

Urban IoT Ontologies for Sharing and Electric Mobility

Mario Scrocca, Ilaria Baroni and Irene Celino

Cefriel – Politecnico di Milano, Milano, Italy

E-mails: mario.scrocca@cefriel.com, ilaria.baroni@cefriel.com, irene.celino@cefriel.com

Abstract. Cities worldwide are facing the challenge of digital information governance: different and competing service providers operating Internet of Things (IoT) devices often produce and maintain large amounts of data related to the urban environment. As a consequence, the need for interoperability arises between heterogeneous and distributed information, to enable city councils to make data-driven decisions and to provide new and effective added value services to their citizens. In this paper, we present the Urban IoT suite of ontologies, a common conceptual model to harmonise the data exchanges between municipalities and service providers, with specific focus on the sharing mobility and electric mobility domains.

Keywords: Sharing Mobility, Electric Mobility, IoT, Smart Cities

1. Introduction

According to the United Nations, today 55% of the world's population lives in urban areas¹, a proportion that is expected to increase to 68% by 2050². For the last decade, our cities have been digitally instrumented in many different ways, becoming the producers of a continuously increasing wealth of data, that spans across multiple human activities and business domains. The large availability as well as the decreasing cost of Internet of Things (IoT) devices have been leading to an unprecedented flow of digital information about urban environments.

Municipalities and city councils are facing every day the challenge of governance over their digital sources: the amount and heterogeneity of such information require specialised technological infrastructure but, on the other hand, offer the opportunity to create data-driven solutions to support decision-making and to offer value-added services to citizens. City governments need to manage and interact with a large set of service suppliers, from utilities to transport and logis-

tics, from telecommunication to local businesses, each of which generates information flows that are of potential interest for urban planning and management.

In this context, mobility is also undergoing a profound change and transformation: on the one hand, sustainability and environmental concerns are pressing travellers and transport stakeholders to invest in eco-friendly solutions with a rising interest in electric mobility; on the other hand, new transport modes and mobility habits are growing, with a stronger attention to micro-mobility (especially bicycles, scooters and motorcycles) and transport-on-demand services based on the sharing economy principles.

At urban level, this implies a steady increase in the number of different and competing service providers which act as mobility suppliers for the city. They are often independent organizations with their own digital infrastructure and adopting different data formats and standards in their internal processes. As a consequence, exchanging data with the city councils and between organizations becomes a challenge: a strong urgency for interoperability arise, with the need for common languages and interfaces.

Our work addresses this interoperability challenge, by designing a modular suite of ontologies for Urban IoT devices, with specific modules dedicated to sharing mobility (car sharing, bike sharing, etc.) and elec-

¹2019 statistics, cf. <https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS>

²2018 Revision of World Urbanization Prospects, cf. <https://population.un.org/wup/>

1 tric mobility (vehicle charging infrastructures). Those
 2 ontologies have the goal to constitute the reference
 3 model for data exchange between service providers
 4 and municipalities; the model can indeed be used to
 5 define and annotate APIs. This effort was initiated
 6 thanks to the sponsorship of the municipality of Mil-
 7 an in Italy with its Information Systems and Digital
 8 Agenda Department (in Italian: Direzione Sistemi In-
 9 formativi e Agenda Digitale – SIAD), which has the
 10 visionary and ambitious goal to effectively manage all
 11 the IoT flows thanks to an integrated data governance
 12 powered by open data and Semantic Web technologies.
 13 We were supported by the domain and technical ex-
 14 perts of the city of Milan in all phases of our ontology
 15 engineering process. Thanks to the large applicability
 16 of the usage scenarios defined and the investigation of
 17 the relevant international standards, however, the re-
 18 sults of our work are valid for any urban environment.

19 The remainder of this paper is organized as follows:
 20 Section 2 discusses relevant standards, project and vo-
 21 cabularies in the considered domains; Section 3 briefly
 22 summarises the adopted ontology engineering method-
 23 ology; Section 4 reports the performed domain anal-
 24 ysis and the identified requirements; Section 5 illus-
 25 trates the modules of the Urban IoT ontologies; Sec-
 26 tion 6 provides the evaluation of the ontologies consid-
 27 ering automatic pitfalls detection and ontology evalua-
 28 tion criteria; Section 7 describes the choices for the on-
 29 line publication; Section 8 exemplifies the intended us-
 30 age of the ontologies; Section 9 discusses the potential
 31 long-term impact of the proposed vocabularies; finally,
 32 Section 10 draws the conclusions.

33 2. Related Work

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 35
 36 In the context of smart cities, several efforts have
 37 been conducted to define shared vocabularies and stan-
 38 dards to guarantee the interoperability of data collected
 39 within a city, in particular from IoT devices. Consider-
 40 ing sharing and electric mobility services in the urban
 41 area, in the following we describe some of the most
 42 widely adopted standards to represent data in those do-
 43 mains, we mention some previous works investigat-
 44 ing Semantic Web technologies for IoT interoperabil-
 45 ity, and we present a review of ontologies and vocabu-
 46 laries to describe mobility services in an urban context.

47 2.1. Domain Standards

48
 49
 50 The *General Bikeshare Feed Specification* (GBFS) [1]
 51 is a data format for real-time/read-only data describing

1 the status of vehicles made available by sharing mobil-
 2 ity service providers. The format specification, origi-
 3 nally defined by Google, is currently lead by the North
 4 American Bike Share Association (NABSA). GBFS
 5 is used by hundreds of services worldwide³ and it is
 6 supported by several user applications offering mobil-
 7 ity services. Although the first releases of the standard
 8 only allowed to describe station-based bike-sharing
 9 services, the latest versions embrace also free-floating
 10 services and micro-mobility vehicles. The specifica-
 11 tion prescribes the regular publication of a feed com-
 12 posed by several JSON files describing the sharing
 13 mobility service (hours, calendar, area, pricing plans,
 14 alerts), the status of free-floating vehicles, the stations
 15 (if available) and their status (number of vehicles avail-
 16 able, number of docks available, etc.).

17 The *Mobility Data Specification* (MDS) [2] defines
 18 a set of Application Programming Interfaces (API)
 19 based on a shared vocabulary for sharing mobility ser-
 20 vices (bicycle, car, motorcycle, micro-mobility vehi-
 21 cles). Originally designed for the Los Angeles Munic-
 22 ipality, the specification is now led by the *Open Mobil-
 23 ity Foundation* (OMF)⁴, gathering different municipal-
 24 ities and companies to support the definition of open-
 25 source solutions for Mobility in cities. The specifica-
 26 tion identifies two main roles: mobility providers offer-
 27 ing sharing mobility services to users, and regula-
 28 tory agencies (e.g., the municipality) governing that
 29 services in a given region.

30 The MDS defines three main endpoints: (i) *Pro-
 31 vider API*: implemented by providers, data pulled
 32 by agencies, provides a historical view of data on
 33 the service operations (e.g., trips and vehicle status
 34 changes); (ii) *Agency API*: implemented by agen-
 35 cies, data pushed by providers, encompasses real-time
 36 events in the system (e.g., new vehicle registration or
 37 a user trip); (iii) *Policy API*: implemented by agencies,
 38 data pulled by providers, provides updates about lo-
 39 cal rules/policies that may affect the mobility service
 40 operation (e.g., maximum number of vehicles concu-
 41 rrently placed in a city area at a given time). The MDS
 42 specification is designed for communications between
 43 mobility providers and regulatory agencies and pre-
 44 scribes GBFS as a format to share real-time data on
 45 the services with users.

