTER of line 31. The third part of the WHERE clause (line 32 to 38) causes the triple to be updated in the DELETE and INSERT clauses, in case the rule is triggered.

Listing 4 presents the SPARQL template for the session's Maximum Matched Energy constraint defined in Equation (6).

Listing 4. Session's Maximum Matched Energy SPARQL template.

```
1 PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
2 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
3 PREFIX emo: <http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#>
4 PREFIX lmo: <http://www.gecad.isep.ipp.pt/ieso/local-market/>
5
6 DELETE {
7   GRAPH ?g {
8    ?power emo:value ?powerVal .
9   }
10 }
11 INSERT {
12   GRAPH ?g {
13    ?power emo:value “0”^^xsd:double .
14   }
15   GRAPH <http://temp/graph/session> {
16     <http://temp/session> <http://temp/updated> true .
17   }
18 }
19 WHERE
20   { <[PLAYER]>
21                 lmo:setSessionConstraint ?constraint .
22       ?constraint   rdf:type          lmo:MaximumMatchedEnergy ;
23                 emo:hasPower          ?constPower .
24       ?constPower   emo:value          ?cVal
25       GRAPH <http://temp/graph/session>
26         { <[PLAYER]>
27                    lmo:totalTransactedEnergy   ?tte .
28            ?tte        emo:value              ?tEnergy
29         }
30       FILTER ( ?tEnergy > ?cVal )
31       GRAPH ?g
32         { <[PLAYER]>
33                    emo:placesBid    ?bid .
34            ?bid        emo:hasOffer     ?offer .
35            ?offer      emo:hasPower     ?power .
36            ?power       emo:value       ?powerVal
37         }
38   }
```

The Maximum Matched Energy constraint is the opposite of the Minimum Matched Energy. This rule template has only two differences when compared with the one shown in Listing 3. First, the FILTER on line 30 has the opposite sign (> instead of <). Secondly, the FILTER on line 29 of Listing 3 is unnecessary since, if a player does not trade, then they will not exceed the maximum energy determined by the constraint.

Listing 5 shows the SPARQL template for the period's Minimum Matched Energy constraint defined in Equation (7).

Listing 5. Period's Minimum Matched Energy SPARQL template.

```
1 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
2 PREFIX emo: <http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#>
3 PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
4 PREFIX emr: <http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl#>
5 PREFIX ind: <http://www.gecad.isep.ipp.pt/ind/>
6 PREFIX lmo: <http://www.gecad.isep.ipp.pt/ieso/local-market/>
7
8 DELETE {
9    GRAPH <http://temp/graph/[PERIOD]> {
10     ?power emo:value ?powerVal .
11   }
12 }
13 INSERT {
14   GRAPH <http://temp/graph/[PERIOD]> {
15     ?power emo:value "0"^^xsd:double .
16     <http://temp/period/[PERIOD]> <http://temp/updated> true .
17   }
18 }
19 WHERE
20   { <[PLAYER]>
21                    lmo:setPeriodConstraint   ?constraint .
22     ?constraint   rdf:type                  lmo:MinimumMatchedEnergy ;
23                    emo:placedInPeriod     ?period ;
24                    emo:hasPower           ?constPower .
25     ?period     emo:number              "[PERIOD]"^^xsd:unsignedInt .
26     ?constPower    emo:value           ?cVal
27     GRAPH <http://temp/graph/[PERIOD]>
28       { <[PLAYER]>
29                         emo:placesBid      ?bid .
30         ?bid            emo:hasOffer       ?offer .
31         ?offer          emo:hasPower       ?power .
32         ?power           emo:value         ?powerVal .
33         ?pr             emr:fromPlayer     <[PLAYER]> ;
34                         emr:fromSession   ind:iHourAheadSession ;
35                         emr:gotResult      ?br .
36         ?br              lmo:wasTraded     true ;
37                         emo:hasPower       ?p .
38         ?p              emo:value          ?brVal
39       }
40     FILTER ( ?brVal < ?cVal )
41   }
```

When examining Listing 5, it is perceptible that the rule structure is similar. However, since it is a period's constraint, the previous graph variable (?g) is replaced by the respective period graph (line 9). The DELETE clause (lines 8 to 12) defines the triple to be deleted from the period's temporary graph in case the WHERE clause (lines 19 to 41) is true, while the INSERT clause (lines 13 to 18) defines the triples to include. In this case, the player is removed from the period's pool (line 15) once it is not possible to satisfy the minimum required amount of energy. For the period's constraints, the temporary triple, to inform the system that the current pool must rerun, is included in the period's temporary graph (line 16). The WHERE clause searches for the period's Minimum Matched Energy constraint value (lines 20 to 26), the submitted energy value (lines 28 to 32) to update if the rule is triggered, and the traded energy value (from lines 33 to 38) from the bid's result to check if it is lower than the constraint value (FILTER on line 40). In the period's constraints, the SPARQL templates include a [PERIOD] tag in addition to the [PLAYER], ensuring correct data management. The [PERIOD] tag is replaced by the period number.

Listing 6 presents the SPARQL template for the period's Maximum Matched Energy constraint, defined in Equation (8).

Listing 6. Period's Maximum Matched Energy SPARQL template.

```
1 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
2 PREFIX emo: <http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#>
3 PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
4 PREFIX emr: <http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl#>
5 PREFIX ind: <http://www.gecad.isep.ipp.pt/ind/>
6 PREFIX lmo: <http://www.gecad.isep.ipp.pt/ieso/local-market/>
7
8 DELETE {
9    GRAPH <http://temp/graph/[PERIOD]> {
10      ?power emo:value ?powerVal .
11    }
12 }
13 INSERT {
14    GRAPH <http://temp/graph/[PERIOD]> {
15      ?power emo:value ?cVal .
16      <http://temp/period/[PERIOD]> <http://temp/updated> true .
17    }
18 }
19 WHERE
20    { <[PLAYER]>
21                lmo:setPeriodConstraint   ?constraint .
22      ?constraint    rdf:type           lmo:MaximumMatchedEnergy ;
23                emo:placedInPeriod   ?period ;
24                emo:hasPower          ?constPower .
25      ?period      emo:number          "[PERIOD]"^^xsd:unsignedInt .
26      ?constPower   emo:value           ?cVal
27      GRAPH <http://temp/graph/[PERIOD]>
28       { <[PLAYER]>
29                  emo:placesBid      ?bid .
30          ?bid        emo:hasOffer       ?offer .
31          ?offer      emo:hasPower       ?power .
32          ?power      emo:value          ?powerVal .
33          ?pr         emr:fromPlayer     <[PLAYER]> ;
34                      emr:fromSession    ind:iHourAheadSession ;
35                      emr:gotResult      ?br .
36          ?br         lmo:wasTraded      true ;
37                      emo:hasPower       ?p .
38          ?p          emo:value          ?brVal
39       }
40      FILTER ( ?brVal > ?cVal )
41    }
```

The main differences between Listings 6 and 5 are lines 15, 22, and 40. Unlike the previous rules, this restriction does not remove the player from the pool but reduces the amount of energy offered to the constrained value (line 15). Line 22 searches for the lmo:MaximumMatchedEnergy constraint instance. On line 40, it is visible in the FILTER using the opposite sign (> instead of <).

4. Case Study

The case study presented in this section illustrates the application of the proposed solution to solve constrained bid transactions in local electricity markets from the perspective of an aggregator. The case study is inspired by a community microgrid adapted from [53], with twenty-three residential houses and four public buildings. Of these, four residential houses and three public buildings are equipped with photovoltaic (PV) panels (prosumers). The other players are ordinary consumers.

Real data resulting from recent data measured by the authors of the present paper were used for the preparation of the case study.

To show the application of our solution, we consider one hour of market operation (a session from 14:00 to 15:00), split into periods of 15 min, in which each player participates with buy or sell bids and, when desired, the respective constraints. The players will be bidding on an hour-ahead basis, meaning that this local market session will run in the hour before (between 13:00 and 14:00). The local market proposed is based on the symmetric market pool [35,36], where both buyers and suppliers can compete by submitting their bids.

The session starts with the aggregator sending the call for proposals for the next local market session. The players interested in participating submit their bids for each period and the desired constraints from 13:15 to 13:45. Table 2 presents the considered local market players, their bids, and the instant at which the aggregator received each proposal. The golden color gradient identifies the prices ordered from the darkest (higher) to the lightest (lower). Likewise, the green gradient distinguishes the higher and lower demand energy, while the blue concerns the energy surplus.

Table 2. Payers' bids for the local market hour-ahead session.

Player	Bids								Instant
	14:00		14:15		14:30		14:45		
	kWh	EUR	kWh	EUR	kWh	EUR	kWh	EUR	
House 1	0.1127	0.1392	0.1127	0.1103	0.1127	0.0987	0.1127	0.0959	13:40:29.266
House 2	0.2921	0.1211	0.2852	0.1659	1.1293	0.0985	2.5599	0.0982	13:39:53.629
House 3	0.4485	0.1104	0.2806	0.1183	0.6164	0.0979	0.2806	0.0974	13:16:34.193
House 4	−0.2303	0.1132	−0.2751	0.1092	−0.263	0.0974	−0.3623	0.0968	13:20:54.956
House 5	1.2121	0.1598	0.5244	0.1646	0.506	0.0985	0.7107	0.0959	13:19:02.981
House 6	1.0373	0.1609	0.4554	0.1388	0.8096	0.0985	0.0736	0.0972	13:15:59.810
House 7	0.2346	0.1738	2.093	0.1901	1.7526	0.0977	0.2576	0.096	13:42:55.789
House 8	−0.3854	0.1213	−0.4069	0.1118	−0.6145	0.0959	−0.6224	0.0987	13:33:27.166
House 9	0.8142	0.1597	0.8142	0.1766	0.6049	0.0977	0.6647	0.0972	13:31:01.235
House 10	0.0621	0.1827	0.0598	0.172	0.0552	0.0955	0.1173	0.0962	13:26:34.783
House 11	0.5244	0.1016	0.5589	0.1305	0.6762	0.0966	0.2806	0.0958	13:39:24.004
House 12	0	0	0	0	0	0	0.1058	0.0978	13:25:23.407
House 13	0.4255	0.0972	0.3036	0.1286	0.6578	0.0985	0.3565	0.0984	13:43:18.609
House 14	0.1725	0.1126	0.1771	0.1207	0.1794	0.0961	0.2691	0.0961	13:21:20.237
House 15	0.1909	0.1718	0.1817	0.1552	0.2047	0.095	0.2047	0.0975	13:23:38.991
House 16	0.5497	0.1542	0.5497	0.1277	0.5198	0.0979	0.5589	0.0977	13:40:11.062
House 17	0.1817	0.1768	0.1771	0.1784	0.3496	0.0966	0.2277	0.0973	13:34:18.168
House 18	0.5474	0.13	0.529	0.1672	0.2852	0.0977	0.3726	0.0983	13:44:53.266
House 19	0.299	0.1377	0.2921	0.1134	0.2921	0.0966	0.2737	0.097	13:25:00.754
House 20	0.1817	0.1072	0.1955	0.1742	0.1932	0.0957	0.2047	0.0986	13:31:39.420
House 21	−0.2499	0.1697	−0.9392	0.137	−0.1929	0.0968	−0.3825	0.0968	13:18:27.320
House 22	0.2438	0.1065	0.2346	0.1696	0.2438	0.095	0.2438	0.0964	13:24:34.370
House 23	−0.181	0.1745	−0.2355	0.192	−0.2014	0.0961	−0.1756	0.0979	13:26:29.464
Culture Hall	7.9245	0.1043	8.512	0.1406	10.499	0.28	9.427	0.1226	13:24:34.014
Library	−2.4055	0.0996	−0.3615	0.1135	−3.282	0.1214	−3.3615	0.2316	13:15:34.989
City Hall	−2.332	0.1394	−3.006	0.1134	−2.75	0.2471	−2.345	0.2431	13:31:11.450
Municipal Market	−1.987	0.0998	−1.8907	0.1134	−1.8507	0.2937	−1.127	0.2198	13:42:13.688

When analyzing Table 2, it is possible to verify that all twenty-seven players decided to participate in the current hourly session. The instant the aggregator receives each proposal is important so that they can arrange the bids with equal prices by order of arrival. The bids with negative energy values are sell bids, while the positive energy values represent buy bids. In the current session, House 4, House 8, House 21, House 23, Library, City Hall, and Municipal Market all sell bids. These are all the available prosumers in the community. Prosumers calculate the difference between consumption and generation forecasts to determine the available surplus energy that they can offer in the market for each period. Since these prosumers depend on renewable generation, their generation is unstable. In this specific case, it depends on the solar radiation, time of day, and time of year. Thus, there are several situations in which generation is not enough to supply each player demand. In those situations, there is no surplus energy to be sold in the local market. Bid prices are defined strategically based on the base tariff of each player. Table 3 shows the generation and consumption tariffs contracted by each player.

Table 3. Players' base tariffs.

Player	Consumption Tariffs (EUR/kWh)				Generation Tariff (EUR/kWh)
	14:00	14:15	14:30	14:45	
House 1 to House 23	0.1962		0.0988		0.0950
Culture Hall, Library, City Hall, Municipal Market	0.1445		0.3000		

When looking at Table 3, it is possible to see that both residential and public building players contract multi-hourly tariffs. Additionally, the generation tariff is constant for all prosumers during all day. These data are based on real tariff data, although the multi-hourly tariffs periods do not change at this specific time of day. The decision to change the tariff in the middle of the session aims to verify how the proposed local market behaves in this scenario. Through these tariffs, each player defined the prices for each period, keeping in mind that prices lower than the generation base tariff will not attract prosumers and prices higher than the base consumption tariff will not attract consumers. Prices defined as in between are used strategically by each player to reach their goals. Consumers want to minimize costs, while prosumers intend to maximize their profits. A different and complementary type of strategy is the use of (period/session) constraints in which—if they are not satisfied—players may decide not to participate in the market pool or to update their bids accordingly. Tables 4 and 5 present the constraints submitted in the current session and periods, respectively.

Table 4. Players' session constraints.

Player	Maximum Cost		Minimum Income		Maximum Matched Energy (kWh)	Minimum Matched Energy (kWh)
	EUR	EUR/kWh	EUR	EUR/kWh		
House 1	0.0437	0.0970				
House 4					1.1000	
House 8					2.0000	1.0000
House 23						0.6500
Library			0.9000	0.1000		
M. Market			1.2040	0.1817	6.5000	3.5000

Table 5. Players' period constraints.

Player	Maximum Matched Energy (kWh)				Minimum Matched Energy (kWh)			
	57	58	59	60	57	58	59	60
House 1					0.1000	0.0900	0.1100	0.1000
House 8				0.6077				
House 23					0.1500	0.2000		
Culture Hall							8.0000	
M. Market	1.9000	1.8000	1.8000	1.0000	1.0000	1.0000	1.0000	1.0000

When inspecting Tables 4 and 5, it is perceptible that the Library and House 4 players only submitted a session constraint, while the Culture Hall player submitted one restriction for period 59. The Municipal Market is the player that submitted all types of constraints (since it is a seller, it makes no sense for it to submit the Maximum Cost constraint). The House 1, House 8, and House 23 players also submitted their strategic constraints, trying to achieve their goals.

As explained in Section 3, the local auction-based market library receives these input data as an RDF KB file. The KB file, as well as the configuration file and the resource files, are available online (http://www.gecad.isep.ipp.pt/mdpi/energies/845690/), as well as the input and output files of the various symmetrical pool executions for test and proof purposes. To avoid distracting the reader from the purpose of this work, this case study will focus on describing the triggered local market constraints.

The system starts by querying it to get the ordered periods of the session and creates a temporary graph for each period. Next, it queries the graph of period 57 (dividing the day into periods of 15 min, from 14:00 to 14:15 is the period 57) to get the players' demand and supply bids, ordered by price, to run the symmetrical algorithm. The output of the algorithm is added, afterwards, to the KB period's graph. The next step is to apply the players' constraints to the pool results. For this, the system queries the KB to get the suppliers' and demanders' constraints. These are ordered by bid price (ascending in the case of suppliers/descending in the case of demanders), time of arrival and priority, so that the players' restrictions are applied in the same order as the pool bids. As presented above, for the period constraints, players can define a maximum and minimum matched energy amount. This starts by applying the suppliers' constraints. The suppliers House 23 and Municipal Market submitted restrictions for period 57 (Table 5). House 23 did not trade in this period, while Municipal Market traded the total offered amount of energy, namely 1.987 kWh (Table 2). However, Municipal Market also defined a Maximum Matched Energy restriction at 1.9 kWh (Table 5). By applying this constraint, the Municipal Market bid is reduced to 1.9 kWh and the market pool rerun for period 57. As explained in Section 3.1, this restriction does not remove the player from the market pool but reduces the offered amount of energy to the constraint value.

The system reruns period 57, and no other restriction is triggered. It runs the market pool for period 58 by following the same process, but on a different graph. Once again, the Municipal Market triggers the Maximum Matched Energy constraint, this time set at 1.8 kWh, being the traded energy amount 1.8907 kWh. Its bid is updated by the rule, and the market reruns for period 58. Again, no other constraints were triggered. The system continues its execution by running the period 59 pool. This time, the Culture Hall is removed from the market pool because of the Minimum Matched Energy constraint, set at 8 kWh. Its traded amount was 7.3038 kWh. After removing the Culture Hall player from the period's pool, the system executes it again, and this time no more issues are found. The system continues for period 60. In this period, the Maximum Matched Energy restriction, set by House 8, is triggered. House 8 defined a maximum value of 0.6077 kWh. However, the pool result was 0.6224 kWh. As in periods 57 and 58, the rule reduces the bid amount of energy, and the market continues smoothly.

After the execution of all periods ends, the system updates the KB with the players' aggregated results, namely the total transacted energy, the total bought/sold energy, and the session's total cost/income. Next, the system queries the KB to get the session's constraints ordered by the time of arrival and priority. In this case, the supply and demand bids are not discriminated, since a player can buy in one period and sell in the next one. The first rule to trigger is the constraint set by the Library player. This player is removed from the session because of the Minimum Income constraint set at EUR 0.9, and the total income of this player was EUR 0.2806. The Minimum Income constraint states that if the player's total income or the price per kWh is below a predefined amount, then he must be removed from the pool since he does not want to participate if those conditions are not met. Due to this constraint, Library player is removed from this local market session, not trading in any period, as illustrated in Figure 3.

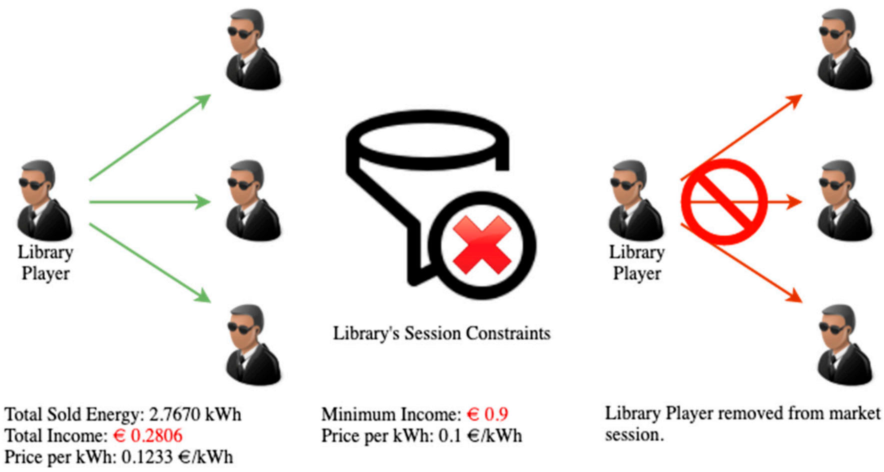

Figure 3. Library player session results after applying session constraints.

