The UDSA Ontology: An Ontology to Support Real Time Urban Sustainability Assessment

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1 ABSTRACT

Urban sustainability assessment frameworks have emerged during the past decade to address holistically the complexity of the urban landscape through a systems approach, factoring in environmental, social and economic requirements. However, the current assessment schemes are (a) static in nature, and as such don't reflect the dynamic and real-time nature of urban artefacts, (b) are not grounded in semantics (e.g. BIM and GIS), and (c) are at best used to assist in regulatory compliance, for instance in energy design, to meet increasingly stringent regulatory requirements. Information and communication technologies provide a new value proposition capitalizing on the Internet of Things (IoT) and semantics to provide real-time insights and inform decision making. Consequently, there is a real need in the field for data models that could facilitate data exchange and handle data heterogeneity. In this study, a semantic data model is considered to support near real-time urban sustainability assessment and enhance the semantics of sensor network data. Based on an extensive review of urban sustainability assessment frameworks and ontology development methodologies, the Urban District Sustainability Assessment (UDSA) ontology has been developed and validated using real data from the site of "The Works", a newly refurbished neighbourhood in Ebbw Vale, Wales. This novel approach reconciles several domain-specific ontologies within one high-level ontology that can support the creation of real-time urban sustainability assessment software. In addition, this information model is aligned with 29 authoritative urban sustainability assessment frameworks, thus providing a useful resource not only in urban sustainability assessment, but also in the wider smart cities context.

2 INTRODUCTION

The past decades have seen a sharp evolution toward sustainability at building block and district levels with a growing interest in good operational and managerial practices as evidenced in Gil and Duarte review article on urban sustainability evaluation tools [1] or in Ameen et al. review article on environmental assessment tools [2]. Urban District Sustainability Assessment (UDSA) frameworks such as LEED-ND (Leadership in Energy and Environmental Design for Neighborhood Development) [3], BREEAM Communities (Building Research Establishment Environmental Assessment Method) [4] or CASBEE-UD (Comprehensive Assessment System for Built Environment Efficiency for Urban Development) [5], are examples of three of the widely used frameworks by the architecture, engineering and construction (AEC) industry to evaluate the sustainability of built environment projects [6]. These frameworks represent a baseline for the definition of sustainability at the urban level. However, they are often static, i.e. locally and temporally bounded [7]. Hence, it is essential to develop tools that can track changes and adapt to continuous changes in the built (and natural) environment [8]. On that matter, Information and Communication Technologies (ICTs) pave the way to a new paradigm for sustainability assessment and cities development in general as discussed by Sein and Harindranath in their article about the role of ICTs [9], or by Hollands and Kitchin in their respective article on the meaning of a “real time city” [10], [11]. Wide sensor networks and monitoring systems are implemented in order to capture various information that lead to a better understanding of the city metabolism [12]. Nevertheless, in this new prospect where various aspects are measured by multiple stakeholders via multiple means, Bischof et al. [13] and Kazmi et al. [14] have raised in their respective article, the essential question of data heterogeneity, interpretability and exchange. Semantic web technologies such as OWL ontologies introduce a common taxonomy to a specific domain and explicit real world concepts' interrelationships, which can ultimately help tackle data heterogeneity and facilitate information discovery [15].

If good examples exist, a high-level ontology that can reconcile domain-specific data models to deal with data heterogeneity is missing. Moreover, in a field where consensus is difficult to reach, such ontology is an attempt to initiate agreement over an information model by synthetizing 29 authoritative urban sustainability frameworks; theirs recurrent terms, features and relationships.

This paper presents the urban district sustainability assessment ontology and its different modules; linking sensor networks' readings with sustainability Key Performance Indicators (KPIs), urban objects, time and location concepts. It is based on the NeOn methodology [16] and is described in details from the development of competency questions to the iterative concepts modelling and the selection of reusable ontological and non-ontological resources. The aim of the study is to contextualise urban system metrics, measured by sensor networks, using semantics providing a holistic coverage of the complex urban landscape. Such a data model is believed to improve the management of heterogeneous data, to facilitate information exchange and to better capture urban metrics interrelationships for fully leveraging effective real time urban sustainability assessment.

Section 3 summarises previous work related to: (a) technological background, (b) methodologies for ontologies development, (c) current urban sustainability assessment schemes, and (d) ontologies related to urban sustainability. Section 4 gives a detailed description of the methodology employed in the development of the proposed UDSA ontology. This includes a brief description of the NeOn methodology, an introduction to the newly developed urban district sustainability assessment framework, the specification of requirements for the ontology, and the ontology detailed description including its main features and the semantic resources used. In section 5, the ontology is then evaluated against a number of queries relevant in various real-world applications. Finally, some issues on the current implementation of the ontology for data access are discussed and recommendations for future development work are given in section 6.

3 RELATED WORK

The development of an urban sustainability assessment ontology requires a good understanding of the sustainability domains. Moreover, the development of a reliable, reusable and understandable ontology to support these domains, implies a rigorous methodology with the inclusion of already existing domain ontologies. This section reviews the technological assets and issues, thus giving an overall picture of where the semantic web stands in the ICT landscape. Additionally, different methodologies for ontologies development are reviewed as well as urban sustainability assessment schemes available across the world. Finally, the existing urban sustainability ontologies have been investigated in order to frame the current state of this specific field.

3.1 *ICTs, data heterogeneity and interoperability*

The domain of decision support and assessment is evolving with the multiplication of information and communication technologies. Domains such as the energy sector have already integrated the use of data and processing as an important mean to measure and inform decision making [17]. Although, data are increasingly considered by urban actors when it comes to decision support [18], real-world applications are still challenging due to the great variety of data sources [19]. Additionally, the interdisciplinary nature of sustainability makes data processing more complex, due to a lack of unified domain and data models [20]. Consequently, one of the most demanding task for a seamless data integration lies in the development of methods and data models that can deal with interoperability across platforms, domains and scales [21], [22]. In a domain that involves various actors and organisations, interoperability is essential for decision support as it standardises information flows between them [23] and ensures quality of data storage, including using cloud-based services [24]. In this current vision, semantic modelling and ontologies present a valuable perspective to overcome interoperability challenges, and a plethora of semantic repositories have been deployed to host domain-specific semantic models, as discussed in Section 3.4.

3.2 *Methodologies for ontologies development*

An ontology is a formal representation of a domain through concepts and ideas across different levels of abstraction [15]. A domain ontology should not only be generic enough to be reusable but also specific enough to avoid an over-generalization that can lead to omit relevant domain knowledge [25]. An ontology must find the right balance between generalization and specification and be designed in a way that maximises subsequent reuse and extensibility [26]. Therefore, the development of sustainability assessment ontology cannot be done without following an adapted methodology. The literature reveals a wide range of methodologies for ontology development such as: Ushold and King's methodology [27]–[29], METHONTOLOGY [30] , NeOn [16], On-to-knowledge methodology (OTKM) [31] , or UPON [32]. METHONTOLOGY considers the ontology entire life cycle and involves different stages namely, planning, specification, conceptualization, formalization, integration, implementation and maintenance. Equally, the methodology emphasises parallel activities that must be carried out throughout the entire process, such as knowledge acquisition, documentation and evaluation. OTKM is meant to help enterprises that wish to develop knowledge-based management applications. The methodology makes the distinction between knowledge meta-processes and knowledge processes where the first ones support ontologies development, while the second ones support their usage. The UPON methodology takes a software engineering approach in the development of an ontology by integrating the widely used standards that are the Unified Software Development Process (UP) and the Unified Modeling Language (UML). This approach aims to improve efficiency and quality by aligning UP components (cycles, phases, iterations, and workflow) with the ontology development stages. The process is in essence iterative and incremental and involves domain experts and knowledge engineers within each step to achieve desired levels of scalability and flexibility of the ontology criteria. Finally, the NeOn methodology is derived from the METHONTOLOGY [33]. It has been developed as an extended version of the METHONTOLOGY under the supervision of the experts that created it. This last methodology has been used for the development of the urban district sustainability ontology and will be more detailed in section 4.1.

3.3 *Urban sustainability assessment schemes*

In the last twenty years, many urban sustainability assessment schemes have been designed, targeting various domains and locations. The development of the UDSA ontology has required the review of an extended amount of schemes used across the world. In total, 61 frameworks spread across 21 different countries have been studied [34]. Out of the 61 frameworks, 32 appeared to be irrelevant for a full representation of the domain knowledge because of a lack of information or a too specific focus on a particular aspect of sustainability. Consequently, 29 frameworks have been studied in depth [4], [5], [35]–[61] (see Appendix). In most cases, the frameworks follow a hierarchical scheme "Theme-Criteria-Indicators" where themes can be referred as broad topics [62], criteria as required objectives to achieve sustainability [63], and indicators as quantitative or qualitative metrics [64]. The recurrence of indicators and their spread within these 29 schemes have been investigated. Overall, the addressed indicators vary from framework to framework, which highlights a lack of consensus on the very definition of sustainability. This issue has been pointed out in many studies on the topic [2], [8], [62]. In the presence of such differences and lack of consensus, it is difficult to objectively select one particular framework to be the core of the ontology. Thus, a new framework that synthesizes the 29 retained frameworks has been created. Indicators that occur in numerous frameworks, and are thus critical to sustainability assessment, can form a solid basis for the creation of a new framework with a view to design an ontology.

