Revista Facultad de Ingeniería (Rev. Fac. Ing.) Vol. 33, No. 69.
L-ISSN: 0121-1129, e-ISSN: 2357-5328.

DOI: 10.19053/01211129.v33.n69.2024.17959

TOOLS FOR DEVELOPING APPLICATIONS IN THE SEMANTIC WEB OF THINGS: A SYSTEMATIC LITERATURE REVIEW

Herramientas para el desarrollo de Aplicaciones en la Web Semántica de las Cosas: Una revisión sistemática de la literatura

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Received / Recibido: 03/05/2024
Accepted / Aceptado: 23/07/2024

ABSTRACT
The Internet of Things (IoT) has revolutionized various sectors. Despite several years since its inception, developing interoperable smart object environments remains challenging due to hardware and software heterogeneity and the difficulty in applying formal software development methods to ensure quality. The Semantic Web of Things (SWoT), combined with a set of best software development practices, presents a promising solution to ease the development of semantically interoperable IoT environments. This paper conducted a systematic review of tools for SWoT application development to establish the best decisions for developing these environments, while also seeking a proper balance to manage heterogeneity and quality. The findings highlight best practices, emerging trends, and future opportunities in SWoT development. Key trends, approaches, and tools used in SWoT application development were identified. Additionally, it is confirmed that the adoption of international standards and the use of semantic technologies are crucial to overcoming interoperability and quality challenges in IoT applications.

Keywords: Internet of Things; Semantic Web; interoperability; software development; quality assurance.

RESUMEN
La Internet de las Cosas (IoT por sus siglas en inglés) ha transformado diversos sectores. Aunque han pasado varios años desde su creación, aún es difícil desarrollar entornos de objetos inteligentes interoperables debido a la heterogeneidad de hardware y software, así como, la dificultad de aplicar métodos de desarrollo de software formales que aseguren la calidad de los desarrollos. La Web Semántica de las Cosas (SWoT por sus siglas en inglés), unida a un conjunto de buenas prácticas de desarrollo de software, se presenta como una solución prometedora para facilitar el desarrollo de entornos de interoperabilidad semántica de objetos inteligentes de la IoT. Este artículo realizó una revisión sistemática de herramientas

Esta edición se financió con recursos del Patrimonio Autónomo Fondo Nacional de Financiamiento para la Ciencia, la Tecnología y la Innovación, Francisco José de Caldas, Minciencias

Cómo citar este artículo: M. Galindo-Semanate, M. Niño-Zambrano, "Tools for Developing Applications in the Semantic Web of Things: A Systematic Literature Review", *Revista Facultad de Ingeniería*, vol. 33, no. 69, e17959, 2024. https://doi.org/10.19053/01211129.v33.n69.2024.17959

para el desarrollo de aplicaciones de la SWoT, con el fin de establecer las mejores decisiones para el desarrollo de dichos entornos, buscando al mismo tiempo un equilibrio adecuado para gestionar la heterogeneidad y la calidad. Los resultados destacan las mejores prácticas, las tendencias emergentes y las oportunidades futuras en el desarrollo de la SWoT. Se identificaron las principales tendencias, enfoques y herramientas utilizados en el desarrollo de aplicaciones de la SWoT. Asimismo, se corrobora que la adopción de estándares internacionales y el uso de tecnologías semánticas son claves para superar los desafíos de interoperabilidad y calidad en aplicaciones IoT.

Palabras clave: Internet de las cosas; Web semántica; interoperabilidad; desarrollo de software; aseguramiento de calidad.

1. INTRODUCTION

The proliferation of the Internet of Things (IoT) has created a continuously expanding technological ecosystem, thus revolutionizing the way we interact with the world. The Web of Things (WoT) enables real-world IoT objects to gather contextual information, user data, and processes to generate intelligent behaviors among themselves and interact with users, transforming them into Smart Things.

The vision of a world interconnected by Smart Things represents the pinnacle of Web 4.0 and the Semantic Web of Things. However, achieving this vision requires addressing and developing tools to manage several key challenges:

- Heterogeneity of Hardware and Software: The diversity of devices from different manufacturers, with varying capabilities and communication protocols, presents a complex landscape where Smart Things must be context-aware and able to access the meta-information of their peers. This capability is essential to establish a semantic interaction pathway, enabling the creation of joint services.
- Diverse Knowledge Models: Addressing the previous challenge involves creating data models and shared knowledge across all nodes in the IoT ecosystem. However, this solution introduces the problem of heterogeneous models, as there is no consensus on the standard vocabularies and ontologies to be used, leading to challenges in achieving uniform interpretation.
- Scalability: The IoT generates vast volumes of data, with thousands of devices connecting to the ecosystem daily. This directly impacts data storage repositories and the network's capacity to reduce latency in service responses.
- Security and Privacy: The WoT has immense potential to capture sensitive data from individuals and organizations, ranging from real-time heart rate monitoring to spying on behaviors and conversations. Additionally, unauthorized intrusions into critical systems, such as nuclear plant sensors or electrical systems, pose significant risks to individuals' honor and lives. Therefore, establishing mechanisms to protect against unauthorized access while allowing necessary access to create interoperable and context-aware services requires the network of objects to provide robust security mechanisms with minimal impact on scalability.
- Reusing the Installed Ecosystem: Integrating IoT technologies into existing systems and technologies is challenging. It requires balancing the need for constant adaptation and updates to maintain reliability while enhancing the usability of already installed technologies and other Smart Things.