The session is rerun, and this time there are no period restrictions triggered. In turn, the Maximum Matched Energy session constraint triggers for the House 4 player. This player set this constraint at 1.1 kWh. However, it trades at 1.1307 kWh in the complete session, which removes it from the market pool. The session is rerun. This time, the session's Minimum Matched Energy constraint triggers for player House 23. This player traded 0.377 kWh but has set a minimum value of 0.65 kWh for the session. As such, House 23 is removed from the session's pool. The session reruns and the Maximum Matched Energy restriction set by House 8 removes it from the pool. House 8 set a maximum of 2 kWh for the session and trades at 2.0145 kWh.

In the next run, the Maximum Cost rule is triggered for player House 1. This player defined a maximum cost of EUR 0.0437 and a maximum price per kWh of EUR 0.097. In this market session, the House 1 player only traded in period 59, 0.1127 kWh for EUR 0.0974 per kWh. The total cost is EUR 0.0437, which is accepted by the rule defined by House 1. However, the price per kWh is higher than the EUR 0.097 determined in the constraint. The market pool reruns again. This time, the Municipal Market player is removed from the pool due to the Minimum Income constraint. The Municipal Market set a minimum income of EUR 1.204 and at least EUR 0.1817 per kWh. This player only achieves an income of EUR 0.5115 and is removed from the pool. The seventh run of the session pool concludes the local market execution. No more constraints are triggered, and the system returns the final results. Table 6 presents the aggregated results of the local market session.

Table 6. Local market session aggregate results.

Energy Volume (kWh)	Price Volume (EUR)	Minimum Price (EUR/kWh)	Maximum Price (EUR/kWh)	Average Price (EUR/kWh)
6.8526	0.9221	0.0974	0.1394	0.1181

The total amount of traded energy in the local market was 6.8526 kWh, with a monetary volume of EUR 0.9221. The minimum price of the session was of EUR 0.0974 in period 59. Period 57 presented the highest price of EUR 0.1394. The average price of the session was EUR 0.1181. Figure 4a shows the players' transacted energy in each period, and (b) the period's total traded energy, the market prices, and the number of players dispatched.

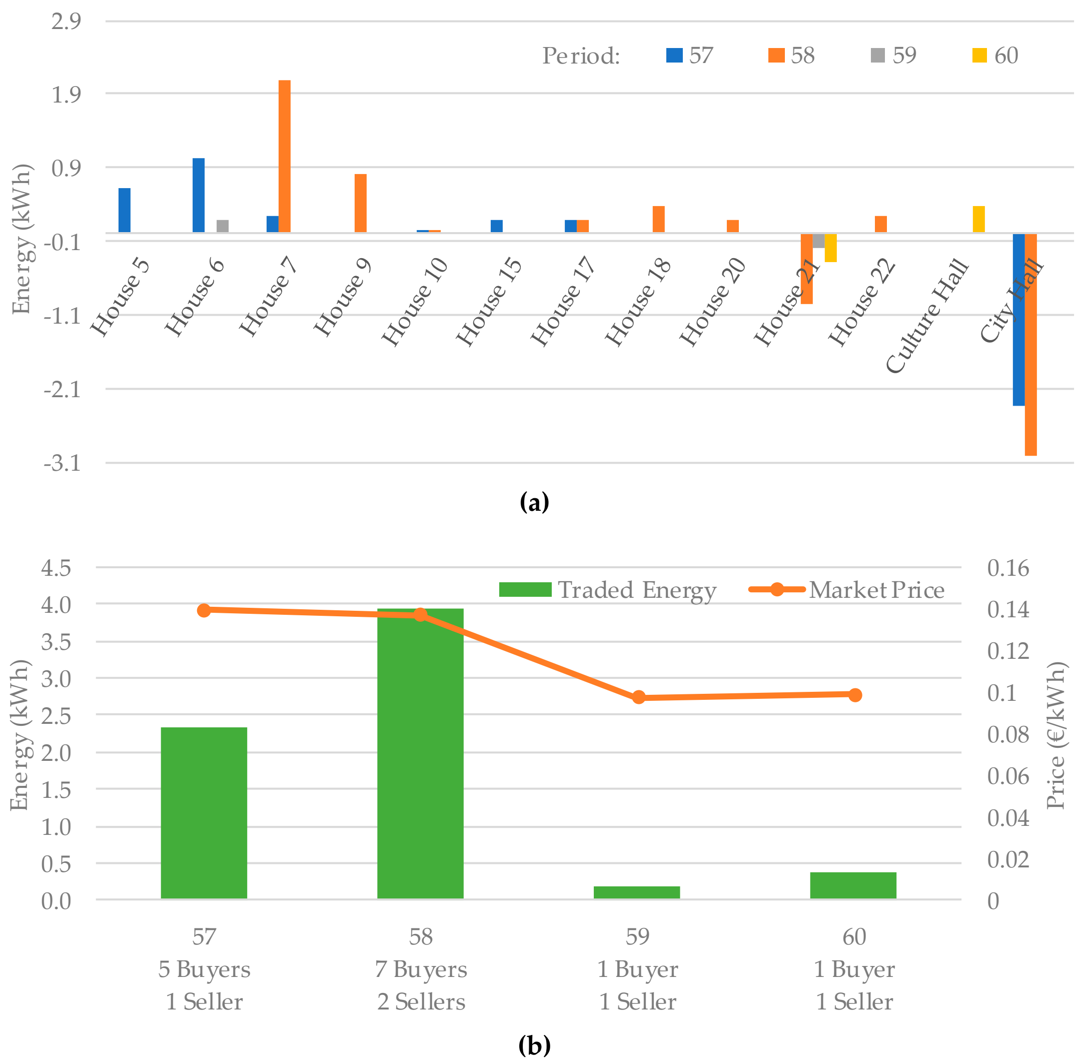

Figure 4. Local market players' results: (**a**) players transacted energy per period; (**b**) period's total traded energy, market price, and no. of dispatched players.

When analyzing Figure 4a, it can be seen that only thirteen players were able to trade in this session (less than 50%). From these, only two players are prosumers since the remaining players were removed due to their constraints. These prosumers are identified by the negative energy, as in Table 2. In Figure 4b, it can be seen that the first two sessions had more traded energy and dispatched players than the next two. On one hand, the first two periods had more available energy to trade; on the other, the player with more energy surplus (Municipal Market) was removed from the session due to their constraints.

To demonstrate the ease of changing the rules of the local electricity market, without the need to reprogram and recompile the system, we will add a new constraint. The new restriction is a new version of the Minimum Income rule that removed the Library player from the market session (see Figure 3). The difference between this constraint and the new one is that, in the original proposal, both the total income and price per kWh must be higher or equal to the values predetermined by the player, while, in the second version, if one of the values is higher than those determined by the player, then the rule will not be triggered and the player will not be removed from the pool. Figure 3 illustrates that, although the Library player achieved a price per kWh higher than the minimum value accepted, he was removed from the market session due to not achieving the minimum total income defined. With the new version of this rule, the Library player will not be removed and will be able to trade in the market session.

The first step is to add the new constraint to the semantic model (http://www.gecad.isep.ipp.pt/mdpi/energies/845690/#onto-lmo-v2). Since the constraint's attributes will be the same as the MinimumIncome class defined in Table 1, the new rule can be simply defined as a subclass of MinimumIncome, i.e., MinimumIncomeV2 extends MinimumIncome, inheriting its attributes, namely the properties hasTotalIncome and pricePerkWh, as well as the priority inherited from the class Constraint. Afterwards, the new constraint template must be added to the configuration file (http://www.gecad.isep.ipp.pt/mdpi/energies/845690/#in-conf-v2). When looking at Listing 1, the difference between MinimumIncome and MinimumIncomeV2 is in line 36, where the operator || (OR) is replaced by the operator AND (&&). Finally, the instance of the Library player in the KB file (http://www.gecad.isep.ipp.pt/mdpi/energies/845690/#in-kb-v2) is also updated to use the MinimumIncomeV2 constraint instead of MinimumIncome.

After the first iteration of the execution of the market session, it is possible to verify that the Library player was not excluded from the market pool. His results were the same; however, the MinimumIncomeV2 constraint did not trigger since the price per kWh is higher than the minimum value predetermined by the player. Figure 5 illustrates this scenario.

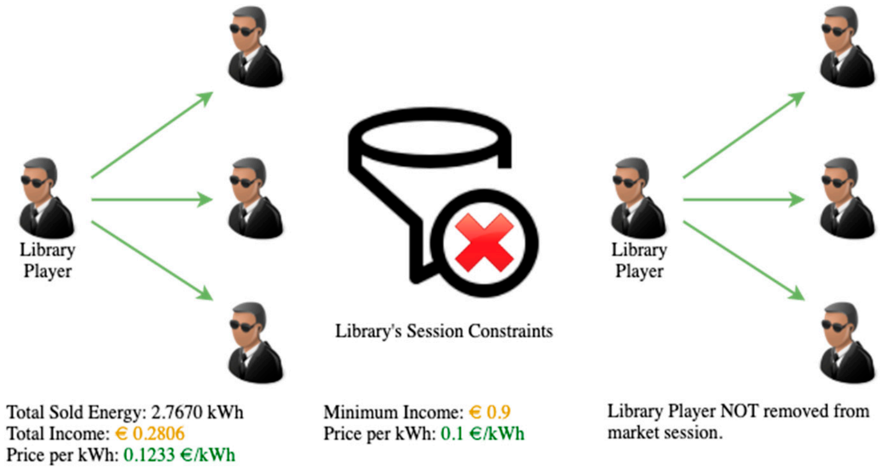

Figure 5. Library player session results after applying session constraints.

The above example has the purpose of showing the simplicity and flexibility of the system when adding a new rule. On the other hand, one could update the MinimumIncome template to accomplish the constraint defined by MinimumIncomeV2. This flexibility is of great value when the main purpose of the system is to enable the study of different possibilities.

The developed system is agnostic to the constraint rules configured, as well as to the semantic models used. Their use is an advantage when developing systems that evolve rapidly since, when a rule must be updated, or added, there is no need to reprogram the system. To update a rule, the developer will only need to rewrite it in the configuration file. To add a new constraint, the developer must add it to the semantic model (as a subclass of Constraint class) and add the respective SPARQL rule to the configuration file. Finally, it is also possible to use a different semantic model. For such, it is only necessary to update the resource files in order to get the required data for the system to solve the local auction-based market pool.

5. Conclusions

Energy markets are constantly evolving due to the large-scale implementation of RES and DG in response to the environmental targets imposed worldwide. Recent directives invest in the design, development, and implementation of local electricity markets to fulfill these targets, taking advantage of the increased use of RES and DG to keep the grid balanced and avoid the use of fossil fuels to produce electricity. Several works propose varied solutions to solve local electricity markets for different purposes.

This work proposed the use of constrained bid transactions in local electricity markets. To this end, it presents the design and development of a library that takes advantage of semantic web technologies to be flexible and agnostic to the data model and business rules. In this way, it avoids the need to reprogram the system any time a rule is added, removed, or updated. The solution proposed had in mind the constant evolution of the markets, allowing its users to spend more time on studying and testing different market alternatives than on programing a new alternative. The focus was given to distributed generation, so the respective owners can profit better from their participation in local markets, increasing the amount of energy negotiated.

This document provides a background overview of auction-based electricity market types, local market bid constraints, and the advantages of using ontologies and semantic web technologies instead of coding data models and business rules, as well as the solution's architecture, the proposed constraints, the application ontology, and the rules' SPARQL templates. The case study illustrates a scenario based on real data executed in the proposed solution, describing the bid constraints triggered. It demonstrates the advantage of using semantic web technologies in the development of solutions toward constantly evolving domains such as the electricity market. A community of 27 consumers was used in the case study, showing the effectiveness of the proposed methodology. The next steps are to improve the players' constraints and design and to implement aggregator restrictions, while considering the grid constraints. The players' constraints can be improved by suggesting new ones or by updating the ones proposed, regarding, for example, the players' targets and preferences in a complete day, in the total results of all the sessions. To achieve this, studies and experiments must be performed to analyze how these may or may not benefit the players that use them. A scalability study will also be performed to enable the use of the proposed solution in larger communities.

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Core Publication IV

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Resumen

Los sistemas de gestión de edificios (BMS por sus siglas en inglés) están siendo implementados ampliamente por las industrias en las últimas décadas. Sin embargo, los BMS se centran en dominios específicos y, cuando se instalan en el mismo edificio, carecen de interoperabilidad para funcionar en una interfaz de usuario centralizada. Por otro lado, la interoperabilidad de BMS permite la implementación de reglas complejas basadas en contextos multidominio. El sistema basado en el conocimiento del razonamiento del edificio para el control inteligente (BRICKS por sus siglas en inglés) es un sistema basado en reglas semánticas consciente del contexto para la gestión inteligente de la energía y la seguridad de los edificios. Utiliza ontologías y tecnologías web semánticas para interactuar con diferentes dominios, aprovechando el conocimiento entre dominios para aplicar reglas basadas en el contexto. Este trabajo actualiza la versión anterior de BRICKS al incluir servicios para el consumo de energía y pronóstico de generación, respuesta a la demanda, una interfaz de usuario de configuración (UI) y una interfaz de usuario dinámica de monitoreo y administración de edificios UI. El estudio de caso demuestra BRICKS implementado en diferentes niveles de agregación en el edificio del laboratorio de los autores, gestionando un evento de respuesta a la demanda e interactuando de forma autónoma con otras instancias de BRICKS. Los resultados validan el correcto funcionamiento de la herramienta propuesta, que contribuye a la flexibilidad, eficiencia y seguridad de los sistemas energéticos del edificio.

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Article

Upgrading BRICKS—The Context-Aware Semantic Rule-Based System for Intelligent Building Energy and Security Management

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Abstract: Building management systems (BMSs) are being implemented broadly by industries in recent decades. However, BMSs focus on specific domains, and when installed on the same building, they lack interoperability to work on a centralized user interface. On the other hand, BMSs interoperability allows the implementation of complex rules based on multi-domain contexts. The *Building's Reasoning for Intelligent Control Knowledge-based System* (BRICKS) is a context-aware semantic rule-based system for the intelligent management of buildings' energy and security. It uses ontologies and semantic web technologies to interact with different domains, taking advantage of cross-domain knowledge to apply context-based rules. This work upgrades the previously presented version of BRICKS by including services for energy consumption and generation forecast, demand response, a configuration user interface (UI), and a dynamic building monitoring and management UI. The case study demonstrates BRICKS deployed at different aggregation levels in the authors' laboratory building, managing a demand response event and interacting autonomously with other BRICKS instances. The results validate the correct functioning of the proposed tool, which contributes to the flexibility, efficiency, and security of building energy systems.

Keywords: context-aware knowledge-base systems; intelligent control ; interoperability; semantic reasoning; semantic rule-based systems

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1. Introduction

Several solutions have been developed in the building energy management area in the past decades [1], particularly with the emergence of new technologies, standards, and protocols. These solutions often focus on specific domains such as heating, ventilation, and air conditioning (HVAC) systems, lighting control systems, shading control systems, energy management systems, among others. However, there are no solutions capable of integrating all building management solutions into a single system, ensuring optimized management of the energy resources [2]. The only option being to manage each domain independently. Nowadays, buildings are key elements in the smart grid (SG) domain [1,3] and relevant sources of energy flexibility in the demand response (DR) context [4,5]. A building itself is not enough to provide the needed consumption reduction. However, a DR aggregator collecting each building's contribution reaches the required energy reduction [6,7].

Building management systems (BMSs) have limitations in terms of energy efficiency, such as the need for effective retrofitting of the building's equipment and systems and the need for the detailed identification of the energy consumption points [6,7]. It is even more relevant with the rising demand for dynamic and intelligent building management, enabling consumers to participate actively in energy consumption management, considering the priorities of the loads according to the current context [8]. Current BMSs rely on simplistic controls that require the user to enter the information manually. However, intelligent systems should calculate and understand all of these context variables autonomously [9]. Critical buildings (such as hospitals or airports) have a technological ecosystem composed of several closed systems to control equipment and functions of specific domain areas and, therefore, do not allow information exchange nor interoperability between them. It could be interesting to take advantage of the heterogeneous systems' knowledge to provide a more intelligent building management. Additionally, BMSs should integrate renewable energy sources (RES) components, adopting a dynamic resource management philosophy, taking into account several time horizons, and functioning in an isolated mode or connected to the distribution grid [10,11].

The SEmantic SmArt Metering–Services for Energy Efficient Houses (SESAME-S) [12] project developed a semantic smart home energy management system to provide residential users informed decision support for their energy consumption. It takes advantage of semantic web technologies to provide a personalized, intuitive, and efficient tool interoperable with heterogeneous devices and simple to extend, maintain, and upgrade. Constantin et al. [13] present an agent-based building comfort and energy management system for non-residential buildings, using semantic communications. The agents work to balance the trade-off between the occupant's comfort and the energy savings. Howell et al. [14] present a cloud-based building energy management system, supported by semantic middleware, integrating a sensor network with advanced analytics and accessible by a web interface. The proposed system promotes reusability and extensibility as it can be deployed in other buildings without having to redesign its underlying technologies. Muñoz López et al. [15] use ontologies to describe automation and combine it with a system's architecture to provide contextual services. Deployed in a smart office scenario, it connects devices through web services. The use of ontologies enables semantic interoperability and expressiveness in the automation rules' modeling and definition. In turn, Kučera and Pitner [16] present a semantic BMS, which allows using building automation data in facility benchmarking. The semantic BMS provides facility managers with user-friendly, flexible, and dynamic querying over the building automation data for benchmarking and decision support. Petrushevski et al. [17] concentrate on the semantic representation of building systems' information to support advanced data analytics algorithms and improve building energy efficiency. To this end, they extend the model developed in [18] and implement rules to find anomalies in the building monitoring data. However, their approach does not take advantage of semantic reasoners as there is the need to develop functions to execute the rules when they trigger. To reduce the energy gap near real-time, Yuce and Rezgui [19] propose a semantic mapping process to define the most prominent variables. It uses an artificial neural network (ANN) to learn semantic mapping patterns and a genetic algorithm-based optimization tool to generate the energy-saving rules in multiple objectives and constraints. Finally, Tamani et al. [20] introduce a rule-based model for the supervision and management of smart buildings. This proof of concept highlights the potential of declarative rules dealing with building management and supervision.

On one hand, some BMSs focus on buildings' energy efficiency [12,14], while others are pure building automation systems (BAS) without considering the energy management domain [15,16]. The work of Constantin et al. [13] goes a step further by adding the user's comfort to the equation. On the other hand, there are only a few semantic rule-based systems in the building's domain, and not all of them are taking advantage of semantic reasoners, as seen in [17]. Moreover, each of these systems focuses only on solving a specific problem. It would be advantageous to have a configurable tool gathering heterogeneous services for building management from energy efficiency to the building's automation and security, where the user decides which services to use and rules to apply. Although using ontologies, these solutions are not taking full advantage of semantic web technologies and hold onto the semantic models they use. In other words, these solutions are not agnostic to the ontologies they use, and when the model or business rules change, these systems must be coded accordingly to reflect those changes. Additionally, with the SG and DR advent, it would also be beneficial to have in the same BMS the possibility to add DR contracting and management, where the user could set different contracts and the devices available for each contract and their priorities. Even more interesting would be to have a tool able to automatically interact in DR events, respecting the users' preferences and contracts made.