3.4 *Urban sustainability related ontologies*

Several ontologies in connection with urban sustainability assessment can be found in the literature concerning for instance building structure [65], water quality [66] or personal health information [67]. Some remarkable examples include the following ontologies. The Ontology for Global City Indicators has been developed in the frame of the PolisGnosis project [68] for the semantic representation of ISO 37120, a standard that contains over 100 indicators for city's quality of life and sustainability [69]. The ontology is compliant with analytical, statistical, geo-spatial, temporal ontologies as well as meta-knowledge representation such as provenance, validity and trust ontologies. It is divided into modules representing a specific domain of sustainability namely, Education, Energy, Environment, Finance, Fire and Emergency, Public, Recreation, Shelter, Telecommunications and Innovation [70]. The OSMoSys ontology introduced a knowledge representation for smart cities that can integrate heterogeneous data from various sources [71]. Even though the ontology does not formally develop sustainability KPIs, it describes different city systems such as energy, waste, water, transport, buildings etc. and associates them with data sources. The usefulness of the ontology has been demonstrated in a use case where social media sources were parsed and semantised, allowing the discovery of demographic insights of certain events during a festival in Amsterdam. Additional ontologies can be found that focus on more specific domains rather than covering the entire sustainability domain. For instance, the SEMANCO [72], the ee-district [73] or the Ambassador [74] ontologies are semantic models that aim at representing energy systems at the urban level. These specialised ontologies have been designed in the frame of European projects where ontology designers and domain experts were working together on developing a consistent and relevant knowledge representation of urban energy systems. The end goal was to help stakeholders in better managing energy systems at the urban level. In a different domain, a smart water ontology has been developed in the WISDOM project that targets water management through the integration of Geographic Information System (GIS) and topological network descriptions, telemetry data, BIM, smart metering, and smart appliances semantic models [20]. A final example is the Transport Disruption ontology that describes travel and transport related events, assessing their disruptive impact on mobility at the urban level [75]. These ontologies are examples of the efforts made in semantic development for urban sustainability or sustainability sub-domains representation. However, none of these ontologies abstracts the high-level concepts required by UDSA, as the existing models provide a fragmented view of the whole domain. Moreover, they are not necessarily aligned with current assessment schemes present in the literature (see section 3.3).

3.5 *Summary*

This section has introduced the state of the art in the field of urban district sustainability assessment. It has argued the case for a novel UDSA semantic data model and ways in which this could solve core problems inherited from the smart city movement such as data heterogeneity, interpretability and exchange in view of creating real-time UDSA tools.

Before engaging in ontological development, several methodological frameworks have been reviewed as rigor is essential for the creation of a well-designed ontology. The NeOn methodology has been chosen as it is an extension of the METHONTOLOGY, one of the most renowned methodology in the domain, and its well-detailed scenarios.

The methodology requires the review of ontological and non-ontological resources in order to draw core requirements and gaps in the current data model landscape for urban sustainability. The study of 29 established UDSA frameworks has enabled the construction of a set of terms and requirements that the future ontology should meet. The review of urban sustainability or sustainability sub-domain ontologies has evidenced the lack of a high-level ontology that addresses the frameworks' requirements holistically. This forms a key gap addressed by the present paper to reconcile currently available UDSA frameworks and existing low-level domain-specific ontologies.

4 URBAN DISTRICT SUSTAINABILITY ASSESSMENT (UDSA) ONTOLOGY

In this section, the NeOn methodology framework is first presented as the methodological background for the ontology development. Then, the development process of an UDSA ontology is described step by step, from the intended application to the definitive UDSA ontology schema, following the NeOn methodology.

4.1 *Methodology Background: The NeOn Methodology*

A review of the literature has shown that METHONTOLOGY is often cited as a reference in terms of semantic development, such as in Janowicz's article on the development of a geo-ontology [76] or in Garrido's and Requena's study of an ontology to support abstract environmental impact assessment [77]. Additionally, a survey conducted among ontology engineering experts has shown that the NeOn methodology was favoured over its parent METHONTOLOGY, because of the following features: (a) ease of understanding, (b) scenario-based approach, and (c) availability of supporting documentation [16]. This has motivated the selection of the NeOn methodology for the development of the urban district sustainability assessment ontology.

As an initial stage, NeOn and METHONTOLOGY have introduced the Ontology Requirement Specification (ORS) [33], [78]. This includes the development of competency questions that aim at determining the scope of the ontology as Grüninger and Fox mentioned it in their early research on ontology design and evaluation methodologies [27] or Staab et al. in their article on tools and methodologies for ontology-based knowledge management systems [79]. Ultimately, the ORS via the use of competency questions enables to identify (a) the purpose of the ontology to be developed; (b) the intended uses and users of the ontology; (c) the set of requirements that the ontology should satisfy [79].

Following the ORS, the ontology expert can then investigate the relevant knowledge resources at his/her disposition for the creation of the ontology. Two types of knowledge resources can be used and integrated in the future ontology: non-ontological (such as glossaries, taxonomies, thesauri, dictionaries etc.) and ontological resources. The reuse of ontological resources allows a less time and cost consuming development and the creation of a more generic semantic framework. Therefore, the use of already existing ontologies to represent certain concepts is highly recommended.

Finally, selected resources might have to be adapted to best fit the purpose of the new ontology. Terminologies and concepts must be aligned, which potentially requires the removal or addition of axioms, the restructuring of the architecture, and translation. The overall consistency must then be verified and the model reworked in an iterative process until reaching complete validity.

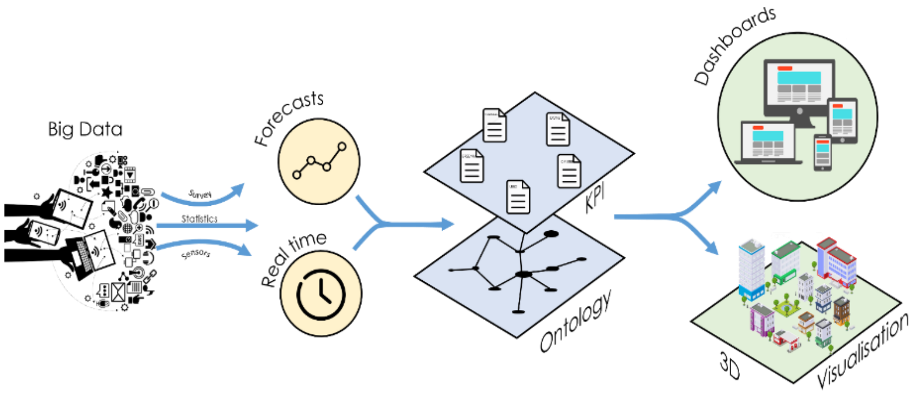

Figure 1 Real-time UDSA Framework

4.2 *Real Time Urban district sustainability Assessment Framework*

In this section, the intended use of the ontology within a real time urban district sustainability assessment is given to contextualise its development. The diagram shown in Figure 1 depicts the main features of the future application. Data are collected from various sources such as smart meters, survey or statistical datasets. They are instantiated into the ontology and analysed in other data processing tools. The ontology aims to give meaning to the different elements of the built environment, environmental indicators, possible actions and impacts etc and describes their possible multidomain and multiscale connections. It gives a picture of the overall concepts and theirs influences rather than simply considering them individually. Additionally, as mentioned earlier in Section 3.1, the ontology allows to deal with data heterogeneity by introducing a core data model for a seamless information flow. These elements are underlying a 3D graphical user interface. The 3D interface gives a meaningful representation of the urban environment, enables user-friendly navigation and provides the labelling of various components. Finally, a dashboard displays the main outcomes such as the key performance indicators based on the framework definition, the real time information, scenario predictions, alerts, recommendations, reports etc.

Consequently, looking at the intended application for a real-time framework, several requirements can be foreseen: (1) the ontology must be able to describe concepts such as data and control systems, including sensors; (2) it must capture geospatial and urban structures information; (3) it must link sustainability domains and concepts with real world objects and; (4) it must be able to represent time related information.

4.3 *UDSA Ontology Requirements Specification*

The ORS includes several specific tasks. These tasks have been undertaken following the ontology requirements specification documentation (ORSD) shown in Table 1.

Table 1 ORSD

Goal of the ontology	The main goal of the ontology is to give the user insight on the impact of their actions on the sustainability indicators, criteria and themes. It requires to map actions, objects, agents and sustainability KPIs, including relationships with each other.
Domain and Scope	Urban district sustainability assessment, built environment, operational actions, temporal changes, people, geolocation.
Uses and Users	• Users: city managers, stakeholders, governmental institutions, inhabitants • Use Case 1: Visualisation of sustainability indicators, criteria and themes interconnection • Use Case 2: Visualisation of Indicators-Action-Objects-Agents interconnection • Use Case 3: Association of indicator with regulation and benchmarks • Use Case 4: Spatial definition • Use Case 5: Evaluation of temporal changes in real time paradigm
Knowledge resources	Existing urban sustainability assessment frameworks, published papers, experts consultation
Requirements	See competency questions (Table 2, Table 3, Table 4)
Prioritizing	See competency questions (Table 2, Table 3, Table 4)
Terminology	See competency questions (Table 2, Table 3, Table 4)

4.3.1 *Goal, domains and scopes*

The ontology aims to cover multiple goals and domains. The primary purpose of the ontology is the representation of the existing interconnections between the constituents of urban sustainability assessment schemes (e.g. indicators, criteria, sub-themes, themes). It specifies which indicator participates in which criterion, and in turn, which criterion participates in which sub-theme and theme. Explicit and implicit relationships between indicators are therefore described. Overall, complex relationships between themes, subthemes, criteria and indicators can be described accurately.

