DigiEV: A digital twin for electric vehicle charging infrastructure in the E4C ecosystem

Report of End of Studies Internship (IS.3001)

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Je, soussignée Daphne Tuncer, maître de stage de l'élève Isep, ZHAO Chao, atteste avoir pris connaissance du cahier des charges du rapport de stage Isep, avoir lu et évalué le présent rapport au regard du cahier des charges et des pratiques de mon employeur, et autorisée sa transmission à l'Isep.

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Abstract

The success of electric mobility requires not only advanced electric vehicles but also an integrated infrastructure that combines electricity provision, information distribution, and intelligent system control. Digital twin technology has emerged as a powerful approach to manage complex infrastructure operations and evaluate deployment strategies for electric vehicle charging networks [1].

This report describes the work conducted during my six-month internship at Laboratoire Ville Mobilité Transport (LVMT) - École nationale des ponts et chaussées (ENPC), focusing on the design and development of a digital twin system to simulate the energy impact of electric vehicle charging infrastructure. The project employed FIWARE technology as the core framework, utilizing Python for system development and data processing to model the complex interactions between energy consumption and user behavior in charging station.

The developed digital twin system successfully established a comprehensive platform for simulating charging station operations, built upon NGSI-LD standard compliance to ensure semantic interoperability. The system utilizes MongoDB and CrateDB as backend databases for efficient data storage and time-series analysis, while providing RESTful API interfaces for seamless system integration and external interactions. This platform enables real-time monitoring and analysis of charging infrastructure performance, providing valuable insights for optimizing charging station deployment, predicting energy demand patterns, and improving overall system efficiency. The work contributes to enhanced decision-making capabilities for electric vehicle charging infrastructure planning and management through standardized data models and accessible programming interfaces.

This internship significantly enhanced my technical expertise. Additionally, I strengthened my research skills through extensive literature review and analysis of current challenges in sustainable transportation infrastructure. The experience provided valuable insights into the interdisciplinary nature of smart city technologies and the critical role of digital twins in managing complex urban systems.

Keywords Digital Twin, Simulator, Semantic Model, Electric Vehicle, Charging Infrastructure, FIWARE

Contents

Introduction

The global transition toward electric mobility is regarded as a cornerstone of efforts to decarbonize the transport sector and meet international climate targets. According to the International Energy Agency, electric car sales reached nearly 14 million in 2023, and are projected to exceed 17 million in 2024, representing more than one-fifth of global car sales [2]. However, this rapid diffusion of electric vehicles (EVs) poses systemic challenges that extend beyond vehicle manufacturing. The widespread adoption of EVs crucially depends on the development of robust charging infrastructure and the integration of energy systems capable of supporting increasing loads while ensuring reliability and user acceptance [3].

Charging infrastructure represents both a key enabler and a potential bottleneck in the electrification of mobility. Without adequate charging coverage, prospective EV users may face range anxiety, undermining confidence in the technology and slowing adoption [3]. At the same time, deploying charging networks entails high capital costs and introduces technical challenges related to grid integration, station placement, and operational optimization. France, for instance, has set ambitious goals of 400,000 publicly accessible charging points by 2030, yet as of 2023 fewer than 100,000 had been deployed, revealing the scale of investment and coordination required [4]. This "chicken-and-egg" problem—insufficient infrastructure limiting EV adoption, while weak demand discourages infrastructure investment—highlights the importance of strategically planned deployment [5].

To address these challenges, advanced modeling and simulation tools have been proposed to guide infrastructure planning and management. Digital twin technology, in particular, offers a powerful approach to replicate complex physical systems in a virtual environment, enabling real-time monitoring, scenario evaluation, and predictive analytics. Recent studies highlight the potential of digital twins to support the integration of charging infrastructure with smart grids, optimize location and capacity decisions, and enhance decision-making under uncertainty [6, 3].

This report builds upon this context by presenting the work conducted during a six-month internship at the Laboratoire Ville Mobilité Transport (LVMT), École nationale des ponts et chaussées (ENPC). The project focused on the design and development of a digital twin system for simulating the energy impact of EV charging infrastructure, employing the FIWARE framework and NGSI-LD standards to ensure interoperability. By coupling backend databases (MongoDB, CrateDB) with real-time APIs, the system provides a scalable platform for monitoring charging operations and assessing deployment strategies. The work contributes to ongoing research in sustainable mobility by demonstrating how digital twins can support the optimization of EV charging infrastructure within smart city ecosystems.

This report is organized into seven main chapters, each addressing specific aspects of the internship work and its broader context:

Chapter 2 (**Context**) presents the institutional framework of the internship, including the presentation of ENPC, LVMT, E4C, and Saclay campus, along with supervisor introductions and the background context of energy and climate research, EV charging infrastructure, digital twin technologies, and semantic data modeling.

Chapter 3 (**Literature Review**) examines existing research and technologies, including FIWARE, BRICK, Web of Things (WoT), and related digital twin implementations. This chapter identifies current challenges and positions our contribution within the existing body of knowledge.

Chapter 4 (**Methods**) details the system architecture, semantic data modeling approach using NGSI-LD, backend database implementation, API development, and frontend visualization components. It concludes with an analysis of contributions, difficulties encountered, and deviations from initial specifications.

