From Snapshots to Processes Description – Spatiotemporal Modelling using RDF Datasets and Formal Ontologies

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Abstract

Today, the primary aim of spatial development management, including spatial planning, is to find safe equilibrium between social-economic development and natural environment protection. Such challenge needs more complex approach for research and design methods involved in decision-making processes. The crucial problem is to look at the spatial development and at its impact on environment as a dynamic reality. It is the precondition for making a proper prognosis and a reliable impact assessment, which is the basis for relevant planning decisions. This work is a step in the search for new technologies which can give spatial planners and decision makers the methods for analysing data and describing spatial development with its temporal context in a new manner as well as presenting changes as effects of events and processes. The authors present here the usage of RDF datasets and the method for interpreting them using formal ontologies (also called foundational or upper ontologies).

Keywords: Spatio(temporal) Data Modelling and Reasoning, Spatio(temporal) Data Analysis, Semantic Web and GIS, Spatio(temporal) Data Mining and Knowledge Discovery Spatial Semantics and Spatiotemporal Ontologies, Modelling and Spatial Analysis of Urban Dynamics, GIS for Change of Land use.

1 Introduction

Modern civilisation faces a tremendous challenge – how to maintain fast growth while simultaneously preserving the natural resources on which it is ultimately dependent.

Reconciling these contradictions needs more sophisticated methods of spatial development management, which are necessary for responsible decision making in this area.

The spatial development problems have dynamic nature and we need tools which can make it possible to look at reality in this manner.

Our research is aimed to propose such methods by using RDF Datasets [34] and domain ontologies [10] built upon templates of formal ontologies, known also as foundational or upper ontologies [9, 13].

RDF Datasets seem to be useful for storing information obtained from various sources accessible on Web, including Linked Data resources [4], to preserve their temporal contexts. Formal ontologies can refer such data to processes and events which makes it possible to discover how they impact the state of spatial objects.

Dynamics of spatial phenomena can be recognized on two different levels: the first refers directly to real objects, describing their changing states, and the second refers to data used as a representation of these objects, describing how and when information about the real objects was collected.

Another distinction reflects the two areas in which we can consider processing of information in decision-making or designing procedures. The first refers to data collecting, harmonisation and storing. The second refers to a knowledge representation, needed to perform these analyses.

Data used in spatial management derives from multiple sources and it is served in different models. However, the model which we use in our analyses should be coherent and homogeneous. For such purpose, it is a good idea to use formal ontologies as templates for domain ontologies, building a common multidisciplinary logic structure [21].

The time factor is an additional problem which we have to solve when we try to describe the dynamics of the real world. Urban planners rely on source data but they have no ability to influence their model, quality, completeness or credibility, including description of the history of objects. The source data, in most cases, represents the state of spatial phenomena in the moments when we collected this data. We can consider such datasets as snapshots describing reality. Therefore, we have to transform the information about the history of data into information about the real objects' histories.

Among the different manners of data publication the form of Linked Data has recently become increasingly popular. Multidisciplinary spatial information released in such form could provide a great advantage. Such data uses a domain neutral structure based on semantics provided by statements using vocabularies rather than on application schema in the traditional meaning [22].

The problem discussed by the authors in this article concerns the way how to collect the data retrieved in different moments from heterogeneous resources and how to interpret the acquired information using coherent and unified models. Data in the form of RDF structures, collecting information from heterogeneous external resources, uses simple taxonomic ontologies as a terminological component (TBox). Subsequently, the proposed knowledge representation needed for the interpretation of the dynamics of phenomena uses, as a TBox, domain ontologies built upon the BFO formal ontology template [9]. The present article shows the advantages of ordering data in the form of RDF Datasets with their spatiotemporal context [6] for discovering changes in space and for further interpretation of their nature, using categories borrowed from formal ontologies.

2 RDF datasets in spatiotemporal representation

Our purpose is the utilisation of opportunities provided by Resource Description Framework (RDF) structures for spatial planning information obtained from heterogeneous sources, including SDI or widely understood online resources, in particular in the form of Linked Data. The advantage of such representation is the flexibility of potential applications in various areas. The rapid development of these technologies made it possible to use them for problems of spatial development management and planning.