Moreover, an indicator makes sense only when associated with a reference. In the present case, sustainability is formally described through benchmarks that are compared against the actual value of an indicator. Thus, the ontology must include the linkage between an indicator and its references.

The second goal is the representation of indicator values coupled with the location and time. The aim is to capture information such as: what these values are, where are they from, which instruments/methods are being used for their determination. Sensor networks and ICTs are already considered in that matter and thus, must be taken into account.

Another goal to consider is the illustration of the relationship between the actions applied within an urban area and their impacts on specific indicators, criteria or themes.

Finally, the last objective is to link the different objects present within an urban area with the indicators. Therefore, urban furniture, building components or even human agents can be identified, and indirectly associated to an indicator via semantic network.

4.3.2 *Use and Users requirements*

Several use cases are being considered. Some have been introduced in the previous section, such as the in-depth representation of the theme-criteria-indicator scheme commonly found in the UDSA. The user must be able to query those relationships and better understand that the improvement of some aspects can positively or negatively affect some others. It would promote vision on sustainability as a holistic, interconnected system. Equally quoted in the previous section, the actions/impact relationship would give a better insight to people on the after-effect of their actions. They must be able to query the system on the possible actions that can be done in order to improve a specific indicator, or vice versa, query which indicators are affected by an action. Moreover, indicators and other scorable elements can be linked to people and object, allowing the user to better visualise what and who affects sustainability at the urban level. Finally, indicators are often subject to regulations with targets and objectives that change with place and time. Therefore, the ontology must support

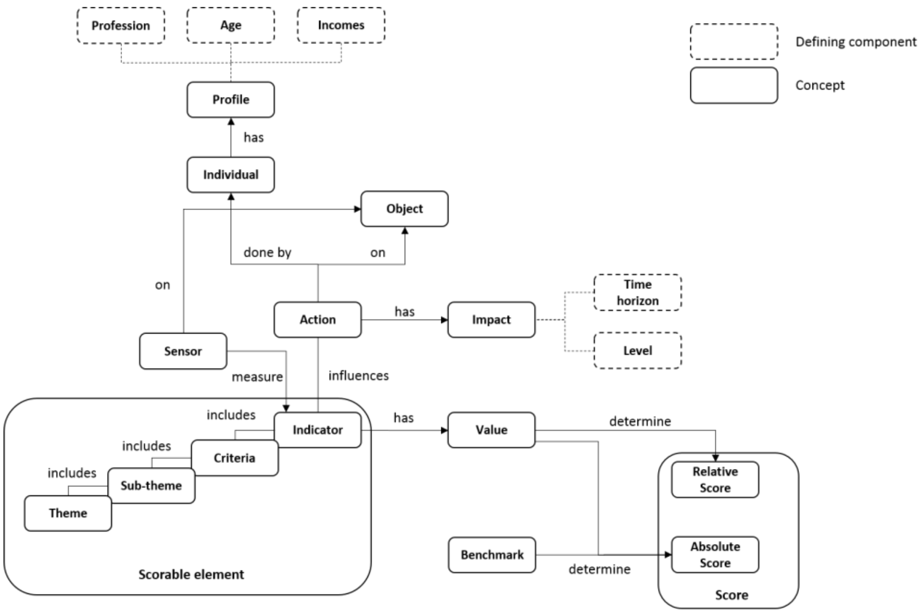

Figure 2 Knowledge mind map

linked data so that modification of certain parameters, such as benchmark values for instance, can be taken into account dynamically within the scheme.

The ontology is meant to be used by everyone involved in one way or another within a community such as governmental institutions, associations, stakeholders, city managers, engineers, architects, urban planners, tenants etc. Depending on the user, the tool will serve different purposes. City stakeholders will see the tool as a support for decision-making, while in the case of simple citizens, the ontology will raise awareness on sustainability.

4.3.3 *Competency questions*

The competency questions require an in-depth development. The first stage has been to develop a mind map of the different elements that constitute the domain (as shown in Figure 2). This mind map is a first draft; it is not intended to reflect the entire complexity of knowledge but to guide the formulation of the competency questions.

Thus, some relationships are better conceptualized, for instance, which objects within the urban environment affect which indicators, what is the average impact of a certain type of individual or the association between benchmarks and indicators. These relationships come as questions and it is through the development of these questions that knowledge takes shape.

With the help of the previous steps, a primary terminology of the domain has been developed which is then used to define the competency questions. The competency questions have been divided into three different groups shown in Table 2 to Table 4: the first group relates to the relationship between different scorable elements (Themes, Sub-Themes, Criteria, Indicators); the second group relates to querying the values of certain scorable elements as well as their respective weight, location, reference date and unit; and the third group relates to the connections between actions, objects, individuals and their impact on scorable elements.

Table 2 Scorable elements competency questions

Question	**Subjet**	**Property**	**Object**
Which scorable element has scorable element X?	Scorable Element	hasScorableElement	Scorable Element
Which Theme has scorable element X?	Theme	hasScorableElement	Scorable Element
Which SubTheme has scorable element X?	SubTheme	hasScorableElement	Scorable Element
Which Criteria has scorable element X?	Criteria	hasScorableElement	Scorable Element
Which scorable element has criteria X?	Scorable Element	hasCriteria	Criteria
Which Theme has criteria X?	Theme	hasCriteria	Criteria
Which SubTheme has criteria X?	SubTheme	hasCriteria	Criteria
Which scorable element has indicator X?	Scorable Element	hasIndicator	Indicator
Which criteria has indicator X?	Criteria	hasIndicator	Indicator
Which Theme has indicator X?	Theme	hasIndicator	Indicator
Which SubTheme has indicator X?	SubTheme	hasIndicator	Indicator
Which scorable element has SubTheme X?	Scorable Element	hasSubTheme	SubTheme
Which Theme has SubTheme X?	Theme	hasSubTheme	SubTheme

Table 3 Value and score competency questions

Question	**Subjet**	**Property**	**Object**
Which Indicator has element value X?	Indicator	hasElementValue	ElementValue
Which benchmark is associated to indicator X?	Benchmark	has Associated Indicator	Indicator
Which scorable element has score X?	Scorable Element	hasScore	Score
Which scorable element has absolute score X?	Scorable Element	hasAbsoluteScore	AbsoluteScore
Which scorable element has RelativeScore X?	Scorable Element	hasRelativeScore	RelativeScore
Which scorable element has TemporalRelativeScore X?	Scorable Element	hasTemporalRelativeScore	TemporalRelative Score

Which scorable element has SpatialRelativeScore X?	Scorable Element	hasSpatialRelative Score	SpatialRelative Score
What is the value of Element value X?	Element Value	hasValue	Float/double
What is the Unit of Element value X?	Element Value	hasUnit	String
What is the reference date of Element value X?	Element Value	hasReferenceDate	DateTime
What is the location of Element value X?	Element Value	hasLocation	String
What is the value of Benchmark X?	Benchmark	hasValue	Float/double
What is the Unit of Benchmark X?	Benchmark	hasUnit	String
What is the reference date of Benchmark X?	Benchmark	hasReferenceDate	DateTime
What is the location of Benchmark X?	Benchmark	hasLocation	String
What is the value of Score X?	Score	hasValue	Float
What is the Unit of Score X?	Score	hasUnit	String
What is the reference date of Score X?	Score	hasReferenceDate	DateTime
What is the location of Score X?	Score	hasLocation	String

Table 4 Action/Impact and Urban Objects competency questions

Question	Subjet	Property	Object
Which action has influenced scorable element X?	Action	hasInfluenceOnScorableElement	ScorableElement
Which action has impact X?	Action	hasImpact	Impact
Which action has associated urban object X?	Action	hasAssociatedUrbanObject	UrbanObject
Which Indicator are associated to urban object X?	Urban Object	hasAssociatedUrbanObject	UrbanObject
Which impact has associated scorable element X?	Impact	hasAssociatedScorableElement	Scorable Element
Which person has done action X?	Person	hasDoneAction	Action
What are the details of Person X ?	Person	hasDetails	String
What is the start date of action X?	Action	hasStartDate	DateTime
What is the end date of action X?	Action	hasEndDate	DateTime
What is the level of impact X?	Impact	hasLevel	Float
What is the StartDate of impact X?	Impact	hasStartDate	DateTime
What is the EndDate of impact X?	Impact	hasEndDate	DateTime

4.4 *Resources reuse*

As mentioned in section 4.1, the efficient development of an ontology rests on the reuse of previously designed ontologies. This will ensure the development of an ontology that is grounded in authoritative more abstract ontologies and is, as such, compliant with reliable domain-specific ontological resources.