Chapter 5 (**Case Studies and Experiments**) presents the definition and initialization of three experimental scenarios, results obtained using both real and synthetic data, and validation of the digital twin system performance.

Chapter 6 (**Management Analysis**) addresses social and environmental responsibility aspects of the project and discusses innovation management and digital tools for decision-making in resear

Context

1 Institutional Framework

This six-month internship was conducted at the **Laboratoire Ville Mobilité Transport (LVMT)**, a research unit affiliated with **École nationale des ponts et chaussées (ENPC)**, with funding provided by the **Energy4Climate interdisciplinary center (E4C)**. This institutional arrangement reflects the collaborative nature of contemporary energy and mobility research to address complex challenges in sustainable transportation infrastructure. The following sections detail the structure, missions, and research orientations of these three interconnected organizations that provided the framework for this research project.

ENPC represents one of France's most prestigious engineering institutions. Founded in 1747 by Daniel-Charles Trudaine, ENPC is among the oldest French Grandes Écoles, historically focused on training engineering officials and civil engineers. The school has evolved to offer wide-ranging education including computer science, applied mathematics, civil engineering, mechanics, finance, economics, innovation, urban studies, environment and transport engineering. In July 2024, ENPC became the sixth member school of Institut Polytechnique de Paris (IP Paris), joining École polytechnique, ENSTA Paris, ENSAE Paris, Télécom Paris and Télécom SudParis.

Located on the Champs-sur-Marne campus, ENPC maintains a strong international presence with 43% of its students obtaining double degrees abroad and 30% of the engineering cohort being international students. The institution's research excellence is supported by 12 research laboratories, covering domains crucial to ecological, digital, and energy transitions, positioning it as a key player in addressing contemporary sustainability challenges.

LVMT serves as the direct host institution for this research project. Created in 2003, this multidisciplinary research laboratory operates as a joint research unit between Université Gustave Eiffel and École nationale des ponts et chaussées. Celebrating its 20th anniversary in 2023, LVMT brings together nearly 90 researchers in social sciences and engineering sciences, with expertise spanning economics, anthropology, sociology, geography, urban planning, technical economics, mathematical modeling, and computer science.

The laboratory's scientific objective centers on understanding and modeling interactions between mobility practices, transport infrastructure, and spatial organization and development. Research activities are organized around four thematic axes: mobility practices and urban access; territorial dynamics and public action; city-transport interactions; and economic analysis and transport modeling. LVMT researchers collaborate extensively with national and international laboratories as well as public and private transport and urban planning stakeholders, including territorial authorities, public decision-makers, ADEME, RATP, SNCF, and Transdev. This collaborative approach combines quantitative methods and qualitative analyses, positioning the laboratory at the interface between academic research and action research.

E4C provides the funding framework and broader research context for this internship. Launched in June 2019 by IP Paris and ENPC, E4C addresses energy transition through research, training, and innovation. The center gathers 21 laboratories from Institut Polytechnique de Paris and 5 associated laboratories from ENPC, creating a unique interdisciplinary platform for energy and climate research.

Nearly 30 laboratories work within E4C on four cross-cutting themes designed to reduce greenhouse gas emissions, improve energy efficiency, deploy renewable energy, and propose relevant energy policies. The center combines diverse scientific disciplines including social and economic sciences, materials sciences and engineering, applied mathematics, computer science, and geophysics. E4C develops instrumental platforms, models for energy forecasting and prediction, and maintains a comprehensive data center: the E4C DataHub.

The framework of this internship within E4C directly aligns with the center's mission to foster interdisciplinary collaboration addressing energy transition challenges. The digital twin development for EV charging infrastructure contributes specifically to E4C's objectives of improving energy efficiency and supporting the deployment of sustainable transportation solutions, demonstrating the practical application of interdisciplinary research in addressing real-world sustainability challenges.

2 Research Supervision and Project Framework

2.1 Research Supervision Team

This internship project was conducted under the joint supervision of two tutors, reflecting the interdisciplinary nature of digital twin technologies and their application to energy mobility systems.

Dr. Daphné Tuncer is my supervisor from ENPC, specializing in digitalisation in the energy and mobility sectors. Prior to joining ENPC, She spent many years in the UK Higher Education. Her research keywords include electric mobility, cyberphysical systems, data management, and applied data science.

Dr. Georgios Bouloukakis from Télécom SudParis, provides co-supervision with expertise in IoT/Edge-driven middleware and distributed software systems. He is an experienced researcher and educator with over one decade of teaching and mentoring of students, having supervised 2 postdoctoral researchers, 4 Ph.D. thesis, 4 R&D developers and 48 bachelor/master theses.

2.2 Research Project Integration and Continuity

This internship project represents a strategic extension of ongoing research within the E4C framework, building upon foundational work completed by previous interns while expanding into new application domains. The project directly follows the work of **Niemat Khoder**, who conducted her internship focusing on smart building energy management systems.

Niemat's research established important precedents for this work by demonstrating the application of NGSI-LD data models and semantic technologies in the building energy domain. Her thesis introduced a collaborative approach to optimizing energy management and enhancing occupant comfort through cross-building collaboration, leveraging NGSI-LD data models and developing the CCDUIT software tool for cross-federation collaboration. She successfully established "a modular, scalable, and interoperable framework for building data exchange" that enabled "enhanced energy efficiency through dynamic, real-time collaboration across energy management platforms."