46 The *Open Charge Point Interface* (OCPI) [3] is a
 47 well-established protocol to guarantee interoperabil-
 48

49
 50 ³<https://github.com/NABSA/gbfs/blob/master/systems.csv>

51 ⁴<https://www.openmobilityfoundation.org/members/>

ity between the eMobility Service Providers (eMSP), offering services to the owners of electric vehicles, and the Charge Point Operators (CPO), operating the recharging stations and their Electric Vehicle Supply Equipment (EVSE). The same organization can perform both roles, however, this distinction allows to regulate hubs and enables roaming scenarios where recharging stations of a CPO can be used by customers of different eMSPs. The OCPI protocol defines data exchanges between those two involved actors and it is not designed for data sharing with third parties (agencies or final users). However, this specification adopts and define the terminology largely used in this domain, therefore its modules can help to identify the data to be produced and collected in order to describe the infrastructure, the real-time status and the recharge sessions.

2.2. IoT Semantic Interoperability

Different solutions have been proposed to build an ecosystem within smart cities where different IoT devices, providers of services and authorities can share and access data to create additional value. To implement the envisioned ecosystem, it is important to guarantee horizontal interoperability for different types of users (es. providers, authorities, users of the service) accessing the same dataset, but also vertical interoperability among different datasets describing the same domain. Most importantly, the mentioned interoperability should be both structural, i.e., from the point of view of the technologies employed, but also semantic, i.e., considering shared vocabularies and definitions. Several works in the literature and research projects showcase how Semantic Web solutions can offer a complete framework to tackle these issues with IoT devices [4].

The work of Kolbe et al. [5] describes a prototype developed within the *bioTope* project⁵ and showcases how ontologies applied on-top of the lower-level messaging specifications can effectively guarantee interoperability in the context of a parking scenario with connected vehicles emitting data.

Similarly, Yoo et al. [6] present a semantic model to gather data from electric vehicles enabling interoperability between different IoT data provides. They also discuss how this interoperability can enable new services, such as a charging location search optimised with traffic information.

⁵<https://biotope-project.eu/>

Both papers refer to the *Semantic Sensor Network* (SSN) ontology [7] as a suitable model to describe data collected from IoT devices. SSN is an extensive ontology to describe actuators and sensors, their observations, the data collection procedures, the investigated features of interest, the sampling approach, the performed samples and the observed properties. For the last few years, the SSN ontology has become a de-facto standard for IoT interoperability [4], given its simplicity in representing IoT devices as sensors, or group of sensors, collecting observations and samples. One aspect favouring its wide adoption is related to the ontology modularity and the possibility to cover most of the use cases with its lightweight and self-contained core module SOSA (Sensor, Observation, Sample, and Actuator) [8]. A more dedicated vocabulary is the IoT-Lite Ontology [9] specialising a small subset of classes and properties of the SSN to represent IoT platforms through a simpler model.

The *SynchroniCity* project⁶, funded by the European Union's Horizon 2020 programme, aimed at implementing an ecosystem for IoT-enabled smart city solutions. To guarantee interoperability, the project defined a set of *SynchroniCity* data models⁷. By gathering different actors and initiatives (e.g., manufacturers and system integrators) they defined the data models in collaboration with the *Open & Agile Smart Cities* (OASC) consortium as city stakeholders. The JSON specifications of the models are based on the FIWARE Data Models⁸ and were developed taking into account also the IoT Big Data Harmonised Data Models developed by the GSM Industry Association, the Schema.org vocabulary and the SAREF ontology [10]. The *SynchroniCity* data models describe also IoT devices in the sharing and electric mobility domain through the *CarSharingStation*, the *BikeHireDockingStation* and the *EVChargingStation* models.

2.3. Mobility Vocabularies and Ontologies

Considering urban mobility services, interoperability should not be limited to the employed IoT devices, but it should be extended to other data, such as the description of user services, the historical usage data, the description and the geographical representation of the involved facilities and areas, etc. Analysing the literature and using Semantic Web tools, like the *Linked*

⁶<https://synchronicity-iot.eu>

⁷<https://gitlab.com/synchronicity-iot/synchronicity-data-models>

⁸<https://github.com/smart-data-models/data-models>

1 *Open Vocabularies* (LOV) portal [11], it is possible
2 to identify well-adopted ontologies already defining
3 these concepts.

4 The *Velopark* project [12] collects information on
5 bicycle parkings providing a pre-defined data model
6 to describe facilities and services. The *Velopark Rich*
7 *Snippets Generator*⁹ allows the user to insert informa-
8 tion through a graphic interface and to obtain an RDF
9 representation in JSON-LD [13]. The obtained snippet
10 can be uploaded to the Velopark portal where the
11 user can access details on all the different bicycle park-
12 ings in a uniform way. The vocabulary to describe the
13 parkings mainly relies on classes and properties from
14 Schema.org¹⁰ and a set of additional concepts defined
15 in the Velopark Vocabulary¹¹. Moreover, the *Open Mo-*
16 *bility Vocabulary*¹² (MobiVoc) was reused. This on-
17 tology, developed with the support of industrial part-
18 ners, is mainly based on Datex II¹³, the European stan-
19 dard for traffic information and traffic data, and cur-
20 rently describes electric charging points, parking facil-
21 ities and highway roadworks sites.

22 To represent service providers, service users and ge-
23 ographic locations, a set of standardised vocabular-
24 ies have been defined by the Semantic Interoperability
25 Community (SEMIC) group of the European Commis-
26 sion ISA2 Programme on Interoperability for public
27 administrations. The defined *e-Government Core Vo-*
28 *cabularies*¹⁴ include the following modules: Location,
29 Business, Person and Public Organisation. Each of
30 these vocabularies can be further specialised through
31 the definition of national profiles¹⁵. The Location [14]
32 module offers a generic abstraction for geographical
33 data that can be implemented using the well-adopted
34 GeoSPARQL [15] and Basic Geo Vocabulary¹⁶ based
35 on WGS84.

36 It is also worth mentioning the ongoing *Ciudades*
37 *Abiertas*¹⁷ project that is developing a set of vocab-
38 ularies to make Spanish municipalities data semanti-
39 cally interoperable. In particular, the *Vocabulary for*
40 *the representation of data about the public bicycle sys-*
41

42 ⁹<https://velopark.ilabt.imec.be/rich-snippets-generator/>

43 ¹⁰<https://schema.org/>

44 ¹¹<https://velopark.ilabt.imec.be/openvelopark/vocabulary>

45 ¹²<http://schema.mobivoc.org/>

46 ¹³<https://www.datex2.eu/>

47 ¹⁴[https://joinup.ec.europa.eu/solution/](https://joinup.ec.europa.eu/solution/e-government-core-vocabularies)
48 *e-government-core-vocabularies*

49 ¹⁵Cf. for example the Italian profiles definition at <https://github.com/italia/daf-ontologie-vocabolari-controllati>

50 ¹⁶<http://www.w3.org/2003/01/geo/>

51 ¹⁷<https://ciudadesabiertas.es/>

1 *tem*¹⁸ offers a well-designed example of how to model
2 station-based bike-sharing services.

3. Ontology Engineering Methodology

4
5 In this work, we applied the *Linked Open Terms*
6 methodology (LOT) [16], a consolidated industrial
7 method to develop ontologies and glossaries. In this
8 section, we summarise the main phases of the method-
9 ology and we explain how we applied them to the Ur-
10 ban IoT ontologies design and development.

3.1. Ontology Requirements Specification

11
12 The first activity is aimed to specify the ontology re-
13 quirements. Based on a domain analysis, including an
14 investigation on the existing data flows, we identified
15 a set of use cases and user stories.

16 Then, we defined a set of "competency questions",
17 i.e. the definition of the information that should be re-
18 trieved from data modelled with the target ontology,
19 and a set of "facts", i.e. the requirements associated
20 to the domain specific terminology (e.g., attributes de-
21 scribing a specific term, etc.). In this phase, we heavily
22 involved domain experts and stakeholders, to ensure
23 a comprehensive set of requirements and an effective
24 ontology specification.

25 Details are included in Section 4.

3.2. Ontology Implementation

26
27 The second step is the actual ontology implementa-
28 tion. We started the conceptualisation process with the
29 identification of a glossary of terms, starting from the
30 facts and competency questions.