- Quality of Service: Developing intelligent environments where Smart Things interact demands not only software development knowledge but also expertise in hardware deployment and information networks. The goal is to create intelligent services for users, which must meet adequate quality standards. IoT applications face significant quality challenges, particularly in terms of reliability, robustness, maintenance, and support.
- Software Development and Maintenance: Applying formal software development methods to ensure the quality and reliability of IoT systems poses significant challenges. Managing software and firmware updates across a wide variety of geographically dispersed devices presents a significant challenge in establishing a trusted network among Smart Things.
- Intelligent Energy Management and Carbon Footprint: One of the critical challenges is energy achieving autonomy for increasingly connected devices. Their dependence on the current energy grid not only overloads the system but also elevates the carbon footprint of these devices contributing to the ecosystem.

Addressing these challenges requires a multidisciplinary approach that integrates software engineering, cybersecurity, data management, and distributed systems design, along with close collaboration among regulators, manufacturers, and developers.

Furthermore, generating semantic interoperability solutions in the WoT is crucial to addressing these challenges, and the SWoT emerges as a promising solution by providing meaning to the information generated by IoT devices and proposing an infrastructure that has proven to be efficient and effective in the current Semantic Web framework.

Moreover, Software Engineering enhances the quality of applications through a series of practices, methodologies, and tools that ensure software is robust, reliable, maintainable, and efficient. Applying these techniques to the development of SWoT applications can effectively manage existing issues in the IoT ecosystem of smart objects.

This research aims to enhance the quality of service, development, and maintenance of semantic interoperability environments for IoT smart objects by utilizing the SWoT in conjunction with established Software Engineering practices. This approach facilitates the creation of more intelligent, context-aware applications.

To achieve this, a systematic literature review has been conducted. This review intends to investigate the practices the tools employed in the development of applications using SWoT, given that SWoT is a relatively recent technology that requires the integration of multiple concepts.

2. METHODOLOGY

This study employs a systematic mapping methodology following the guidelines of Budgen et al. [1], Petersen et al. [2], and Kitchenham [3]. The PICOC (Population, Intervention, Comparison, Outcome, Context) strategy was used to define the scope of the review. The selected bibliometric databases include Scopus, Web of Science, PubMed, and Dimensions. The search focused on titles, abstracts, and keywords to ensure the relevance of the selected studies. Initially, 69 studies were identified, which were narrowed down to 30 documents after the removal of duplicates and irrelevant studies.

The selection process involved evaluating the quality of the studies using predefined criteria, ensuring that only those with robust methodologies and relevant results were included. Data extraction was performed systematically and results were analyzed to identify emerging patterns and trends in the field of SWoT.

A. PICOC Criteria

- Population (P): Developers and professionals in IoT and Semantic Web who are interested in creating applications for the Semantic Web of Things.
- Intervention (I): The proposed framework for developing applications in SWoT, which prioritizes semantic interoperability between devices and applications.
- Comparison (C): There is no direct comparison specified in the objectives, but all proposals that generally or specifically apply existing development practices in IoT and Semantic Web, and consider their effects on the development process, will be considered as comparable elements.
- Outcomes (O): Identification of best practices for developing applications in SWoT that prioritize semantic interoperability, scalability, and efficiency.
- Context (C): Focuses on the convergence of the Semantic Web and the Internet of Things in application development, emphasizing the semantic interoperability of smart objects.

B. Review Questions

Based on the context and focus derived from the PICOC strategy, key questions and a precise search string were developed to guide the literature review.