Although there are very important contributions in the literature on BMSs, there is a need to integrate the different systems for more intelligent and efficient management, taking advantage of combining knowledge from the various tools to provide users with advanced solutions adaptable to their needs. This highlights the need to develop an intelligent and secure system to integrate energy management while promoting interoperability between all services. To overcome these issues, the *Building's Reasoning for Intelligent Control Knowledge-based System* (BRICKS) [21] emerged, providing an intelligent, integrated, efficient, and optimized building management and control. It was designed to integrate both Supervisory Control And Data Acquisition (SCADA) systems and smart appliances and to provide intelligent building management by applying contextual rules given the knowledge available from the different sources. BRICKS is modular and can easily be reused in any building, significantly reducing development and deployment costs. The semantic context-aware rule-based system supporting it is agnostic to the semantic model and rules; this way, there is no need to reprogram the system each time the rules or the model update. BRICKS was initially developed as a Java library [21] to deploy both in a software agent or a web service, covering both simulation and real-world environments. The former version of BRICKS contributed:

- a flexible, configurable, and context-aware building management system;
- overcoming the complexity of interaction between heterogeneous devices in a building;
- keeping the system abstracted from the hardware installed and respective communication protocols to avoid reprogramming the system every time a device is installed or removed;
- a rule-based system agnostic to the rules and data, enabling advanced machine intelligence;
- a tool suitable to different buildings by using it or parts of it in other building facilities for which the same semantic model, semantic converter, or semantic rules apply; and
- a centralized interface to manage heterogeneous cross-domain monitoring and alarms.

As the world evolves towards advanced energy management and its efficient use, traditional electricity end-consumers are becoming prosumers who have access to renewable-based generation and energy storage equipment. Prosumers are active players in distributed energy generation (DER), local energy trading, and DR programs [22]. Utilities see industrial and commercial players as economically suitable players for DR due to the amount of energy of their controllable loads [23,24]. However, there are already residential consumers participating in DR programs through direct load control of their appliances [22]. It is hard to motivate residential users to participate in DR programs, mostly when the bill saving is not satisfactory enough to be worth the effort. Additionally, most end-users have limited knowledge or are not aware of the benefits of participating in such programs [25], nor that electricity prices vary according to periods [26]. DR aggregators play an important role as intermediates between utilities and electricity end-users. Aggregating and managing enough loads and DER from consumers and prosumers, aggregators provide a system capacity that fulfills the requirements to participate in wholesale electricity markets, ancillary services, capacity reserves, and balancing provisions [27,28]. These issues motivate the upgrade of BMSs to include DR aggregation and participation, taking advantage of building automation and energy management. Additionally, it would also be interesting to develop a BMS that is able to adapt to different players, from the aggregator to the building manager (industrial, commercial, or residential) to the end-user (residential or commercial), which will allow configuring multiple contracts and different aggregation levels. By aggregation levels, we mean, for instance, a building manager aggregating loads of residential consumers while being aggregated by a DR aggregator.

In the literature, there are several studies on the hierarchical aggregation of demand-side management. Amarasekara et al. [29] propose a hierarchical aggregation methodology for distribution grids composed of multiple microgrids that consider the consumers' constraints and preferences. Bazmohammadi et al. [30] introduce a hierarchical stochastic energy management system for the operation of interconnected microgrids coordinated by the aggregator. Ju et al. [31] present a hierarchical control strategy, from the independent system operator (ISO) to the aggregators and end-users, to coordinate aggregated air-conditioning loads for power regulation and system stability. Du and Li [32] propose a hierarchical market structure for the participation of microgrids, aggregated by the distribution system operator (DSO), in wholesale balancing markets. Yu and Hong [33], in turn, present a hierarchical incentive-based DR model from the grid operator to multiple service providers and their customers. Huang et al. [34] suggest a hierarchical DR control to optimize the operation of a large scale of buildings, where a virtual building represents an aggregation of buildings to be optimized, overcoming the computational load challenge. Tavakoli et al. [35] address a two-stage hierarchical control approach for energy management in DR programs of commercial building microgrids based on local wind power and plug-in electric vehicles. Finally, Wu et al. [36] introduce a hierarchical control framework consisting of a load aggregator, a central controller, and multiple local controllers of residential heating, ventilating, and air-conditioning (HVAC) loads for primary frequency regulation.

These are very relevant works presenting frameworks, models, or strategies for hierarchical DR. However, these are only tested in laboratory environments, leaving their real-world application in BMSs aside. Furthermore, BMSs focus only on specific domains, such as, for instance, HVAC, lighting, or DR. There is a need to overcome this gap so that BMSs become a reality in most buildings and contribute to the buildings' energy efficiency and, consequently, to the distribution system's efficiency. Additionally, to the best of the authors' knowledge, there are not yet BMSs that provide the flexibility of multi-level aggregation of DR in buildings with a building manager aggregating the loads of building apartments, offices, or departments. This work does not propose a new hierarchical algorithm, methodology, or strategy for DR aggregation or control. It presents a tool capable of integrating different services and algorithms for DR at different levels with a simple configuration. Furthermore, it has the flexibility of configuring multiple DR contracts at different levels, as the case study demonstrates, giving the user the versatility of defining its DR contracts with the aggregators that best reward them for each specific case. The new and upgraded version of BRICKS also aims to be flexible enough to be deployed at any aggregation level, from the aggregator to the building manager or end-consumer. This way, it can be used by any player of the domain independently of its role. This work extends the former version of BRICKS by adding new functionality layers to the previously published Java library. The goal is to extend the previously developed version to include tools for DR programs, including contracts, aggregation levels, user's comfort and priorities, and services integration. In addition to the above contributions, the new BRICKS version includes:

- a new *BRICKS Core Module* featuring:
  - an improved *BRICKS Engine* (formerly BRICKS [21]) Java library;
  - a hierarchical DR aggregation management library deployable at any aggregation level from the aggregator to the end-user;
  - the capability to aggregate other BRICKS instances, SCADA systems, and smart appliances as well;
  - the possibility of, as a client, defining multiple DR contracts with different aggregators and devices concurrently;
  - the automatic control of appliances, according to the aggregation contract, for automated DR;
  - the autonomous interaction between BRICKS instances in DR events;
  - a consumption and generation forecast web service;

  - a database for the system's configurations and real-time and historical measurement data;
  - the connection to external web services for players' aggregation, DR programs, players' remuneration, or forecast algorithms;
- an intuitive semantic configuration module; and
- a dynamic user web interface module for the building's management, monitoring, and DR participation, rendered at a runtime given the building's aggregation level.

This way, BRICKS contributes to the evolution of the SG paradigm, the buildings' participation in DR events, and the integration of renewable-based energy sources. It optimizes the use of renewable energy, takes advantage of the loads' flexibility, allows buildings to become active players capable of reducing energy costs, and adopts business models returning profits through real-time management of the buildings' resources [37].

The remainder of the paper is structured as follows. Section 2 overviews the previous work. Section 3 presents the upgraded version of BRICKS, highlighting the novelty in comparison to the previously published work. The case study presented in Section 4 demonstrates the new features of BRICKS in a DR event deployed at the authors' laboratory building. Section 5 asserts the final conclusions and future work.

2. BRICKS Engine Overview

The first version of BRICKS introduced "*a context-aware semantic rule-based system considering context-based profiles for intelligent management of buildings' energy and security.*" [21]. It was developed as a Java library and designed to be easily extended and integrated with existing software and hardware. This library is now named *BRICKS Engine* in the newly upgraded version of BRICKS.

BRICKS Engine provides a centralized interface for building monitoring and alarms, integrating different SCADA systems and smart appliances using both Modbus TCP/IP (https://modbus.org/, accessed on 25 May 2021) protocol and the Hypertext Transfer Protocol (HTTP) with Representational State Transfer (REST) [38] architectural style. It uses appliances' and sensors' data to trigger notifications, alarms, or automatic control as defined by the system's administrator. The system's administrator defines [21]: the ontology, or ontologies, to use; the SPARQL Protocol and RDF Query Language (SPARQL) (SPARQL is a recursive acronym: https://www.w3.org/TR/rdf-sparql-protocol/, accessed on 25 May 2021) constructs templates to update the KB when translating raw data into the semantic model; the mappings between the raw data and the SPARQL templates tags; the SPARQL queries to get data from the KB; the timestep; and the SWRL or SPARQL semantic rules. The use of ontologies enriches the data gathered from the different devices. The use of semantic web technologies provides the necessary abstraction to avoid re-coding the system anytime the ontology or rules update. The rules are at the software level; thus, *BRICKS Engine* does not depend on any installed device nor communication protocol. To keep the system agnostic to the ontologies and rules, BRICKS uses JavaScript Object Notation (JSON) (http://www.json.org/, accessed on 25 May 2021) data models instead of Java classes, SPARQL CONSTRUCT templates to translate raw data to the semantic model, and SPARQL queries returning JSON strings respecting given JSON schemas. SPARQL CONSTRUCTs are queries returning RDF graphs constructed by substituting variables in a set of triple templates. SPARQL CONSTRUCT templates are SPARQL queries with tags to be replaced by data values. For such, mappings between tags and values' sources are configured in JSON files.

In addition to the devices' data, the *BRICKS Engine* takes advantage of different REST web services to obtain weather data and the correct device's profile for the current context. The data is added to the system's KB to validate the rules and check if any are triggered. To control the building's appliances, *BRICKS Engine* enables both using REST requests to smart devices or existing BAS and Modbus TCP/IP requests to SCADA systems. Currently, it uses a local Weather Service (https://meteo.isep.ipp.pt/, accessed on 25 May 2021) to get solar radiation data to validate photovoltaic (PV) generation; a Context-Profiles Service [39] for an intelligent profile definition; and a Device Reader and Controller Service [40] for the data acquisition and devices' control in the laboratory building. Regarding the semantic rules, it is the responsibility of the system's administrator to write the rules according to the ontologies defined and set the correct execution order. SWRL rules run first to take advantage of the SWRL engine inferences (which turn implicit knowledge explicit), and the SPARQL rules execute after, taking advantage of the inferred knowledge. The *BRICKS Engine* outputs two types of data, namely monitoring data at each timestep and a list of notifications, alarms, or control actions if any rule triggers. The notifications and alarms are meant to be shown to the system's administrator in the UI, while the control actions are automatically executed by *BRICKS Engine* accordingly.

Finally, the first version of BRICKS had two disadvantages that are improved by the new *BRICKS Engine* library. Firstly, its initial configuration was a costly job since it was manually made using a text editor to write the necessary configuration files. Secondly, the minimum acceptable time step was around 30 s and now is reduced to less than 5 s. This improvement is two-fold: primarily, the appliances' readings are made in parallel using threads; and formerly, we have updated all SWRL rules to SPARQL, which, besides being more flexible than SWRL, it allows us to add only the necessary knowledge to the KB, improving inference performance. To be continuously working, *BRICKS Engine* is fault-tolerant, avoiding runtime exceptions if, for instance, a reading fails due to a hardware communication failure. Specific details on the functioning of the different features of the library are available in [21].

3. Proposed BRICKS Upgrade

This section presents the upgrades made and the new features added to BRICKS—the context-aware semantic rule-based system for intelligent building energy and security management. This new version aims to be as flexible and inclusive as its former version. It does not change the previously presented system but uses it as its core module, incrementing new modules and layers to solve additional issues. Its development was carried out within the scope of projects with companies, being part of their commercial products, that do not allow its public availability as open source for copyright reasons. To address the gaps identified in Section 1 a new and improved BRICKS arose by extending the previously developed version to add new features. BRICKS' new version includes a semantic configuration module, a building's management and monitoring UI, a flexible and configurable DR management service, a database for BRICKS' configuration and real-time and historical data, and a triple-store for the KB, on top of all the features reviewed in Section 2. Figure 1 presents BRICKS architecture.

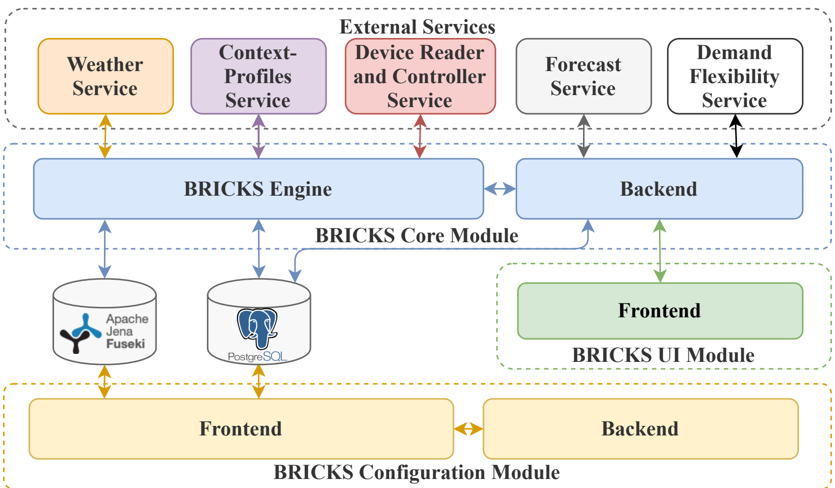

Figure 1. BRICKS' architecture
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BRICKS is now a containerized distributed system featuring three modules: the *BRICKS Core Module*, the *BRICKS UI Module*, and the *BRICKS Configuration Module*. The *BRICKS Core Module* is the main module of BRICKS and is composed of *BRICKS Engine* and *Backend* libraries. Following the initial design principles, this module uses external services for distinct purposes. To improve the *BRICKS Engine* library, the former configuration text files were dropped and replaced by database records and RDF triples in the KB. The system's administrator configures which database and RDF store to use. The relational database holds all static configuration data from *BRICKS Engine* that, formerly, was made on JSON or SPARQL files. These include SPARQL template files, the respective JSON template tags mappings files, SPARQL queries, and the SWRL and SPARQL rules (more details on these configuration files are available at [21]). Additionally, it also stores the real-time and historical measurement data gathered by the *Backend* library, as well as data related to the DR management, such as the appliances and their priorities, contracts, aggregation levels, among others. The triple-store KB, in turn, stores the ontologies and individuals (instances) configured in BRICKS, which were previously managed in both text files (static information) and in-memory (real-time measures and rules' inferences). Currently, the use of ontologies and semantic web technologies is limited to the *BRICKS Engine*.

The *Backend* library is a REST service, providing the necessary endpoints for the management and communication among different BRICKS instances. It includes the configuration and management of DR contracts, the appliances assigned to each contract, the assets' priority during a DR event, the Modbus and REST connections to control the devices, the communications with client BRICKS instances, the external services (including algorithms) to use, and the database and KB connections. The newly developed BRICKS aims the deployment at different aggregation levels, from the aggregator to the office or residential consumer. To this end, BRICKS can aggregate client BRICKS instances, smart appliances, and devices connected to programmable logic controllers (PLCs) using the Modbus protocol. Each BRICKS instance gathers data from its local measurements and from its clients without a BRICKS instance. As a client, BRICKS enables multiple DR contracts with different aggregators, assigning separate devices to each contract. BRICKS automatically controls its appliances and the contracted appliances of clients without BRICKS. During DR events, BRICKS interacts autonomously with other BRICKS instances from the aggregator to the end consumer. BRICKS allows the configuration of different services for the aggregator and client levels, such as the consumption/generation forecast service and the demand flexibility clustering and remuneration service. By default, BRICKS includes an artificial neural network (ANN)-based forecast service [41]. It is up to the system's administrator to use it or configure another option.

The *BRICKS UI Module* provides a user-friendly, configurable, and dynamic user web interface. This module is configured beforehand for the respective BRICKS instance and its clients (without BRICKS). To configure the *BRICKS UI Module*, the system's administrator only needs to define the BRICKS base Uniform Resource Locator (URL), the refresh rate timestamp (in milliseconds) to get updated monitoring measurements from BRICKS, and a unique identifier to the respective BRICKS instance or one of its clients. Only the system's administrator has access to the unique identifiers. With this configuration, the *BRICKS UI Module* builds the UI according to the data provided by the *BRICKS Core Module* for the respective unique identifier. The UI rendering depends on the aggregation level BRICKS is configured or on the client's configuration (in a client without BRICKS). This way, the aggregator's UI differs from the UI of its aggregated clients; the UI of a client with BRICKS (that also aggregates other clients) is also different from the UI of a client without BRICKS (e.g., a building manager aggregating various offices or apartments). Figure 2 shows an example UI of a business building.

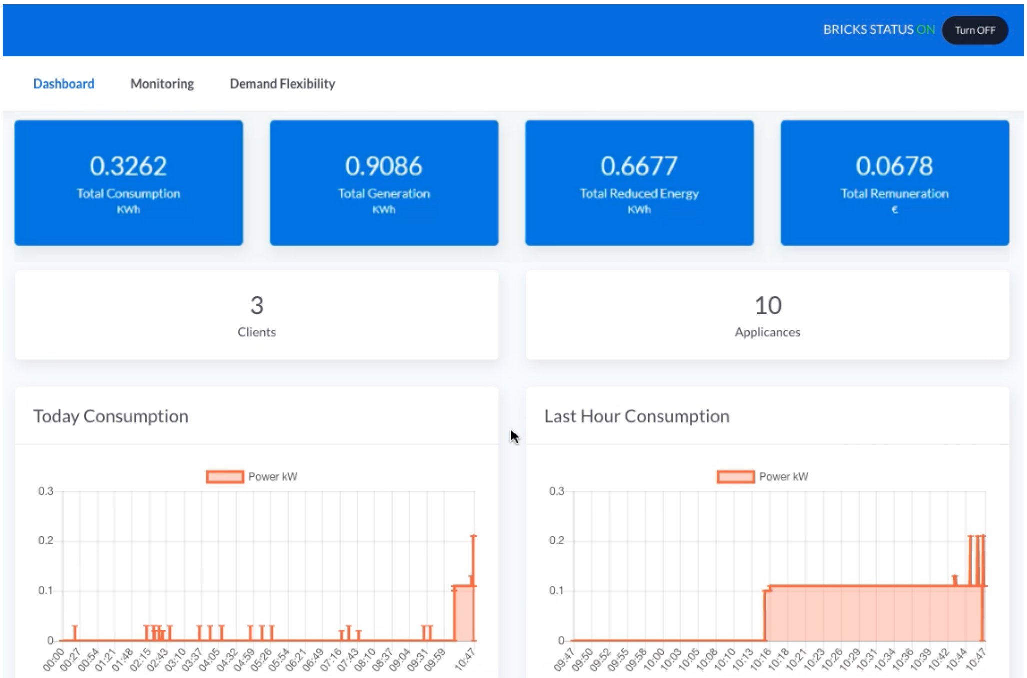

Figure 2. The business building dashboard.

The business building of Figure 2 aggregates three clients, controlling a total of 10 appliances. Due to privacy issues, only the aggregator can visualize the consumption/generation of clients without BRICKS. Additionally, the total consumption/generation available in the dashboard of an aggregator only considers their measurements (without clients' data).

Finally, the *BRICKS Configuration Module* provides a web-based and intuitive administration service to configure the semantic models, instances, and rules of the *BRICKS Engine*. The need to develop this module arises so that any user can configure the system, even without any knowledge about ontologies or semantic web technologies. Besides, it also aims to avoid human errors when writing text files and reduce the time needed to configure a building and its rules. Although this tool abstracts the user from ontologies and semantic web technologies, an advanced mode is also available for expert users. At the first deployment, the system's administrator must import the ontologies to BRICKS' KB. The system allows importing both local ontology files and online using the ontology's URL. The system provides, by default, a base URI for the ontology individuals that the administrator can change at their will. Using the uploaded ontologies, BRICKS UI dynamically provides the user with the available classes, properties, and relations to create the required individuals to represent the building's topology, the devices, including how to read data from them and control them, the services, and the semantic rules. The next step is to create the ontology individuals describing: the building, its areas, the devices per area, how to read devices' measurements, the commands for controllable devices, among others. Figure 3 depicts a snippet of the configuration of a building partition instance using the *BRICKS Configuration Module*.