31 Then we produced a first conceptual model with the
32 required set of classes and properties; in line with the
33 best practices of ontology engineering, we analysed
34 the relevant and existing ontological models to assess
35 their reuse. In this phase, we found it useful to create a
36 graphical representation of the model to ease the con-
37 ceptualisation.

38 Finally, we proceeded with the actual ontology cod-
39 ing in the OWL language, including the import or ref-
40 erence to the selected reused ontologies, and we val-
41 idated the output, both with the support of automatic
42 diagnosis tools and by manually assessing the imple-
43

44 ¹⁸[http://vocab.ciudadesabiertas.es/def/transporte/](http://vocab.ciudadesabiertas.es/def/transporte/bicicleta-publica)
45 *bicicleta-publica*

mented axioms with respect to the requirement specification (facts and competency questions).

Details are presented in Sections 5 and 6.

3.3. Ontology Publication

The third activity is the documentation and publication of the ontological model. In particular, after selecting the suitable licence and agreeing on the hosting modalities with our stakeholders, we published the ontology online following a content-negotiation mechanism, making the resource available in different formats which are both human-readable and machine-readable. The ontology is also assigned with a unique and permanent Web identifier.

The outputs of this activity are the ontology itself in different formats (Turtle, RDF/XML, JSON-LD, N-Triples) and the associated HTML documentation containing meta-data, the classes and properties description and graphical representation. In the documentation we also included some illustrative examples, identified with the support of the domain experts.

3.4. Ontology Maintenance

The maintenance is the final activity of the methodology. The purpose is to update or add new requirements, to identify and correct errors, and to schedule new development iterations for the ontology. In our case, since the Urban IoT ontologies are new, we simply set up a mechanism to facilitate the collection of suggestions and requests from the ontology adopters.

Details on both publication and maintenance are offered in Section 7.

4. Urban IoT Ontology Requirements

This section discusses the activities and the outcomes of the ontology requirements specification phase. Figure 1, summarises the steps performed and the artefacts produced in this phase.

4.1. Domain Experts

As mentioned, the need for the Urban IoT ontologies came from the Milan Municipality. Therefore, in the requirements phase, we involved fifteen different experts, who helped us eliciting their needs and analysing the two identified domains of sharing and electric mobility. The city stakeholders were from the

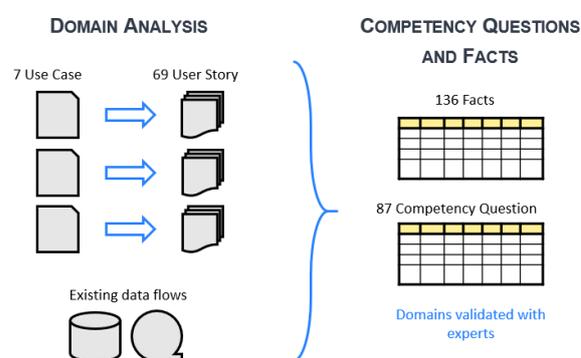


Fig. 1. LOT ontology requirement specification phase and its outputs for the Urban IoT ontologies.

Mobility Area (Area Pianificazione e Programmazione Mobilità), the municipality team responsible for mobility and transport planning and governance, which participated with six experts, and from the Data Area (Area Gestione ed Integrazione dati), which engaged four experts in interoperability and open data. In addition, we involved two domain experts from AMAT, the municipal agency for mobility and environment, which is in charge of collecting and processing mobility data for the city. Last but not least, three colleagues inside our institution participated to provide additional expertise on the selected domains.

4.2. Domain Analysis

The original demand was related to the IoT-collected data originating from sharing mobility and electric mobility providers: the municipality goal is to harmonise the data flows between such service suppliers and the city. To ensure the definition of comprehensive requirements on the considered sharing and electric mobility domains, we set up focused interviews with the mentioned experts during the ontology requirements phase, with the goal to collect not only their expertise but also some ontological and non-ontological resources to support our effort.

Interviewing the Mobility Area experts, we were able to identify the relevant terminology, to define potential user stories, and to delimit the scope of the ontologies. During these interviews, we also collected a set of relevant documents: council resolution for the creation of a digital urban ecosystem, public tenders for sharing services and charging stations, information on the active sharing services with related processes and structures, customer satisfaction questionnaires used to evaluate the services.

Most importantly, the city mobility experts suggested us to consider relevant domain-specific international standards: GBFS, MDS, and OCPI. During the interviews, the sharing mobility domain required a wider investigation due to the information complexity, but we could benefit from the already available guidelines, defined by the municipality for service providers, that helped us in identifying the main data to be modelled. For the less complex electric mobility domain, similar normative guidelines were not available. Therefore, we organised multiple meetings in which the electric mobility experts gave us additional insights on the national regulations, on the different actors and technologies involved, and on the current governance and planning implemented in Milan.

From the Data Area experts, we collected information on the already available open data in the selected domains, i.e., formats, information represented and naming conventions, from their Open Data portal¹⁹, as well as from their previous efforts to generate Linked Open Data²⁰.

Additionally, we interviewed the mobility experts from AMAT to understand the analysis that they are currently performing on the already available data sources, and the additional potential investigations that they would like to implement, in case the service suppliers would provide further data from their IoT infrastructure.

Finally, to get a broader view of the domain, also beyond the specific case of Milan, we considered other similar efforts in public and private projects. To this end, we contacted the experts within our own institutions to discuss their views on the sharing and electric mobility domains. They indicated relevant European and national related projects: *SynchroniCity* proposing data models to support interoperability in the urban environment, *SharingCities*²¹ defining useful scenarios and KPIs, and *eMoticon*²² investigating transnational interoperability for electric mobility; they also suggested related initiatives in other cities, and public APIs already available in the considered domains.

As a result of the domain analysis, we collected transcripts of the meetings and investigated a wide set of ontological and non-ontological resources, some of them already discussed in details in Section 2.

¹⁹<https://dati.comune.milano.it/>

²⁰<https://dati.comune.milano.it/sparql/home.html>

²¹<http://www.sharingcities.eu/>

²²<https://www.alpine-space.eu/projects/e-moticon/en/home>

4.3. Use Cases and User Stories

From the information collected during the domain analysis, we defined 7 use cases for the sharing and electric mobility domains (cf. first column of Table 1).

Six use cases separately cover the two domains (sharing mobility and electric mobility): for each of them, we distinguished the analyses of static data, real-time data, and data made openly available to third-party users (e.g., the citizens). A seventh use case was defined to investigate the combined use of data from both domains and from other IoT devices. To investigate this aspect, we leveraged the concept of Mobility Area, used in Milan but common also to other cities, i.e. a physical place aggregating public transport stops, sharing services stations, charging stations and additional mobility-related services to facilitate a seamless experience for the user (e.g. WiFi hotspots).

In the Urban IoT ontology repository²³, a full description of the use cases is available, highlighting the main actors and the information flow; in the following, we provide a short summary.

Actors. The use cases identify different actors. The Municipality is the facilitator actor who makes the collected data available for others; it also uses data for internal purposes: to analyse the existing services, to make statistical assessments, or to evaluate the need to activate new services, with the support of the Urban Mobility Manager. The Mobility Service Providers (sharing service operators and charge point operators, both active suppliers and willing to be authorised) need to provide data from their IoT infrastructure to the city, in compliance with the Mobility requests. The benefits from the urban IoT data management should advantage the final Users of the mobility services (citizens or tourists, including both existing and potential mobility service subscribers).

Static data use cases. The Municipality analyses current and historical information, shared by different operators active on the territory. The Mobility Service Providers provide data related to the subscribed Users, databases of the performed trips or charges. The Urban Mobility Manager executes the elaborations on the collected data on behalf of the Municipality, which uses the results to promote sustainable mobility, mobility services, and to evaluate the activation of new tenders.

Dynamic data use cases. The Mobility Service Providers make available their dynamic data (vehicles

²³<https://github.com/Comune-Milano/ontologie-iot-urbani/wiki> (in Italian)

Table 1

The list of the sample *user stories* and *competency questions*, one for each of the seven described *use cases*.