The current project extends these foundational concepts from the building domain to electric vehicle charging infrastructure, maintaining the core principles of semantic interoperability and collaborative optimization while addressing the distinct challenges of mobility energy systems. Where Niemat's work focused on static building environments with predictable occupancy patterns, this project tackles the dynamic, spatially distributed nature of EV charging networks with highly variable user behavior and energy demand patterns.

Several key technical continuities link the two projects. Both leverage NGSI-LD as the semantic data modeling standard, ensuring consistency in data representation and interoperability approaches within the E4C research ecosystem. Both projects employ FIWARE as the core IoT platform, building institutional knowledge and technical expertise in this technology stack. The modular, scalable framework architecture pioneered in the building domain provides design principles that informed the charging infrastructure platform development.

However, the transition from buildings to mobility infrastructure required substantial methodological adaptations. The charging infrastructure domain demands real-time processing of energy consumption data across geographically distributed networks, necessitating the integration of time-series databases (CrateDB) alongside traditional document storage (MongoDB). The mobility context also requires more sophisticated simulation capabilities to model user behavior patterns and energy demand forecasting, leading to the development of comprehensive API interfaces for external system integration.

This project continuity reflects E4C's strategic approach to building cumulative research capabilities across related energy domains. By maintaining technical consistency while expanding application scope, the research program develops transferable methodologies and reusable technical components that can support future projects in sustainable energy system management.

The collaborative supervision model ensures both domain expertise in energy mobility (Dr. Tuncer) and technical depth in distributed IoT systems (Dr. Bouloukakis), providing the interdisciplinary foundation necessary to advance from building-focused research to the more complex challenges of transportation infrastructure digitalization.

3 Research Background

3.1 Energy and Environment Challenges in Transport

Transport is a central contributor to both energy use and environmental pressures. In France, it represented about 32% of final energy consumption in 2023 [7], and around 66% of total final consumption of oil products is attributable to transport [8]. It is also the largest national source of greenhouse-gas (GHG) emissions, accounting for approximately 32% of territorial emissions in 2022, with road transport—cars and heavy vehicles—being the dominant contributors [9].Beyond climate impacts, transport significantly contributes to local air pollution. The European Environment Agency notes persistent exposure to NO_2, $PM_{2.5}$, and ozone in urban areas with substantial health impacts [10].

Meeting these challenges requires a rapid shift toward low-carbon energy in transport. Electricity demand in France is projected to rise to 580-640 TWh by 2035, driven partly by electromobility; according to RTE, this scenario is feasible only with accelerated renewable deployment and smart charging strategies [11]. Therefore, electrifying mobility must be accompanied by a decarbonized electricity supply and effective demand-side management to deliver benefits for climate, air quality, and energy security.

3.2 Electric Vehicles and Charging Infrastructure

The rapid growth of electric vehicles (EVs) is transforming the transport and energy sectors. Global EV sales neared 14 million in 2023, accounting for 18% of all new cars, with projections of around 17 million in 2024, or more than one-fifth of global car sales [2]. Yet the acceleration of EV adoption depends critically on the availability of suitable charging infrastructure.

EV charging infrastructure (EVCI) is both an enabler and a potential bottleneck of EV transition. Research highlights a persistent "chicken-and-egg" problem: users hesitate to purchase EVs without adequate charging coverage, while investors are reluctant to finance charging stations without a critical mass of EV users. Studies show that strategic deployment of charging points is more cost-effective than merely enlarging battery capacity, as infrastructure provision directly reduces range anxiety and supports large-scale diffusion [3].

From a planning perspective, charging infrastructure must address three dimensions: *technical*, *economic*, and *user acceptance*. Technical issues involve compatibility of charging standards, grid integration, and power demand management. Economically, the high costs of fast-charging stations require careful location and sizing strategies. User acceptance hinges on convenience, accessibility, and charging time, which significantly influence EV adoption [12].

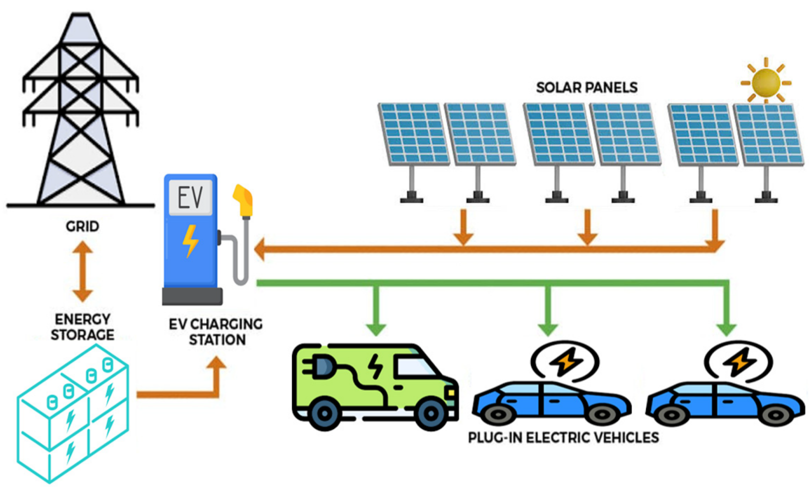

Fig. 2.1 **A typical EV charging infrastructure** [13]
Including electricity grid, renewable generation (solar panels), energy storage systems, charging stations, and plug-in electric vehicles. This integrated system highlights the importance of coordinating generation, storage, and charging to ensure reliable and sustainable operation.

