Appendix

Here we provide syntax and semantics of our domain modeling formalism.

A.1 Abstract Syntax and Semantics of Domain Specifications

Domain specification is a process that generates domain-specific patterns by applying an operator to the schema.org vocabulary. Through such patterns, the generic complexity of schema.org is reduced, and its domain specificness is increased. Moreover, it can provide restrictions and constraints to the vocabulary in order to make it suitable for a specific task. The generic complexity of schema.org comes from its wide but shallow coverage of multiple domains and its flexible data model. Domain specification process removes types and properties from the vocabulary and extends it when needed to have a finer-grained coverage of specific domains. By default, the schema.org data model supports properties with global ranges. Domain-specific patterns apply the restrictions on ranges through local properties (i.e., property ranges are defined per domain) for properties. In this appendix, we introduce three different types of domain specification processes. We propose an abstract syntax based on the Shapes Constraint Language (SHACL) (Knublauch and Kontokostas 2017) and the semantics for verification of annotations against domain-specific patterns. This work is based on Şimşek et al. (2019b), where also additional explanations and examples are provided.

D. Fensel et al., *Knowledge Graphs*, https://doi.org/10.1007/978-3-030-37439-6

A.1.1 SHACL (As We Adopt)

SHACL is a recent W3C recommendation for defining constraints over RDF data. The language does not have a normative abstract syntax nor a formal semantics.[1] A syntactically well-formed SHACL shape is ensured by a set of shapes that implement[2] the SHACL Syntax Rules.[3] For the domain specification language, we use a subset of SHACL-CORE[4] elements. In this section, we give a brief introduction to the SHACL elements we adopt for the syntax of our language.

A shape is identified with an IRI or a blank node and fits at least one of the following conditions:

1. A SHACL instance of sh:NodeShape or sh:PropertyShape
2. Subject of a triple that has sh:targetClass, sh:targetNode, sh:targetObjectsOf or sh:targetSubjectsOf as predicate
3. Subject of a triple that has a parameter as a predicate
4. A value of a shape-expecting, non-list-taking parameter such as sh:node
5. A member of a SHACL list that is a value of a shape-expecting and list-taking parameter such as sh:or

SHACL Core Vocabulary defines two different kinds of shapes, namely, node shapes and property shapes. Node shapes target a set of nodes in an RDF data graph. These targeted nodes are called focus nodes. Property shapes target the values of specific properties of focus nodes. Target specifications select the focus nodes in an RDF graph. There are several ways to select a set of focus nodes as the target in SHACL; however, for domain specifications, we are only interested in class-based targets.

A *class-based* target selects a set of nodes in an RDF graph that are instances of the specified class as the value of the property sh:targetClass.

Shapes can define certain constraints on focus nodes and property values. Our constraints are defined by constraint component instances attached to a shape with parameters. In the domain specification language, we are only interested in a subset of the constraint components, namely, value type (sh:class and sh:datatype), cardinality (sh:minCount), shape-based (sh:node and sh:property), and logical constraint components (sh:or).

A *value type* constraint component specifies a constraint on the range of a property for a domain. For our domain specification language, we adopt the sh:class and sh:datatype parameters in order to constrain the type of property value.

[1] See https://www.w3.org/TR/shacl-abstract-syntax/ for details and a link to a proposed abstract syntax and semantics. Last accessed on 23.03.2019.

[2] https://www.w3.org/ns/shacl-shacl

[3] https://www.w3.org/TR/shacl/\#syntax-rules

[4] sh prefix is used for SHACL-Core namespace.

A *cardinality constraint* component defines a cardinality constraint on number of values of a given property. We utilize the sh:minCount parameter for minimum cardinality constraints.

A *shape-based* constraint component defines a constraint where the value nodes need to conform to the specified shape. For our domain specification language, we use property shape constraints with sh:property parameter to specify the remaining properties on a type and node shape constraints with sh:node parameter to define local ranges (typically a more restricted version of a type in the global range) for properties of a type.

A *logical constraint* component implements common logical operators AND, OR, NOT, and XOR on a list of shapes. For the domain specification language, we adopt only the OR operator with sh:or parameter for specifying disjunction of value type and node shape constraints.