Use Cases	User Stories	Competency Questions
UC1 [<i>Sharing Mobility</i>] Urban sharing services usage statistics	The Municipality wants to analyse the beginning and end locations of all the trips, in order to enable the combined use with public transport	What are the final locations of trips that started from a specific sharing station in a day?
UC2 [<i>Sharing Mobility</i>] (Near) Real-Time data elaboration for urban sharing services	The Municipality analyses the events associated to individual vehicles to obtain statistics on maintenance and removal from the fleet of vehicles by operators. The purpose is to assess the reliability of the vehicles made available (life cycle) and the number of vehicles actually available in the various time slots and types of days (weekdays/pre-holidays/holidays)	How many sharing service vehicles are currently unavailable due to breakdown, rebalancing, recharging, disposal?
UC3 [<i>Sharing Mobility</i>] Sharing services data publishing in open formats	The user wants to know the fuel/charge levels of the sharing vehicles available around him, to evaluate if these vehicles are able to cover the route needed	What is the charge/fuel level of the vehicles currently available in a specific area?
UC4 [<i>Electric Mobility</i>] Urban electric charging infrastructures usage statistics	The Municipality wants to analyse the city areas where the highest number of charges by occasional users take place, to plan the placement of high -power charging infrastructures and/or information points for users coming from other cities	How many charging sessions are carried out by occasional users on a specific day for each charging station location?
UC5 [<i>Electric Mobility</i>] (Near) Real-Time data elaboration for urban electric charging infrastructures	The Municipality wants to analyse the distribution of the "in charge" columns during the different moments of the day to evaluate the city areas where the demand for charging infrastructures is concentrated	Which EVSEs, for each charge category, are currently reported as "in charge"?
UC6 [<i>Electric Mobility</i>] Electric charging infrastructure data publishing in open formats	A user wants to identify all the charging infrastructures compatible with its vehicle and available in a specific moment in a defined point of the city	What are the charging stations with at least one EVSE having a certain connector type and being currently available?
UC7 [<i>Mobility Area</i>] Data integration for Mobility Areas	The Municipality wants to analyse the charges and the trips made within a Mobility Area to evaluate the effective use of the services	How many charges and how many trips have started within a specific mobility area in one day?

or charging points in use or available) in near-real time. The Urban Mobility Manager executes data analysis on such data, to let the Municipality investigate, on the one hand, the available vehicles placement, flow, state, etc. and, on the other hand, the distribution of the available charging points, their location and their usage.

Open data use cases. Some static and dynamic data can be made available by the Municipality to possible Users of the mobility services or to other third-parties (e.g. broker services which provide an aggregated view of the available services in the city via a mobile app).

Mobility area use case. The Municipality integrates static and dynamic data related to the different available services in the Mobility Areas, to execute analysis whose results are made available in an open format (open data, linked open data and service). In this case, the different operators (not only for sharing and charging point, but also providers of smart parking, public transport or other Mobility Area providers) make available their static or dynamic data accordingly to the contractual requests of the Municipality. The Urban Mobility Manager integrates all data to provide

open data and services with added value to users or third parties.

From the definition of those seven use cases, we elaborated and defined 69 user stories (also available in the repository), which are described following the template: [*actor*] wants [*something*] in order to get [*benefit*]. A small selection of user stories, one for each use case, is in the second column of Table 1.

4.4. Requirement Specification

From the use cases and user stories of the domain analysis phase, we derived the actual requirement specification, in the form of Facts and Competency Questions. Hereafter, we clarify the purpose and scope of our ontology engineering and then we detail the final requirements, which underwent a validation phase with the involvement of the domain experts.

4.4.1. Ontology Purpose and Scope

The use cases and user stories were the basis for drawing the boundary of our ontology scope and, as a consequence, the purpose of our engineering effort.

Indeed, we based most of our modelling on the existing standards (MDS, GBFS and OCPI), but they do not consider the information related to the final user; therefore, we decided to extend our modelling by including a very basic user profile, with features that allow for socio-demographic analysis on the service usage, while guaranteeing user anonymity.

On the other hand, the data currently collected by Milan municipality do not include information about service pricing or maintenance, but the investigation with the domain experts revealed the need to consider them. In this respect, we decided to include in our scope some parts of those aspects. Regarding maintenance, we introduced a detailed description of the events associated to the vehicles fleet, useful to analyse maintenance activities or vehicle re-balancing. Regarding pricing, we extended our scope to incorporate basic fee typologies (e.g., hourly price or cost per kWh), to allow for some comparative analysis, still preserving each service provider confidential business information (e.g., we excluded details related to specific promotions or to individual usage session costs).

4.4.2. Facts

Facts represents preliminary definitions for concepts identified in the domains. For the sharing mobility, the main concepts defined are sharing service operator, sharing service, offer, user, trip, vehicle, sharing station, dock, sharing station state, dock state and vehicle state. Similarly, for the electric mobility there are the charge point operator, the charging station, the Electric Vehicle Supply Equipment (EVSE), the EVSE state, the connector, the e-mobility service provider, the offer, and the charging session. A further Mobility Area concept was defined to describe physical places dedicated to both services.

4.4.3. Competency Questions

Competency questions identify the inquiries that an ontology adopter should be able to express on the data. Therefore, for each identified user story, we defined one or more related competency question that express the user need. In Table 1, a selected set of competency questions is presented in the third column (related to the user stories offered in the same table).

4.4.4. Requirements validation

The combination of facts and competency questions constituted our Ontology Requirement Specification Document (ORSD). The formalised requirements were presented back to the domain experts that supported our domain analysis for their validation.

They went through the lists of facts and competency questions and thoroughly assessed the clarity, accuracy, completeness with respect to their needs, and the fitness-for-use. In this phase, they suggested minor adjustment of vocabulary and some additional interesting queries that we added to the final version of the ORSD.

The complete list of 136 facts and 87 competency questions is available in the requirements folder of the ontology repository²⁴.

5. Urban IoT Ontology Implementation

Based on the requirements gathered and formalised in the previous steps, we then proceeded to the implementation phase. This section describes our conceptualisation effort and the resulting modular suite of Urban IoT ontologies.

5.1. Ontology Conceptualisation

In the conceptualisation step, we designed a modular solution to facilitate adaptability and extensibility. In particular, as both the domains needed a representation of providers operating IoT-based services, offered to users in a city, it was decided to create a common *Core* module as general as possible.

We designed the *Core* module as a base vocabulary that can be easily specialised to define Urban IoT modules, which extend the core to describe specific services. We developed the *Sharing mobility* and *Electric mobility* modules as extensions of the *Core* module; the former adds all the specific contents related to the sharing mobility domain, while the latter describes in detail the electric mobility domain. In the future, new Urban IoT modules can be added to model other city services encompassing a sensor infrastructure.

Moreover, despite the fact that the involved domain experts were from Milan, the resulting suite of ontologies is generic and covers the needs of any city, as already discussed; however, this modular approach allows also for local specialisations, in case a specific urban environment needs its peculiar extensions to the provided modules.

During the implementation of the three modules, we considered and re-used existing relevant vocabularies to model identified concepts and relations. For the first conceptualisation of the three modules, we adopted a

²⁴<https://github.com/Comune-Milano/ontologie-iot-urbani/blob/master/requisiti> (in Italian)

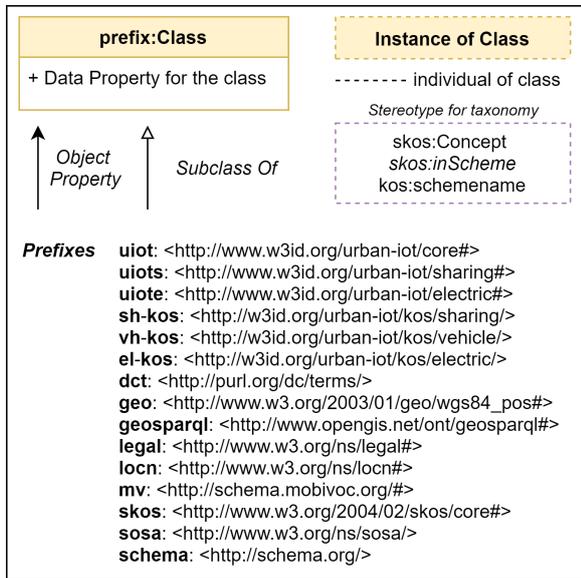


Fig. 2. Legend and prefixes used in the ontology diagrams.

graphic approach to better visualise the overall structure, the connection between the *Core* concepts and the ones for the specific domains, and the relations with other existing vocabularies. Once the conceptualisation was completed with the graphic model, we encoded the ontology modules using OWL axioms.