Emerging solutions aim to overcome these challenges. Dynamic charging, for instance, enables wireless on-road power transfer and has shown potential to reduce detours and charging time compared to conventional stations, though infrastructure costs remain high [14]. At the same time, digital twin technology is increasingly viewed as a powerful tool to manage the complexity of charging networks, enabling real-time monitoring, scenario analysis, and integration with renewable power and storage systems [1]. Such innovations highlight the importance of linking physical deployment with digital management systems to ensure reliability, sustainability, and scalability.

In summary, while EV adoption continues to expand rapidly, the success of the transition is inseparable from charging infrastructure. Planning, optimization, and digitalisation of charging networks will determine whether electrified transport can scale sustainably and equitably.

3.3 Digital Twin and Simulation

The increasing complexity of electric vehicle (EV) charging networks, their tight coupling with the power grid, and the variability of user behaviour make planning and operation challenging. Digital twin technology has emerged as a powerful approach to address these issues. A digital twin is defined as a "live digital coupling of the state of a physical asset or process with a virtual representation that produces functional output" [15]. Unlike conventional models or static simulations, digital twins establish a continuous bi-directional link between the physical system and its digital replica, enabling real-time monitoring, predictive analytics, and feedback control [16, 17].

In the context of EV charging infrastructure, digital twins offer several advantages. First, they enable multi-scale simulation of charging demand and grid interaction, supporting optimal siting and sizing of charging stations. Second, they allow scenario analysis under uncertainty, including stochastic EV arrivals and variable renewable generation, thereby enhancing grid stability and resilience [18]. Third, digital twins provide a platform for testing cyber-physical interactions, including cybersecurity assessment, without disrupting operational systems [19]. These capabilities make digital twin frameworks particularly suitable for managing charging networks within smart cities and integrating them into future vehicle-to-grid (V2G) and vehicle-to-building (V2B) systems.

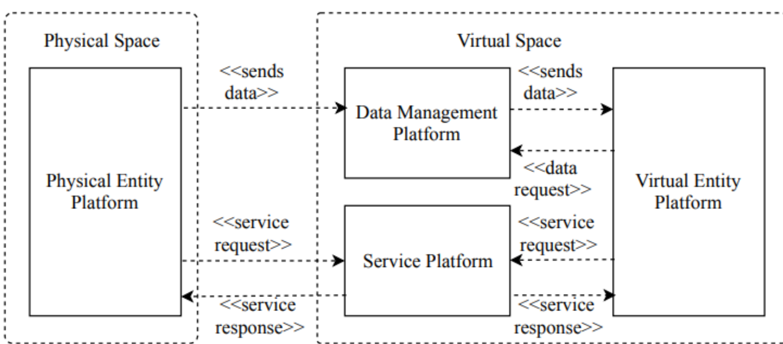

Fig. 2.2 **A Typical Digital Twin Framework** [20]
The entities comprising the Physical Entity Platform send specific data to the Data Management Platform. On request, this platform sends data to the Virtual Entity Platform. The Virtual Entity Platform can request concrete services from the Service Platform and it receives back concrete information. Furthermore, the underlying Physical Nodes of the Physical Entity Platform can also send a service request to the Service Platform and receive an appropriate response.

Simulation remains at the core of digital twin applications. Studies classify applications into *simulation*, *monitoring*, and *control* purposes [17]. For EV charging, simulation provides the foundation to evaluate control strategies, optimize energy flows, and quantify environmental impacts. Discrete-event simulation platforms, such as OPTIMUS, extend these capabilities by integrating building energy use, grid events, and charging policies, allowing benchmarking of control algorithms under realistic conditions [18].

In summary, digital twins bridge physical EV charging infrastructure with advanced simulation environments, enabling not only better operational decision-making but also long-term strategic planning. Their role as predictive, adaptive, and testable cyber-physical representations underscores their potential in achieving sustainable, resilient, and user-centric charging ecosystems.

3.4 Data Models and Interoperability in Digital Twins

Digital twins function as high-fidelity virtual counterparts of physical systems, supporting real-time monitoring, simulation, and control. However, realizing their full potential hinges on seamless data interoperability—the ability of multiple systems to exchange, interpret, and act upon shared information. Without standardized representations, digital twin implementations often remain siloed, each relying on proprietary formats that limit aggregation and coordinated analysis across domains [21]. Addressing this fragmentation requires robust standards and transformation mechanisms to align heterogeneous digital twin models, such as the Digital Twin Definition Language (DTDL) and the Asset Administration Shell (AAS) [22].

Data models and ontologies play a crucial role in enabling interoperability. They provide a shared vocabulary and structure that allow systems to interpret information consistently across semantics, constraints, and behaviors [23]. Semantic technologies, knowledge graphs, and ontology-based integration frameworks are increasingly used to bridge modeling languages and domains, facilitating automated data fusion and richer collaboration between digital twins [24]. In addition, conceptual interoperability frameworks, such as those proposed by the Digital Twin Consortium, define atomic data entities and standardized messaging patterns to support modular composition of digital twins across system boundaries [25].