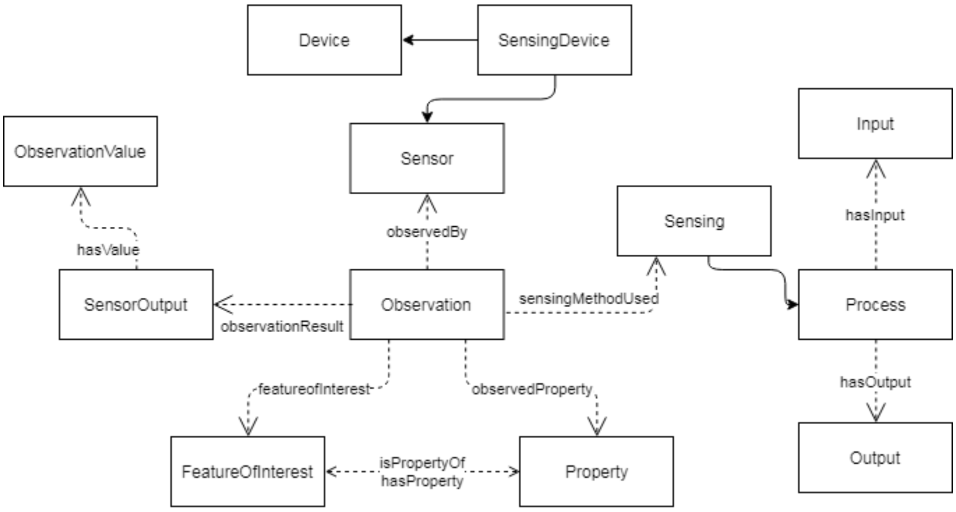

Figure 3 The SSN ontology entity relationship diagram , key concepts and relations adapted from [80]

The urban district sustainability assessment framework relies on the collection of data through various means such as sensor devices, surveys or statistical databases. These data are meant to define the values of the indicators either by direct reading or with calculation methods. The core components of the UDSA ontology must therefore focus on the representation of sensors and sensor readings. In the past decade, several ontologies have been designed to represent the abstract notions of sensor and observation. A notable framework found in the literature is the Semantic Sensor Network (SSN) ontology. The W3C Semantic Sensor Network Incubator group (SSN-XG) defined an OWL 2 ontology to describe the capabilities and properties of sensors, the act of sensing and the resulting observations [80]. The entity-relationship diagram in Figure 3 shows that SSN extends O&M by adding a formalism that covers the representation of sensors and their relations. Therefore, the SSN ontology has been chosen in the frame of the study since it covers additional important aspects such as the presence of sensors or sensing devices. Moreover, this ontology relies on the DOLCE+DnS Ultralite ontology or DUL, an upper ontology that aims to capture the semantic categories underlying natural language and human common-sense [81].

The future framework will require the use of geospatial reference and structure as well as the different units of measurement associated with the indicators. Those two features are often required in new ontology development and therefore benefits from well-developed schemes that achieve consensus within the community. Geospatial references can be queried through the GeoSPARQL language, which includes Well Known Text (WKT) and Geography Markup Language (GML), and a standard way to query relationships between spatial entities [82]. In the case of the units of measurement, NASA have developed the Ontology for Quantities, Units, Dimensions and Data Types or QUDT ontology that supports any existing unit [83].

Finally, an UDSA user could directly associate urban objects and people within an urban system with models expressed in other knowledge/data representations such as BIM (e.g. complying with the IFC specification using ifcOWL) [84] or cityGML [85] and the Friend of a Friend (FOAF) ontology [86].

When it comes to reusing non-ontological resources, the authors have chosen the most frequently encountered KPIs within the frameworks reviewed in Section 3 for the development of their own framework, thus guaranteeing a well-defined framework that takes into consideration the most important features of urban district sustainability. The end result is a graph structure with interconnected themes, sub-themes, criteria and indicators, including 8 Themes, 26 sub-themes, 90 criteria and 197 indicators.

4.5 *The UDSA ontology schema*

Figure 4 shows a schema abstraction of the UDSA ontology. The development of the UDSA ontology has required many efforts in aligning the terms defined in the competency question with the terms present in the reused ontological resources that are SSN, DUL, QUDT and GeoSPARQL. Equally, new interrelationships between elements have been defined. The ontology is composed of several modules: the observations module, the UDSA framework module, the spatio-temporal module and the urban objects module. Detailed representations of those modules are given in the following sections.

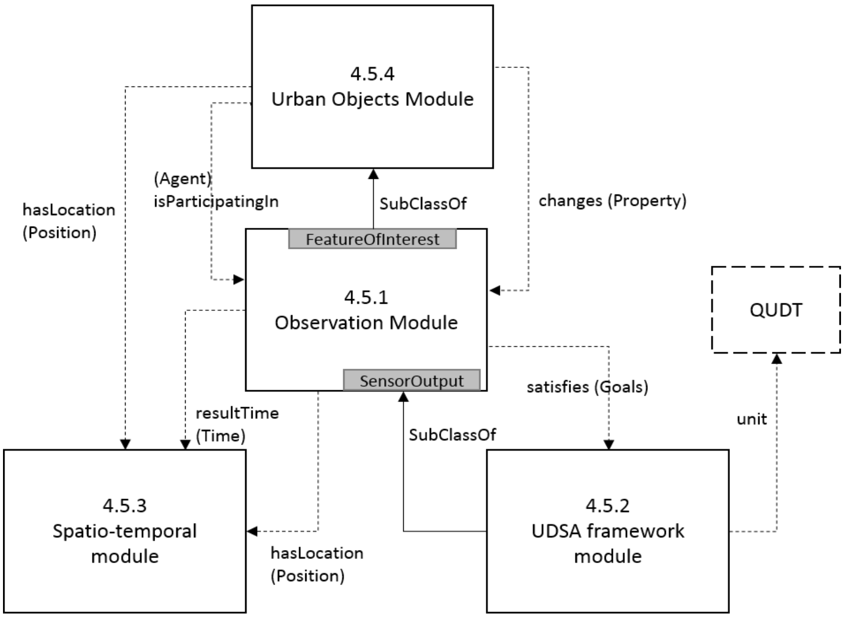

Figure 4 UDSA ontology modular entity relationship diagram

Note that the following section contains some elements expressed in Description Logic syntax. The syntax used is briefly explicated below:

→ ⊑ correspond to concept inclusion (is subclass of)

→ ≡ correspond to concept equivalence (is equivalent of)

→ ⊓ correspond to the intersection operator (AND)

→ ⊔ correspond to the union operator (OR)

→ ∃ correspond to an existential restriction (SOME exist in)

4.5.1 *Observation module*

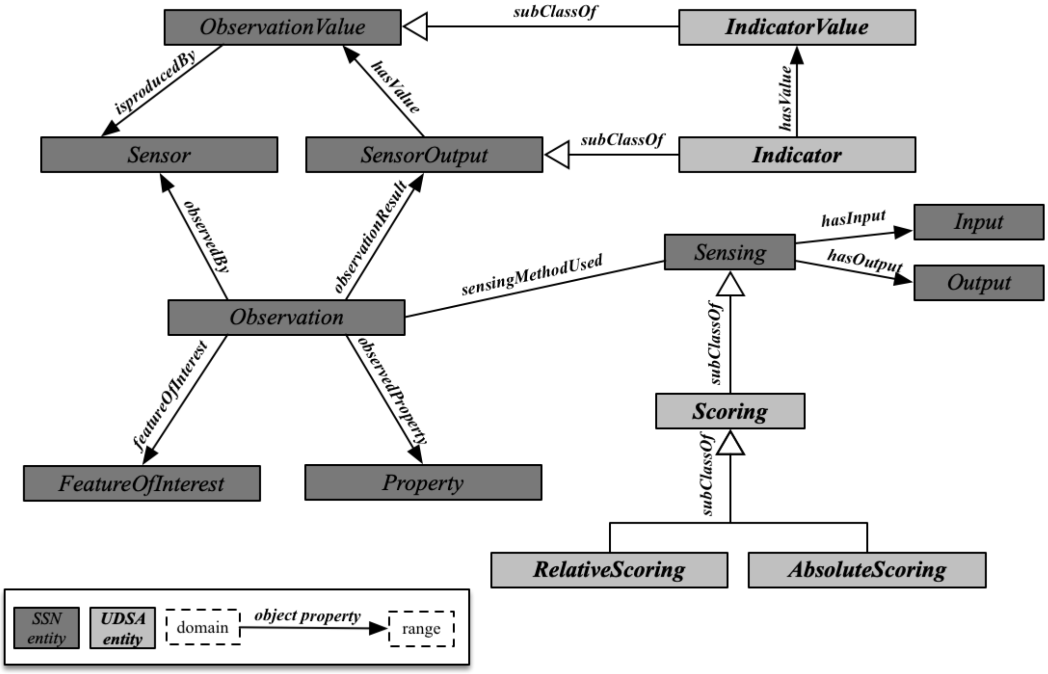

Figure 5 UDSA observation module entity relationship diagram

Figure 5 presents the observation module. The observation module is the core of the UDSA ontology. Essentially based on the SSN ontology, this module allows the description of an indicator as the output of an observation. In SSN, an observation is a situation in which a property of a feature of interest is observed by a sensor via a sensing method. Therefore, this links the abstract notion of indicator to both a real phenomenon and a sensor network (potentially bridging UDSA with IoT networks).

In other terms, the SSN alignment is done via *udsa:Indicator* $\sqsubseteq$ *(ssn:SensorOutput* $\sqcap$ $\exists$ *ssn:hasValue.udsa:IndicatorValue)* where *udsa:IndicatorValue* $\sqsubseteq$ *ssn:observationValue*.