Observing Figure 3, one can see, after the Individual Name input field (filled with *common-area*), four select fields with the classes of each uploaded ontology, so the user can pick the class of the new instance to create (set as *BuildingPartition* class). In the predicates list, the user determines the data properties of each individual (e.g., *common-area name "Common Area"*) and the relations of it with other instances (e.g., *common-area isPartOf office-building*). Finally, the system's administrator can define SWRL and SPARQL rules for alarms, notifications, and the automatic control of appliances.

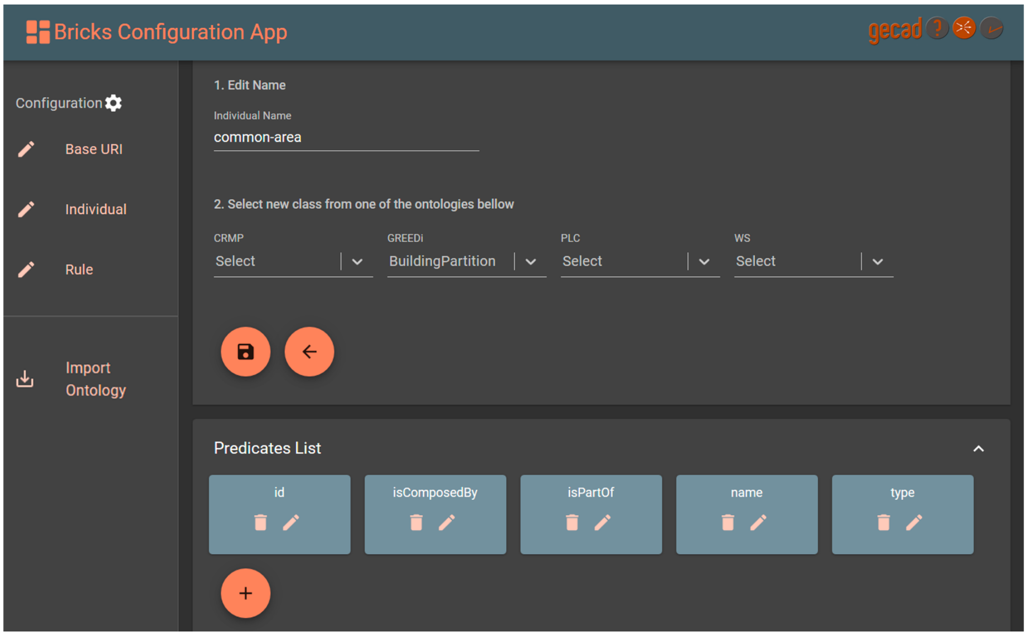

Figure 3. The configuration of a building's partition using the *BRICKS Configuration Module*.

4. Case Study

The following case study aims to show the functioning of the newly added features of the upgraded version of BRICKS, namely the multi-level aggregation of consumption flexibility for DR, the ability to manage contracts with multiple aggregators considering different assets, and the integration of external services for distinct purposes. It demonstrates BRICKS' execution in the authors' research lab during a DR event, considering different aggregation levels and contracts. It does not address the *BRICKS Engine* configuration and functioning since it is available in our previous work [21], and the building's assets, including the reading and control hardware, are the same. With other systems, building administrators must install them independently, program the rules according to each system, and use the services provided by the company. Besides not taking advantage of the available knowledge, these tools do not interoperate with external services.

The case study scenario considers an energy flexibility Aggregator with 20 clients, namely a Business Building, two offices (Office 1 and Office 3), a Hospital Building, and 16 dummy clients. From Office 1, he is aggregating the air-conditioning (AC) consumption, and from Office 3, a Smart Plug. From the Business Building, he is aggregating the building's photovoltaic generation and the consumption of the common areas and aggregated offices. From the Hospital Building, he is aggregating the heating, ventilation, and air conditioning (HVAC) system of a non-critical nursery floor. The Business Building, in turn, besides managing the building's common areas, aggregates assets from three offices, namely: the lights of Office 1; the lights and AC of Office 2; and the AC of Office 3. This type of aggregations is only possible due to the proposed system, including using heterogeneous services for specific purposes for distinct types of buildings and devices. Office 1, Office 2, and Office 3 represent three office zones of the authors' research lab, while the Business Building represents the left side of the same building. The Hospital Building, in turn, is emulated in the lab [42]. Additionally, these players use data measured in real-time, while the dummy clients use real-measured data from different departments of the authors' institute. Figure 4 illustrates the case study scenario.

As Figure 4 shows, BRICKS is deployed at the Aggregator, Business Building, Hospital Building, and Office 1. The Aggregator's BRICKS instance interacts with the BRICKS instances of the Business Building, the Hospital Building, and Office 1. It is also configured to monitor and control the Smart Plug of Office 3 autonomously. Similarly, the Business Building monitors and controls the lights and AC of Office 2 and the AC of Office 3 and interacts with the BRICKS instance of Office 1. The Business Building demonstrates a

BRICKS instance at an intermediate level, interacting with the systems of the Aggregator and Office 1. Office 1 and Office 3, in turn, demonstrate multiple contracts at different levels. As a provider, BRICKS aggregates other BRICKS instances, smart appliances, and devices connected to PLCs, gathering their measurement data. Furthermore, it automatically controls its appliances and the appliances of clients without a BRICKS instance. As a client, BRICKS enables assigning different devices to separate DR contracts with distinct aggregators.

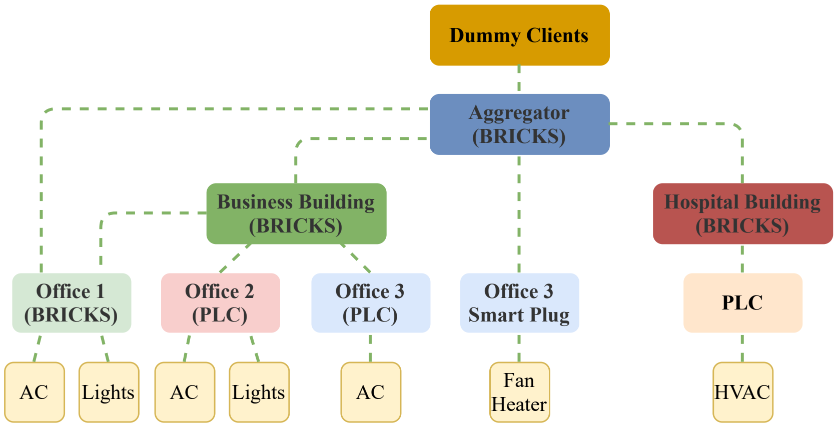

Figure 4. The case study scenario.

The DR events occur every 15 min and, for our case study, we will be looking at the event from 16:00 to 16:15. The period duration of DR events is configurable at the Aggregator's level. For each event, the Aggregator requests their players for the load flexibility available for the next period. This request is performed automatically by BRICKS to the aggregated clients' systems in cascade as, during DR events, it autonomously interacts with other BRICKS instances from the Aggregator to the end consumer. To determine the load flexibility for the next period, each client runs a forecast algorithm. BRICKS allows the configuration of external services for both the aggregator and client levels, such as the consumption/generation forecast service and the demand flexibility clustering and remuneration service. This case study considers BRICKS' default ANN-based forecast service [41] for the consumption/generation forecast and the Demand Flexibility service published by [43] for the aggregator's demand flexibility clustering and remuneration. BRICKS runs the forecast of clients without a BRICKS instance. Thus, when the BRICKS system of the Business Building receives the load flexibility request, it automatically sends a forecast request to the BRICKS system of Office 1 and forecasts the load flexibility of Office 2 (lights and AC), Office 3 (AC), and the building's common areas. Likewise, the Aggregator forecasts the load flexibility of Office 3's Smart Plug. Table 1 presents the load forecasts sent to the Aggregator for the next 15 min.

Table 1. Load forecasts received by the Aggregator.

Client	Load Forecast (kW)
Office 1 (AC)	0.3748
Business Building	2.9665
Hospital Building (HVAC)	2.0843
Office 3 (Smart Plug)	0.7046

After receiving the forecasts, the Aggregator's BRICKS instance runs a Demand Flexibility Service [43] to classify players by clusters, determine the load reduction of each client, and set the remuneration tariff per cluster. The service responds with the Load Forecast, the Reduction, the Cluster, and the Remuneration Tariff for each client. With the results, the Aggregator's BRICKS instance automatically sends reduction requests to client

BRICKS instances and acts accordingly in the appliances of the clients without a BRICKS instance. Table 2 shows the Demand Flexibility Service results.

Table 2. Demand Flexibility Service results.

Client	Load Forecast (kW)	Reduction (kW)	Cluster	Remuneration Tariff (EUR/kWh)
Dummy Client 1	1.2300	1.2300	2	0.1426
Dummy Client 2	0.9021	0	1	0.1652
Dummy Client 3	1.3306	1.3306	2	0.1426
Dummy Client 4	6.6394	0	3	0.1016
Dummy Client 5	5.8934	0	3	0.1016
Dummy Client 6	1.7092	0	2	0.1426
Dummy Client 7	0.5923	0.5923	1	0.1652
Dummy Client 8	3.9525	0	3	0.1016
Dummy Client 9	12.0639	0	3	0.1016
Dummy Client 10	4.6157	0	3	0.1016
Dummy Client 11	7.1017	0	3	0.1016
Dummy Client 12	2.3030	0.2186	2	0.1426
Dummy Client 13	12.0112	0	3	0.1016
Dummy Client 14	3.4986	0	3	0.1016
Dummy Client 15	2.8493	0	2	0.1426
Dummy Client 16	0.0236	0	1	0.1652
Office 1 (AC)	0.3748	0.3748	1	0.1652
Business Building	2.9665	2.9665	2	0.1426
Hospital Building	2.0843	2.0843	2	0.1426
Office 3 (Smart Plug)	0.7046	0.7046	1	0.1652

Observing Table 2, it is perceptible that the demand flexibility algorithm returned three clusters and a remuneration tariff for each. Furthermore, all of the four clients are requested to reduce their total amount of forecasted load flexibility. The load reduction is only effective from 16:00 until 16:15. In this period, each BRICKS system reduces the requested amount by turning off or shifting devices or decreasing the lights' intensity, for example, respecting the appliances' priorities and the user's preferences. At the end of the DR event, BRICKS calculates the remuneration according to the effective reduction provided. The results of the DR event, the remuneration, and its tariff are displayed in the clients' BRICKS UI.

Table 3 presents the Effective Reduction and Remuneration for each player.

Table 3. Effective Reduction and Remuneration.

Client	Effective Reduction (kW)	Remuneration (EUR/kWh)	Remuneration Tariff (EUR/kWh)
Office 1 (AC)	0.3748	0.0155	0.1652
Business Building (Common areas)	0.6677	0.0238	0.1426
Office 1 (Lights)	0.8201	0.0292	0.1426
Office 2 (AC and Lights)	0.7415	0.0264	0.1426
Office 3 (AC)	0.7372	0.0263	0.1426
Hospital Building (HVAC)	0.1523	0.0054	0.1426
Office 3 (Smart Plug)	0.7046	0.0291	0.1652

Analyzing Table 3, only the Hospital Building was unable to accomplish the total reduction required by the Aggregator (2.0843 kW). The remaining players fulfill the requested amount since the load forecast of the Business Building results from the sum of the forecasts of its clients and the building's common areas. A hospital's context, in turn, changes very rapidly, and the load flexibility forecasted 5 min earlier may no longer be valid. This way, the Hospital Building was only able to reduce a small amount of energy consumption. The results demonstrate the advantage of using BRICKS, and it was only possible due to the aggregation of different levels and devices introduced by the tool proposed in this paper.

5. Conclusions

Nowadays, there are several BMS solutions available for several domains, such as: building security, user comfort, and energy management, to name a few. However, solutions aggregating different systems in the same framework in an interoperable manner are expensive. To the best of the authors' knowledge, there is not yet a solution able to interoperate with heterogeneous equipment, gathering their data and taking advantage of this knowledge for cross-domain context-based rules, with the flexibility of seamlessly adding/removing devices and services, making available DR programs and contracts at different levels. To overcome this gap arises BRICKS, an improved and extended semantic rule-based system considering context-based profiles for intelligent building energy and security management.

BRICKS provides an intelligent, integrated, efficient, and optimized building management and control solution. It can be deployed independently or at different DR aggregation levels for integrated building management. It also supports the direct aggregation of appliances of clients without a BRICKS system. It overcomes the main building automation and management issues, such as high costs, installation, complexity, and compatibility. The use of semantic web technologies allows BRICKS to be agnostic to the ontologies used and semantic rules applied. Inference may result directly in actions over the building assets and notifications or alarms to the system manager. The system does not need to be reprogrammed or recompiled for new building equipment since it is independent of the used devices and communication protocols. It can be reused for other buildings or parts of buildings for which the same semantic model and/or rules apply. Additionally, this new version of BRICKS allows the definition of multiple DR contracts with different aggregators simultaneously; the automatic cut, shift, or reduction of devices' consumption; the autonomous interaction among BRICKS systems; and the configuration of external services for distinct purposes. Furthermore, it also provides a user-friendly building monitoring UI and an intuitive semantic configuration interface.

The case study demonstrates BRICKS' use at various levels during the execution of a DR program. It focuses on the autonomous interactions of BRICKS with other BRICKS instances and appliances deployed in the authors' laboratory building using real-time data. The results confirm the expected functioning of the system regarding the various types of aggregation contracts and levels, expressing the system's autonomy in executing DR events while accomplishing the users' needs and priorities. With the proposed system, it is easier to apply DR, meeting worldwide initiatives in terms of flexibility and efficiency of electrical energy consumption and security of the energy system.

There are still some limitations and future work to do to improve BRICKS. A relevant issue to deal with is the amount of data gathered from real-time measurements. To this end, the use of a time-series database is one of the next steps to improve the system's performance. A significant upgrade in progress is the extension of the *BRICKS Configuration Module* to enable the complete configuration and deployment of BRICKS in a new site, as it currently only allows to configure *BRICKS Engine*. *BRICKS UI Module* can also be improved to provide management tools to end-users, and not only to system administrators, which additionally requires the inclusion of users' access management. Another valuable feature would be to give end-users the option of defining an external service to choose which appliances to control at a DR event in a given context, considering the devices' priorities and users' preferences. Finally, the system should be flexible to provide a broader range of aggregation contracts. For instance, at the moment, the remuneration tariff is always set by the aggregator's algorithm, and it would be interesting to have different options where the client and aggregator could negotiate the remuneration tariff.

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B.T.; resources, G.S., T.P., Z.V., R.C., B.T. and C.R.; data curation, G.S., R.C. and B.T.; writing—original draft preparation, G.S. and T.P.; writing—review and editing, T.P., Z.V. and C.R.; visualization, G.S. and B.T.; supervision, T.P., Z.V. and C.R.; project administration, Z.V.; funding acquisition, Z.V. All authors have read and agreed to the published version of the manuscript.

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Core Publication V

Gabriel Santos, Tiago Pinto, Zita Vale, "Multi-agent Systems Society for Power and Energy Systems Simulation", in Davidsson P., Verhagen H. (eds) Multi-Agent-Based Simulation XIX. MABS 2018. Lecture Notes in Computer Science, 2019, vol 11463, pp. 126-137. Springer, Cham. DOI: 10.1007/978-3-030-22270-3_10.

Resumen

Un desafío clave en el campo de la potencia y la energía es el desarrollo de sistemas de apoyo a la toma de decisiones que permitan estudiar los grandes problemas en su conjunto. La interoperabilidad entre sistemas de agentes múltiples que abordan partes específicas del problema global es esencial. Las ontologías facilitan la interoperabilidad entre sistemas heterogéneos proporcionando un significado semántico a la información intercambiada entre las distintas partes. El uso de ontologías dentro de las redes inteligentes se ha propuesto con base en el Modelo de Información Común (Common Information Model en inglés), el cual define un vocabulario común que describe los componentes básicos utilizados en el transporte y distribución de electricidad. Sin embargo, estas ontologías se centran en las necesidades de las empresas. Es fundamental el desarrollo de ontologías que permitan la representación de diversas fuentes de conocimiento, con el objetivo de apoyar la interacción entre entidades de distinta naturaleza, facilitando la interoperabilidad entre estos sistemas. Este artículo propone un conjunto de ontologías para permitir la interoperabilidad entre diferentes tipos de simuladores basados en agentes, principalmente en lo que respecta a los mercados eléctricos, la red inteligente y la gestión energética residencial. Un estudio de caso basado en datos reales muestra las ventajas del enfoque propuesto para permitir estudios completos de simulación de sistemas de energía.

Core Publication VI

Gabriel Santos, Alda Canito, Rui Carvalho, Tiago Pinto, Zita Vale, Goreti Marreiros, Juan M. Corchado, "Semantic Services Catalog for Multiagent Systems Society", in Frank Dignum, Juan Manuel Corchado, and Fernando De la Prieta (eds.) Advances in Practical Applications of Agents, Multi-Agent Systems, and Social Good. The PAAMS Collection, 2021, vol. 12946. Springer Cham. DOI: 10.1007/978-3-030-85739-4_19.

Resumen

Las herramientas de simulación basadas en agentes han encontrado muchas aplicaciones en el campo de los sistemas de potencia y energía, ya que pueden modelar y analizar las complejas sinergias de sistemas dinámicos y en continua evolución. Si bien se han realizado algunos estudios respecto a simulación y apoyo a la toma de decisiones para los mercados eléctricos y las redes inteligentes, todavía existe una limitación generalizada referida a la falta significativa de interoperabilidad entre sistemas desarrollados de forma independiente, lo que dificulta la tarea de abordar todas las interrelaciones relevantes existentes. Este trabajo presenta el Catálogo de Servicios Semánticos (SSC por sus siglas en inglés), desarrollado e implementado para el registro, descubrimiento, composición e invocación automáticos de servicios web y basados en agentes. Al agregar una capa semántica a la descripción de diferentes tipos de servicios, esta herramienta admite la interacción entre sistemas heterogéneos de múltiples agentes y servicios web con distintas capacidades que se complementan entre sí. El estudio de caso confirma la aplicabilidad del trabajo desarrollado, en el que múltiples herramientas de simulación y apoyo a la toma de decisiones trabajan juntas gestionando una microrred de edificios residenciales y de oficinas. Al usar SSC, además de conocerse entre sí, los agentes también aprenden sobre las ontologías y lenguajes que deben usar para comunicarse entre sí de manera efectiva.

Core Publication VII

Gabriel Santos, Tiago Pinto, Zita Vale, Juan M. Corchado, “Semantic Interoperability for Multiagent Simulation and Decision Support in Power Systems”, in Fernando De la Prieta, Alia El Bolock, Dalila Durães, João Carneiro, Fernando Lopes, and Vicente Julián (eds.) Highlights in Practical Applications of Agents, Multi-Agent Systems, and Social Good. The PAAMS Collection, 2021, vol. 12946. Springer Cham. DOI: 10.1007/978-3-030-85710-3_18.

Resumen

Los mercados de la electricidad son entornos complejos y dinámicos con características muy particulares. Los objetivos ambiciosos, incluidos los establecidos por la Unión Europea, fomentan un mayor uso de la generación distribuida, esencialmente basada en fuentes de energía renovables. Esto requiere cambios importantes en los mercados de la electricidad y los sistemas energéticos, principalmente a través de la adopción del paradigma de redes inteligentes. El uso de herramientas de simulación y el estudio de los diferentes mecanismos de mercado y las relaciones entre sus grupos de interés son fundamentales. Uno de los principales desafíos en esta área es el desarrollo de herramientas de apoyo a la toma de decisiones para abordar el problema como un todo. Este trabajo contribuye a incrementar la interoperabilidad entre sistemas heterogéneos, es decir, basados en agentes, dirigidos al estudio de los mercados eléctricos, la operación de redes inteligentes y la gestión energética. Para ello, este trabajo propone el uso de ontologías para facilitar la interacción entre entidades de diferente naturaleza y el uso de tecnologías web semánticas para desarrollar herramientas más inteligentes y flexibles. Una sociedad de sistemas multiagente, compuesta por varios sistemas multiagente heterogéneos, que interactúan utilizando las ontologías propuestas, se presenta como prueba de concepto.