For infrastructures such as electric vehicle (EV) charging networks, interoperable data models are indispensable. They enable cross-system coordination between charging stations, grid services, and building energy systems; support automated integration of sensor data, user behavior, and energy flows; and provide a foundation for composable architectures where charging, storage, and renewable generation twins can interact within a unified ecosystem. Ensuring accurate, semantic-level interoperability is thus a prerequisite for building comprehensive, reliable, and scalable digital twin systems that can address the challenges of sustainable and intelligent mobility.

Related work

1 Brick

Brick is a uniform metadata schema designed to represent building entities—such as equipment, sensors, and spatial locations—and the relationships between them using an ontology-based framework [26]. The project was initiated by a consortium of U.S. and European universities and research institutes, including UC Berkeley, UCLA, Carnegie Mellon University, UC San Diego, University of Virginia, University of Southern Denmark, and IBM Research Ireland. The work was first presented at ACM BuildSys 2016 and continues to evolve under the open-source Brick Schema community (`https://brickschema.org`).

It addresses the interoperability challenges of heterogeneous Building Management Systems (BMS), where vendor-specific naming and label inconsistencies hinder the portability of applications. Brick defines a normalized vocabulary (tags and tag sets) along with fundamental relationships like *hasPoint*, *isPartOf*, *feeds*, and *controls*, enabling semantic queries over RDF-based knowledge graphs via SPARQL.

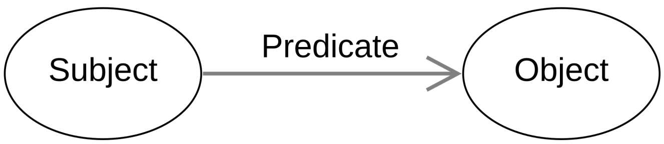

Fig. 3.1 An RDF graph with triple connecting:
a subject, predicate, and object

A key design choice of Brick is its reliance on the Resource Description Framework (RDF). RDF is a W3C standard data model for representing information as a graph of triples, each consisting of a *subject*, *predicate*, and *object*. For example, a triple may state that "Room 101 *hasPoint* Temperature Sensor". This graph-based representation allows entities and their relationships to be linked in a uniform, machine-readable way, and queried with the SPARQL language. By adopting RDF, Brick benefits from decades of semantic web research, existing toolchains for reasoning, and the ability to interoperate with other ontologies.

Brick's key strengths include its clarity, expressiveness, and demonstrated portability. In a validation involving six heterogeneous buildings totaling approximately 630,000 ft^2 and about 17,700 BMS data points, Brick achieved mapping coverage of around 98% of the metadata and supported eight representative applications— such as occupancy analytics, fault detection, demand response, and energy apportionment—without modification [26]. These results highlight how a compact, orthogonal schema can significantly reduce integration costs and enable cross-site reuse of analytics and control logic.

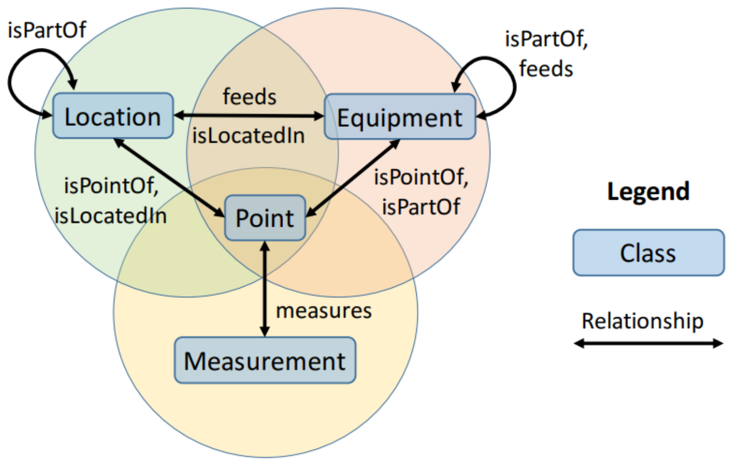

Fig. 3.2 **Information concepts in Brick and their relationship to a data point** [26]

However, Brick also has limitations when considered in the context of transportation systems. Its focus on static subsystems within buildings means it lacks native constructs to represent *temporal events* (e.g., EV charging sessions), *mobile entities* (e.g., vehicles), or domain-specific regulatory and forecasting aspects. For example, a recent evaluation of semantic technologies in building energy flexibility found that Brick could represent only about 16% of EV charging–related concepts, and entirely failed to capture regulatory constraints or environmental forecast information. Therefore, while Brick is effective in building-scale modeling, it must be complemented with dynamic, context-aware frameworks such as NGSI-LD for applications in EV charging infrastructure and smart mobility systems.

In summary, Brick combined with RDF provides a powerful and well-structured way to model static building metadata, making equipment, sensors, and spaces machine-readable and portable across sites. The use of RDF triples and SPARQL enables interoperability and semantic reasoning that are essential for digital twin applications at the building scale. Nevertheless, Brick is less suited to domains that require continuous handling of dynamic, time-varying data and mobile entities, such as transportation systems and EV charging infrastructures. These scenarios demand data models capable of representing temporal events, context updates, and cross-domain interactions in real time.