Furthermore, the notion of sensing method is defined (*ssn:Sensing*) as the process that results in the estimation or calculation, of the value measuring a phenomenon. This process takes some *ssn:Inputs* and gives back some *ssn:Outputs*. UDSA ontology uses these concepts in order to defined the process of scoring (*udsa:Scoring*) and its subclasses. Therefore:

→ *udsa:Scoring* $\sqsubseteq$ *ssn:Sensing*;

→ *(udsa:AbsoluteScoring ⊔ udsa:RelativeScoring) ≡ udsa:Scoring*;

Where *udsa:AbsoluteScoring ⊑ (∃ ssn:hasOuput.udsa:AbsoluteScore)*

→ *(udsa:SpatialRelativeScoring ⊔ udsa:TemporalRelativeScoring) ≡ udsa:RelativeScoring*;

Where *udsa:RelativeScoring ⊑ (∃ ssn:hasOutput.udsa:RelativeScore)*

→ *(udsa:Assessing ⊔ udsa:Forecasting) ≡ udsa:TemporalRelativeScoring*.

4.5.2 *UDSA framework module*

Figure 6 shows the framework module with the relationships between entities.

Table 5 summarises the existential restrictions that exist between the different scorable elements.

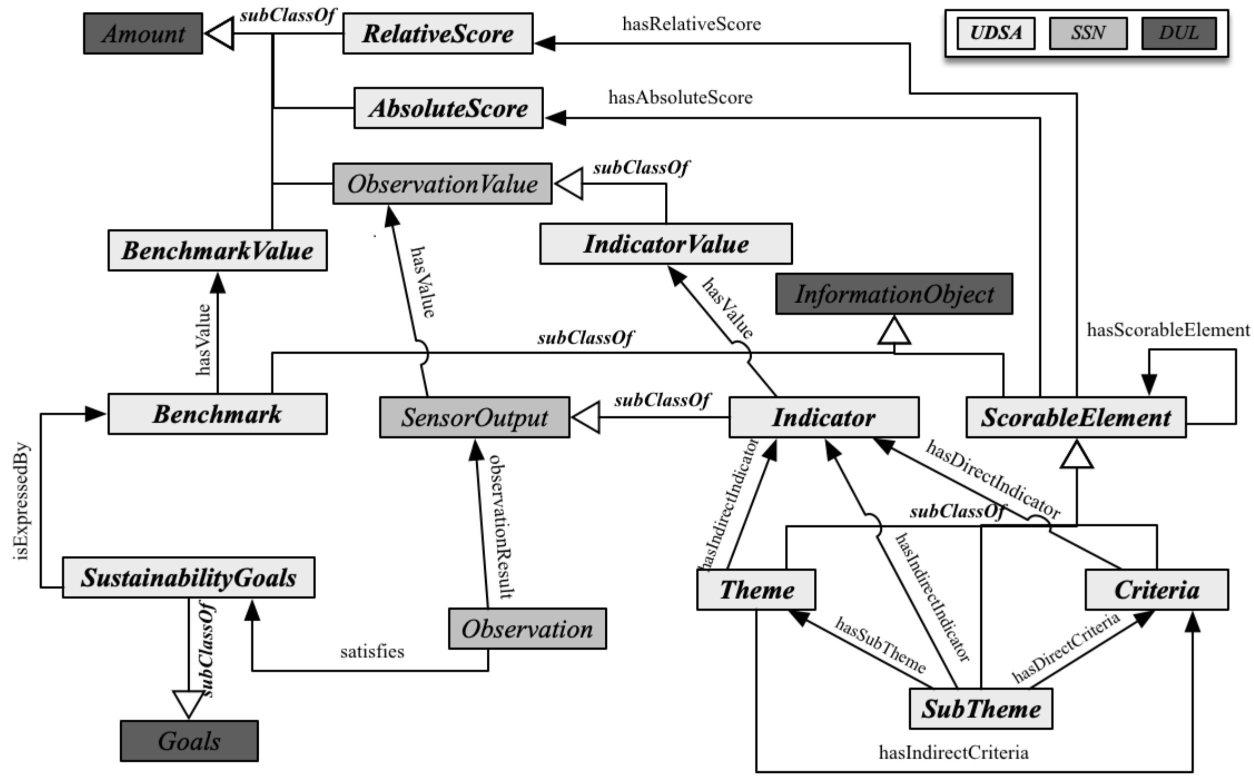

Figure 6 UDSA framework module entity relationship diagram

Table 5 Existential Restriction between scorable elements

	udsa:Indicator	**udsa:Criteria**	**udsa:SubTheme**	**udsa:Theme**	**udsa:ScorableElement**
udsa:Indicator	-	udsa:isDirect IndicatorOf	udsa:isIndirect IndicatorOf	udsa:isIndirect IndicatorOf	udsa:isIndicatorOf
udsa:Criteria	udsa:hasDirect Indicator	-	udsa:isDirect CriteriaOf	uudsa:isIndirect CriteriaOf	Udsa:isCriteriaOf
udsa:SubTheme	udsa:hasIndirect Indicator	udsa:hasDirect Criteria	-	udsa:isSubTheme Of	udsa:isSubThemeOf
udsa:Theme	udsa:hasIndirect Indicator	udsa:hasIndirect Criteria	udsa:hasSubTheme	-	-
udsa:ScorableEleme nt	udsa:hasIndicator	udsa:hasCriteria	udsa:hasSubTheme	-	udsa:hasScorableElement udsa:isScorableElementOf

In addition to the table, the following axioms are present:

→ *(udsa:Theme ⊔ udsa:SubTheme ⊔ udsa:Criteria ⊔ udsa:Indicator) ≡ udsa:ScorableElement;*

→ *(udsa:isDirectIndicatorOf ⊔ udsa:isIndirectIndicatorOf) ≡ udsa:isIndicatorOf.;*

→ *(udsa:hasDirectIndicator ⊔ udsa:hasIndirectIndicator) ≡ udsa:hasIndicator;*

→ *(udsa:isDirectCriteriaOf ⊔ udsa:isIndirectCriteriaOf) ≡ udsa:isCriteriaOf.;*

→ *(udsa:hasDirectCriteria ⊔ udsa:hasIndirectCriteria) ≡ udsa:isCriteriaOf*.

Moreover, indicators (*udsa:Indicator*) are considered as an information object (*dul:InformationObject*). They must be linked to their actual values *(∃ ssn:hasValue udsa:IndicatorValue*) whereas the totality of the scorable elements (*udsa:ScorableElement*) must be linked to a score (*udsa:AbsoluteScore* and/or *udsa:RelativeScore*). Ideally, observations must satisfy some sustainability goals (*udsa:SustainabilityGoal*) that are expressed by benchmarks (*udsa:Benchmark*). The values of the benchmarks are then assigned via the class *udsa:BenchmarkValue*.

Besides, given the high number of indicators, criteria, subthemes and themes considered in this ontology, Figure 6 is not exhaustive. In practice, the *udsa:Indicator* class contains as many subclasses as there are indicators within the scheme. The same applies to criteria, subthemes and themes. Each scorable element is then defined by specific relationships. An example is given below of how the ontology is structured to define what the total energy demand from buildings indicator is and how it relates to the other entities of the UDSA framework:

→ $udsa{:}ResourcesAndClimateTheme \sqsubseteq (udsa{:}Theme \sqcap \exists\, udsa{:}hasSubTheme$ $udsa{:}EnergySubTheme);$

→ $udsa{:}EnergySubTheme \sqsubseteq (udsa{:}SubTheme \sqcap \exists\, udsa{:}hasDirectCriteria$ $udsa{:}EnergyUseCriteria);$

→ $udsa{:}EnergyUseCriteria \sqsubseteq (udsa{:}Criteria \sqcap \exists\, udsa{:}hasDirectIndicator$ $usaTotalEnergyDemandIndicator);$

→ $usaTotalEnergyDemandIndicator \equiv (udsa{:}Indicator \sqcap \exists\, udsa{:}isObservationResultOf$ $(ssn{:}Observation \sqcap (\exists\, ssn{:}featureOfInterest.udsa{:}TotalEnergyDemand) \sqcap (\exists$ $ssn{:}observedProperty.udsa{:}EnergyProperty)))$

As demonstrate above, an indicator is seen as the result of an observation that combines a specific feature of interest with a specific property. For example, *udsa:TotalEnergyDemandIndicator* combines *udsa:TotalEnergyDemand* feature of interest with the *udsa:EnergyProperty*. Thus, from 193 indicators, 37 different properties and 187 different features of interest have been identified and introduced within the ontology. For illustrative purpose, those have not been introduced and the figure 6 only presents a sample of the actual ontology schema.

4.5.3 *Spatio-temporal module*

The spatiotemporal module shown in Figure 7 helps to understand how time and location are integrated within the scheme. The idea is to provide each observation (and thus KPI) with a place and a time of validity. The sampling start and end times (*udsa:SamplingStartTime* and *udsa:SamplingEndTime*) are the dates that frame the validity of an observation (often the time in between two logs) whereas the result time (*udsa:ResultTime*) is the time at which the observation is acquired by the observer. On the other hand, the class *udsa:UrbanSystem* represents the area for which an observation is valid. The geometry of the area is represented by the *udsa:SamplingGeometry* class and is encoded via a WKT Literal or GML Literal, a vector of coordinates that allows definition of a geo-referenced polygon. In the same way, sensor positions are defined via the *udsa:Position* class and encoded as WKT Literal or GML Literal with a pair of coordinates.