In the following paragraphs, we present the main classes and properties of the three modules, using the mentioned graphic model split in different diagrams to support the explanation. Figure 2 reports the legend to understand the adopted notation for classes, instances, object properties, sub-classes and SKOS elements. The full documentation of the three modules of our suite of ontologies is available online²⁵.

5.2. Core module

The *Core* module (prefix `uiot`) defines the concepts and the principal properties that will be reused in other modules. In particular, it designs the aspects related to a service provider who manages the IoT devices in the urban area, the service usage by the users and the modelling of an IoT device which collects and sends data. The concepts defined from the *Core* module are expressed at a high level of abstraction and are declined in the specific domain inside the other modules of the

Urban IoT suite that imports it (as the *Sharing mobility* module and the *Electric mobility* module). The *Core* module was implemented by reusing different vocabularies, some of them discussed in details in Section 2: `schema.org`, extending it to support specific requirements on the domain of interest; Sensor, Observation, Sample, and Actuator (SOSA) for the modelling of the IoT devices and the data collected from them; the Core Vocabularies defined from Semantic Interoperability Centre Europe (SEMIC.EU); the Time Ontology²⁶ and the Dublin Core²⁷.

The main concepts of the *Core* module have been modelled by extending the `schema.org` vocabulary, as described in the Figure 3, in the graph on the left. A service provider can be modeled as a `schema:Organization` that provides one or more `schema:Service`. The offered service can make available for the users some `uiot:ServiceResource` that can be used by the user in a `uiot:UsageSession`. The offer for the service usage can be modelled as a `schema:Offer`; all the offers can be associated with the service that made them available. Furthermore, the specific offer, if applied to a usage session, can be directly associated with the latter.

Service users are modeled as `uiot:ServiceUser` and can be `uiot:ServicePrivateUser`, namely physical persons (subclass of `schema:Person`) subscribed to a service, or `uiot:ServiceBusinessUser` namely legal entity (subclass of `legal:LegalEntity`) subscribed to a business contract. Only a `uiot:ServicePrivateUser` can perform a `uiot:-UsageSession`. A `uiot:ServiceBusinessUser` can enable a list of `uiot:ServicePrivateUser` to the service usage and to be associated to a usage session. However, it is necessary to specify the physical person that used the service by the specific business contract.

For the modelling of an IoT urban device the *Core* module uses the pattern SOSA defined in the related ontology, see Figure 3, the graph at the bottom right. Intuitively, an IoT urban device can be seen as a `sosa:Sensor` (or an aggregation of sensors) that emits `sosa:Observation`, which reports the sampled value of a series of `sosa:ObservableProperty`. The following pattern guarantees the extensibility of sampled properties from a sensor, allowing the definition of different types of `sosa:Observation` associ-

²⁵ *Core* module: <https://www.w3id.org/urban-iot/core>,
Sharing mobility module: <https://www.w3id.org/urban-iot/sharing>,
Electric mobility module: <https://www.w3id.org/urban-iot/electric>

²⁶ <http://www.w3.org/2006/time>

²⁷ <https://www.dublincore.org/specifications/dublin-core/dcmi-terms/>

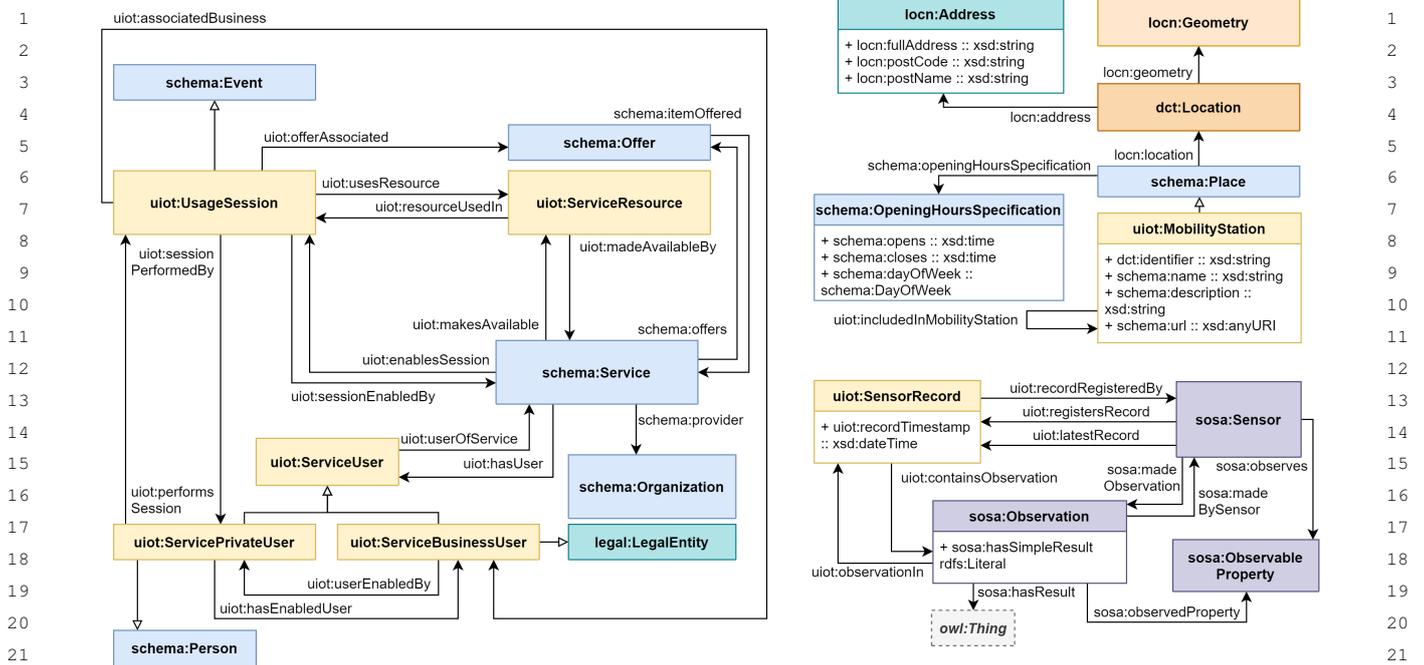


Fig. 3. Core module, with specific details on sosa and locn usage.

ated with a sensor. In the *Core* module, `uiot:SensorRecord` is defined as an aggregation of data received by a sensor at the same moment. In particular, a `uiot:SensorRecord` can contain a series of `sosa:Observation`. A `sosa:Sensor` is associated to the `uiot:SensorRecord` it has emitted, with the specification of the last record by the property `uiot:latestRecord`.

To address the requirements about Mobility Areas, the *Core* module defines also a `uiot:MobilityStation` as a place where different services related to urban mobility are aggregated (see in Figure 3 the top right graph), like for example sharing stations for the sharing mobility or charging stations (defined respectively in the *Sharing mobility* and *Electric mobility* modules). A `uiot:MobilityStation` is a place (`schema:Place`) described by a `dct:Location` that can be defined by an address (`locn:Address`) and/or a spatial representation by geometry (`locn:Geometry`). `locn:Geometry` defines the abstract concept and can be serialized in different formats as indicated in the Core Location ontology, e.g., using GeoSPARQL. A `uiot:MobilityStation` can be modeled as an aggregation of specialised `uiot:MobilityStation` for a specific service, using the `uiot:includedInMobilityStation` property.