Appendix B. Preprint Publications

Preprint I

Gabriel Santos, Luis Gomes, Tiago Pinto, Pedro Faria, Zita Vale, "MARTINE's real-time local market simulation with a semantically interoperable society of multi-agent systems", Research Gate, Preprint, August 2021, [Accessed: 26-Aug-2021], DOI: 10.13140/RG.2.2.22220.33921/1.

Resumen

El uso cada vez mayor de fuentes de energía renovables es una de las principales causas de las diversas transformaciones que se están produciendo en la operación y gestión de los sistemas eléctricos y energéticos. Existe una creciente complejidad, volatilidad e imprevisibilidad en el sector que endurece el proceso de toma de decisiones. Para ello, resulta fundamental el uso de herramientas adecuadas de apoyo a la toma de decisiones y plataformas de simulación. Este artículo presenta la plataforma de infraestructura en tiempo real para energía basada en agentes múltiples (MARTINE por sus siglas en inglés) que permite la simulación y emulación en tiempo real de cargas, recursos e infraestructuras. La gestión y operación de MARTINE se realiza mediante sistemas multiagente que se conectan a recursos físicos y también pueden representar jugadores simulados adicionales que no están físicamente presentes en el entorno de simulación y emulación, lo que permite la creación de escenarios complejos para pruebas y validación. La novedad de MARTINE es la perfecta integración de la emulación en tiempo real con recursos físicos y simulados simultáneamente en un entorno de simulación único, que solo es posible mediante la compatibilidad con sistemas multiagente. Además, MARTINE es parte de una sociedad de sistemas multiagente desarrollada para la prueba, estudio y validación del sector de sistemas de energía. El uso de ontologías y tecnologías de web semántica facilita la interoperabilidad entre los sistemas heterogéneos. El escenario del estudio de caso demuestra el uso de MARTINE en la simulación de un mercado de electricidad de una comunidad local que combina datos en tiempo real de dispositivos físicos con datos simulados y el uso de técnicas de web semántica para hacer que el sistema sea interoperable, configurable y flexible.

MARTINE's real-time local market simulation with a semantically interoperable society of multi-agent systems

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Abstract

The increasing use of renewable energy sources is one of the main causes of the several transformations occurring in the operation and management of power and energy systems. There is a growing complexity, volatility, and unpredictability in the sector that hardens the decision-making process. To this end, the use of proper decision support tools and simulation platforms becomes essential. This paper presents the Multi-Agent based Real-Time INfrastructure for Energy (MARTINE) platform that allows real-time simulation and emulation of loads, resources, and infrastructures. The management and operation of MARTINE is done using multiagent systems that connect to physical resources and can also represent additional simulated players that are not physically present in the simulation and emulation environment, enabling the creation of complex scenarios for testing and validation. MARTINE's novelty is the seamless integration of real-time emulation with simulated and physical resources simultaneously in a unique simulation environment, which is only possible by supporting multiagent systems. Additionally, MARTINE is part of a multiagent systems society developed for the test, study, and validation of the power system sector. The use of ontologies and semantic web technologies eases the interoperability between the heterogeneous systems. The case study scenario demonstrates the use of MARTINE in simulating a local community electricity market that combines real-time data from physical devices with simulated data and the use of semantic web techniques to make the system interoperable, configurable, and flexible.

Keywords: Cyber-Physical Simulation, Local Electricity Market, Ontologies, Semantic Interoperability, Society of Multiagent Systems

1. Introduction

The electricity sector has been experiencing significant changes over the last 20 years, intending to end the existing monopolies while making it fairer and more competitive [1,2]. These factors led to high penetration of renewable energy sources (RES) and their intrinsic intermittency, which brought the need to evolve power and energy systems (PES), making them more flexible, intelligent, and sustainable [3,4]. Consequently, electricity markets (EM) also had to adapt to the new reality and develop new models and rules to meet the new policies. More recently, the Directive (EU) 2019/944 of the European Parliament and of the Council, of June 5, 2019, "*on common rules for the internal market for electricity and amending Directive 2012/27/EU*" [5] was released, reinforcing the empowerment of electricity end-users. This directive restructures existing business models and EM. It creates new business opportunities, paving the path towards more competitive EM prices while ensuring high service standards and contributing to the supply's security and sustainability [6]. In this context, the final customer chooses the type of energy he/she buys (i.e., green vs brown energy) to whom he/she is buying. Additionally, the final customer can become a prosumer, participate in energy citizen communities, and use its generation for self-consumption and sell its surplus in a seamless way [7].

The European Commission is incentivizing the use of RES with information and communication technology (ICT) to form energy communities able to trade electricity among them [5]. Environmental and financial concerns led to promoting the integration of distributed generation (DG) to reduce carbon emissions and improve the power systems' security and affordability [8]. Microgrid and smart grid (SG) pilots are already a reality [9–13]. ICT enables the bi-directional flow of energy, the automated monitoring, control, and protection of the grid [14], supplying economical, secure, and sustainable electricity while promoting end-users active participation. In this scope, end-users can be energy consumers and suppliers who can generate, store, curtail, and trade their surplus electricity [14,15]. In addition to enabling small-scale players to trade, local electricity markets promote local balance, reduce the cost of electricity bills, incentivize investment in RES, and support a self-sustained energy community [16,17]. The electricity sector became more competitive with the participation of new types of players and new regulatory frameworks. However, it also became more complex and unpredictable, challenging its participants by increasing their decision-making difficulty and forcing them to rethink their strategies and behaviors [18–20]. In this context, stakeholders and participants need to study and analyze the new mechanisms and relations, looking for each market model's best possible outcome.

Despite the guidance and experience provided by the implemented market models of some pioneer countries, it is still premature to make definitive conclusions. In this context, the use of decision support tools becomes essential to deal with the new challenges, as these tools enable participating entities to study, test, analyze, and comprehend how to deal with the sector's complexity and unpredictability [21,22]. System and market operators must ensure transparency and competitiveness in EM while market players intend to maximize their profits and minimize their costs [23]. Simulation and decision support tools must handle the sector's evolving reality to guarantee appropriate means for different entities to acquire experience to adapt themselves to the changing economic, financial, and regulatory environment. To this end, agent-based tools already proved to be particularly suitable to model complex interactions of dynamically evolving and competitive and cooperative systems, such as PES [24].

The distributed and independent nature of multiagent systems (MAS) makes them adequate to model the PES entities, policies, mechanisms, and constraints to model their reality [25,26]. MAS can model complex entities and their interactions while decomposing the problem to solve it into simpler blocks. On the other hand, MAS ease the integration of new business and data models and local- and grid-level marketplaces while allowing the representation of different types of players and operators and their interactions [27–29]. Several tools emerged for the simulation, emulation, and study of several PES subdomains, such as the wholesale and retail EM [22,28,30], MG and SG [31–33], demand response (DR) programs [34,35], among others. However, these tools only address specific sub-domains in the field, losing the realism and precision required as sub-domains have a significant influence over each other, impacting the results [36].

There are several proposals in the literature to address the lack of interoperability between these tools. Some works defend using standard data models for the communication between heterogeneous systems [37–39]. This solution implies that all PES developers must comply with the same standards. However, this solution is not easy to implement since private companies usually prefer to keep interoperability within their tools. Another solution is the use of co-simulation tools [40–42]. Co-simulation tools are like middleware capable of translating data from a tool's model to the next model and manage the complete simulation timeline, inputs, and outputs of each system. This way, the development of translations between heterogeneous models is not a concern of the companies that developed these tools but of the users taking advantage of the co-simulation tool. However, this option also has its downside, i.e., for each simulation scenario, the user has to (re)program the co-simulation middleware.

More recently, another solution to solve the interoperability issue is being explored and is gaining impact in the literature, proposing the use of ontologies and semantic web technologies for achieving semantic interoperability between heterogeneous tools [43–45]. There are several approaches to use ontologies and semantic web technologies, such as: for communication purposes only [46] where different tools share the same vocabulary; for reasoning, purposes allowing to infer new knowledge from the already existing one or to validate data or set alarms/notifications through the use of semantic rules [47]; to represent the systems' knowledge-base [48]; among others. The downside of this approach is its high development cost due to the required time and human expertise. Developing ontologies is an iterative process as they are evaluated and revised throughout their entire lifecycle [49]. However, when using mature semantic web technologies, it is possible to abstract the semantic data models from the programming code [47,50], which is advantageous since it avoids the need for systems' code rewriting every time the ontology is updated.

Beyond interoperability issues, PES management solutions lack testing and validation infrastructures, in which complex studies considering realistic scenarios and conditions can be performed. Therefore, the proposed solutions must be tested using simulation tools capable of emulating and connecting to real-world operational infrastructures. This work introduces the Multi-Agent based Real-Time INfrastructure for Energy (MARTINE), a platform that provides an emulation and simulation infrastructure for PES, gathering artificial intelligence-based optimization, decision support, and negotiation approaches with real building and grid operation and control. MARTINE integrates multiple MAS developed for distinct but complementary PES subdomains. These range from the physical resources' control to the simulation of players and operators and the emulation of not physically present environments. These MAS use ontologies to cooperate and interact with each other, communicating with semantic meaning, whereas some tools take advantage of semantic reasoning to validate data and business models. MARTINE thus enables the seamless combination of simulation, emulation, and physical resources for the study, test, and validation of PES methodologies for EM, DG, microgrids, SG, smart buildings, and smart homes. The infrastructure and equipment integrated into MARTINE is detailed in [51]. This paper focuses on the presentation of MARTINE MAS and its coexistence within a complex agent-based simulation environment.

Section 2 presents relevant background on (co-)simulation and emulation infrastructures for PES after this introductory section. Section 3 details MARTINE, starting with describing the real-time simulation and emulation infrastructure and the cyber-physical MAS platform installed in the authors' laboratory building. After, different MAS and services that can be plugged into MARTINE to achieve more complete PES simulations are overviewed. The section ends with a subsection regarding the use of ontologies for semantic interoperability in MARTINE. The following section 4 presents a case study to illustrate MARTINE's use. The case study addresses the simulation of a local electricity market using real data. Section 5 draws the final conclusions of the work.

2. Background

The scientific and industry communities face several challenges to integrate SG technologies in the PES interconnected grids [52]. To overcome these challenges, new methods for validating operation, control, distributed energy resources (DER), grid stability, interoperability, and cybersecurity, to name a few, are being studied and developed. Real-time simulation, hardware-in-the-loop, and co-simulation tools are novel techniques used in laboratory testing to validate PES solutions in trusted environments. These techniques enable the validation of physical equipment and controllers' performance in real-time simulations. On the other hand, co-simulation also provides new information about cyber-physical environments' interactions.

Reference [53] presents a MAS-based distributed framework for microgrid management with a focus on seamless islanding. The MAS has a modular design that adapts to the types of assets, their availability, and connection/disconnection to the microgrid. It includes three generic agent types (i.e., DER agent, Load agent, and Regulation agent) assigned to each asset. Each type of agent has a significant role in keeping the overall microgrid integrity. Suppose the microgrid enters a planned islanding operating mode. In that case, a consensus algorithm oversees the transition from grid-connected to islanded mode coordinating load curtailment and distributed energy resources (DER) output. Otherwise, a fast under-frequency load shedding strategy mitigates unplanned islanding. This strategy depends on a priority queue algorithm. The distributed control system was validated using a Controller Hardware-in-the-Loop (CHIL) test bench and the CIGRE medium voltage (MV) distribution network as a microgrid [54]. As for shortcomings, the authors point to the importance of better tunning the agent control parameters and the delay caused by the consensus algorithm in time-controlled settings.

In turn, [55] proposes a CHIL platform for distributed control applications of microgrids, providing a testbed to validate microgrid controller performance, respecting the requirements of the IEEE standard 2030.7. It enables the realization and test of distributed control strategies with real hardware. The platform can emulate the operation of microgrid distributed controllers. It uses scalable and modular software to implement distributed control algorithms in hardware [56]. The developed CHIL emulates a microgrid operation environment where were integrated the distributed controllers. Real devices integrated with the real-time simulator provide a practical system response. The real-time platform is open-source and suited for distributed control algorithms and performance benchmarking of microgrid control systems. Its runtime environment for the design, test, implementation, and deployment of microgrid control systems provides time synchronization, operations' real-time scheduling, and fault-tolerance.

In [57], the Distribution System Solver Network (DSSnet) testbed is presented. It incorporates an electrical power distribution system simulator and a communication network emulator based on software-defined networking technology [58]. DSSnet framework leverages a prior container-based virtual time system ensuring the correct and efficient synchronization of time and events between emulation and simulation. DSSnet scalability, fidelity, and usability are enhanced to provide a full-feature testbed and deployment platform for SG research planning and evaluation. The communication network is managed by the Open Networking Operating System (ONOS) [59] as it supports distributed controller environments. This way, the network's size to emulate is significantly increased, and it enables the study of resilient controllers. Besides enhancing DSSnet's usability with unique features such as host-to-host intents, multipath forwarding, reactive forwarding, and traffic statistic monitoring, the ONOS native user interface is used for the configuration and visualization of experimental networks. DSSnet has the capability of real-time process monitoring of all the virtual-time-specific states and can be used to model and simulate power flows, communication networks, smart grid control applications, and evaluate network applications' effect on the smart grid.

In [60], the author presents a real-time open-access platform for smart grid applications proof of concept, ongoing at the Smart Energy System Laboratory of Aalborg University. The platform comprises three main layers: the physical domain layer, i.e., the electrical grid and assets; the ICT & network emulation layer; and the control layer. It includes a toolbox developed for OPAL-RT that encloses several models of controllable assets, stochastic power sources for wind and solar power plants, real consumption data, and electrical grid components. This way, it simultaneously incorporates different real-time aspects of power systems, ICT & communication networks, and control functionalities. In this way, it provides the users with functionalities to perform complex experiments, enabling otherwise impossible tests in real-life conditions. This platform introduces a new mechanism for setting and integrating ICT and network emulation for real-time HIL SG laboratories. This work demonstrates the practical implementation taken to capture the SG key components and PES subdomains from energy markets to smart assets in a real-time HIL platform.

Paper [61] details how to build a virtual power system emulator connected to a real excitation cubicle to electrical power systems. Power network components such as dynamic models of a turbine, generator, power transformer, line, load, and an external grid (for the entire excitation system) have been modeled in the MATLAB/Simulink environment. The loop between software models and the excitation cubicle is closed using LabVIEW and related hardware. Thus, showing the applicability and efficacy of HIL real-time simulation in PES. It is a low-cost solution since the MATLAB/Simulink tool can simulate with high capability the complete power plant, except the device under test, i.e., in this case, the excitation cubicle. Such an emulator of PES is suitable to test new controllers and related devices before being installed in the real power plant. Distinct scenarios are executed without any risk, helping operators perform complex experiments safely and learn how to react under critical conditions. The tool is flexible and expandable through the generated MATLAB *.dll files as LabVIEW inbuilt functions, enabling the user to model the desired hardware with low cost compared to commercial solutions by omitting unnecessary hardware modules.

The related works presented in this section allow the simulation of novel models conceived and developed for PES. However, the existing solutions usually focus on either the hardware-level or software-level simulation, lacking the ability to integrate intelligent solutions for energy management with physical or emulated resources. The powerful combination of virtual and real worlds enables the creation of complex scenarios that can be used for testing novel models. Therefore, seamless integration of virtual simulated energy resources, real emulated energy resources, and real resources will better answer the testing needs in PES. Moreover, the use of artificial intelligence (AI) to support distinct PES entities and end-users regarding smart grid and microgrid management has been demonstrated as a viable solution. Therefore, validation platforms supported by AI-based models that enable experimentation and validation in real physical infrastructures are relevant and urgently needed.

3. MARTINE

The Multi-Agent based Real-Time INfrastructure for Energy (MARTINE) [51,62] is a platform that allows the simulation and emulation of microgrids, considering the individual simulation and emulation of end-users and the grid. The MARTINE MAS agent architecture overview can be seen in Figure 1, and the four layers of MARTINE presented in [51]. The infrastructure of MARTINE enables the seamless integration of (i) simulation resources using a real-time simulator, (ii) emulation resources using physical equipment (e.g., energy loads, line models, and generators), and (iii) real resources raging from individual equipment to complete buildings, which can be directly integrated and controlled, or integrated into the real-time simulator using Hardware in the Loop (HIL). Located in a lab, the MARTINE platform can create, test, and validate energy management solutions conceived and developed for microgrid and small grid contexts [63]. A differentiation aspect of MARTINE is its ability to interact with other MAS to enrich the quality of its testing. Some examples are the active interaction of MARTINE agents with the Multi-Agent Smart Grid Simulation Platform (MASGriP) [31,32] agents; with the Multi-Agent Simulator of Competitive Electricity Markets (MASCEM) [27] agents to transact energy in wholesale and community-level markets, and with Adaptive Decision Support for Electricity Markets Negotiations (AiD-EM) [22] agents for decision support of market players negotiations. MARTINE can also make use of intelligent decision support (IDeS) models for different purposes, e.g., energy resources management and demand response, through its connection to specific services. All these capabilities allow creating a complete platform to efficiently validate energy-related solutions using large batteries of complex test scenarios [51].

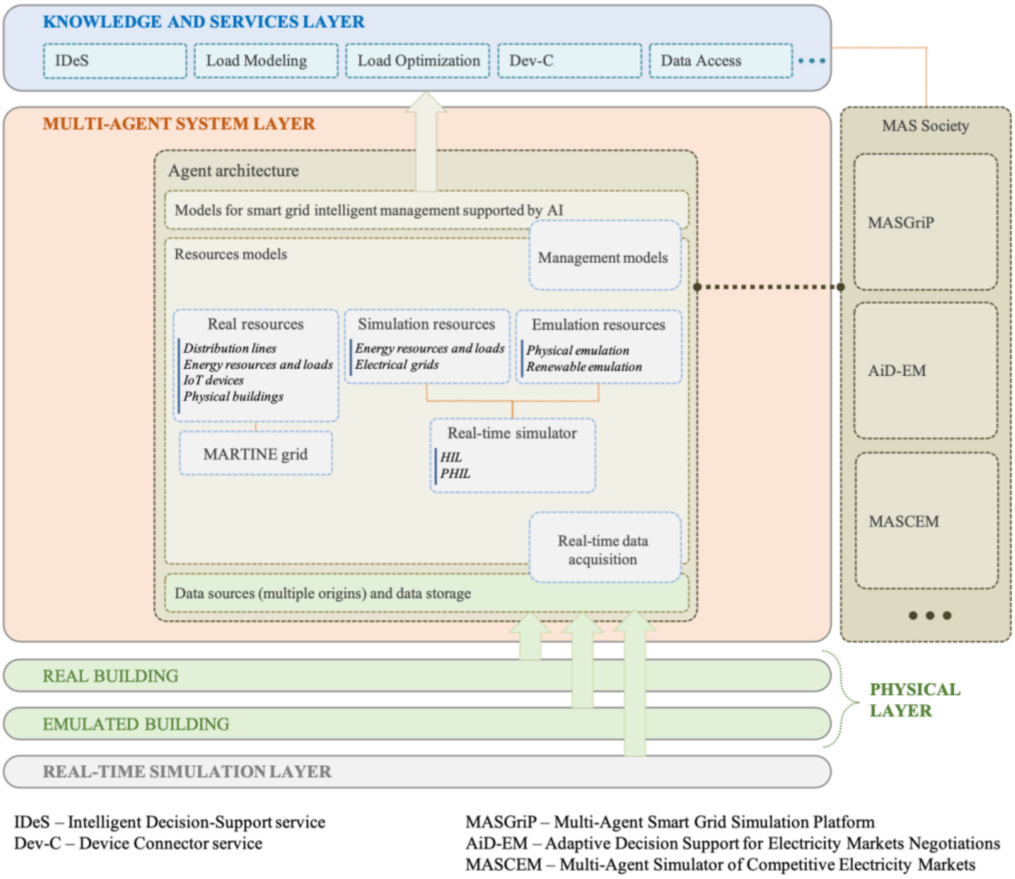

Figure 1. MARTINE layers with detail on the agent's architecture and communication.