1. What are the best development practices for the Semantic Web of Things in IoT? Search string: *('Semantic Web of Things' OR SWoT) AND ('best practices' OR 'Software design' OR 'software development') AND ('IoT' OR 'Internet of Things')*
2. How is semantic interaction between devices prioritized in the development of Semantic Web of Things applications? Search string: *('Semantic interaction' OR 'device interaction' OR 'semantic interoperability') AND ('IoT application development' OR 'Semantic Web of Things application')*
3. What scalability approaches are used in the development of Semantic Web of Things applications? Search string: *('Scalability' OR 'scalability techniques') AND ('Semantic Web of Things' OR SWoT) AND ('IoT' OR 'Internet of Things')*
4. How are efficiency and effectiveness achieved in the communication and operation of devices in the development of Semantic Web of Things applications? Search string: *(('Efficiency' OR 'effectiveness') AND ('communication' OR 'interoperability')) AND ('Semantic Web of Things' OR SWoT) AND ('IoT' OR 'Internet of Things')*
5. What are the outcomes of implementing best practices in developing Semantic Web of Things applications? Search string: *('Results' OR 'outcomes' OR 'benefits') AND ('Semantic Web of Things' OR SWoT) AND ('IoT' OR 'Internet of Things') AND ('application development' OR 'Software design' OR 'software development')*

C. Search Execution

The results obtained from the databases are summarized in Table 1. The following results were obtained after applying the search criteria in the selected engines.

Duplicate references were filtered, resulting in 35 references plus 2 conference papers found via Scopus, which were manually reviewed:

1. *10th Annual International IEOM Conference, IEOM 2020*: Articles related to this event were not available through open bibliographic resources or accessible libraries.
2. *2016 IEEE 3rd World Forum on Internet of Things, WFIoT 2016*: Information was accessible due to its organization by IEEE. Four relevant documents for Question 2 were selected according to Scopus.

From the reviewed databases, 3 publications could not be accessed, and 6 were excluded due to confusion with the term SWoT, which is associated with Strengths, Weaknesses, Opportunities, and Threats. Finally, 30 documents were evaluated. Fig. 1 summarizes the process.

Table 1. *Search results by database and question*

Database	Question	Results
Scopus [Abstract title, abstract, keywords]	1	9
	2	5
	3	12
	4	10
	5	1
Web of Science [Topic]	1	0
	2	2
	3	2
	4	4
	5	0
PubMed [All fields]	1	0
	2	2
	3	1
	4	0
	5	0
Dimensions [Title, abstract]	1	3
	2	2
	3	9
	4	7
	5	0
Total		69

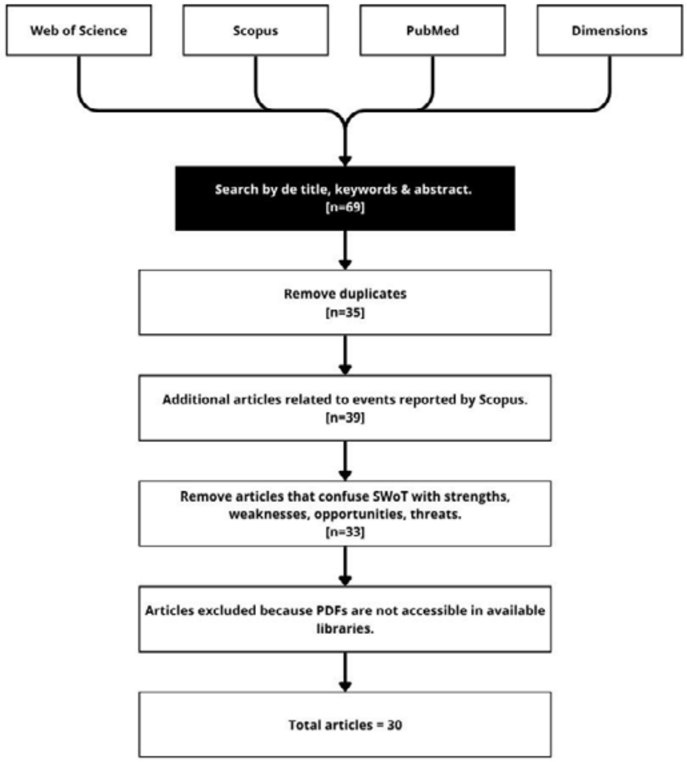

Fig. 1. *Article filtering process.*

3. RESULTS

A. Research Question 1: What are the best development practices for the Semantic Web of Things in IoT?

Total results: 5, see Table 2.

Table 2. *Results for Research Question 1*

Ref.	Motivation	Proposal
[4]	Improve security aspects of ETSI's oneM2M initiative.	Design an ontology to gather knowledge on security issues associated with IoT technologies to ensure knowledge availability.
[5]	How to interoperate domain-specific IoT applications.	Proposes the M3 framework utilizing semantic technologies to achieve interoperability.
[6]	Compilation of best practices and methodologies for the Semantic Web based on the experience of the IERC AC4 cluster.	Enumerates a set of best practices for ontology engineering and useful tools to ensure the standardization of Semantic Web applications.
[7]	Increasing density and complexity of IoT applications such as smart cities require tools to facilitate interoperability.	Proposes an Entity-Component Attribute structural pattern automatically applied for the semantic enrichment of smart objects to be interpreted in a W3C Linked Data layer.
[8]	To standardize an ontology, it is crucial to validate and publish it for Reuse.	A web tool that increases the quality, classification, and accessibility of domain-oriented ontologies.