A.1.2 Conceptual Description of Domain Specification

We define the following types of domain specifications:

- A *Simple Domain Specification* (SDS) generates a Simple Domain Specific Pattern (SDSP) through removing types and properties from the schema.org vocabulary.
- A *Restriction Domain Specification* (RDS) generates a Restricted Domain Specific Pattern (RDSP) by restricting the ranges of the remaining properties of the remaining types in an SDSP.
- An *Extension Domain Specification* (EDS) generates an Extended Domain Specific Pattern (EDSP) by adding new types and properties to an SDSP or RDSP.

In the remainder of this section, we describe these domain specification types and their relationship conceptually. Additionally, we give examples.

A.1.2.1 Simple Domain Specification (SDS)

The SDS generates an SDSP through following steps:

1. Remove types and properties from the schema.org vocabulary.
2. For a remaining type, define local properties from the remaining properties, as a set of (type, property) pairs where property has type in its domain.
3. For each local property on a type, define a range as a set of ((type, property), rangeType) where rangeType is one of the remaining types and in the range of property.[5]

[5] As we may exclude some types and given the disjunctive nature of value ranges in schema.org this may already imply a restriction of the range of a property as a side effect.

The following example (see Table A.1) is an SDS operator in SHACL syntax[6] that defines local properties and ranges on schema:Hotel.[7]

A.1.2.2 Restriction Domain Specification

The RDS process deletes a type in the range of a property in an SDSP or replaces it with a subtype and generates an RDSP. The example in Table A.2 is an RDS operator in SHACL syntax that replaces the range of schema:location property on schema:Hotel with a more restricted subtype of schema:PostalAddress.

A.1.2.3 Extension Domain Specification

An EDS process generates an extended domain-specific pattern by extending an SDSP or an RDSP through:

- Adding new types and properties from an external vocabulary
- Defining new properties to an existing type from an external vocabulary
- Adding types from an external vocabulary to the ranges of properties on an existing type

The example in Table A.3 shows an EDS operator in SHACL syntax. It adds a new property, totalNumberOfBeds, to the type schema:Hotel from an external extension of schema.org.

A.1.3 Abstract Syntax

The abstract syntax below specifies how the SHACL components are utilized to define Simple Domain Specification (SDS), Restriction Domain Specification (RDS), and Extension Domain Specification (EDS) operators. We describe the abstract syntax for domain specifications with "EBNF for XML" notation.[8] We extend the notation with the [..] structure for describing special sequences in natural language (e.g., [a valid URI]).

An SDS operator is a node shape that is identified with a URI or a blank node. An SDS operator has a target type from the schema.org vocabulary and contains one or more property shapes, each of which represents the definition of a local property on the target schema.org type.

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[6]The examples in SHACL syntax replace schema.org datatypes such as Text with XSD datatype such as string for compatibility with existing Semantic Web stack.

[7]*schema* is the prefix for schema.org namespace.

[8]https://www.w3.org/TR/2004/REC-xml-20040204/#sec-notation

Table A.1 An SDS operator in SHACL syntax

```
@prefix sh: <http://www.w3.org/ns/shacl#>.
@prefix schema: <http://schema.org/>.
@prefix ds-tourism: <https://ds.sti2.org/tourism/>.
@prefix xsd: <http://www.w3.org/2001/XMLSchema#>.

   ds-tourism:Hotel a sh:NodeShape;
       sh:property [
           sh:path schema:name;
           sh:datatype xsd:string;
           sh:minCount 1;
       ];
       sh:property [
           sh:path schema:checkInTime;
           sh:datatype xsd:time;
           sh:minCount 1;
       ];
       sh:property [
           sh:path schema:checkOutTime;
           sh:datatype xsd:time;
           sh:minCount 1;
       ];
       sh:property [
           sh:path schema:location;
           sh:class schema:PostalAddress;
           sh:minCount 1;
       ].
```

SDS ::= **NodeShape, SDOTargetType, SDSPropertyShape+;**
NodeShape ::= **Identifier, NodeShapeType;**
Identifier ::= [a URI] | [a BlankNode];
NodeShapeType ::= [URI of the SHACL NodeShape Type];
SDOTargetType ::= [a class-based target whose value is a URI of a schema.org type];

A property shape in an SDS consists of a schema.org property and one or more type specifications for the range of the property. It may also optionally contain a cardinality constraint to specify whether a property is required. A property shape may specify a range with multiple disjunct types.