The several components of MARTINE make it unique. A complete system where novel models for microgrids and small grids can be tested and validated using a seamless combination of virtual simulation, emulation, and real devices placed in uncontrollable environments. The components of Figure 1 are available in MARTINE but are not mandatory. For instance, it is possible to only use simulated loads and resources without using emulation and real resources. In other words, the user can set up the testing environment using several building blocks, enabling to test and study specific parts of the system. For such, MARTINE is interoperable with other MAS and web services previously developed, providing the means to perform more realistic simulations using real data and physical devices in real-time.

a. Simulation and emulation

MARTINE includes a physical model for a grid, MARTINE grid, with four electrical lines with four buses where loads can be connected using three-phase electrical cables, as seen in Figure 2. The four lines can be remotely connected and disconnected and are monitored in real-time using two energy analyzers in each line, at the beginning and the end of the line. The fourth line, identified in Figure 2, can be connected in three possible configurations, enabling different grid configurations. The lines are emulated using resistors, each line being modeled employing four resistors representing the three phases and the neutral wire. The resistors can be manually adjusted to represent lines with different lengths.

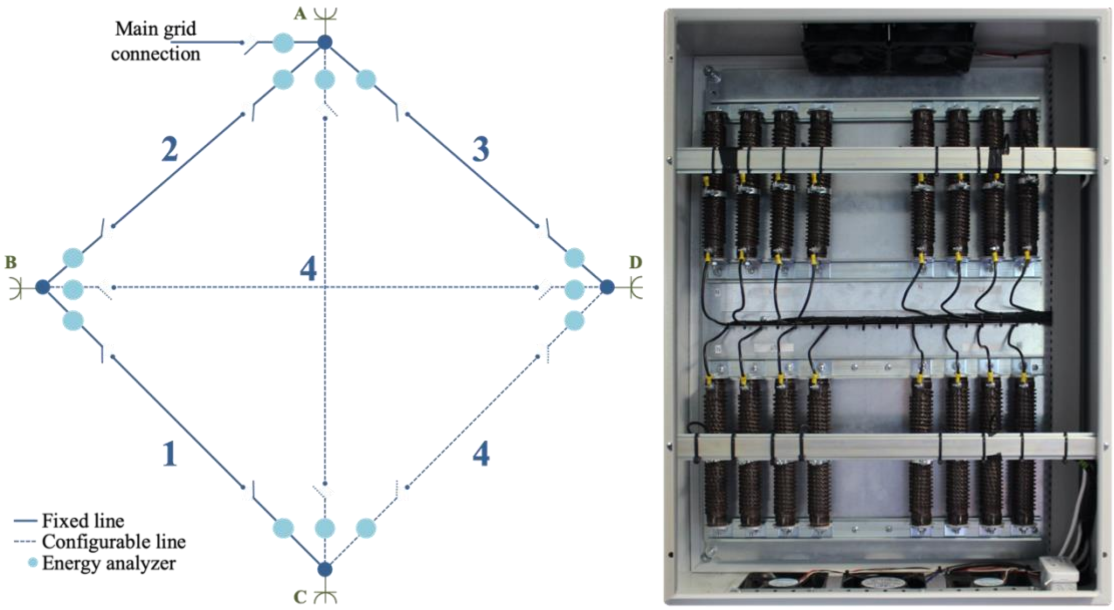

Figure 2. MARTINE grid lines.

MARTINE integrates multiple emulation resources that can be connected to the four-line grid [33]. These emulation resources are connected to the simulation units as well as MAS to enable the remote control. The available emulation resources are:

- One 3 kW resistive load that can be controlled from 0.5 kW to 3 kW;
- One 30 kW load that can be controlled in 1 kW steps;
- Two 1.5 kW induction motors;
- Three load benches of 16 kW each controlled in 200 W steps;
- Two 8 kW loads controlled in 400 W steps;
- Two 1 kW photovoltaic inverters;
- One 3 kW synchronous generator;
- One 1.2 kW wind turbine;
- One 3 kVA power amplifier.

The emulation resources can be connected (i) to the MARTINE grid or (ii) to other emulated resources. The ability to connect emulation resources with others enables prosumers' configuration, where an emulated generator can be connected to an emulated load. Then this group of emulation resources can be connected to a grid bus.

Real-time simulation simulates resources that are not available to be physically integrated into the MARTINE infrastructure. Real-time simulation enables synchronizing simulated resources with emulated and real resources making it possible to mix simulated, emulated, and real-world resources in the same study in a synchronized way. The real-time simulation is supported by OPAL-RT OP5600 as the main unit, and OPAL-RT OP4510, as the secondary unit. These real-time simulator units are based on MATLAB/Simulink. These units provide users with several digital and analog input and output boards and RS485 communication boards to control and communicate with real devices outside of the simulation environment.

The MARTINE grid lines can be virtualized and expanded in Simulink, enabling the test and validation of bigger microgrids. This interoperability of simulation, emulation, and also real resources makes MARTINE a HIL system. Besides the HIL capabilities, the power amplifier's integration makes MARTINE a power-hardware-in-the-loop (PHIL) system able to close the cycle between simulation, emulation, and real resources.

b. Cyber-physical multiagent system

The control and monitoring of the MARTINE's simulation and emulation resources are done using a MAS. The MAS, developed in Java using the JADE[1] framework, allows the control of the simulation units and the emulation resources. This cyber-physical MAS also brings an advantage to the MARTINE platform, allowing the integration of physical resources available in the lab, such as internet of things (IoT) devices and the integration of entire buildings. The MARTINE platform enables the integration of three buildings, seen in [64]. These buildings are located in the university campus and have dedicated supervisory control and data acquisition (SCADA) systems with hypertext transfer protocol (HTTP) communication application programming interface (API). The MAS can have dedicated agents representing the buildings and monitoring and controlling the SCADA system in real-time.

The MAS agents represent players in the microgrid scenario, such as a consumer, a producer, a prosumer, or the microgrid operator. The agent can represent simulated, emulated, or real resources without compromising their communication abilities. Therefore, all agents in the MAS can communicate and negotiate in a similar manner, where each agent has its own individual goals, such as the decrease of energy cost. The agents are simultaneously event-triggered and self-triggered, enabling the pro-activity and reaction of agents, and organized as a team trying to achieve a common goal in the microgrid.

c. MAS-Society

MARTINE is part of a MAS-Society [65] composed of several heterogeneous MAS directed to different areas of PES. The various systems cover the energy system from wholesale EM simulation to the energy management of end-users. It has the flexibility to model the PES as a whole or partially, considering only the essential blocks for the intended study. The different MAS tools are developed in Java using the FIPA[2] (Foundation for Intelligent Physical Agents) compliant JADE framework. To achieve systems' interoperability, the MAS-Society uses shared ontologies [66] for semantic communications. This way, it addresses the lack of appropriate means to enable the effective interoperability between different systems, algorithms, and PES methods as the agents can interact with each other meaningfully. Using ontologies, agents speak the same language and understand the same concepts and terms, preventing different interpretations of the same knowledge.

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[1] https://jade.tilab.com/
[2] http://www.fipa.org/

MASCEM [27,67] provides a diversity of wholesale EM models based on three European markets, namely: MIBEL[3], EPEX[4], and NordPool[5], for simulating the EM reality. Besides the simulation of each European market, it is also possible to combine models to test, study, and validate new non-existent approaches. MASCEM's multiagent model includes the main EM stakeholders and players from the market and system operators to the buyer, seller, and aggregator agents. Additionally, MASCEM enables the participation of external agents through semantic interoperability. For such, external agents make use of the MASCEM's publicly available ontologies[6].

For the simulation of SG environments, we use MASGriP [31,34]. MASGriP models players and stakeholders at the SG and microgrid level from local prosumers to community aggregators. It provides management and control of simulated and real assets, enabling alternative testing approaches in realistic settings. MASGriP simulations include local EM, energy resources management (ERM), demand response (DR), and negotiation procedures.

The AiD-EM [22] MAS is a decision support system for EM participating players. It comprises multiple agent-based sub-systems designed to solve and support decisions on different market types, such as bilateral negotiations and auction-based EM. Each sub-system uses several AI methodologies to provide players with adaption in the planning and negotiation phases. AiD-EM agents also perform portfolio optimization for EM participation, context-awareness to adapt players' strategies to the current context, and an Efficiency/Effectiveness (2E) balance management mechanism to determine the balance between the achieved quality of results and the execution time of the simulation.

The Tools Control Centre (TooCC) [68] is an innovative agent-based system designed and developed for the simulation and control of the MAS-Society. It provides an interface where the MAS and services that are part of the MAS-Society can be executed independently or integrated into joint simulations, including some systems in the agents' society. Additionally, TooCC also eases the automatic analysis of results in an integrated manner [45]. Using TooCC, different complex dynamics between heterogeneous MAS are realized, customized, configured, and analyzed.

The main advantage of the MAS-Society is the possibility to model, test, study, and explore a diversity of complex scenarios involving one or more tools directed to the PES's distinct problems. This way, the PES can be simulated and studied as a whole, or it is also possible to explore a very specific part. The most relevant players of each PES sub-domain are represented through software agents in the respective sub-systems.

d. Services

The MAS of MARTINE is supported by several services that were developed to provide intelligence to the agents. The AI methods are available outside the agents to enable the deployment of an agent in single-

[3] https://www.mibel.com/
[4] https://www.epexspot.com/
[5] https://www.nordpoolgroup.com/
[6] http://www.mascem.gecad.isep.ipp.pt/ontologies/

board computers. This way, the AI methods, which usually require more computation power, can still be executed in a cloud-based approach using the cloud resources. The available services are integrated as web services or as new agent communities to communicate and exchange information and data with the MARTINE. Currently, MARTINE has available the following web services:

- Intelligent Decision Support (IDeS) service;
- Device Connector service;
- Data Access service.

The IDeS service provides several forecasts, optimization, and decision support algorithms to agents in the MAS-Society community. Currently, IDeS provides a couple of energy forecasting algorithms using artificial neural networks (ANN) and support vector machines (SVM), a deterministic optimization algorithm to minimize energy costs, ERM algorithms for SG and microgrid, DR programs, among others.

The Device Connector (Dev-C) service is the service responsible for controlling the physical devices. This service enables reading real devices' data at a given timestep and actuates on controllable devices in real-time. This way, it allows testing scenarios in a real environment, applying the results to physical devices, making them act accordingly. The controllable devices (such as lights, sockets, HVAC, doors, and shades) can be smart devices accessible by REST data protocols (such as MQTT[7] or AMQP[8]) or dummy devices connected to a Programmable Logic Controller (PLC) using ModBus[9] protocol.

IDeS and Dev-C web services started as MAS [65,69], namely IDeSMAS and PLCMAS, respectively. However, a software agent must have determined characteristics (such as autonomy, learning, reasoning, among others) that were not present in the systems' agents. These agents, in turn, were only reactive and responded to service requests. For this reason, IDeSMAS and PLCMAS were deprecated and converted to web services. Additionally, PLCMAS was only able to work with Modbus protocol. With its restructuring, REST protocols were included in Dev-C for the interaction with smart appliances.

The Data Access service is the service responsible for the database access to the devices' historical and near real-time data. This service collects data from each device at a predefined time step to make it available to the different MAS and services.

Finally, the Semantic Services' Catalog (SSC) service provides a centralized platform where services are registered to be made available to the MAS-Society community. Services are registered in SSC using and extending OWL-S [70] ontology as needed. Registered services can be both agent and web-based [71]. Software agents search for the required service. The response details the service description, the location, the accepted input, and output models, and the requests made available by the searched service. Using SSC, agents can autonomously request the execution of a forecast or scheduling algorithm without the need for user interaction to configure the service any time the service is updated since its description in SSC is updated accordingly.

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[7] https://mqtt.org/
[8] https://www.amqp.org/
[9] https://modbus.org/

e. Ontologies for semantic interoperability

The interoperability of MARTINE with the other MAS is made at the semantic level using ontologies. Ontologies are used as shared vocabularies agreed between the several parties to disambiguate the meaning of the concepts in the messages exchanged. This way, agents of heterogeneous systems exchange data and knowledge without misunderstandings. In addition to semantic interoperability, using ontologies has other advantages. In the scope of MAS-Society, ontologies also [50,65,66]:

- allow the alignment between concepts of different ontologies;
- provide reasoning and inference mechanisms to validate rules or extract knowledge from the existing one;
- ease the process of converting heterogeneous sources data into a unique semantic data model;
- enable the development of flexible software tools agnostic to the semantic model used and business rules applied.

MARTINE, and the remaining MAS of MAS-Society, use ontologies of two levels, i.e., domain and applicational ontologies. Domain ontologies are representative of specific domain areas containing concepts and relations transversal to several systems. These describe the vocabulary shared between the different MAS. On the other hand, applicational ontologies are semantic models developed for each tool. Applicational ontologies import, extend and reuse concepts and relations of domain ontologies to describe the applications' data models, define their business rules, and set validation and inference rules to draw conclusions and extract new knowledge.

The used ontologies were previously presented in the literature [65,66]. The reuse of existing and widely accepted ontologies in the literature is mandatory for heterogeneous systems interoperability. This way, the Smart Energy Aware Systems (SEAS) [72] and the Smart Appliances REFerence (SAREF) [73] ontologies are used as domain ontologies and extended as needed for each tool. SEAS ontology was designed to provide semantic interoperability in the SEAS project ecosystem. SEAS ecosystem includes IoT services and smart devices to ensure stability and efficiency of the power grid. SAREF ontology is a semantic model aiming to ease the match of smart appliances assets. It gathers the semantics of buildings and residential smart devices, their sensing/control capabilities, and available functionalities, fitting into the machine-to-machine (M2M) architecture of the European Telecommunications Standard Institute (ETSI). Both SEAS and SAREF are used to describe data at the SG and microgrid level, including residential and office buildings appliances.

For the EM domain, the Electricity Markets Ontology (EMO) [74] is used. EMO was developed specifically to provide interoperability with the MASCEM simulator. It is a modular ontology where the main module describes abstract concepts and hypotheses from the EM domain. In contrast, the remaining modules extend those concepts to specific markets present in MASCEM, i.e., MIBEL, EPEX, and NordPool. Additional module imports and extends EMO to describe AiD-EM's tool knowledge, providing interoperability with the AiD-EM decision support tool. Furthermore, several applicational ontologies were developed to describe different optimization, scheduling, and forecasting algorithms available at IDeS.

4. Case Study

This case study illustrates the use of MARTINE for the simulation of a community in a local electricity market and the use of semantic web techniques that make the system interoperable, configurable, and flexible. The case study considers a local market scenario, where several agents interact to perform their transactions. These agents represent both real resources as well as fully simulated players. Interactions and communications between the MARTINE agents using ontologies are shown and explained, and the results for this specific study scenario are discussed.

The local market library and the ontologies used in this case study have been previously presented and explained in [50]. The scenario for this case study considers a community composed of two local solar energy producers, two residential prosumers with solar generation, and three residential consumers – each one represented by a software agent. Producer1 has a generation capacity of 3.5kW, and Producer2 of 2.5 kW. Prosumer1 and Prosumer2 have installed generation capacity equal to 1 kW and 0.5 kW, respectively. This case study uses real data measured in the authors' research unit building. Figure 3 illustrates this scenario.

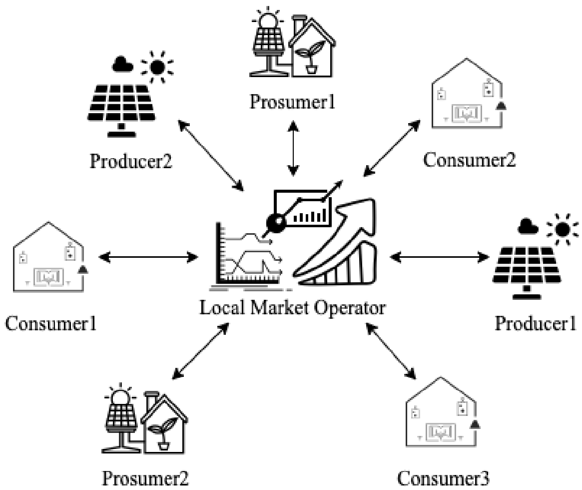


Figure 3. Case study scenario.

The local electricity market considers hour-ahead operations split into 15 minutes and is an asymmetric pool market [75,76]. Being hour-ahead means that the market runs in the hour before the actual energy delivery. Selling bids are composed of the amount of energy to sell in the period and the minimum price per kWh. On the other hand, buying bids only include the amount of energy to buy in each period. This case study simulates a market session executed between 14:00 and 15:00, meaning that the market pool runs from 13:00 to 14:00.

The simulation starts with the local market operator sending the call-for-proposals for the next hourly session to all registered players at 13:10. All players interested in participating in this market session must submit their bids by 13:40. After this deadline, no more bids are accepted. The local market session results are sent to each player at 13:50, giving them time to make the required adjustments before the execution period starts at 14:00.

Before bidding, each player forecasts its generation availability and/or consumption needs to bid in the market. To make the case study details easier to follow, special attention will be paid to Prosumer1. Readers can access files with i) the communications exchanged between the Prosumer1 agent and the various systems, and ii) the necessary conversions between syntactic and semantic models available in [77].

Figure 4 details the steps that are undertaken in the simulation.

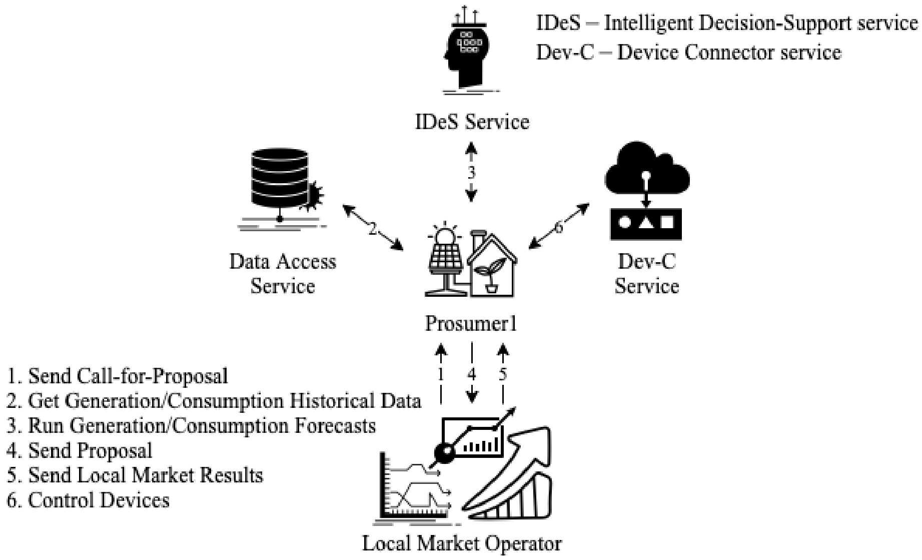


Figure 4. Case study steps from the perspective of Prosumer1.