The results predominantly feature publications by Dr. Amelie Gyrard, who has actively worked in the Semantic Web field. Her articles highlight the evolution of her proposed best practices for ontology design [6], summarized in the following 16-step list:

1. Find a good name for the ontology.
2. Choose a good namespace for the ontology.
3. Share the ontology online.
4. Add metadata to the ontology.
5. Add *rdfs:label, rdfs:comment, and dc:description for each concept and property.*
6. *Name classes with an initial capital letter and properties with an initial lowercase letter.*
7. *Submit the ontology-to-ontology catalogs.*
8. *Reuse and link to other ontologies.*
9. *Ensure the URI is dereferenceable; when pasting the ontology namespace URL into a web browser, it should return the code.*
10. *Validate the ontology with a syntax validator.*
11. *Add documentation to the ontology.*
12. *Include visualization of the ontology.*
13. *Improve the design of the ontology.*
14. *Enhance URI dereferencing and content negotiation.*
15. *Ensure the ontology can be loaded into ontology editors (e.g., Protegè).*
16. *Register the ontology in prefix catalogs.*

In the article [5], the same author proposes the M3 framework, which —when complemented with the previously mentioned best practices— results in a highly useful set of tools for implementing Semantic Web in an IoT application defined by this set of layers:

1. *Perception Layer: Comprised of sensors and actuators.*
2. *Data Acquisition Layer: Raw data from the sensors is collected and transformed into RDF (Resource Description Framework) or XML (eXtensible Markup Language) data compliant with the M3 ontology, which is an extension of the W3C SSN (Semantic Sensor Network) ontology.*
3. *Persistence Layer: The formatted data is stored in a semantic database like SPARQL.*
4. *Knowledge Management Layer: Data is semantically enriched by considering the context.*
5. *Reasoning Layer: The enriched data gains reasoning capabilities by applying the framework's rules, allowing for sensor data inference.*
6. *Knowledge Query Layer: Enables the execution of SPARQL queries to infer data.*
7. *Application Layer: Presentation of information and results.*

Finally, this proposal includes the online tool PerfectO [8] that was designed to facilitate the accessibility and classification of domain-based ontologies. This tool, along with the LOV4IoT repository [9], is highly convenient for ensuring the reuse of existing ontologies applied to IoT, thereby enabling the interoperability of future applications.

B. Research Question 2: How is semantic interaction between devices prioritized in the development of Semantic Web of Things applications?

Total results: 10, see Table 3.

Semantic interaction between heterogeneous devices is fundamental in developing Semantic Web of Things (SWoT) applications. To address this challenge and prioritize such interaction, various approaches and techniques leveraging Semantic Web technologies have been proposed. These approaches aim to facilitate semantic interoperability, enabling devices from different manufacturers and platforms to interact and share data meaningfully. The main strategies include:

1. Automatic generation of device descriptions:

- Use RDF constraint languages like SHACL and ShEx to model and validate IoT device capabilities and variations [16].
- Implement automatic generators for semantically enriched device description templates (Thing Descriptions) based on SHACL/ShEx constraints [16] [18].
- Employ and extend iot.schema.org with RDF shapes to represent device capabilities and interaction patterns [16] [18].
- Apply Model-Driven Engineering (MDE) techniques to handle the diversity of IoT devices [14].

2. Ontology catalogs and methodologies:

- Reuse existing ontologies from relevant domains (smart cities, agriculture, etc.) in catalogs like LOV4IoT [10] [11] [15].
- Apply methodologies such as KE4WoT to automatically extract key topics/concepts from existing IoT ontologies using machine learning techniques (word2vec, K-means) [17].
- Enrich catalogs with new application ontologies that meet quality criteria (OWL serialization, documentation, etc.) [15].
- Promote interconnection and linking between datasets and ontologies to enhance interoperability [15].

3. Adaptive middlewares and architectures:

- Implement middlewares based on the MAPE-K model to monitor, analyze, plan, and execute dynamic adaptations in response to device changes [13].
- Utilize AI-based planning techniques and ontologies like OWL-S to derive adaptable workflows [13].
- Apply policy-based orchestration and control loops to achieve semantic interoperability in heterogeneous IoT environments [14].

- Adopt distributed and flexible architectures that allow component integration based on specific needs [12].

4. Semantic annotation and stream processing:

- Semantically annotate real-time IoT sensor data streams using lightweight ontologies (SSN, OWL-S, etc.) [12]. Process RDF streams using languages like CSPARQL and CQELS for event detection and adaptive reasoning [12].
- Integrate multiple data sources (weather, regulations, etc.) using semantic processing pipelines [12].
- Utilize dynamic knowledge bases that allow constant revision and correction of information [14].