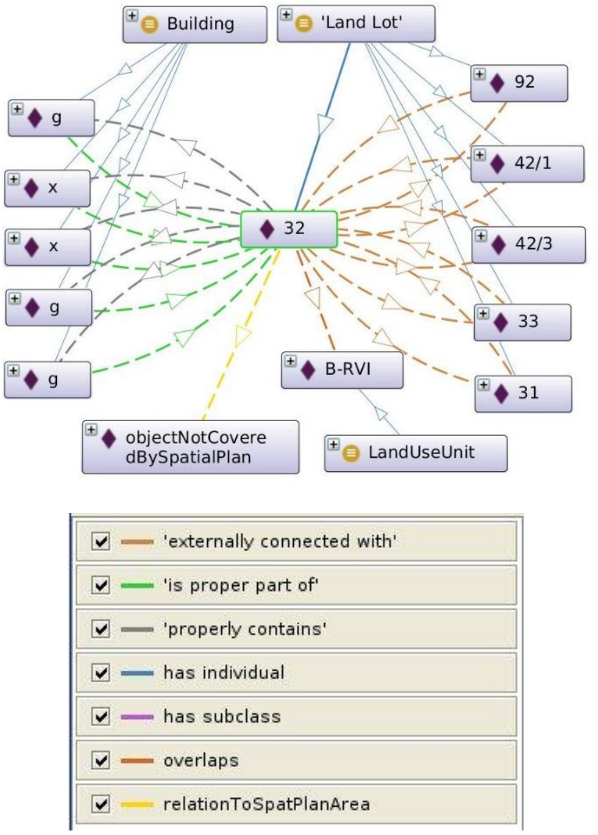
Semantic Web [2] technologies supply us with solutions for representing spatial aspects such as WGS84 vocabulary [37], the GeoSPARQL ontology (a part of the GeoSPARQL project [25], which extends the SPARQL query language). GeoSPARQL gives us syntax for recording geometry and predicates for representing topological relationships between them, using RCC8 operators. Alternatively we can use the NeoGeo vocabulary [30] (Figure 1).

Temporal description of phenomena is made possible by using simple XML datatype literals, such as “date”, “time”, “dateTime” or “duration”. However, temporal representation needs also specific classes and relationships. There are several ready-to-use simple ontologies, like Time Ontology (owl-time) [36], which provide us with such entities as time periods (Instant, Interval). Relationships between temporal periods can be expressed using Allen’s operators [1, 7].

Basic approach to providing direct description of the history of objects uses their own properties. In the simplest situation we need to get one mandatory piece of information about the moment of creation of an entity and optionally a second piece of information about the moment of its destruction. What is more sophisticated is an indirect description of a temporal context, when an entity is related to some event or process with a given moment or a period in which it takes place.

On the other hand, representation of a temporal context of data (as data) is feasible using named graphs, as a part of RDF Datasets. In such situation the temporal context plays the role of metadata.

Figure 1: RDF graph describing spatial relationships between land lots and buildings using RCC8 operators.



In most cases, it is a suitable way to discover how entities “behave” in time when direct information about the changes of their state and their relationships to other entities is not accessible. Usually it is not possible to acquire complete information about the history of objects which we need. However, we often have different kinds of indications about the time context. We know when we obtained the datasets containing the representations of entities with their current state. This temporal context can be treated as alterable information about the changes of entities. [22]

There are several structures to provide data in this manner, such as the temporal RDF graphs [11], the annotated RDF [29], dedicated ontologies [5], and others [23]. We have chosen the construction of RDF datasets, which was introduced in RDF 1.1 version. [33, 34]

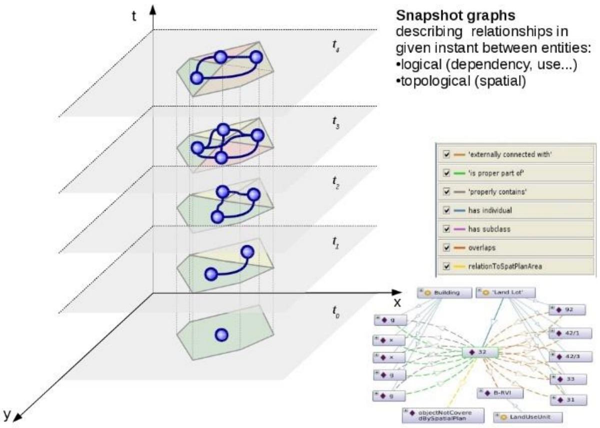
The concept of datasets provides a new structure, useful for ordering triples in great sets of data. The RDF dataset is a collection of RDF graphs [33]. It should be composed of exactly one default graph and any number of the so-called “named graphs” [6]. We can consider a named graph as a context in which given assertion (triple) is true.