5.3. Sharing mobility module

The *Sharing mobility* module (prefix `uiots`) defines classes and properties modelling the sharing mobility service providers, the vehicles for sharing and the sharing stations (acting as IoT devices), and the trips performed by the users. The concepts defined from the *Sharing mobility* module reuse and extend the *Core* module already described, which is imported from the ontology. The module is complemented with the definition of SKOS vocabularies used in the ontology to describe: car supply, European emission standard, propulsion type, vehicle category, sharing mobility vehicle state, sharing mobility vehicle event, and dock state in sharing station.

Figure 4 presents the main classes and properties of the *Sharing mobility* module. In the considered domain, a service provider can be modeled as a `uiots:SharingMobilityProvider` (subclass of `schema:Organization`) which delivers one or more `uiots:SharingMobilityService` (subclass of `schema:Service`). A service provides users with a series of `uiots:SharingMobilityVehicle` which form a network of Urban IoT devices on the city soil, and they are subclasses of `schema:Vehicle` and `uiot:ServiceResource`. The vehicles can be used through the service in trip sessions (`uiots:Sharing-`

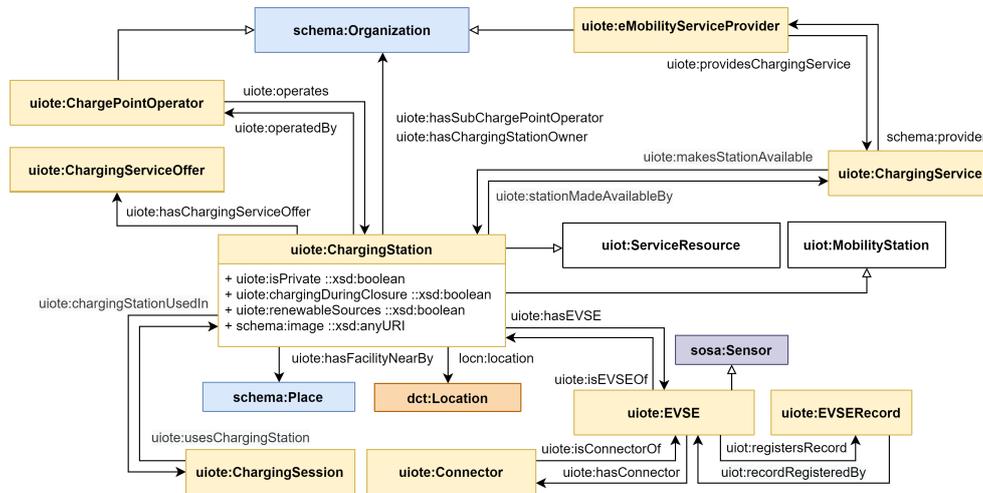


Fig. 5. Electric mobility module detail.

referring to the actor operating the charging stations (`uiote:ChargingStation`), and the `uiote:eMobilityServiceProvider` managing the charging service for the users. In case both roles are performed by the same operator, a unique organization would be instance of both classes. A `uiote:ChargingService` (subclass of `schema:Service`) is a charging service managed by a `uiote:eMobilityServiceProvider`. The `uiote:ChargingService` makes available specific `uiote:ChargingStation` operated by `uiote:ChargePointOperators`. The offer for the *Electric mobility* module is represented by `uiote:ChargingServiceOffer` which is a subclass of `schema:Offer` and it is associated with a charging service. It can also be directly associated with a `uiote:ChargingStation` and it represents an offer for occasional users using the station without being registered to any charging service.

A charging station (`uiote:ChargingStation`) is both a `uiot:ServiceResource`, that can specify also an owner (`uiote:hasChargingStationOwner`) and a sub-operator managing it (`uiote:hasSubChargePointOperator`), and a `uiot:MobilityStation`, that can be described through a `dct:Location` and/or specifying near by facilities (`uiote:hasFacilityNearBy`). Inside the charging station several charging columns (Electric Vehicle Supply Equipment, modelled as `uiote:EVSE`) are included. For each `uiote:EVSE` at least one connector (`uiote:Connector`) is associated, describing the available plugs and cables to charge a vehicle. A `uiote:EVSE` is an IoT device and can, therefore, be modelled as a `sosa:Sensor` emitting `uiot:EVSERecord`. An

`uiot:EVSERecord` is associated with the timestamp of collection, to the current EVSE state (`skos:Concept` in `el-kos:EVSE-state`), and to any additional `sosa:Observation` enriching the record.

6. Urban IoT Ontology Evaluation

To complement the description of the Urban IoT ontologies we discuss the evaluation of the modules considering pitfalls detected by automatic tools scanning them, and well-established ontology evaluation criteria.

6.1. Pitfalls detection

To detect pitfalls in the Urban IoT ontologies, we leveraged the automatic scanning utility provided by the *OOPS!* tool [17]. The resulting report identified no *critical* issues, but only *important* and *minor* pitfalls. The automatic scanning allowed us to identify and fix oversights that could not be easily detected by hand. In particular, we added missing annotations (`rdfs:label` or `rdfs:comment`), *inverse relation* axioms, and *domain* and *range* declarations.

The scanning of the final version of the modules only reports *important* pitfalls related to two specific design choices. The first one is related to the choice of not importing in the modules the re-used vocabularies. Since many of them are quite large (e.g., `schema.org`), and not directly bound to the considered domain, we decided to simply re-use the referenced entities via their IRIs. In some cases, to help in the usage of the

ontology, we added also annotations to external classes and properties, e.g. adding `rdfs:labels` in Italian, and/or `vann:usageNotes`. The second design choice is related to the decision of not specifying *disjoint* axioms between sub-classes. In general, we decided to limit the use of logical axioms, preferring to specify intended usage of classes and properties through annotation and documentation, and leaving potential validation to the definition of shapes (e.g., using SHACL); indeed, we do not expect the intended users to exploit reasoning in their systems and analysis.

We also decided not to address the remaining *minor* pitfalls, e.g., inverse relations that we considered useless, and particular naming conventions in IRIs (e.g. `uiote:eMobilityServiceProvider` class).

6.1.1. Evaluation criteria

In this section, we discuss the different modules taking into account well-established criteria for ontology evaluation [18].

Accuracy The ontology development process was assisted by experts and stakeholders about the domain. Moreover, the different modules were designed using well established non-ontological and ontological resources described in Section 2, e.g., de-facto standards in the domains considered (*GBFS*, *MDS* and *OCPI*) and other ontologies developed in these domains (*MobiVoc*, *Ciudades Abiertas*, etc.).

Adaptability The ontology is divided into modules to facilitate its reusability and extensibility. For example, the core module was designed to easily allow the definition of new modules extending it to deal with other services and IoT devices in the urban area (e.g., intelligent parking lots, cameras, access gates, etc.). Moreover, in accordance with the municipality of Milan, and to facilitate the adoption of the ontologies also by other cities, we did our best to design the ontology without introducing any biased modelling decision.

Clarity The custom terms defined in all modules adopt the main terminology defined in the domains considered. A terminological alignment has been specifically carried out in the requirements validation phase with the support of the domain experts. To make the ontology terminology understandable for a broader audience, we decided to use English in the local name of the encoded IRIs of classes and properties, and to provide `rdfs:label` and `rdfs:comment` in both English and Italian.

Completeness A broad set of user stories and competency questions has been defined for the ontologies, interviewing different actors and investigating different aspects of the considered domains (as described in Section 4.2). After the encoding of the ontologies, we double-checked that every defined competency question could be defined and answered using the modelled classes and properties.

Efficiency As commented, we decided to introduce only minor logical constraints as axioms in the ontology. As a result, enabling reasoning does not affect efficiency. Moreover, the modularization allows keeping the size of the different modules limited.