Table A.2 An RDS operator in SHACL syntax

```
@prefix sh: <http://www.w3.org/ns/shacl#>.
@prefix schema: <http://schema.org/>.
@prefix ds-tourism: <https://ds.sti2.org/tourism/>.
@prefix xsd: <http://www.w3.org/2001/XMLSchema#>.

ds-tourism:Hotel a sh:NodeShape;

    sh:property [

        sh:path schema:name;

        sh:datatype xsd:string;

        sh:minCount 1;

    ];

    sh:property [

        sh:path schema:checkInTime;

        sh:datatype xsd:time;

        sh:minCount 1;

    ];

    sh:property [

        sh:path schema:checkOutTime;

        sh:datatype xsd:time;

        sh:minCount 1;

    ];

    sh:property [

        sh:path schema:location;

        sh:class schema:PostalAddress;

        sh:minCount 1;

        sh:node [

                a sh:NodeShape;

                sh:property [

                    sh:path schema:addressCountry;

                    sh:datatype xsd:string;

                    sh:minCount 1;
```

(continued)

Table A.2 (continued)

```
                ];
                sh:property [
                    sh:path schema:addressLocality;
                    sh:datatype xsd:string;
                    sh:minCount 1;
                ];
        ]
    ].
```

SDSPropertyShape ::= **SDOProperty, MinCount?, (ValueTypeConstraint+ | SimpleDisjunctiveConstraint);**
SDOProperty ::= [URI of a schema.org property];

A value type constraint enforces the type of a value. It requires the URI of a type in schema.org vocabulary as the value of sh:class parameter or the URI of an XSD datatype as the value of sh:datatype property.

ValueTypeConstraint ::= **SimpleClassConstraint | DatatypeConstraint ;**
SimpleClassConstraint ::= [A SHACL Class constraint with sh:class parameter and a value t where t is a schema.org type that is more specific than schema: Thing];
DatatypeConstraint ::= [A SHACL Datatype constraint with sh:datatype parameter and a value t where t is a schema.org datatype];

A cardinality constraint enforces the number of values a property can take. It takes only the integer 1 as value for sh:minCount parameters to specify minimum required value occurrences.

MinCount ::= [minimum cardinality constraint with sh:minCount 1];

A simple disjunctive constraint applies logical OR operation to a given list of value type constraints.

SimpleDisjunctiveConstraint ::= [OR(**ValueTypeConstraint+**)] ;

An RDS is a SHACL node shape with a target type from the schema.org vocabulary and one or more property shapes.

RDS ::= **NodeShape, SDOTargetType, RDSPropertyShape+;**

A property shape in an RDS extends a property shape in SDS with range constraints.

Table A.3 An EDS operator in SHACL syntax

```
@prefix sh: <http://www.w3.org/ns/shacl#>.
@prefix schema: <http://schema.org/>.
@prefix ds-tourism: <https://ds.sti2.org/tourism/>.
@prefix xsd: <http://www.w3.org/2001/XMLSchema#>.
@prefix schema-tourism: <https://schema-tourism.sti2.org/ns/>

ds-tourism:Hotel a sh:NodeShape;

    sh:property [

        sh:path schema:name;

        sh:datatype xsd:string;

        sh:minCount 1;

    ];

    sh:property [

        sh:path schema:checkInTime;

        sh:datatype xsd:time;

        sh:minCount 1;

    ];

    sh:property [

        sh:path schema:checkOutTime;

        sh:datatype xsd:time;

        sh:minCount 1;

    ];

    sh:property [

        sh:path schema-tourism:totalNumberOfBeds;

        sh:datatype xsd:positiveInteger;

    ];

    sh:property [

        sh:path schema:location;

        sh:class schema:PostalAddress;

        sh:minCount 1;

        sh:node [
```

(continued)

Table A.3 (continued)

```
                a sh:NodeShape;
                sh:property [
                    sh:path schema:addressCountry;
                    sh:datatype xsd:string;
                    sh:minCount 1;
                ];
                sh:property [
                    sh:path schema:addressLocality;
                    sh:datatype xsd:string;
                    sh:minCount 1;
                ];
        ]
    ].
```

RDSPropertyShape ::= **SDOProperty, MinCount?, (ValueTypeConstraint | RangeConstraint | DisjunctiveConstraint)+;**

A range constraint consists of a value type constraint that declares a type in the range and a node constraint that further constrains the specified type.

RangeConstraint ::= **ValueTypeConstraint, NodeConstraint;**
NodeConstraint ::= **NodeShape, RDSPropertyShape+;**

A disjunctive constraint extends a simple disjunctive constraint in an SDS by applying logical OR operator on a list of value type constraints and range restrictions.