After receiving the call-for-proposal[10], each agent adds it to its knowledge base and queries[11] it to obtain the necessary details to decide whether to bid on the session. These details include the start and end timestamps of the session, each period's duration, and the market type. With these details, each agent queries its historical database to get contextual measurements of generation and/or consumption to make forecasts for the next hour (divided by four periods of 15 minutes). An example database request for the historical consumption data of Prosumer1 is:

```
http://db.gecad.isep.ipp.pt/data/?
                 resource=total-consumption
                 &type=energy
                 &interval=900000
                 &from=1560780000000
                 &to=1560780899999
```

As it is possible to see, the request query string includes the parameters: `resource`, `type`, `interval`, `from`, and `to`. The `resource` parameter identifies the resource from which we want to get the data. It can be a device or an aggregated field, as is the case of the `total consumption`. The `total consumption` aggregates the total consumption of Prosumer1's residence. The `type` parameter identifies the data type. In this specific case, it is `energy`, but it could also be `power`. The difference between both options is the use of the parameter `interval`, which is only available for the `energy` option. The `interval` parameter

[10] See file 1.call-for-proposal.jsonld.
[11] See file 2.get-call-for-proposal-details.sparql.

defines the time interval (in milliseconds) needed to calculate the energy of each 15 minute period between the timestamps defined by the `from` and `to` parameters. The response[12] to the above request is available in [77]. It comes as a JSON object that is mapped to the semantic model of the knowledge base. For such, the agent uses a SPARQL template file[13] and a mappings JSON file[14] to replace the SPARQL template tags with the respective values. Each mapping identifies the tag to be replaced and the JSON Path[15] to the JSON response object's value.

After getting all the needed consumption and generation historical data, Prosumer1 queries its knowledge base to get the forecast algorithm's input. In this specific simulation, Prosumer1 uses an ANN-based forecast [78]. The SPARQL query file template[16] to get the forecast input is also available in [77]. Prosumer1 forecasts its generation and consumption for each period, saving the results using another SPARQL template file[17], replacing the `[RESULT]` tag with the forecast result. Table 1 presents Prosumer1's forecasted consumption and generation in kWh for each period of 15 minutes of the hour. Note that the period number in the first column of the table regards the period number for the full 24-hour day.

Table 1. Prosumer1's consumption and generation forecasts.

	Forecast	
	Consumption (kWh)	**Generation (kWh)**
14:00 (Period 57)	0.2453	0.1780
14:15 (Period 58)	0.2803	0.2140
14:30 (Period 59)	0.3139	0.3940
14:45 (Period 60)	0.2737	0.2300

The next step is to create the proposal to submit to the local market operator. For such, a SPARQL template[18] is used where the `[AID]` tag is replaced by the agent's name, i.e., Prosumer1. Finally, Prosumer1 gets the proposal from the knowledge base by requesting the generated graph through an HTTP request (`http://kb.gecad.isep.ipp.pt/prosumer1-ds/?graph=http://market/proposal/`) and sends it to the market operator. The proposal[19] submitted by Prosumer1 is also publicly available in [77]. The graph's content was converted from Trig[20] to JSON-LD[21] to ease its reading. Table 2 presents the bids

[12] See file 3.total-consumption-1558962000000.json.
[13] See file 4.sparql-template-cons-gen-history.sparql.
[14] See file 5.measurement-mappings.json.
[15] https://goessner.net/articles/JsonPath/
[16] See file 6.sparql-template-ann-input.sparql.
[17] See file 7.sparql-template-forecast-output.sparql.
[18] See file 8.sparql-template-set-proposal.sparql.
[19] See file 9.proposal.jsonld.
[20] https://www.w3.org/TR/trig/
[21] https://json-ld.org/spec/latest/json-ld/

submitted to the local electricity market session. The blue color gradient identifies the higher (darkest) to the lower (lightest) prices. Likewise, the yellow gradient distinguishes the higher and lower energy demand. In the same way, the green gradient regards to the energy supply.

Table 2. Bids submitted to the local market operator.

Player	Bids								Instant
	14:00		14:15		14:30		14:45		
	kWh	EUR	kWh	EUR	kWh	EUR	kWh	EUR	
Producer1	-0.5610	0.1178	-0.6840	0.1957	-0.9380	0.1392	-0.5690	0.1325	14:36:52.420
Producer2	-0.6230	0.1475	-0.7600	0.1795	-1.0420	0.1112	-0.6330	0.1473	14:40:11.182
Prosumer1	**0.0673**	-	**0.0663**	-	**-0.0801**	**0.1273**	**0.0437**	-	14:42:11.596
Prosumer2	-0.0950	0.1642	-0.1270	0.1577	-0.1900	0.1072	-0.0980	0.1448	14:37:52.328
Consumer1	0.3260	-	0.3160	-	0.3200	-	0.3290	-	14:32:55.311
Consumer2	0.6240	-	0.5870	-	0.5880	-	0.6190	-	14:36:55.820
Consumer3	0.1110	-	0.1110	-	0.1210	-	0.1220	-	14:56:48.034

The negative energy values in Table 2 represent sell bids, while positive energy values are demand bids. The "Instant" column identifies the instant the local market operator received each proposal so that he can set the priority of selling bids with the same price based on their arrival order. Regarding prices, each player uses his strategy to define the price for each period. However, all players have into account the wholesale market prices and retail tariffs. The prosumers' tariff for their energy is 0.095 EUR/kWh, and the consumption tariff is 0.1962 EUR/kWh. Thus, players selling in the local market bid prices higher than the tariff paid for their supply but lower than the consumption tariff. Otherwise, consumers will not have an interest in buying energy in the local market.

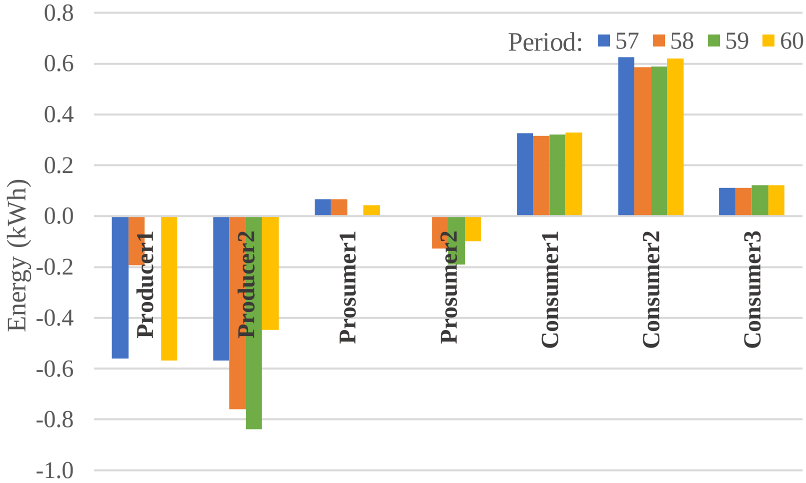
After the bid submission period closes, the local market operator clears the local market session, and the session results are sent individually to each player. The session results[22] sent to Prosumer1 are publicly available in [77]. Table 3 presents the aggregated market results.

Table 3. Local market aggregated results.

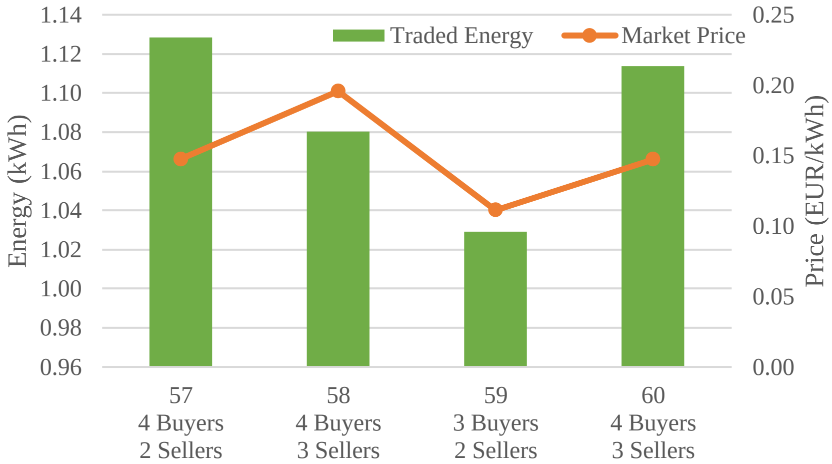
Energy Volume (kWh)	4.3513
Economic Volume (EUR)	0.6563
Minimum Price (EUR/kWh)	0.1112
Maximum Price (EUR/kWh)	0.1957
Average Price (EUR/kWh)	0.1504

[22] See file 10.local-market-result.jsonld

The energy volume traded in the local market session was 4.3513 kWh, with a monetary volume of EUR 0.6563. The minimum market price was EUR 0.1112 in period 59, and period 58 had the highest price of EUR 0.1957. The average market price was EUR 0.1504. Figure 5 shows the individual transactions of each player **(a)** and each period, transacted energy, market price, and the number of dispatched players **(b)**.



(a)



(b)

Figure 5. Players individual results: a) transacted energy per period; b) market price, total traded energy, and number of dispatched players per period.

Analyzing Figure 5(a) shows that all players traded in the local market session. Producer1 and Prosumer1 did not trade energy in period 59 as they presented the highest sell prices, and the demand was lower than the supply. Period 59 was the only period that Prosumer1 offered a bid to sell its surplus energy to the local community. In the same way, Prosumer2 was not able to trade in Period 57. The remaining players were able to transact in all session periods. Figure 5(b) shows that periods 57 and 60 had more traded energy, meaning that, in those periods, the demand was higher than in the periods in between.

Upon receiving the results, Prosumer1 realizes that in period 59, he will have surplus energy. He has two options: i) sell it to the grid for a low price, or ii) shift some consumption to period 59 to take advantage of the free generated energy. Prosumer1 sends a request to the Dev-C service to turn on the HVAC between

14:30 and 14:45. The content of the request[23] made to Dev-C is also publicly available in [77]. MARTINE uses the BroadLink RM Pro+ device to send infrared signals to the HVAC unit. The integration of BroadLink RM Pro+ with MARTINE is done using the Home Assistant[24] platform that enables the integration of IoT devices currently available to users in the market. The communication between MARTINE and the Home Assistant is done using HTTP requests. The complete communication flow, from the Prosumer1 agent to the HVAC unit, is shown in **Error! Reference source not found.**.

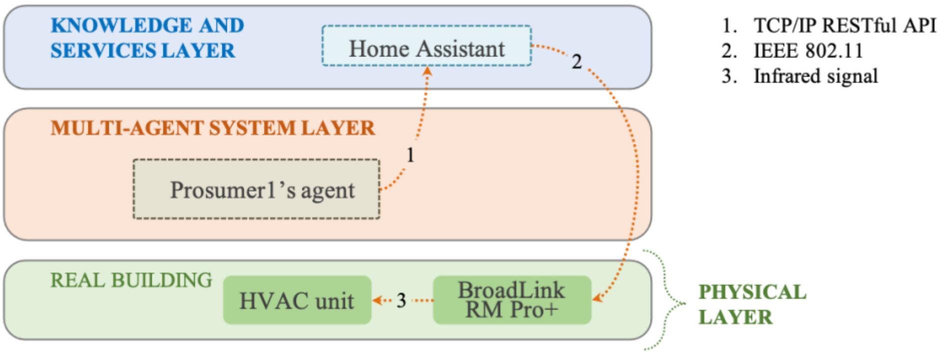


Figure 6. MARTINE to HVAC communication flow.

The control of the HVAC system allows Prosumer1 to be able to use the generated energy for free. Otherwise, he would have sold it to the grid at a lower price and paid more to consume the same amount from the grid.

5. Conclusions

This work presents the MARTINE platform, a multi-agent-based real-time infrastructure for power and energy systems simulation and emulation. The MARTINE platform complements real-time simulation with the emulation of energy loads and resources, and physical environments, gathering artificial intelligence-based optimization, decision support, and negotiation approaches with real assets. Such infrastructure enables the test and study of existing and envisaged solutions before implementing them in the real world.

MARTINE is interoperable with existing multiagent systems to execute more complex and complete power and energy simulations. Such interoperability is achieved through the use of ontologies. Ontologies not only provide the means for heterogeneous systems interoperability, but they also ease the alignment of concepts of different semantic models, provide reasoning and inference capabilities, facilitate the process of converting heterogeneous data sources into the same semantic model, and enable the development of flexible software tools agnostic to the ontologies used and business rules.

The presented case study illustrates the application of MARTINE in the simulation of a local energy market using semantic web techniques to design interoperable, configurable, and flexible software tools. It considers the use of real data collected from a building and the control of the available assets. The modeling and simulation of players negotiating in the local market, their communications, and the actual control of

[23] See file 11.control-request-body.jsonld.
[24] https://www.home-assistant.io/

air conditioning devices were illustrated as examples of integrating simulation with a real building. MARTINE is a solid infrastructure for the seamless integration of simulated, emulated, and physical resources that allows the broad and detailed testing capabilities needed to validate energy management models in buildings, microgrids, and energy communities. This type of infrastructure is essential for researchers to prepare to deal with the ever-changing environment of power and energy systems.

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Resumen

Los cambios significativos que ha venido sufriendo el sector eléctrico en las últimas décadas incrementaron la complejidad e imprevisibilidad de los sistemas de potencia y energía (PES por sus siglas en inglés). Para hacer frente a un entorno tan volátil, hay diferentes herramientas de software para simular, estudiar, probar y apoyar las decisiones de las distintas entidades involucradas en el sector. Sin embargo, al estar desarrolladas para subdominios específicos de PES, estas herramientas carecen de interoperabilidad entre sí, lo que dificulta la posibilidad de lograr escenarios de simulación, gestión, operación y soporte de decisiones más complejos y completos. Este artículo presenta la Ontología de Sistemas de Energía Inteligente (IESO por sus siglas en inglés), la cual proporciona interoperabilidad semántica dentro de una sociedad de sistemas multiagente (MAS por sus siglas en inglés) en el marco de PES. Esta aprovecha el conocimiento de modelos semánticos existentes y disponibles públicamente desarrollados para dominios específicos para lograr un vocabulario compartido entre los agentes de la sociedad MAS, superando la heterogeneidad existente entre las ontologías reutilizadas. Además, IESO proporciona a los agentes razonamiento semántico, validación de restricciones y uniformización de datos. El uso de IESO se demuestra a través de un estudio de caso que simula la gestión de una red de distribución, considerando la validación de las limitaciones técnicas de la red. Los resultados demuestran la aplicabilidad de IESO para la interoperabilidad semántica, el razonamiento a través de la validación de restricciones y la conversión automática de unidades. IESO está disponible públicamente y cumple con los requisitos preestablecidos para compartir ontologías.

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.

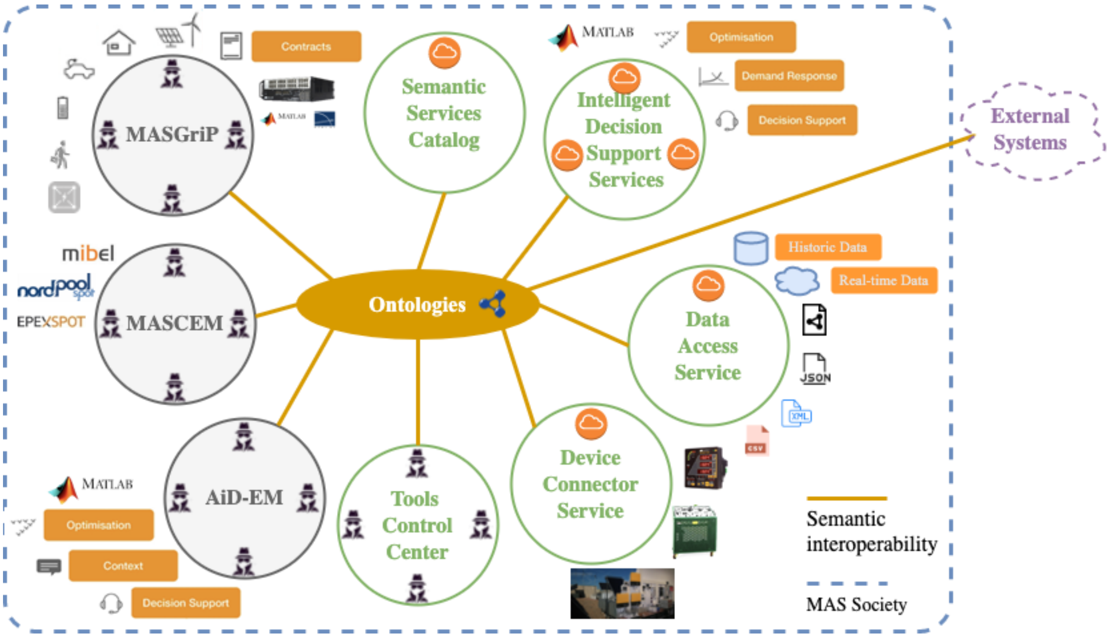

Figure 1. MAS Society architecture (adapted from [47]).

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

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[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

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[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.

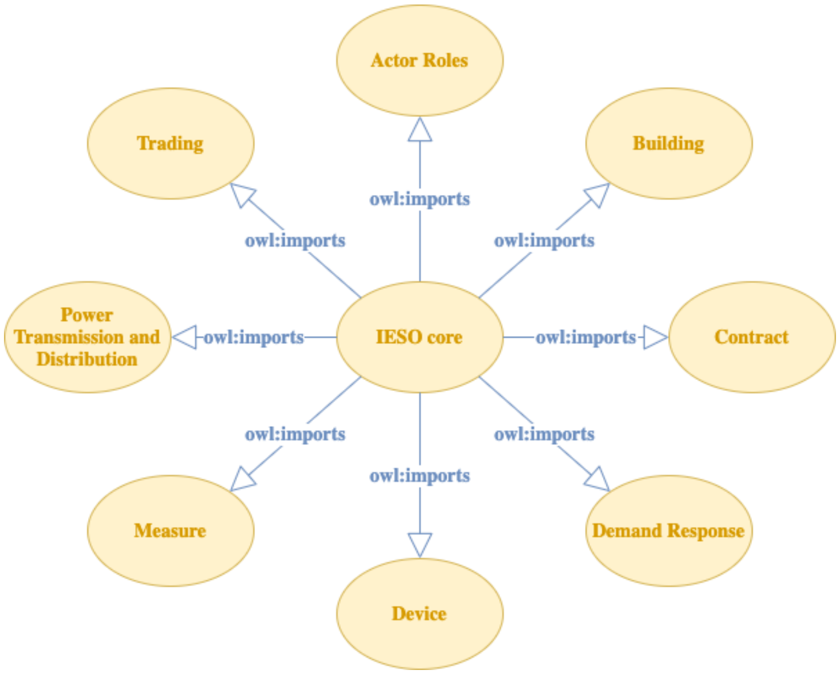

Figure 2. IESO's domain modules.

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.

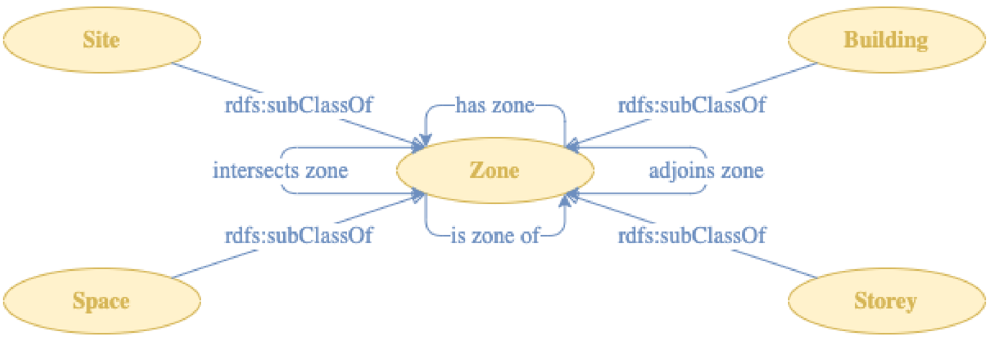

Figure 4. Building module core concepts.