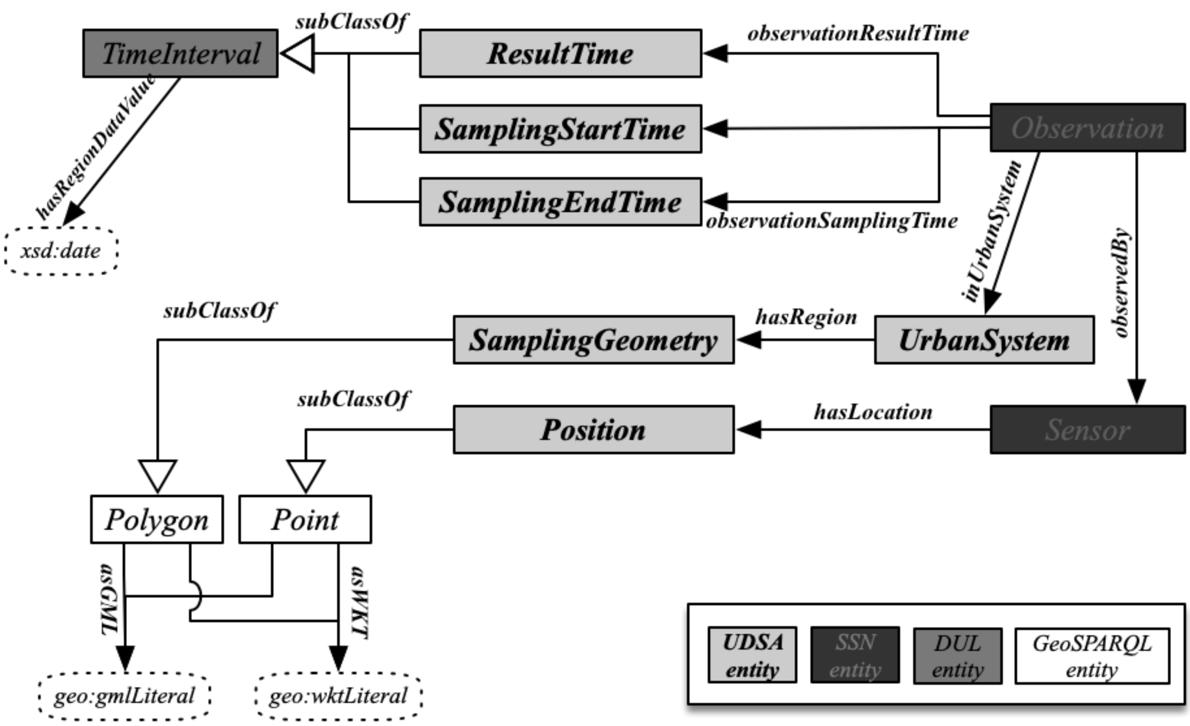

Figure 7 UDSA Spatiotemporal module entity relationship diagram

4.5.4 *Urban objects module*

Figure 8 shows a more detailed version of the UDSA urban object module. The DUL ontology [81] defines an object as being "Any physical, social, or mental object, or a substance. Following DOLCE Full [81], objects are always participating in some event (at least their own life), and are spatially located." This class allows to define features of interest as actual object entities present in an urban system and confers additional meaning to the object. Consequently, some efforts have been made in the breakdown of each of the 187 features of interest into set of "simpler" objects in order to populate the ontology with relevant objects within an urban area.

For instance:

→ *udsa:HazardousWaste* ⊑ *(udsa:HazardousObject* ⊓ *udsa:Waste)*;

→ *udsa:HeatFromRenewableSources* ⊑ *(udsa:Heat* ⊓ ∃ *dul:isParticipantIn. udsa:EnergyGeneration)* where *udsa:EnergyGeneration* ⊑ dul:*Event*

This breakdown of the features of interest into sets of several different objects led to the

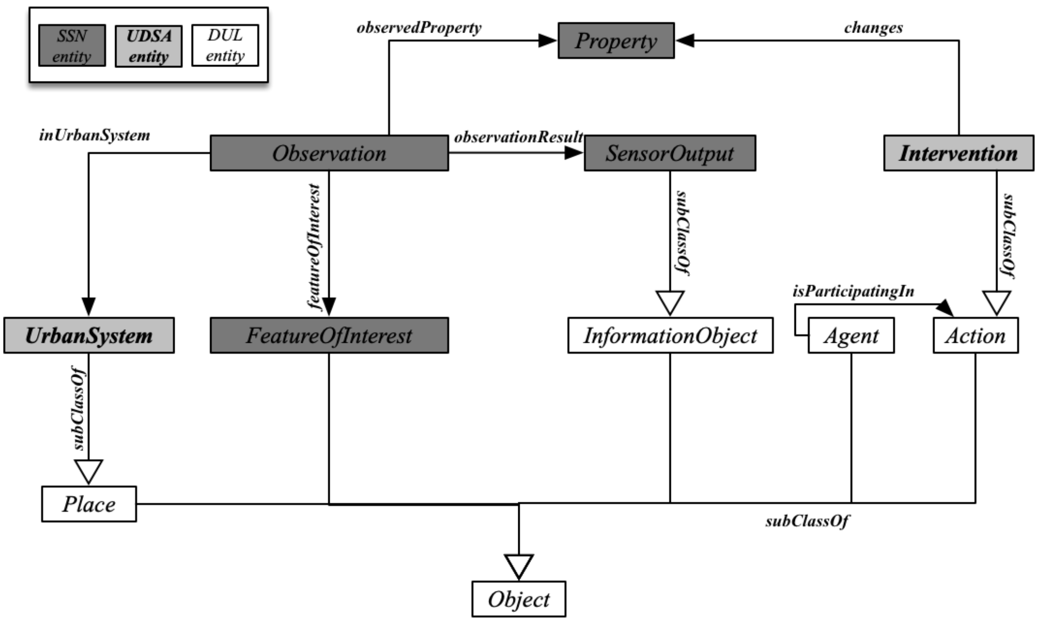

Figure 8 UDSA urban object module entity relationship diagram

creation of around 234 new classes and 14 new object properties. These additional classes give a better insight for feature of interest definition and enable the linkage between indicators and actual objects present in an urban system. Furthermore, some equivalences between those objects and schemas such as cityGML or IFC4 allow their integration within the framework. Additionally, Figure 8 shows the introduction of the class "*udsa:Intervention*". An intervention is seen as an action (*dul:Action*) done by an agent that will change or influence some properties of a feature of interest. This allows the scheme to describe how an indicator can be changed via interventions and to track those changes.

5 EVALUATION

In order to evaluate the reliability of the new ontology, SPARQL queries have been implemented in line with the identified competency questions. SPARQL is a query language that allows the user to perform queries using OWL 2 entities (classes, properties, data properties) in order to retrieve the relevant information from the knowledge base [87].

In the search for validation, the ontology must first be instantiated with example data. The present ontology has the particularity to rely on time series data from sensors. Datasets have therefore been collected from various sensors on the site of Ebbw Vale called "The Works" (Wales, UK) in order to proceed to complete verification. The Works was formerly occupied by steelworks that closed in 2002 and had been regenerated in 2012/2013 with a local district heating with heat provided by a combination of CHP units, biomass boilers and gas boilers. A BMS manages the energy provision and measures heat and electricity production and demand from the different buildings. Data have been taken from sensors readings directly or simulated when unavailable using the energy simulation software EnergyPlus. The sensor data have been pre-processed and cleaned to fit the purpose of the study. Overall, if the time series does not reflect the true phenomenon within the district, efforts have been made to make them realistic.

The result of the evaluation queries against the real case study of “The Work” can be found in Figure 9 and Table 6.

5.1 *Ontop*

When querying data via the ontology, time series appeared to be too voluminous. Indeed, in the ontology, each timestamp of a time series is considered as a single *ssn:Observation* so that they will be at least as many triples populating the triple-store (a database designed to store OWL triple instances) as there are measures from the sensors altogether. This will lead the reasoning engine to infer explicit and implicit relationships over an extremely high amount of triples, which might be computationally impracticable.

On that matter, Protégé’s plugin ONTOP can help. ONTOP is an on-the-fly ontology-based data access framework that populates an ontology on-the-fly with instances extracted from a relational database [88]. It is based on the OWL 2 QL profile, an entailment profile from OWL 2 [89]. OWL 2 QL allows reasoning over a large volume of instance by a trade-off of expressivity. Therefore, some axioms remain, such as subclass axioms, equivalences, inverses, properties etc, whereas some others, such as transitivity, cardinality restrictions or universal and existential restrictions, are not supported.

5.2 *Queries example*

In this section, two types of queries are reported. The first set of queries was done on the TBOX, which contains the terminology, while the second set of queries relates to the ABOX, which contains the assertions. Those requests have been done in Protégé using a desktop computer with 1TB HDD, Intel Core i7-4790 CPU 3.60GHz, 24 GB memory and Windows 7 64-bits.

- TBOX

This set of queries has been run with the HermiT reasoner that allows DL queries (Figure 9). The first query (a) retrieves all the scorable elements (themes, subthemes, criteria and indicators) that compose the UDSA framework while in query (b), only the indicators are retrieved. Query (c) allows the user to get all the scorable elements that contain the indicator "*TotalEnergyDemandIndicator*". Query (d) is an example of a more complex query that can be run in order to obtain the themes and criteria that contain "*TotalEnergyDemandIndicator*". These queries are few examples of the use of the ontology to investigate the UDSA framework structure and therefore can answer the questions present in Table 2.