2 Web of Things (WoT)

The WoT initiative began around 2014 within the World Wide Web Consortium (W3C) Interest Group and was formalized in the WoT Working Group, with the first recommendations—covering the WoT Architecture and the Thing Description—published in 2020 [27].W3C is an international standards organization founded in the United States in 1994 but with a globally distributed membership and governance.

At its core is the *Thing Description* (TD), a machine-readable document based on JSON-LD that specifies the metadata, properties, actions, and events of a device [27]. A TD serves as a semantic contract between a device (the "Thing") and applications, allowing developers to interact with devices through uniform APIs regardless of vendor-specific protocols.

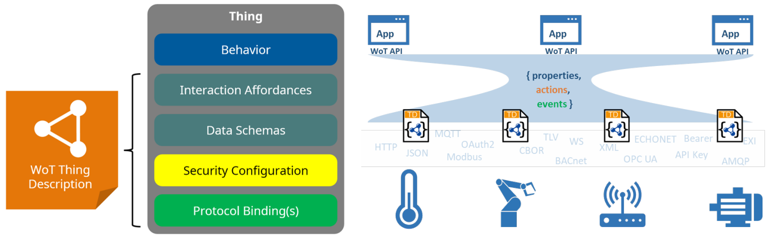

Fig. 3.3 IoT Metadata in TD (left) and WoT mappings (right)
In general, WoT is a protocol agnostic approach and provides a common mechanism to define how specific protocols such as MQTT, HTTP, CoAP or Modbus can be mapped to the WoT's interaction properties-action-event abstraction. [27]

The strengths of WoT lie in its ability to provide a lightweight, technology-agnostic abstraction for devices. By describing functionalities in JSON-LD, WoT enables semantic interoperability between devices that expose different protocols (e.g., HTTP, CoAP, MQTT). This abstraction facilitates integration of IoT devices into larger ecosystems, allowing web applications, gateways, and digital twin platforms to discover and use device capabilities in a consistent way. The WoT standard is also modular, supporting security, binding templates, and scripting APIs, which together ease the deployment of scalable IoT systems.

Despite these advantages, WoT also has limitations when applied to transportation and EV charging infrastructure. WoT focuses on the device level—standardizing access to sensors and actuators—but it does not by itself provide higher-level semantics for systems such as charging networks, mobility services, or energy markets. As a result, WoT alone cannot capture domain-specific relationships (e.g., vehicle arrival events linked to charging tariffs, or the coordination between multiple charging stations). In practice, WoT is most effective when used in combination with higher-level frameworks which can forming a layered approach to interoperability in smart transport systems.

3 FIWARE and NGSI-LD

FIWARE is an open-source platform initiative launched in 2011 under the European Union's Seventh Framework Programme (FP7), initially supported by the European Commission and a consortium of European companies and research organizations. It is now managed by the FIWARE Foundation, a non-profit association based in Berlin, Germany, which coordinates global adoption of FIWARE technologies across smart cities, energy, industry, and mobility. At the heart of FIWARE is the *Context Broker*, the core component that manages context information about entities in the physical and digital world. The most widely used implementation is the Orion Context Broker and its NGSI-LD compliant extension Orion-LD.

The FIWARE Next Generation Service Interfaces (NGSI) define the standard API for context management. NGSI-LD, standardized by ETSI (European Telecommunications Standards Institute) in 2019, extends earlier NGSI versions by adopting linked-data principles and JSON-LD serialization [28]. It provides an entity–property– relationship model that is semantically interoperable and aligned with semantic web technologies. Each NGSI-LD entity can represent a real-world object (e.g., an EV charging station), its properties (e.g., capacity, current load), and its relationships (e.g., connected to a power grid or located in a district).

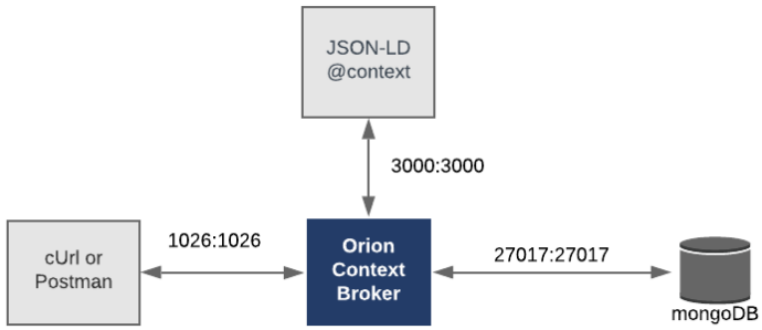

Fig. 3.4 **Orion Context Broker Architecture**

The Context Broker exposes these entities via a publish–subscribe API, allowing real-time updates and notifications.

The strengths of FIWARE and NGSI-LD lie in their ability to handle *dynamic context* at scale. Through the Context Broker, applications can subscribe to changes (e.g., a vehicle starting or ending a charging session) and react immediately. This dynamic and event-driven model is particularly advantageous in domains such as transport and energy, where continuous synchronization with rapidly changing environments is required. FIWARE also provides a broad ecosystem of enablers—such as IoT agents, data processing components, and dashboards—that simplify integration with IoT devices and data platforms, facilitating large-scale deployments in smart cities worldwide [29].