Conciseness In the domain analysis with domain experts, we clearly defined the scope boundaries determining the relevant elements in the considered domains. Moreover, in the encoding of the ontologies we re-used as much as possible already existing vocabularies when dealing with concepts not specifically related to the domain (e.g., CORE Location ontology for addresses and geometries, SOSA for sensors data, schema.org for organizations, etc.). This has the double advantage of keeping the ontologies concise, while clearly stating and referring a model to represent related data.

Consistency No inconsistency was found enabling reasoning (we used the Hermit reasoner v1.4.3.456²⁹).

Organizational fitness The municipality of Milan acknowledged the deployability of the ontologies as the reference model for data that should be provided by service providers in the sharing and electric mobility domains. An additional evaluation will be performed when different providers will start to contribute their data using the proposed model and/or other municipalities will adopt the ontologies.

7. Urban IoT Ontology Publication and Maintenance

The documentation and the hosting of the ontologies described is available on the GitHub pages of the Milan Municipality³⁰. The license adopted is the Creative Commons with Attribution right (CC-BY), which allows licensees to copy and distribute the work and

²⁹<http://www.hermit-reasoner.com/>

³⁰<https://github.com/Comune-Milano/ontologie-iot-urbani>

1 make derivative works, giving the authors proper cred-
2 its.

3 The content negotiation mechanism follows the best
4 practices for publishing vocabularies/ontologies on the
5 Web, in particular the *Recipe 3* [19]. This recipe de-
6 scribes an extended configuration for a vocabulary
7 with a hash namespace, setting the server to pro-
8 vide human-readable (HTML) or machine-processable
9 (RDF) content from the vocabulary URI. We leveraged
10 the *Vapour* tool [20], a linked data validator, to identify
11 and fix issues in the content negotiation mechanism
12 defined for the ontologies.

13 As Linked Data web applications need stable identi-
14 fiers, a permanent URL was requested to the Perma-
15 nent Identifier Community Group and it is registered
16 as <http://w3id.org/urban-iot>. The maintenance is sup-
17 ported by an issue tracker³¹, which allows to propose
18 additions/modifications/removal of use cases and user
19 stories directly as GitHub issues. Such proposals are
20 then evaluated by the team members and possibly im-
21 plemented.

22 8. Urban IoT Ontology Usage Examples

23 This section exemplifies the intended usage of the
24 presented Urban IoT ontologies. We first select some
25 of the competency questions reported in Table 1 show-
26 casing how they can be expressed using our ontologies
27 and the SPARQL query language. Then, we present
28 some usage examples by representing fictitious data
29 through the ontologies as JSON-LD snippets.

30 8.1. Queries and Competency Questions

31 Hereafter, we discuss two SPARQL queries cover-
32 ing, respectively, a dynamic and a static data scenario.
33 The complete set of SPARQL queries encoding the
34 competency questions in Table 1 is made available as
35 an external resource³². Prefixes used in the queries are
36 not reported to ease the readability, but they can be
37 found in Figure 2.

38 Considering dynamic data, we focus on the shar-
39 ing mobility user story described in Table 1. Listing 1
40 defines a SPARQL query for the associated compe-
41 tency question: *How many sharing service vehicles are*
42

43 ³¹[https://github.com/Comune-Milano/ontologie-iot-urbani/](https://github.com/Comune-Milano/ontologie-iot-urbani/issues)
44 issues

45 ³²[https://github.com/Comune-Milano/ontologie-iot-urbani/blob/](https://github.com/Comune-Milano/ontologie-iot-urbani/blob/master/examples/queries.rq)
46 [master/examples/queries.rq](https://github.com/Comune-Milano/ontologie-iot-urbani/blob/master/examples/queries.rq)

1 *currently unavailable due to breakdown, rebalancing,*
2 *recharging, disposal?.* To compose the query pattern,
3 we ask for all the `uiot:latestRecord` associated
4 to a `uiots:SharingMobilityVehicle` that are in
5 the `Unavailable` state. Then, we group the result-
6 ing `uiots:SharingMobilityVehicleRecords` us-
7 ing the `uiot:latestSharingVehicleEvent` to ob-
8 tain different statistics for each possible event causing
9 the unavailability of the vehicle.

```
10
11 SELECT ?event (COUNT(?a) AS ?numVehicles)
12 WHERE {
13   ?smv a uiots:SharingMobilityVehicle ;
14       uiot:latestRecord ?record .
15   ?record uiots:sharingVehicleState sh-kos-state:
16     Unavailable .
17   ?record uiots:latestSharingVehicleEvent ?svEvent .
18   ?svEvent skos:prefLabel ?event .
19 }
20 GROUP BY ?event
```

21 Listing 1: SPARQL query for the competency question
22 on sharing mobility dynamic data formulated

23 Considering static data, we take the example of the
24 electric mobility user story described in Table 1. List-
25 ing 2 defines a SPARQL query for the associated compe-
26 tency question: *How many charging sessions are*
27 *carried out by occasional users on a specific day for*
28 *each charging station location?.* To compose the query
29 pattern, we ask for all the `uiote:ChargingSession`
30 performed by a not registered user. Then, we intro-
31 duce a filter condition to consider only the sessions
32 performed in the specific day of interest, and we ac-
33 cess the data of the `uiote:ChargingStation` asso-
34 ciated to the session to obtain its location. Finally, we
35 group the results by the charging station identifier and
36 position to obtain the desired aggregations.

```
37
38 SELECT ?id ?lat ?long (COUNT(?session) AS ?
39   numSessionsOccasionalUsers)
40 WHERE {
41   ?session a uiote:ChargingSession ;
42       uiote:registeredUser "false"^^xsd:boolean ;
43       uiote:usesChargingStation ?station ;
44       schema:startDate ?sDate .
45   FILTER ( DAY(?sDate) = 23 && MONTH(?sDate) = 12 )
46   ?station a uiote:ChargingStation ;
47       dct:identifier ?id ;
48       locn:location ?loc .
49   ?loc locn:geometry ?pos .
50   ?pos geo:lat ?lat ;
51       geo:long ?long .
52 }
53 GROUP BY ?id ?lat ?long
```

54 Listing 2: SPARQL query for the competency question
55 on mobility area data formulated in Table

8.2. Usage Examples

JSON-LD [13] allows annotating a JSON document to represent Linked Data. In the documentation of the Urban IoT ontologies, we decided to provide the usage examples in this format to help the service providers, often not familiar with RDF, in the definition of semantically annotated APIs according to the defined vocabularies. In the following paragraphs, we discuss some relevant examples, the complete set of examples can be found in the documentation of the different modules available online. The following examples rely on a specific *urban-iot-context.jsonld* context³³.

Listing 3 describes a fictitious `SharingMobilityService`, called *Bike Milano*, operating in the city of Milan. The described service is a station-based (`uiots:allowsFreeFloating` equal to `false`) bike-sharing (`uiots:hasSharingMobilityCategory`) service offered by an imaginary *Bike Milano Provider*. The example data also describe the basic price to use the service, that is 0.60 Euro for each trip minute. The description can be enriched with the encoding of the operation area (`locn:Geometry`) and other geometries describing the service.

```
{
  "@context": "urban-iot-context.jsonld",
  "@id": "http://ex.com/service/BikeMilano",
  "@type": "uiots:SharingMobilityService",
  "schema:name": "Bike Milano",
  "schema:provider": { "@id": "http://ex.com/org/BikeMilanoProvider" },
  "schema:areaServed": { "@id": "http://dbpedia.org/page/Milan" },
  "uiots:hasSharingMobilityCategory": {
    "@id": "uiots:BicycleSharing"
  },
  "uiots:allowsFreeFloating": false,
  "schema:offers": {
    "@id": "http://ex.com/offer/BikeMilanoBase",
    "@type": "uiots:SharingMobilityOffer",
    "schema:name": "Base Bike Milano",
    "schema:priceCurrency": "EUR",
    "uiots:pricePerTripMinute": {
      "@value": "0.60",
      "@type": "xsd:double"
    }
  }
}
```

Listing 3: Usage example describing a mock `uiots:SharingMobilityService` in Milan.