Query (e) examines which indicator is linked to the feature of interest "*UrbanSystem*" coupled with the property "*Noise*". Axioms have been implemented so that the ontology logically returns "*AmbientNoiseIndicator*".

Finally, query (f) is an example of how the restrictions implemented within the axioms stop the query engine from giving wrong object as answer.

- ABOX

Queries regarding the instances are run using ONTOP-SPARQL, a SPARQL query end-point that uses ONTOP 3.0.0 reasoning engine. Table 6 shows a set of queries that have been run over the Works site data. In query (a), the user wants to know which scorable elements are evaluated within the district specified with WKT polygon string. *GHGEmissionsIndicator* is part of the list of 41 elements associated to the evaluation of this specific urban system. Therefore, in query (b), one retrieves the value of the *GHGEmissionsIndicator* within the district. The query gives the date, value and unit of measure of the indicator. In the present case, the user retrieve the entire time series but one could also specified bounding dates to get specific values. In query (c), the user is interested in knowing how GHG emissions scores. The date, score values as well as the benchmark value and its unit are shown. In the next query (d), one can see the different inputs that have been used for the calculation of the

GHGEmissionsIndicator. Therefore, the constants used such as the average emissions factors of the different energy sources (local or external) and the time series involved in the calculation (*sensor1, sensor8, sensor13 …*) are given. The features of interest (*foi, foiname*) of those inputs are then retrieve in query (e) so that the user knows what the sensors refer to. In this same query, one wants to know which building within the urban system is associated to the features of interest. Here, *EbbwVale/LeisureCenter*, *EbbwVale/School*, *EbbwVale/LearningZone* etc are shown. As opposed to the other instances that only exist within the database, those specific instances referring to buildings are present in the ontology and linked to the features of interest via ONTOP mappings. This procedure is essential since it allows the instantiation of cityGML or BIM models objects directly within the ontology and to associate them to others entities that only exist in the database. Finally, the query (f) demonstrates how one can compare values between different dates. The same kind of query can be done to compare different indicators, in different places and different times. Additionally, similar queries could be done to evaluate the impact of certain actions on KPI.

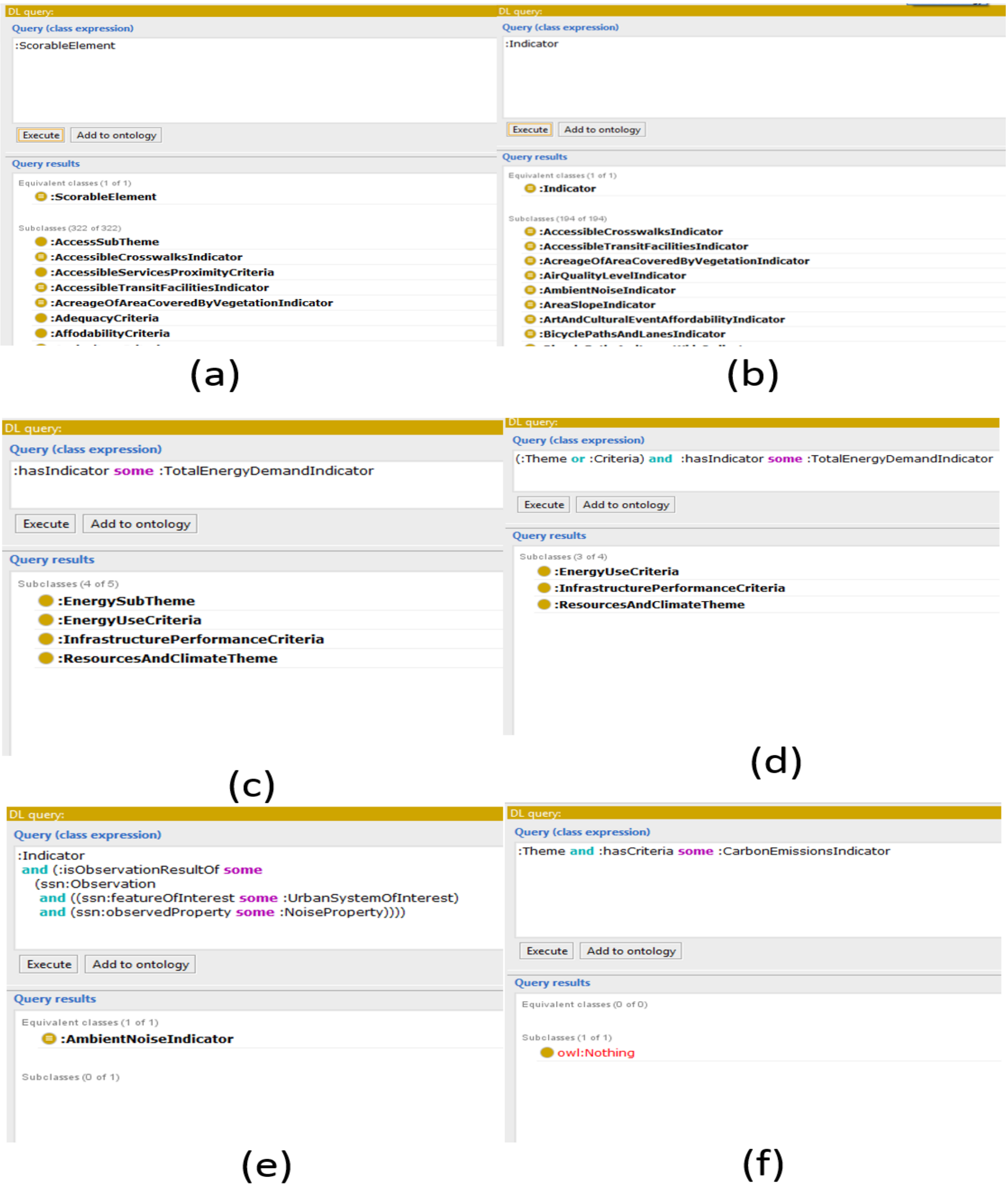

Figure 9 DL queries on the USA framework

Table 6 Example competency questions (prefix statement omitted).

(a) What are the indicators measured in a certain urban system defined by a polygon?

SPARQL query	*Output (41 records in 1.501 sec)*
SELECT DISTINCT ?out WHERE{ ?sensing a ssn:Sensing ; ssn:hasOutput ?out. ?sensingevent a :SensingEvent ; dul:hasParticipant ?us ; dul:hasParticipant ?sensing. ?us a udsa:UrbanSystem; dul:hasRegion ?region . ?region geo:asWKT "POLYGON((-3.2001328468322754 51.77338480231185,-3.2047462463378906 51.77298647746679,- 3.2060980796813965 51.77764665809645,-3.2019782066345215 51.77791218096247,-3.2001328468322754 51.77338480231185))".}	:ElectricalLossesIndicator/1/ :ElectricityFromRenewalbeSourcesIndicator/1/ :GHGEmissionsIndicator/1/ …

(b) What are the readings of GHGEmissonsIndicator/1/ previously found?

SPARQL query	*Output (2016 records in 8.102 sec)*
SELECT DISTINCT ?ob ?tvalue ?value ?unitval WHERE{ :GHGEmissionsIndicator/1/dul:isExpressedBy ?so. ?ob a ssn:Observation ; ssn:observationResultTime ?time ; ssn:observationResult ?so ; ssn:observedBy ?sensor. ?so ssn:hasValue ?obsval; qudt:unit ?unit . ?obsval udsa:hasNumericValue ?value. ?unit qudt:baseUnitDimensions ?unitval . ?time a udsa:ResultTime ; dul:hasRegionDataValue ?tvalue .}	:observation/80641/ "2015-09-17T00:00:00+01:00"^^xsd:dateTime "170"^^xsd:decimal "kgCO2e"^^xsd:string …

(c) What are the scores and benchmark of GHGEmissonsIndicator/1/ ?

SPARQL query	*Output (2016 records in 8.305 sec)*
SELECT DISTINCT ?ob ?tvalue ?score ?benchvalue ?unitbench WHERE{ :GHGEmissionsIndicator/1/dul:isExpressedBy ?so. ?ob a ssn:Observation ; ssn:observationResultTime ?time ; ssn:observationResult ?so ; ssn:observedBy ?sensor; dul:satisfies ?goal ; ssn:observationResult ?so. ?so :hasAbsoluteScore ?obsval. ?ben a udsa:Benchmark ; ssn:hasValue ?benval ; dul:expresses ?goal. ?benval qudt:unit ?unit. ?obsval udsa:hasNumericValue ?score. ?benval dul:hasRegionDataValue ?benchvalue. ?time a udsa:ResultTime ; dul:hasRegionDataValue ?tvalue . ?unit qudt:baseUnitDimensions ?unitbench.}	:observation/80641/ "2015-09-17T00:00:00+01:00"^^xsd:dateTime "100"^^xsd:decimal "0.32102490670373884"^^xsd:decimal "kg/kWh"^^xsd:string …

(d) What are the inputs used for the GHGEmissonsIndicator/1/ calculation?