5. Combination of models and ontologies:

- Develop a semantic interoperability layer that combines information models and ontologies [14].
- Apply a hybrid approach using models for representation and ontologies for reasoning about facts [14].
- Implement a semantic mapping level with lexicons, first-order logic, and ontologies to ensure interoperability [14].

6. Standards, best practices, and tools:

- Adopt W3C standards such as Web of Things (WoT) and iot.schema.org to describe IoT devices [16] [18].
- Use rapid development tools like Node-RED extended with semantics and predefined 'recipes' [18].
- Follow ontology design best practices, detecting issues with tools like OOPS [15].
- Employ visualization (WebVOWL), documentation (LODE), and validation (TripleChecker) tools [15].

7. Generation of semantic recipes:

- Create semantic templates or 'recipes' that describe reusable IoT application patterns [18].
- Automate matching between required capabilities in recipes and existing device capabilities [18].
- Guide non-expert developers in semantics to configure devices consistently using recipes [18].

8. Proxies and rule engines:

- Implement interoperability proxies that translate messages between different IoT platforms (oneM2M, OCF, etc.) [19].
- Use rule engines (e.g., Drools) to automatically identify registered devices and apply semantic rules [19].
- Build web applications to visualize and interact with data from heterogeneous platforms [19].

Table 3. *Results for Question 2*

Ref.	Motivation	Proposal
[10]	IoT application developers may find using SWoT for interoperability challenging.	A template to help IoT developers create semantics-based applications without having to (1) design their own models/ ontologies, (2) design rules for interpreting data, or (3) semantically annotate data.
[11]	The heterogeneity of information in the IoT domain leads to a lack of standards, as many testbeds store data in proprietary formats, making them independent and isolated from each other.	Proposes a comprehensive and lightweight ontology aiming to achieve semantic interoperability among various fragmented testbeds in the IoT domain. The ontology, implemented in the EU FIESTA-IoT project, uses Noy et al.'s ontology construction methodology.
[12]	Existing IoT solutions for agriculture lack flexibility and adaptability.	Agri-IoT, a semantic framework for IoT-based smart agriculture applications. Agri-IoT aims to fill the current gap by providing a flexible and adaptable framework that can process and analyze sensor data semantically in real time.
[13]	The proliferation of devices in the IoT has led to large-scale deployments with thousands of highly heterogeneous devices. The inherent dynamics of these devices, with changes in applications, capabilities, and mobility, have generated semantic interoperability problems.	'InteropAdapt', an adaptive middleware designed to maintain seamless semantic interoperability through dynamic events. The solution focuses on defining ontologies for operations and adaptability to address the dynamics of IoT deployments.
[14]	The lack of a standard model representing the characteristics and behaviors of an IoT device, as well as the information it produces and consumes compromises interoperability. Without a model, scalability is limited, operational costs increase, and future technologies require isolated architectures for integration.	Propose an architecture that combines information and data models with ontologies to provide an extensible semantic interoperability layer. This layer ensures that the meaning of terms and objects in one device or system is not lost or altered when exchanged and used in other devices or systems.
[15]	Implementing IoT-based Smart City applications faces the challenge of interoperability between data generated by IoT devices and complementary data. Although there are multiple ontology catalogs, their use in these applications requires significant effort.	The effective use of ontology catalogs to design and develop Smart City applications. A methodology is presented to enrich catalogs with relevant ontologies, demonstrating their applicability in various domains.
[16]	The lack of specificity in IoT device semantics. Although standards like W3C WoT and iot.schema.org exist to describe devices, they do not address the variability among devices of the same class manufactured by different manufacturers.	Proposes extending iot.schema.org Capabilities with Resource Description Formats (RDF Shapes). These formats allow for the automatic generation of Thing Descriptions (TDs) for device variants. By modeling constraints with RDF shape languages, such as W3C SHACL and Shape Expressions (ShEx), it aims to adapt iot.schema.org Capabilities to represent diverse device variants.
[17]	The lack of interoperability in the IoT threatens its economic value, as the diversity of ontologies for representing IoT devices and their data hinders the efficient development of cross-platform and multi-domain applications.	The development of the KE4WoT (Knowledge Extraction for Web of Things) methodology that uses machine learning techniques to automatically identify the most important topics from existing ontologies in three IoT application domains: home, city, and weather.

Table 3. *Results for Question 2 (Continued)*

[18]	Industrial IoT applications developed with tools like Node-RED are limited to specific devices from certain manufacturers and ecosystems, lacking semantic interoperability.	A semantic extension for Node-RED, introducing semantic definitions such as iot.schema.org semantic models. This extension guides non-experts in semantic technologies, such as industrial engineers or IoT application developers, to semantically configure devices consistently. The proposal includes the introduction of 'Recipes', semantic application templates.
[19]	The difficulty in developing IoT applications due to the diversity of platforms, such as oneM2M and OCF, which require devices and applications to support multiple protocols.	Design and implement an interoperability scheme between two edge servers, oneM2M and OCF, by building proxies that act as bridges and using a rule engine to automatically identify registered devices. They also propose a web application to visualize data.