Listing 4 describes a hypothetical `uiots:SharingStation` associated to the *Bike Milano* sharing service

described in Listing 3. The station is equipped with physical infrastructure (`uiots:PhysicalSharingStation`) and contains four `uiots:Docks`. The docks can be of different `uiots:DockKinds`, that can be defined by the service provider to implement constraints on which dock can be used by a specific vehicle³⁴. In Listing 4, we describe only one of the dock, others can be similarly defined in the array. Moreover, the station is located within a `uiot:MobilityStation`.

```
{
  "@context": "urban-iot-context.jsonld",
  "@id": "http://ex.com/sharing-station/SharingStation9",
  "@type": "uiots:PhysicalSharingStation",
  "dct:identifier": "SharingStation9",
  "schema:name": "Sharing Station Bike Milano Stazione Centrale",
  "uiot:includedInMobilityStation": {
    "@id": "http://ex.com/mobility-station/MobilityStation13"
  },
  "uiots:sharingStationUsedBy": {
    "@id": "http://ex.com/service/BikeMilano"
  },
  "uiots:hasSharingMobilityCategory": { "@id": "uiots:BicycleSharing" },
  "uiots:numberOfDocks": 4,
  "uiots:hasDock": [
    {
      "@id": "http://ex.com/dock/Dock9-1",
      "@type": "uiots:Dock",
      "uiots:hasDockKind": {
        "@id": "http://ex.com/dock-kind/ChargingDock"
      }
    },
    { ... }, { ... }, { ... }
  ]
}
```

Listing 4: Usage example describing a `uiots:SharingStation` associated to the service described in Listing 3.

Listing 5 describes a fictitious status update for a `uiote:ChargingStation`. This type of data can be pushed regularly by charging stations and aggregated to make available the real-time status of charging stations in the city. In Listing 5, the latest `uiote:EVSERecord` of one EVSE in the charging station is reported describing the current `uiote:EVSEState` and the timestamp of the update. The description can be complemented by adding a similar record description for each EVSE in the charging station.

³³All the examples can be edited, viewed or converted to other formats using the JSON-LD Playground already initialised with the Urban-IoT context at the following link <https://tinyurl.com/yy3abvss>

³⁴To complement the description of this constraint, each `uiots:SharingMobilityBicycle` associated to the service should be bound to the `uiots:DockKind` that it can use.

```

1  {
2    "@context": "urban-iot-context.jsonld",
3    "@id": "http://ex.com/charging-station/
4      ChargingStation7",
5    "@type": "uiote:ChargingStation",
6    "uiote:hasEVSE" : [{
7      "@id": "http://ex.com/evse/EVSE7-1",
8      "uiot:latestRecord": {
9        "@type": "uiote:EVSERecord",
10       "uiot:recordTimestamp": {
11         "@value": "2020-08-01T11:00:32",
12         "@type": "xsd:dateTime"
13       },
14       "uiote:EVSEState": {
15         "@id": "el-kos:EVSE-state#InCharge"
16       }
17     }
18   }, {...}, {...}]
19 }

```

Listing 5: Usage example describing a mock status update for a `uiote:ChargingStation`.

9. Long-term Impact

Engineering an ontology is only the first step in the journey for interoperability. We have reported here our effort to build this suite of Urban IoT ontologies and the process we followed to come up with this result. The long term goal, however, is the effective governance of all Urban IoT data flows, overcoming the heterogeneity of information sources with standardised interfaces and the definition of reference APIs for dynamic data exchange.

Indeed, the municipality of Milan has embraced this view for an urban digital ecosystem [21] that coordinates a multitude of different and possibly competing stakeholders, including the sharing mobility and electric charging service providers, adopting a cooperation [22] and API economy perspective. According to this vision, interoperability plays a pivotal role in the city data governance: this is why, for the last few years, the Milan city council has introduced the requirement for specific data provision in all the calls for tenders that the city service suppliers respond to. This means that, to supply sharing mobility and electric charging services, those actors are contractually bound to grant the municipality access to the data produced by their IoT devices and sensors. The ontologies presented in this paper are going to be the reference model for urban IoT data interoperability in Milan in the near future.

As illustrated throughout the paper, even if we started from the requirements of Milan municipality, the presented ontologies have a wide applicability. We indeed addressed use cases and user stories with global relevance and we investigated and included concepts and abstractions coming from international standards

and formats. That is why we believe that the impact of our urban IoT ontologies can be leveraged in any urban context.

With specific reference to sustainable mobility, we are also confident that our effort supports a broader interoperability in the transport sector. There is a growing interest in multimodal travel solutions that integrate different transport modes and mobility solutions. The European Commission, for example, is promoting the setup of the so called national Access Points (NAPs) to share transport-related data in all member states.

In this context, an ontological reference model can play a central role in the construction of a transport knowledge graph that integrates information from different providers [23], including sharing and electric mobility. This impact can be for example achieved with the adoption of an any-to-one centralized mapping approach [24], in which the Urban IoT global conceptual model allows for bilateral mappings between the specific formats used by the mobility stakeholders [25].

Finally, this semantic interoperability governance approach, with the setup of a digital ecosystem for data exchange, provides benefits not only to urban planners and managers, but also to the mobility providers themselves. The rising concept of Mobility-as-a-Service (MaaS) requires stable and clear business agreements between different parties and the adoption of a reference conceptual model can facilitate the information exchange and, as a consequence, the combination of different services into unified offerings.

10. Conclusion and Future Work

In this paper, we presented the first version of the Urban IoT ontologies, developed to promote interoperability of the data exchange between service providers, operating IoT devices in the urban area, and municipalities. With the support of stakeholders and domain experts from the municipality of Milan, we carried out an ontology engineering effort to implement the initial modules to cover the domains of sharing mobility and electric mobility.

Following the consolidated *Linked Open Terms* methodology, we involved throughout the different phases fifteen domain experts, to elicit and specify a comprehensive set of requirements. During the domain analysis, we considered a wide set of ontological and non-ontological resources: on the one hand, this helped

us in analysing already existing data flows and standards at international level; on the other hand, it fostered the re-use of existing vocabularies during the implementation. In the ontology requirement specification phase, we identified 7 use cases and 69 user stories, which then resulted in the definition of 136 *facts* and 87 *competency questions*.

The definition of a global graphical conceptual model, based on these requirements, allowed us to detect similar concepts and relations defining three interconnected ontology modules: a *Core* module to describe service providers, services, users, mobility stations, IoT devices and their status updates; a *Sharing mobility* module specialising the *Core* classes and properties in terms of sharing mobility services, sharing mobility operators, sharing stations, sharing mobility vehicles and trips; finally, an *Electric mobility* module specializing them in terms of charging point operators, e-mobility service providers, charging stations and charging sessions.

The resulting ontologies – published online according to the Semantic Web best practices – underwent a thorough evaluation, both manual and using automatic diagnosis tools, and we can affirm that we managed to guarantee accuracy, adaptability, clarity and completeness of the model. Since the original goal was to allow for a harmonised data exchange between the municipality and service providers, we offered a set of detailed usage examples and we discussed the impact resulting from their adoption to promote interoperability. Together with the municipality of Milan, we already started disseminating this ontological effort both on the local territory and across Europe, to promote its broader adoption and validation.

In the future, we aim at validating the proposed Urban IoT ontologies by involving service providers in piloting activities for the provision of semantically annotated data to the municipality. Moreover, we would like to organise co-design meetings with citizens and potential third-party users to: (i) determine how data collected from sharing and electric mobility providers can be effectively made available and accessed by citizens, and (ii) gather ideas and additional use cases for the definition of added value services that could be built on top of these data. Last but not least, we aim at expanding the current set of modules of the Urban IoT ontologies, by conceptualising additional domains such as intelligent parking lots, surveillance cameras, access gates, etc.

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