SPARQL query	*Output (28 records in 0.292 sec)*
SELECT DISTINCT ?in WHERE{ ?sensing a ssn:Sensing ; ssn:hasInput ?in ; ssn:hasOutput :GHGEmissionsIndicator/1/.}	:sensor/1/ :sensor/8/ :sensor/13/ … :NationalGridGHGEmissionsRate/143/ :EnergySourceGHGEmissionsRate/147/ …

(e) Some inputs previously found are sensors. What are those measuring and where are they located?	
SPARQL query	*Output (10 records in 9.545 sec)*
SELECT DISTINCT ?in ?foiname ?part WHERE{ ?sensing a ssn:Sensing ; ssn:hasInput ?in ; ssn:hasOutput :GHGEmissionsIndicator/1/. ?in a ssn:Sensor. ?ob a ssn:Observation ; ssn:observedBy ?in; ssn:featureOfInterest ?foi . ?foi dul:hasDataValue ?foiname ; dul:hasPart ?part. ?part a udsa:Building.}	:sensor/1/ "Electricity_EnergyDemand"^^xsd:string :EbbwVale/EnergyCenter/ :sensor/8/ "Electricity_EnergyDemand"^^xsd:string :EbbwVale/GeneralOffice/ …
(f) Compare the values of GHGEmissionsIndicator/1/ at 2 different times.	
SPARQL query	*Output (2 records in 9.122 sec)*
SELECT DISTINCT ?obsval1 ?date1 ?value1 WHERE{ :GHGEmissionsIndicator/1/ dul:isExpressedBy ?so1. ?time1 dul:hasRegionDataValue ?date1. FILTER ((?date1 = "2015-10-03T12:00:00.0"^^xsd:dateTime)||(?date1 = "2015-10-18T12:00:00.0"^^xsd:dateTime)). ?ob1 a ssn:Observation; ssn:observationResultTime ?time1 ; ssn:observationResult ?so1. ?so1 ssn:hasValue ?obsval1; qudt:unit ?unit1 . ?obsval1 :hasNumericValue ?value1. ?unit1 qudt:baseUnitDimensions ?unitval1 .}	:observationvalue/82225/ "2015-10-03T12:00:00+01:00"^^xsd:dateTime "226"^^xsd:decimal :observationvalue/83665/ "2015-10-18T12:00:00+01:00"^^xsd:dateTime"181"^^xsd:decimal

Figure 9 demonstrates the data model correctness against a set of exploratory queries. The logical axioms reliability is tested here. The test queries, taken from the set of competency queries, have proven being correct and in line with the novel UDSA framework. Table 6 illustrates the test of the model performance when instantiated with real data from “The Work” case study. It demonstrates how a set of complex queries can be answered in a reasonable time using the UDSA ontology. Beyond performance, it demonstrates how one can link information from heterogeneous sources (e.g. time series and BIM servers).

6 CONCLUSION

This research aimed to develop and implement the urban district sustainability assessment ontology (UDSA). The NeON methodology has been used for the development of the UDSA ontology. The methodology provides guidelines from the creation of competency questions to the iterative process for the integration of ontological resources. It has proven reliable for the ontology development.

A systematic review of the current UDSA frameworks allowed the gathering of core set of terms and requirements common in the field. After studying the available ontologies on urban sustainability or sustainability sub-domains, it appeared that a data model with the right level of abstraction that could fulfil the frameworks' requirements was missing. Therefore, the UDSA ontology has been developed based on the synthesis of the 29 reviewed UDSA frameworks. The novel model tries by no means to present itself as a holistic and consensual model, as such a task is extremely difficult to achieve in the much controversial urban sustainability domain. Instead, it can be seen as an attempt to initiate a solid basis for a mid to high level ontology in the urban sustainability data model landscape.

The UDSA ontology can describe sensors and observations that result from sensing as well as various sustainability key performance indicators, criteria, sub-themes and themes within an urban system. It reuses existing ontologies such as SSN, GeoSPARQL and QUDT ontologies; and is interfaced with BIM, cityGML, ifc4 and the FOAF ontologies.

Its application has been validated through a wide range of queries for sensors and data discovery. Overall, such a semantic model has proven efficient and is believed to help in the creation of linked data for urban district sustainability evaluation. Further work will aim to develop a web service interface on top of the ontology, ideally deployed on a cloud-based infrastructure [90], for a user-friendly experience in the urban metrics discovery and those in real-time. Additionally, an updated version of SSN has been release during the development of the UDSA ontology, and therefore, efforts must be carried out in order to comply with this new version [91].

Even though such a scheme is promising, it is still at the stage of proof of concept. In the future, the urban district sustainability assessment ontology could benefit from an alignment with already existing sustainability or sustainability sub-domain semantic models such as the ones presented in section 3.4 and 4.4, introducing greater detailed concepts within the knowledge map. Additionally, the current state of the OWL 2 language still does not allow queries over the knowledge base in a reasonable computing time and space. This issue can be overcome by using OWL 2 QL as presented in section 5.1. However, this fragment of OWL 2 has limited expressiveness which results in losing the ability to answer more complex queries. Therefore, future work must focus on the development of more efficient reasoners and query engines in order to gain on expressiveness. In the meantime, frameworks such as ONTOP that get around the issue must keep improving with the support of industry and academic experts.

On a more general note, since the early days of web semantic development in the early nineties [92], relatively little has been done in the domain of the sustainable built environment for the OWL representation of the domain knowledge and its adoption by industry [93]. Most applications found in the literature are prototypes and still need to be fully implemented [93]. This is partially due to the nature of the domain itself which has a great plurality in its terms [94] and lack consensus on certain concepts [7]. Great effort are still to be made in the establishment of a common knowledge base where each independently developed ontologies are linked [94]. Nevertheless, the inclusion of semantic data modelling for IoT technologies within the work programme of the European Union Horizon 2020 programme [95] or research project such as the CUSP platform, a semantically based immersive decision support tool to support urban metrics analysis [96] demonstrates a gain of interest, supported not only by ontology experts but also by institutions like the European Union, which strengthens the relevance of such study.

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8 APPENDIX

UDSA frameworks

Tool Name	Provider Name	Launch Year	Base Country	Available Countries	Scale	Reference
BERDE for Clustered Residential Development	Philippine Green Building Council	2013	Philippines	Philippines	Neighbourhood	[43]
BREEAM Communities	BRE Global Ltd	2009	U.K.	Europe, parts of The Middle East and Africa	Neighbourhood	[4]
CASBEE for Cities	Institute for Building Environment & Energy Conservation	2011	Japan	Global	Entire Cities	[58]
CASBEE for Urban Development	Institute for Building Environment & Energy Conservation	2006	Japan	Japan	Neighbourhood	[5]
CEEQUAL for Projects	CEEQUAL Ltd	2004	U.K.	Global	Neighbourhood up to entire cities	[40]
Comprehensive Plans for Sustaining Places	American Planning Association	2014	U.S.	n/a	Entire Cities	[48]
DGNB for Urban Districts	German Sustainable Building Council	2011	Germany	Global	Neighbourhood	[52]
EcoDistricts Protocol	EcoDistricts	2016	U.S.	Global	Neighbourhood up to entire cities	[50]
EcoQuartiers	Ministry of Housing, Equality, and Rural Policy	2009	France	France	Neighbourhood	[41]
ELITE Cities	Ministry of Environmental Protection, China	2012	China/U.S.	China	Entire Cities	[46]
Enterprise Green Communities	Enterprise Partners	2011	U.S.	U.S.	n/a	[44]
EnviroDevelopment	Urban Development Institute of Australia	2006	Australia	Australia	Neighbourhood	[51]
Envision	Institute for Sustainable Infrastructure	2012	U.S.	North America	Neighbourhood up to entire cities	[54]
GBI Township Tool	Green Building Index	2011	Malaysia	Malaysia	Neighbourhood	[42]

Global Sustainability Assessment System for Districts	Gulf Organization for Research & Development	n/a	Qatar	Middle East	Neighbourhood	[53]
Gold Standard Cities	The Gold Standard	2015	Switzerland	Global	Entire Cities	[55]
Green Mark for Districts	Building & Construction Authority of Singapore	2009	Singapore	Singapore	Neighbourhood	[49]
Green Mark for Infrastructure	Building & Construction Authority of Singapore	2009	Singapore	Singapore	Neighbourhood up to entire cities	[57]
Green Star - Communities	Green Building Council of Australia	2012	Australia	Australia	Neighbourhood	[47]
HQE Urban Planning	Cerway/ Certivea/ Cerqual	2011	France	Global	Neighbourhood up to entire cities	[56]
IGBC Green Townships	Indian Green Building Council	2010	India	n/a	Neighbourhood up to entire cities	[60]
LEED for Neighborhood Development	U.S. Green Building Council	2009	U.S.	Global	Neighbourhood	[35]
Living Community Challenge	International Living Future Institute	2014	U.S.	Global	Neighbourhood up to entire cities	[39]
National Green Bldg Std for Land Development	Home Innovation Research Labs	2009	U.S.	U.S.	Neighbourhood	[45]
Pearl Rating System for Estidama - Community	Abu Dhabi Urban Planning Council	2010	Abu Dhabi	Abu Dhabi	Neighbourhood	[61]
PEER	Green Business Certification Inc.	2013	U.S.	Global	Neighbourhood up to entire cities	[59]
STAR Community	STAR Communities	2012	U.S.	North America	Entire Cities	[36]
Symbiocity	SKL International	2008	Sweden	Global	Entire Cities	[38]
Tool for Sustainable Urban Development	Realdania By	2007	Denmark	Denmark	Neighbourhood	[37]