For new structures of RDF 1.1, W3C introduced new methods of serialization (TriG, TriX, N-Quads, JSON-LD).

2.1 Snapshots in RDF datasets

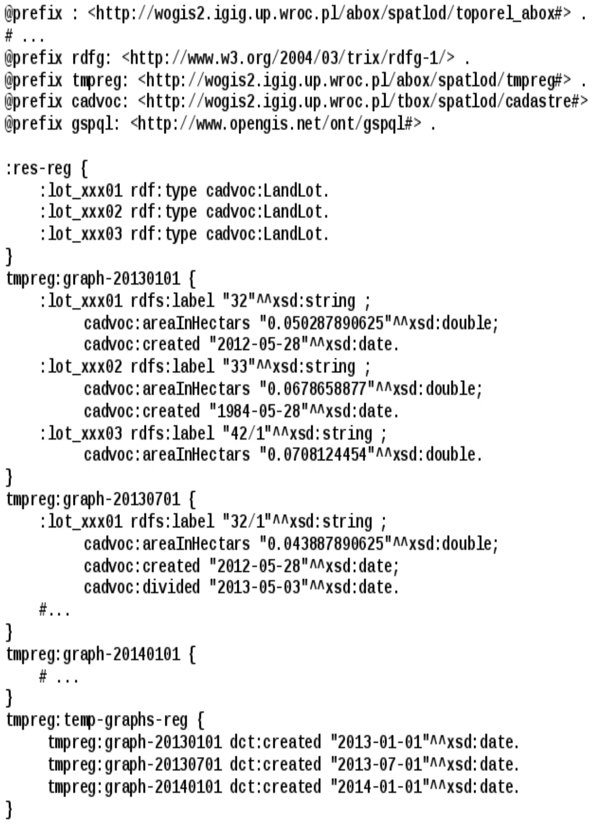
RDF datasets give us possibilities for modelling data which preserve their time context [33]. When we are analysing changes in development for whole datasets, we use, in most cases, snapshots [12]. For data in the form of an RDF graph, we can include snapshots in named graphs (Figure 2) [6]

Figure 2: Snapshots containing RDF graphs.



Each snapshot contains information about the state of objects expressed in the form of a graph of relationships (triples). We must be conscious that the same objects could repeat themselves in subsequent moments. But the context in which each of them appears differs, because it refers to a different moment.

Figure 3: TriG document with named graphs, coding snapshots



```
@prefix : <http://wogis2.igig.up.wroc.pl/abox/spatlod/toporel_abox#> .
# ...
@prefix rdfg: <http://www.w3.org/2004/03/trix/rdfg-1/> .
@prefix tmpreg: <http://wogis2.igig.up.wroc.pl/abox/spatlod/tmpreg#> .
@prefix cadvoc: <http://wogis2.igig.up.wroc.pl/tbox/spatlod/cadastre#>
@prefix gspql: <http://www.opengis.net/ont/gspql#> .

:res-reg {
    :lot_xxx01 rdf:type cadvoc:LandLot.
    :lot_xxx02 rdf:type cadvoc:LandLot.
    :lot_xxx03 rdf:type cadvoc:LandLot.
}
tmpreg:graph-20130101 {
    :lot_xxx01 rdfs:label "32"^^xsd:string ;
          cadvoc:areaInHectars "0.050287890625"^^xsd:double;
          cadvoc:created "2012-05-28"^^xsd:date.
    :lot_xxx02 rdfs:label "33"^^xsd:string ;
          cadvoc:areaInHectars "0.0678658877"^^xsd:double;
          cadvoc:created "1984-05-28"^^xsd:date.
    :lot_xxx03 rdfs:label "42/1"^^xsd:string ;
          cadvoc:areaInHectars "0.0708124454"^^xsd:double.
}
tmpreg:graph-20130701 {
    :lot_xxx01 rdfs:label "32/1"^^xsd:string ;
          cadvoc:areaInHectars "0.043887890625"^^xsd:double;
          cadvoc:created "2012-05-28"^^xsd:date;
          cadvoc:divided "2013-05-03"^^xsd:date.
    #...
}
tmpreg:graph-20140101 {
    # ...
}
tmpreg:temp-graphs-reg {
     tmpreg:graph-20130101 dct:created "2013-01-01"^^xsd:date.
     tmpreg:graph-20130701 dct:created "2013-07-01"^^xsd:date.
     tmpreg:graph-20140101 dct:created "2014-01-01"^^xsd:date.
}
```