C. Research Question 3: What scalability approaches are used in the development of Semantic Web of Things applications?

Total results: 10, see Table 4.

The development of large-scale Semantic Web of Things (SWoT) applications involves addressing significant scalability challenges due to the distributed, heterogeneous, and dynamic nature of the devices, data, and networks involved. This review identifies various approaches proposed to achieve scalability in SWoT application development. These approaches range from distributed architectures and the use of caching proxies to semi-automatic annotation techniques, optimized databases, semantic search engines, blockchain technologies, distributed fog reasoning, parallel rule propagation, rule deployment optimization, and evaluation through large-scale simulations and use cases. These approaches are detailed below:

1. Distributed P2P architectures:

- The use of a distributed P2P network to extend and scale the SWoT without requiring proportional infrastructure adjustment [20] would allow organic network growth as more P2P nodes are added.

2. Caching proxies:

- The 'Smart Service Proxy' (SSP) is proposed as an intermediary between devices/sensors and clients [20] [21]. The SSP implements a caching mechanism to store resource representations, improving availability and scalability.
- The cache can convert representations from one format to another without loss of information, distributing the computational load from the application core.

3. Triple and graph databases:

- It is advantageous to use a triple store as a cache in the SSP that is compatible with multiple engines such as JENA and Luposdate [20]; the latter supports GeoSPARQL for scalable spatial queries.
- The use of graph databases is proposed for efficient and scalable storage of the RDF knowledge graph [23].

4. Semi-automatic annotation:

- Semi-automatic semantic annotation based on entity linking models [22] enhances scalability by partially automating the extraction of semantics from structured resources.

5. Semantic search engines:

- Implementing a semantic search engine that enables scalable SPARQL queries over the constructed knowledge base [22].

6. Blockchain and smart contracts:

- Using blockchain and smart contracts for registration enables the discovery and selection of annotated services/resources [24], ensuring data integrity in a distributed computing and storage architecture.

7. Distributed fog reasoning:

- A distributed reasoning approach (EDR) implemented in Fog nodes for semantic processing distribution [25] [26] [27] [29]. EDR facilitates scalability by allowing rules and data to propagate between Fog nodes.
- A node's knowledge is limited to its direct neighborhood to ensure scalability.

8. Parallel rule propagation:

- Rules are propagated in a distributed and parallel manner across all nodes capable of reasoning [27] [29]. This decentralizes reasoning and promotes processing close to the sensors.

9. Rule deployment optimization:

- Dynamic deployment techniques and optimization strategies are used to improve latency [25] [29].
- This approach requires considering the balance between cloud and fog based on node capabilities.

10. Large-scale simulations and use cases:

- Conducting large-scale simulations and use cases is useful for evaluating scalability [21] [27] [24] [29] and measuring application performance.
- Aspects such as node distribution, variation in network topologies, blockchain size, etc., should be considered.

Table 4. *Results for Question 3*

Ref.	Motivation	Proposal
[20]	In the IoT context, computational capacity can be limited, as well as network extension constrains response times when attempting to acquire information.	An intermediary called SSP that concentrates information in RDF format to ensure information availability with minimal possible delay.
[21]	Addresses the challenge of integrating diverse IoT objects, especially those lacking direct network communication capability.	Case study applying the SSP approach [20] to monitor urban traffic using SWoT.
[22]	The lack of unified representation markup tools and methods in the semantic layer hinders interoperability, integration, and scalable search of things in the Web of Things (WoT).	A framework called 'Semantic Web of Things Framework' to enhance interoperability. This is achieved by creating a Microdata vocabulary extended from the Semantic Sensor Network (SSN) ontology to facilitate manual annotation in HTML-based WoT representations.
[23]	Despite efforts to integrate semantics with the Web of Things (WoT) in cyber-physical systems (CPS), existing knowledge engineering methods based on semantic sensor networks (SSN) still cannot represent the complex relationships between devices during dynamic composition and collaboration.	The Semantic Web of Things framework for CPS (SWoT4CPS). This framework provides a hybrid solution combining ontological engineering methods by extending SSN and machine learning methods based on an entity linking (EL) model.
[24]	SWoT networks face trust and reliability issues. Large-scale decentralized and dynamic infrastructures suffer from unpredictable node volatility, compromising resource availability, and trust and coordination are challenging.	A blockchain-based infrastructure to address trust and reliability issues in the SWoT context. The proposed solution involves using smart contracts and blockchain technology to register, discover, and select annotated services/resources.
[25]	The development of the Semantic Web of Things (SWoT) is challenged by the current IoT architecture, where limited devices are connected to powerful cloud servers responsible for processing remotely collected data.	As an alternative to this cloud-centric architecture, it is proposed to use Fog-enabled architectures to leverage the variety of devices that can be used to partially process data between local sensors and remote cloud servers.
[26]	Cloud processing of enriched data for the Internet of Things (IoT) and Semantic Web of Things (SWoT) leads to cloud centralization, reducing scalability and introducing latency.	An approach called 'Emergent Distributed Reasoning (EDR)', which implements distributed rule-based reasoning on edge nodes, allowing distributed rule evaluation and reducing latency for IoT applications.
[27]	SWoT applications implementing the semantic enrichment layer in the cloud suffer from scalability issues due to the requirement for high centralized computational capacity.	Employ distributed computing capacity in the fog to implement semantics at this network level.
[28]	Security challenges in the 'Semantic Web of Things' (SWoT) domain, which integrates Semantic Web technologies with the Internet of Things (IoT). The need to address heterogeneity, diversity, and dynamicity of devices, data, and networks, which hinder global acceptance of IoT technologies, is highlighted.	Exposes the need for an adaptable infrastructure that can handle security threats in environments with a high number of interconnected devices. Additionally, it emphasizes the importance of integrating semantics and reasoning engines into insecure devices to meet security and privacy requirements.
[29]	The difficulty in successfully deploying the Semantic Web of Things (SWoT) due to the adaptation of Semantic Web principles and technologies to the constraints of the Internet of Things (IoT) domain.	Implementation of a distributed reasoning approach in IoT systems through the hybrid deployment of reasoning rules that leverage the complementarity of cloud and fog computing. The solution, called 'Emergent Distributed Reasoning (EDR).'