Nevertheless, FIWARE and NGSI-LD also present challenges when applied to transportation and EV charging infrastructure. While NGSI-LD defines a generic model, it does not provide detailed domain semantics for vehicles, tariffs, or multimodal transport flows. Developers often rely on the *Smart Data Models* initiative, jointly maintained by the FIWARE Foundation, ETSI, and the Open & Agile Smart Cities (OASC) network, to obtain domain-specific schemas. Furthermore, heterogeneous modeling practices across projects can hinder semantic consistency, and complex cross-domain interactions (e.g., integrating mobility services with energy markets) often require additional semantic integration layers.

4 Internship Challenges and Contribution

The analysis of related frameworks highlights that Brick, WoT, and FIWARE/NGSI-LD each address different layers of interoperability. Brick provides a static ontology for building metadata, WoT enables device-level interoperability via standard Web interfaces, and FIWARE/NGSI-LD offers a scalable framework for dynamic context management in smart environments. Table 3.1 summarizes their origins, strengths, and limitations.

From this comparison, it becomes evident that while Brick and WoT provide valuable capabilities, they are not sufficient for the specific challenges of modeling and managing electric vehicle (EV) charging infrastructure. Brick is too static to capture real-time charging events, and WoT does not extend beyond device-level descriptions. In contrast, FIWARE and its NGSI-LD standard are designed for real-time, cross-domain interoperability and have already been adopted in numerous European smart city and energy projects.

Tab. 3.1 Comparison of FIWARE, Brick, and WoT

Aspect	FIWARE	Brick	WoT
Main focus	Dynamic context management through Context Broker and NGSI-LD API	Semantic ontology framework for building metadata and relationships	Device interoperability via Web standards and protocols
Modeling method	NGSI-LD (Linked Data with JSON-LD serialization)	RDF + OWL ontology with SPARQL queries	Thing Description using JSON-LD and Web APIs
Pros	• Real-time context updates • Subscription mechanisms • Cross-domain interoperability • Scalable REST APIs	• Unified building semantics • Strong reasoning capabilities • Rich relationship modeling • Standardized vocabulary	• Protocol-agnostic access • Standardized APIs • Web integration • Device abstraction
Cons	• Limited domain ontologies • Depends on Smart Data Models • Device-level control constraints	• Weak dynamic data handling • Limited temporal modeling • Mainly static metadata focus	• Weak semantic reasoning • Limited complex system modeling • Primarily device-layer focus
Organization	FIWARE Foundation and ETSI	Brick Schema community	W3C

Given that this research is funded within the European context, FIWARE/NGSI-LD is a natural choice as it is an EU initiative, standardized by ETSI, and actively supported by the FIWARE Foundation. Beyond alignment with funding priorities, FIWARE is also technically best suited for the EV charging scenario, as it provides the necessary dynamic context management, integration of IoT data, and publish–subscribe mechanisms required for real-time infrastructure simulation.

Challenges. Despite these advantages, several research challenges must be addressed:

- *Heterogeneous data sources:* EV charging systems involve multiple actors (vehicles, stations, grid, users) that produce data in diverse formats, requiring semantic harmonization.
- *Dynamic context management:* Unlike static building systems, charging infrastructure generates highly dynamic data such as charging sessions, user arrivals, and fluctuating grid loads, which must be represented in real time.
- *Cross-domain interoperability:* Integration across energy, mobility, and urban systems demands models that can capture relationships beyond the device or building level.

- *Scalability and performance:* Digital twins for large-scale charging networks must support efficient storage, querying, and notification mechanisms under high data volume.

Contributions. Building on this motivation, the main contributions of this work are as follows:

- Design and implementation of a digital twin framework for EV charging infrastructure based on FIWARE and NGSI-LD.
- Development of NGSI-LD compliant data models that capture both charging station characteristics and user behavior in dynamic contexts.
- Integration of databases and APIs for real-time monitoring, simulation, and analysis of charging infrastructure performance.
- Demonstration of how the proposed platform can support deployment strategies, demand forecasting, and optimization of EV charging networks.

Annexe

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Bibliography

[1] Gang Yu, Xianming Ye, Xiaohua Xia, and YangQuan Chen. Digital twin enabled transition towards the smart electric vehicle charging infrastructure: A review. *Sustainable Cities and Society*, 108:105479, 2024.

[2] International Energy Agency. Global ev outlook 2024: Scaling up the transition to electric mobility, 2024. Accessed: 2025-09-07.

[3] Marc-Olivier Métais, Omar Jouini, Yannick Perez, Jaafar Berrada, and Emilia Suomalainen. Too much or not enough? planning electric vehicle charging infrastructure: A review of modeling options. *Renewable and Sustainable Energy Reviews*, 153:111719, 2022.

[4] Charging stations for electric vehicles: the autorité issues its opinion on the competitive functioning of the sector, 2023. Accessed: 2025-09-07.

[5] Yves Bernard and Michael Nicholas. Charging infrastructure needs to support electric vehicle deployment in france, 2021. Accessed: 2025-09-07.

[6] Robert N. Charette. *The EV Transition Explained*. IEEE Spectrum E-book, 2023. Accessed: 2025-09-07.

[7] International Energy Agency. France: Final energy consumption by sector (iea data), 2025. Transport accounted for about 32% of final energy consumption; accessed 2025-09-07.

[8] International Energy Agency. France: Oil products final consumption by sector (iea data), 2025. About 66% of oil consumption is due to transport; accessed 2025-09-07.