DisjunctiveConstraint ::= [OR{(**ValueTypeConstraint | RangeConstraint**)+}] ;

An EDS operator extends an SDS or an RDS operators with types from an external vocabulary.

EDS ::= **NodeShape**, (**SDOTargetType | ExtTargetType**), **EDSPropertyShape+**;
ExtTargetType ::= [URI of type t where t ∈ Text];
EDSPropertyShape ::= (**SDOProperty | ExtProperty**), **MinCount?, (ExtValueTypeConstraint | ExtRangeConstraint | ExtDisjunctiveConstraint)+;**

ExtProperty ::= [URI of property p where p ∈ Pext];
ExtValueTypeConstraint ::= **SimpleClassConstraint | ExtClassConstraint | DatatypeConstraint; ExtClassConstraint** ::= [A SHACL Class constraint with a value t is a type from an external vocabulary];
ExtRangeConstraint ::= **ExtValueTypeConstraint, ExtNodeConstraint;**
ExtNodeConstraint ::= **NodeShape, EDSPropertyShape+;**
ExtDisjunctiveConstraint ::= [OR{(**ExtValueTypeConstraint | ExtRangeConstraint)+**}]

In SHACL syntax, an EDS operator can be seen as an SDS and RDS operator with types or properties from a namespace other than schema.org. There are no syntactic extensions for SHACL needed to define these operators. Therefore, a domain specification operator is also a valid SHACL shape and can be used by existing SHACL tools.

A.1.4 Semantics

An annotation can be verified against a domain-specific pattern that is generated by a domain specification operator. The verification is done by checking an annotation against the constraints defined by a domain specification operator. We define two predicates, namely, *applies* and *verifies*, in order to explain the semantics of domain-specific patterns and annotation verification.[9]

A domain-specific pattern applies to an annotation when the target type of the domain specification operator that produces the pattern is the same type as the root type of the annotation.

- *dso* is a domain specification operator that generates a domain-specific pattern. *anno* is an annotation that is a directed graph with exactly one source node (sn) that has no incoming edges. An annotation consists of a source node (sn), other nodes ($n_1 \ldots n_i$) that are reachable through at least one path from the source node, and labeled edges $e_1 \ldots e_i$. The nodes represent instances of types from schema.org or an extension of schema.org. The edges are properties from schema.org or an extension of schema.org. For any directed edge (e) in anno, e.from represents the source node while e.to represents the target node.

  Formally, applies (dso, anno) holds true when:

- isElementOf (sn, t) holds true where t is the value of **SDOTargetType** in dso

[9]The semantics is described with SDS and RDS operator components from the abstract syntax. Replacing them with EDS operator components is rather trivial.

An annotation is verified, when it conforms to a domain specification operator that applies to it. For anno and dso pair that make *applies* (dso, anno) true, the predicate *verifies* (dso, anno) holds true, iff:

- Given that oe in anno is a directed edge from sn to n, for each oe, there exists a property shape (ps) in dso and *satisfies* (oe, ps) holds true.
- There exists at least one oe, for each ps with a **MinCount**.

satisfies (oe, ps) holds true iff:

- The label of oe is the same as the value of **SDOProperty** in ps.
- For each **ValueTypeConstraint**, **NodeConstraint**, and **DisjunctiveConstraint** (cons) in ps,[10] *satisfiesRangeRestriction* (oe.to, cons) holds true.

satisfiesRangeRestriction (n, cons) holds true iff:

- If cons is a **ValueTypeConstraint** then:
  - isElementOf (n, t_a) and isA(t_a, t_b) and t_b is equal to the value of ValueTypeConstraint.
- If cons is a **NodeConstraint** then:
  - Given that oen is a directed edge from n to n_2, for each oen, there exists a property shape (psnc) in cons.
  - There exists at least one oen for each psnc with a **MinCount**.
  - isElementOf (n, t_c) and isA (t_c, t_d) and t_d is equal to the value of **ValueTypeConstraint** in cons.
  - satisfies (oen.to, psnc) holds true.
- If cons is a **DisjunctiveConstraint:**
  - For the list of constraints (c_1 ... c_n) in cons, satisfies (n, c_1) V satisfies(n, c_2) V satisfies(n, c_3) . . . V satisfies(n, c_4) holds true.

[10]Multiple constraints are treated as conjunction.

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