D. Research Question 4: How can efficiency and effectiveness be achieved in device communication and operation for Semantic Web of Things application development?

Total results: 4, see Table 5.

Table 5. *Results for Question D*

Ref.	Motivation	Proposal
[30]	Concepts like the Semantic Web and Web of Things require extensive study of standards, making applications challenging for beginners.	Present fundamental concepts in Software Engineering, Web, IoT, Semantic Web, and Web of Things to help students, researchers, practitioners, and novices master concepts and apply them in practical contexts.
[31]	The vision of ambient assisted living requires deep integration between devices and users, enabling devices to autonomously improve people's quality of life.	Use a Linked Data Platform (LDP) over the CoAP(Constrained Application Protocol) protocol to facilitate interoperability of IoT devices by applying the Social Internet of Things paradigm.
[32]	The main challenge in IoT is managing the massive and varied amount of data generated, particularly in cloud distributed services.	Enhance the efficiency of a cloud-based SWoT service by applying Service-Oriented Architecture (SOA) optimized for cloud IoT, incorporating Semantic Web recommendations and standards.
[33]	Addresses the problem of data loss in the perception layer of the Semantic Web of Things (SWoT) architecture.	Proposes a 'metric for data recovery' in the SWoT perception layer. This recoverability metric aims to overcome temporal data loss by defining an approach to recover missing data in this layer.

The findings related to this question have been the most interesting in the mapping, as they involve the practical application of SWoT. Consequently, it is possible to combine them and identify key concepts for achieving efficiency and effectiveness:

1. Communication Efficiency:

- Employ distributed computing architectures.
- Intelligent use of communication protocols, combining RESTful and CoAP to minimize network latency without information loss.
- Network management using visual tools like Node-RED, facilitating extension and replication.
- Prefer RDFa over JSON-LD for semantic description, as it is more efficient in terms of lines and characters.

2. Knowledge-Oriented Architecture:

- In distributed computing, semantic enrichment of IoT devices can be applied at various network points, reducing workload in areas where information from the entire network is concentrated, stored, and reasoned.
- Application automation, which facilitates deployment and extension, uses Semantic Web Rule Language (SWRL) business rules executed on the ontology reasoner.

E. Research Question 5: What are the outcomes of implementing best practices in developing Semantic Web of Things applications?

Total results: 1.

The article *Lemons: Leveraging Model-Based Techniques to Enable Non-Intrusive Semantic Enrichment in Wireless Sensor Networks* [34] *presents a study detailing the benefits of implementing best practices using the LEMONS approach. The results reveal significant improvements in efficiency, quality, and interoperability. The author's approach to measuring and comparing the obtained benefits is particularly noteworthy, which is why this article was considered to answer this question. In summary, the qualitative criteria used to determine the margin of improvement are:*

1. Efficiency

- Reduction of effort and complexity in configuring Wireless Sensor Networks (WSN).
- Acceleration of WSN deployment.
- Ease of extension and adjustment of WSNs.
- Integration of development and maintenance processes.

2. Quality

- Reduction of errors in configuration and deployment.
- Improved maintainability and reusability of WSNs.

3. Interoperability

- Enhanced interpretability of measured data.
- Applicability to a wide range of WSNs.