[9] Haut Conseil pour le Climat. France territorial ghg emissions by sector, 2022, 2023. Transport accounted for approximately 32% of territorial emissions; accessed 2025-09-07.

[10] European Environment Agency. France — air pollution country fact sheet 2024, 2024. Health impacts from NO2, PM2.5, ozone in urban areas; accessed 2025-09-07.

[11] RTE / reported by Enerdata. France electricity demand forecast to reach 580–640 twh by 2035, 2023. Forecast includes electromobility-driven demand; accessed 2025-09-07.

[12] Salvatore LaMonaca and Lisa Ryan. The state of play in electric vehicle charging services – a review of infrastructure provision, players, and policies. *Renewable and Sustainable Energy Reviews*, 160:112311, 2022.

[13] S. Deeum, T. Charoenchan, N. Janjamraj, S. Romphochai, S. Baum, H. Ohgaki, N. Mithulananthan, and K. Bhumkittipich. Optimal placement of electric vehicle charging stations in an active distribution grid with photovoltaic and battery energy storage system integration. *Energies*, 16(22):7628, 2023.

[14] Duc Minh Nguyen, Mustafa A. Kishk, and Mohamed-Slim Alouini. Dynamic charging as a complementary approach in modern ev charging infrastructure. *Scientific Reports*, 14(5785), 2024.

[15] Richard J. Somers, James A. Douthwaite, David J. Wagg, Neil Walkinshaw, and Robert M. Hierons. Digital-twin-based testing for cyber–physical systems: A systematic literature review. *Information and Software Technology*, 156:107145, 2023.

[16] Mengnan Liu, Shuiliang Fang, Huiyue Dong, and Cunzhi Xu. Review of digital twin about concepts, technologies, and industrial applications. *Journal of Manufacturing Systems*, 58:346–361, 2021.

[17] Martin Robert Enders and Nadja Hoßbach. Dimensions of digital twin applications – a literature review. In *Proceedings of the 25th Americas Conference on Information Systems (AMCIS)*, Cancun, Mexico, 2019.

[18] Jose Paolo Talusan, Rishav Sen, Ava Pettet, Aaron Kandel, Yoshinori Suzue, Liam Pedersen, Ayan Mukhopadhyay, and Abhishek Dubey. Optimus: Discrete event simulator for vehicle-to-building charging optimization. In *Proceedings of the IEEE International Conference on Smart Computing (SMARTCOMP)*, 2024.

[19] Matthias Eckhart, Andreas Ekelhart, and Edgar Weippl. Enhancing cyber situational awareness for cyber-physical systems through digital twins. In *Proceedings of the 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2019.

[20] Klementina Josifovska, Enes Yigitbas, and Gregor Engels. Reference framework for digital twins within cyber-physical systems. In *2019 IEEE/ACM 5th International Workshop on Software Engineering for Smart Cyber-Physical Systems (SEsCPS)*, pages 25–31, 2019.

[21] Istvan David, Guodong Shao, Claudio Gomes, Dawn Tilbury, and Bassam Zarkout. Interoperability of digital twins: Challenges, success factors, and future research directions. *Proceedings of the Annual Simulation Conference*, 2024. Panel report on interoperability levels in aggregated digital twins.

[22] Christian Schmidt. Increasing interoperability between digital twin standards. *Sensors*, 23(18):7742, 2023.

[23] Erkan Karabulut, Salvatore F. Pileggi, Paul Groth, and Victoria Degeler. Ontologies in digital twins: A systematic literature review. *arXiv preprint arXiv:2308.15168*, 2023.

[24] Daniel Dunbar, Thomas Hagedorn, Mark Blackburn, John Dzielski, Steven Hespelt, Benjamin Kruse, Dinesh Verma, and Zhongyuan Yu. Driving digital engineering integration and interoperability through semantic integration of models with ontologies. *arXiv preprint arXiv:2206.10454*, 2022.

[25] Anto Budiardjo. Digital twin system interoperability framework, 2021. Whitepaper.

[26] Bharathan Balaji, Arka Bhattacharya, Gabriel Fierro, Jingkun Gao, Joshua Gluck, Dezhi Hong, Aslak Johansen, Jason Koh, Joern Ploennigs, Yuvraj Agarwal, Mario Berges, David Culler, Rajesh Gupta, Mikkel Baun Kjærgaard, Mani Srivastava, and Kamin Whitehouse. Brick: Towards a unified metadata schema for buildings. In *Proceedings of the 3rd ACM International Conference on Systems for Energy-Efficient Built Environments (BuildSys '16)*, pages 41–50, 2016.

[27] W3C. Web of things (wot) architecture and thing description. https://www.w3.org/WoT/, 2020. W3C Recommendation (TD 1.0, updated by TD 1.1 in 2023), accessed 2025-09-07.

[28] ETSI. Context information management (cim); ngsi-ld api. Technical Report ETSI GS CIM 009, European Telecommunications Standards Institute, 2019.

[29] Nikolaos Papadakis, Georgios Bouloukakis, and Kostas Magoutis. Enabling dynamic smart spaces using iot-enhanced ngsi-ld data models. In *Proceedings of the 3rd IoT Connected World/Web Semantic Interoperability Workshop (CWSI'22)*, Delft, Netherlands, 2022.