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.

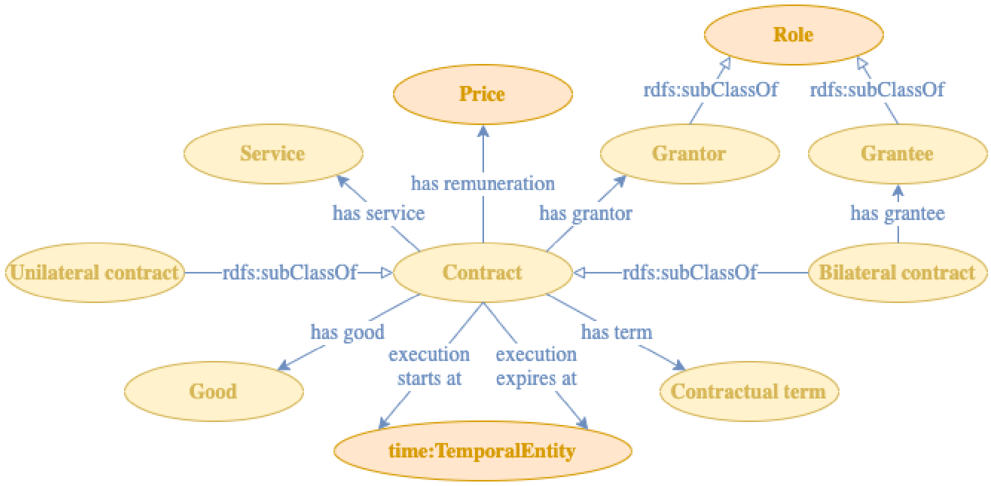

Figure 5. Contract module main concepts.

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 **Condition**s, a set of **Penalty**(ies), and a set of **Promise**s. 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/.

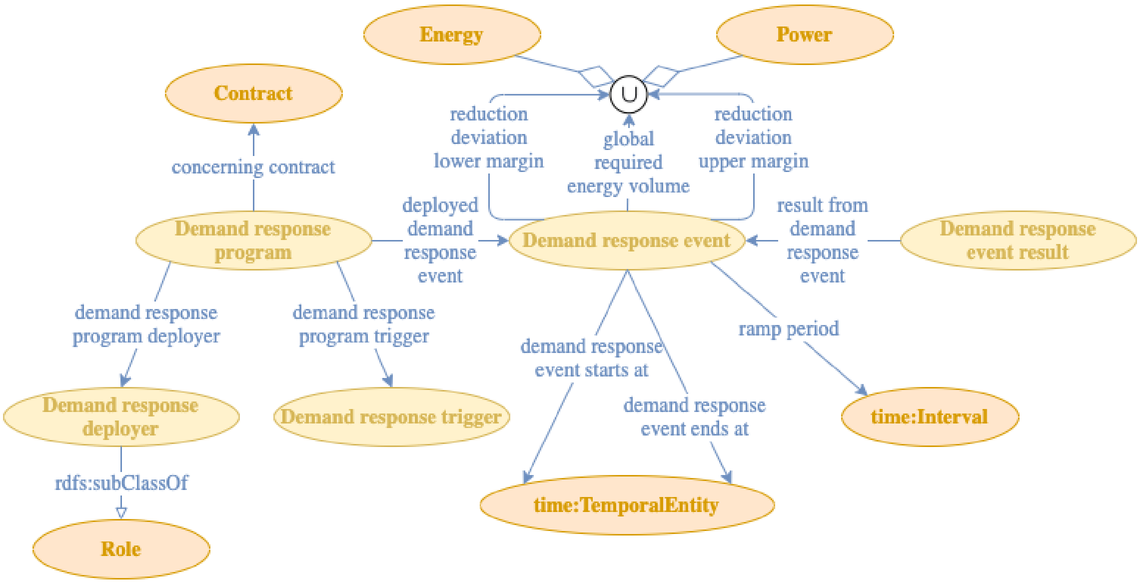

Figure 6. Demand Response module central concepts.

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.

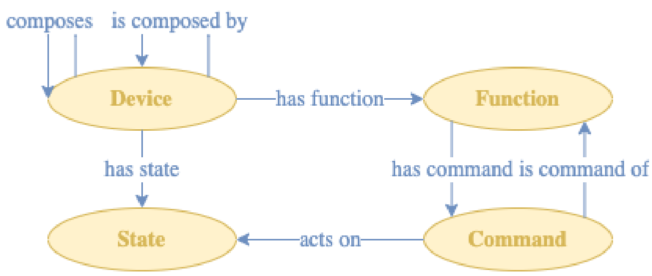

Figure 7. Device module base concepts.

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.

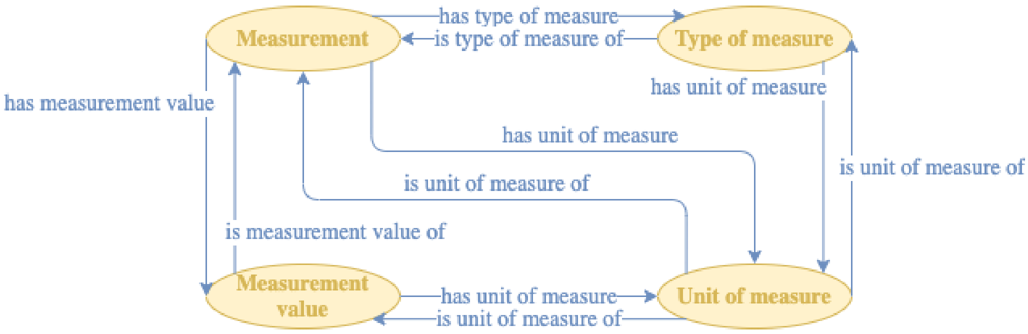

Figure 8. Measure module core concepts.

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.

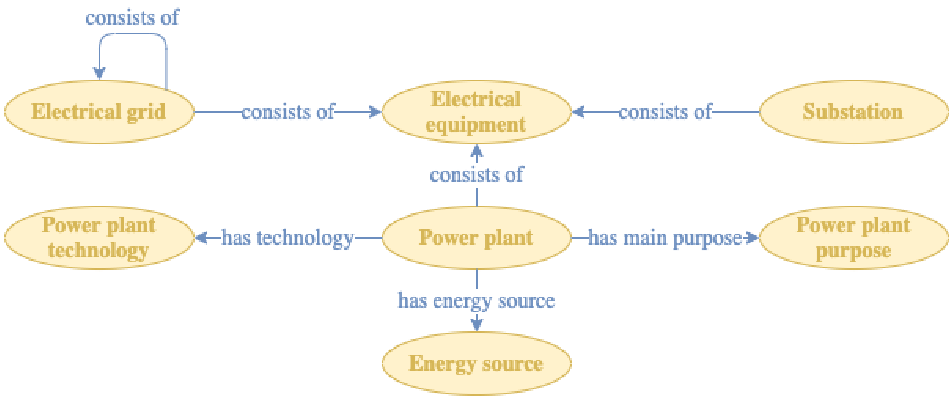

Figure 9. Power Transmission and Distribution module main concepts.

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.

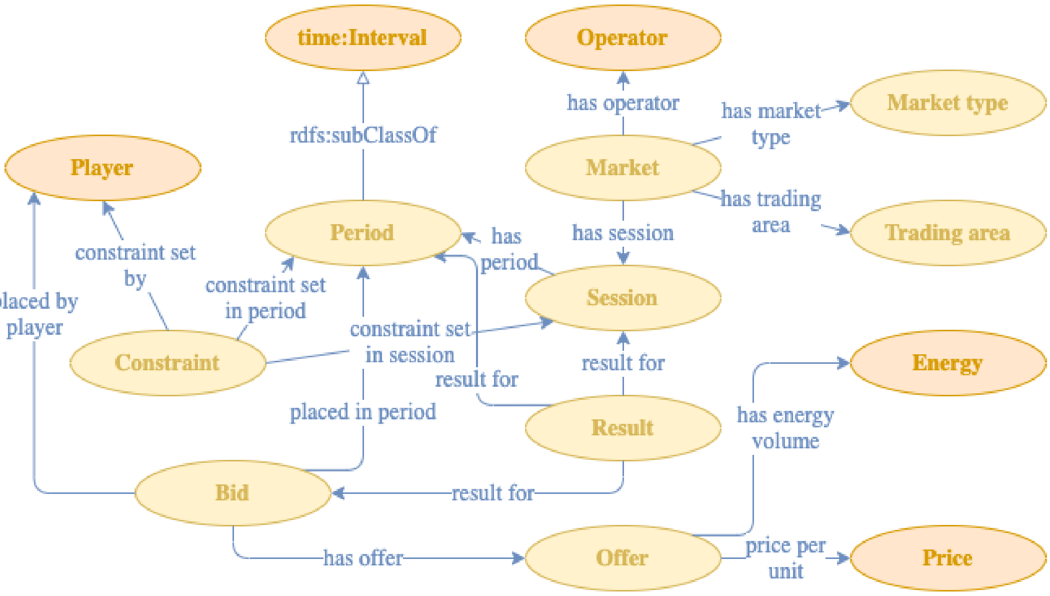

Figure 10. Trading module most relevant concepts.

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.

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

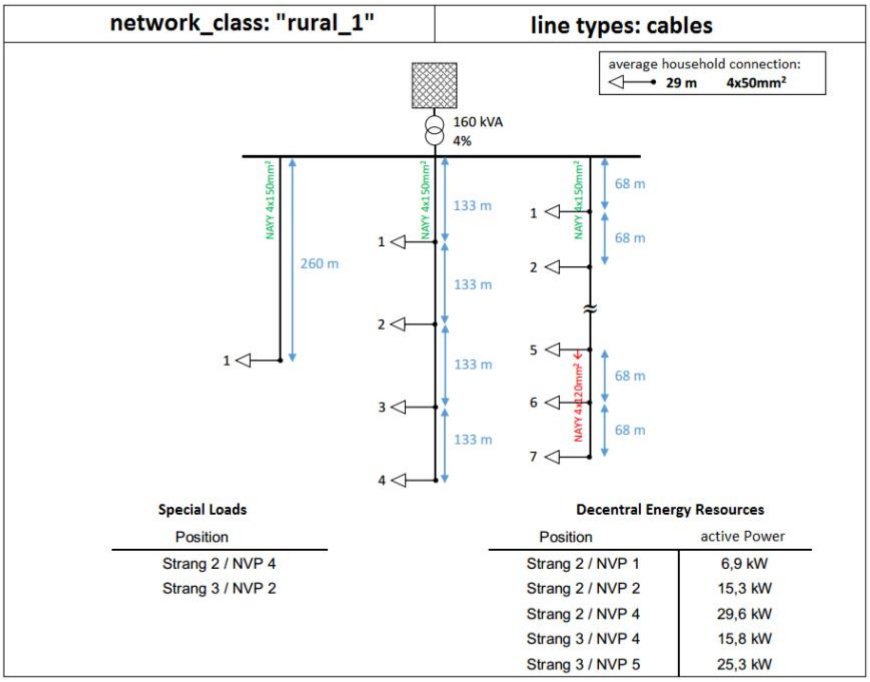

Figure 11. Synthetic voltage control LV rural network [77].

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.

$$0.95\ V_N \leq V_{BUS} \leq 1.05\ V_N \tag{1}$$

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

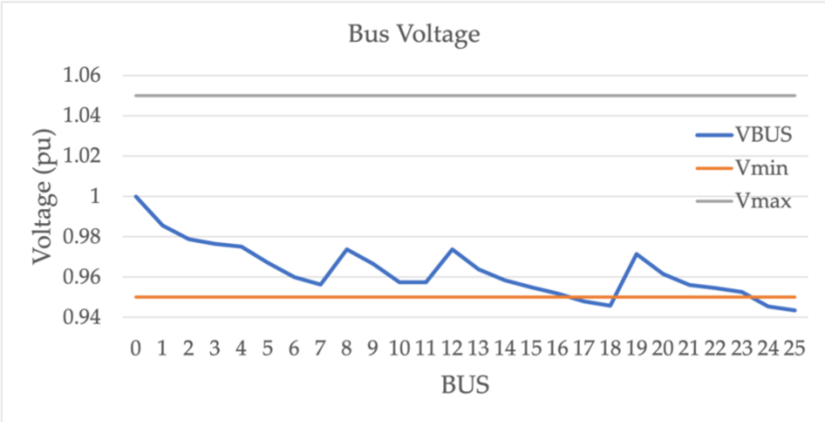

Figure 12. Buses' voltages and nominal voltage limits.

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 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).

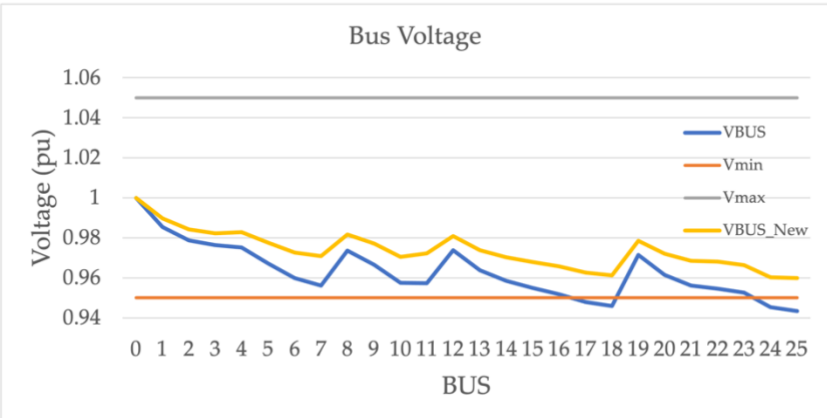

Figure 14. Buses' voltages comparison before and after demand flexibility market.

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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Appendix C. Conclusions in Spanish / Conclusiones en Castellano

Conclusiones Principales y Contribuciones

El sector eléctrico mundial ha experimentado cambios importantes durante las últimas décadas [1], [2]. Los cambios más significativos son el aumento de la penetración de RES y DG [10] lo que llevó a la adopción del paradigma SG y la introducción de un enfoque competitivo en el mercado mayorista de electricidad y, más recientemente, en algunos aspectos de los mercados minoristas [13]. SG evolucionó rápidamente de un concepto ampliamente aceptado por las partes involucradas a una realidad industrial. En Europa, los objetivos de la EU han jugado un papel importante en estos cambios, con los objetivos "20-20-20" [3] y las constantes revisiones de estos objetivos que apuntan actualmente a que la EU sea climáticamente neutra con una economía con emisiones netas de cero GHG para 2050 [5], [6]. La reestructuración de los EM ha sido otra preocupación importante de la EU, en particular con la formación de EM pan-Europeos, concretamente para el mercado diario con el proyecto PCR [14]–[16] y para el mercado intradiario con el SIDC [17].

En este contexto, las herramientas de simulación y apoyo a la toma de decisiones son fundamentales para estudiar los diferentes mecanismos del mercado y las relaciones entre sus grupos de interés. Las herramientas basadas en MAS son particularmente adecuadas para analizar interacciones complejas en sistemas dinámicos, como los PES, debido a la inclusión facilitada de nuevos modelos, mecanismos de mercado, tipos de participantes y diferentes tipos de interacciones. Sin embargo, estas plataformas se enfocan en resolver problemas específicos de áreas o subdominios específicos de los PES. Uno de los principales desafíos en esta área es el desarrollo de herramientas de simulación y apoyo a la toma de decisiones para abordar el problema a nivel global.

A pesar de los importantes avances ya realizados, el uso de estas herramientas individualmente no logra capturar la autenticidad y precisión requerida para la simulación y el estudio del dominio de la energía, ya que los subdominios tienen un impacto significativo entre sí e influyen en los resultados. Existe una clara necesidad de herramientas de estudio y gestión más realistas y precisas en el ámbito de los PES. Es fundamental proporcionar interoperabilidad entre los diferentes sistemas que estudian partes específicas de los PES para superar los problemas de precisión, autenticidad y confiabilidad. La interacción de sistemas heterogéneos promueve el intercambio de modelos y conocimientos, permitiendo estudiar escenarios más complejos y completos más cercanos al mundo real y beneficiando a reguladores, operadores y actores con herramientas adecuadas para aprender de la experiencia y adaptarse a la realidad de los PES. Esta brecha llevó a la concreción de las distintas preguntas de investigación, que fueron la base para definir los objetivos de este trabajo de Doctorado.

Esta tesis concibe una sociedad de MAS para el estudio, simulación, soporte de decisiones, operación y manejo de los PES, conceptualizando un modelo de conocimiento basado en ontologías para representar los conceptos del dominio y proporcionar los medios para apoyar comunicaciones significativas y compartir conocimientos entre los varios sistemas, aplicaciones y servicios considerados. La Sociedad MAS integra los MAS existentes desarrollados para operar distintos subdominios de los PES con herramientas y servicios recientemente desarrollados, superando los problemas identificados que componen el tema principal abordado en este Ph.D.

MASCEM y AiD-EM abordan, respectivamente, la simulación de EM y el apoyo a la decisión. MASGriP, a su vez, modela y simula los entornos de SG y microrred y las respectivas entidades participantes. Las herramientas desarrolladas recientemente tienen como objetivo aprovechar las capacidades de estas herramientas al tiempo que abren el camino para la inclusión de nuevos sistemas que puedan surgir. Para ello, SSC proporciona una plataforma de registro y búsqueda para facilitar el proceso de encontrar servicios disponibles y apoyar las interacciones entre las diferentes herramientas y servicios de forma autónoma. IDeS pone a disposición varios algoritmos de soporte de decisiones para diferentes tipos de operadores y jugadores en SG al registrar esos servicios en SSC. DAS, a su vez, contribuye con datos históricos y en tiempo real que van desde el edificio hasta los SG y EM. Dev-C permite a los agentes y servicios controlar los dispositivos físicos abstrayéndolos de los protocolos de comunicación utilizados. Finalmente, TOOCC proporciona a los usuarios una interfaz centralizada para controlar, configurar, simular y estudiar el PES globalmente o solo una parte específica, según se desee.

Las ontologías desarrolladas facilitan la interoperabilidad entre sistemas heterogéneos dando significado semántico a la información intercambiada entre las distintas partes. La ventaja radica en que todos los miembros de la Sociedad MAS los conocen, comprenden y están de acuerdo con los conceptos allí definidos. Además, la combinación del razonamiento ontológico y las tecnologías de web semántica permitió desarrollar sistemas más flexibles y adaptables capaces de dar seguimiento a la evolución de la realidad rápida y dinámica del sector manteniendo las herramientas agnósticas al modelo semántico y las reglas de negocio que se aplican. Además, también facilita la implementación y validación de nuevos modelos, incluyendo combinaciones de modelos, lo cual es una característica relevante para que reguladores y operadores prueben y certifiquen que se ajustan a la realidad del sector y para que los jugadores aprendan y se adapten a las nuevas realidades.

El trabajo desarrollado ha sido objeto de validación en entornos de laboratorio y del mundo real, utilizando datos históricos, en tiempo real y simulados para asegurar la adecuada integración y funcionamiento de los diversos MAS y servicios en condiciones y escenarios realistas. Los resultados alcanzados muestran el logro de los objetivos determinados para dar respuesta a las preguntas de investigación definidas, contribuyendo a avances significativos en el estado del arte de las plataformas interoperables en general, y en específico para las desarrolladas para el estudio, simulación, soporte de decisiones, operación y gestión en el ámbito de los PES. Los diecinueve artículos científicos publicados como resultado de este doctorado y la contribución del trabajo desarrollado en el logro de las metas de varios proyectos nacionales e internacionales son indicadores claros de la relevancia de los hallazgos alcanzados.