From a quantitative perspective, the following indicators were used to measure improvement when applying the LEMONS approach:

1. Latency: Majority of micro-ontology generation times under 500 microseconds.
2. Size of micro-ontologies: High compression ratio with GZIP compression.
3. Micro-ontology generation time: Consistent, independent of serialization format.

The lack of comparative studies between applications with semantic technologies that measure improvements in interoperability and information availability makes an objective evaluation challenging. However, this study serves as a useful reference for comparison in sensor network applications, which are among the most common in IoT.

4. DISCUSSION

The systematic literature review reveals that, contrary to initial expectations, the development of applications for the Semantic Web of Things is not currently as active an area of research and development as anticipated. Factors such as the COVID-19 pandemic and the growing focus on artificial intelligence development and application have diverted researchers' attention to other areas.

While Semantic Web technologies represent an excellent proposal to address interoperability challenges on the Internet of Things ecosystem, it is necessary to consider the current situation. Major technology companies control a significant portion of Internet traffic, and the availability of Platform as a Service (PaaS) solutions that facilitate interoperability between services, e.g., Zapier, have resulted in a form of silent centralization of the Internet, moving away from the concept of an open and decentralized web.

Furthermore, Semantic Web technologies have a complex learning curve, which reduces the possibilities for widespread adoption and extension. However, recent advances in Large Language Models (LLMs) represent an opportunity to simplify the design and implementation of some SWoT service layers, reducing complexity for developers.

Despite the mentioned challenges, the findings of this review demonstrate that various approaches and solutions have been proposed to address the main challenges in SWoT application development, such as semantic interoperability, scalability, and efficiency. These solutions include the adoption of international standards, reuse of existing ontologies, automatic generation of device descriptions, use of adaptable middlewares, combination of models and ontologies, and implementation of distributed architectures and scalability techniques.

Nevertheless, the widespread adoption of SWoT faces significant obstacles due to the inherent complexity of the technologies involved and the growing centralization of the Internet by large technology companies. In this context, LLMs could play a key role in facilitating the design and implementation of SWoT services, reducing the learning curve and promoting greater adoption.

5. CONCLUSIONS

The Semantic Web of Things presents itself as a promising solution to address quality and interoperability challenges on the Internet of Things ecosystem. Through this systematic review, we have identified the main trends, approaches, and tools used in SWoT application development.

We conclude that the adoption of international standards, such as those promoted by the W3C, and the use of semantic technologies, like ontologies and rule languages, are key to overcoming interoperability and quality challenges in IoT applications. Additionally, the implementation of distributed architectures, scalability, and optimization techniques, and the application of best practices in design and development contribute to improving the efficiency and performance of SWoT applications.

"Fig. 2" highlights the trends and indicate that distributed reasoning and data handling are the most significant factors of interest. These factors facilitate the integration of these services into the cloud. While significant advances have been made in the SWoT, there are still opportunities for future research and development. Some areas to explore include improving integration between heterogeneous devices and platforms, developing more accessible methodologies and tools for professionals not experts in semantics, and evaluating and validating proposed solutions in large-scale, real-world scenarios.

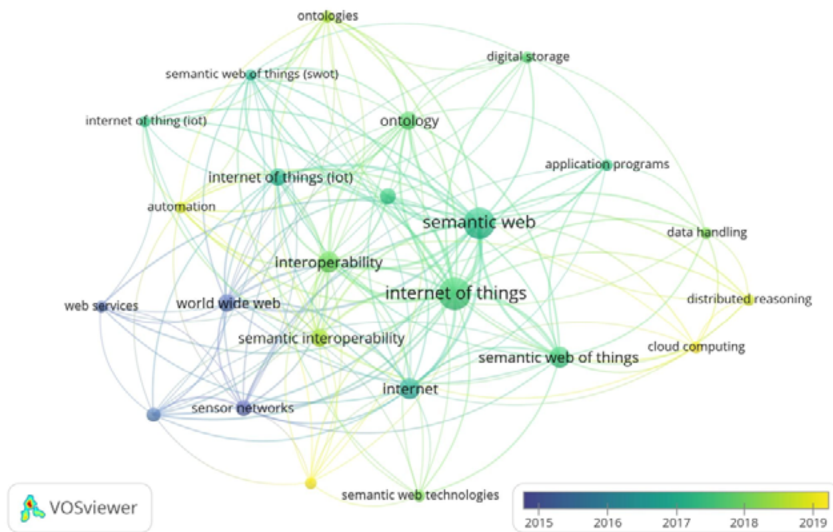

Fig. 2. *Trend graph.*

AUTHOR'S CONTRIBUTION

Manuel Galindo-Semanate: Conception, Data collection, Analysis, Writing-original draft. **Miguel Niño-Zambrano:** Conception, Writing-review and editing, Supervision.

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