RDF datasets give us the possibility to control such distinctions. We can deal with many repeating objects remaining in changing mutual relationships, with reference to the moment, when we observe them.

For example, when we consider cadastral lots, we can present them in different moments, encapsulated in relevant graphs. Graphs representing snapshots, each of them separately, are described in a special graph, which plays the role of a register. (Figure 3 and 4).

2.2 Taxonomic ontologies as a TBox for RDF graphs

General structure of RDF graphs used to represent spatial data with their temporal context is defined in vocabularies in the form of simple lightweight ontologies. Such ontologies, also known as taxonomic ontologies, provide main terminology necessary for defining resources classification (types of representing objects) and relationships between objects of particular classes. Vocabularies, also called TBox (terminological component), define the data model for gathered data. Taxonomic ontologies are simple and differ from axiomatic ontologies used here for further interpretation of data. Formal ontologies, and the domain ontologies derived from them, are axiomatic.

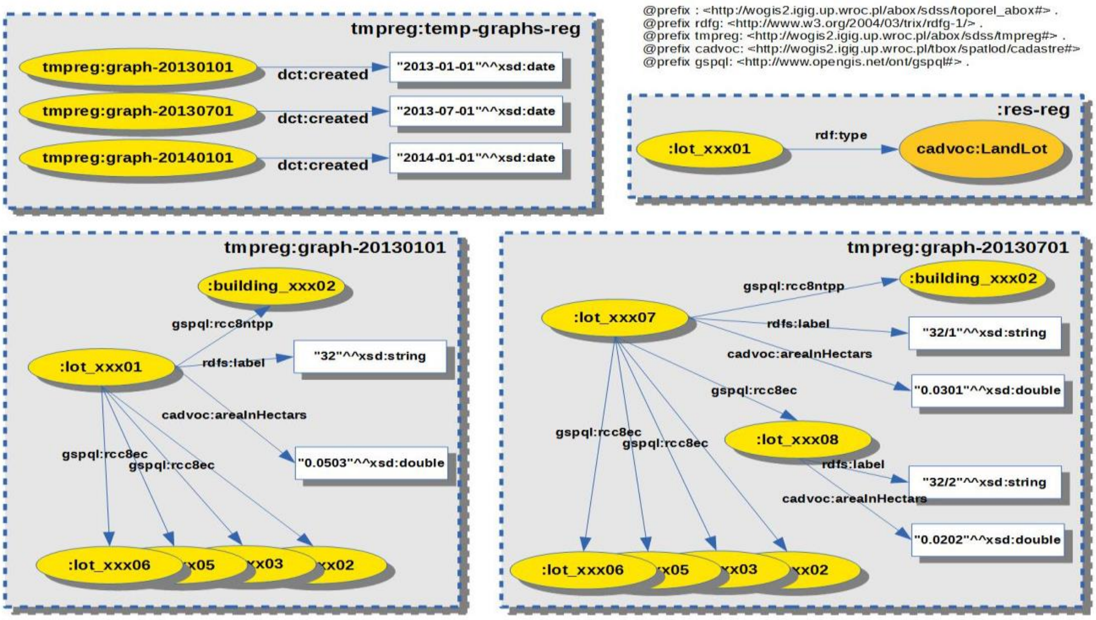
The TBox used for RDF data describing real world issues is provided with domain specific terms and predicates. Classes, properties, and datatypes for spatiotemporal relationships are imported into the TBox from well-known ontologies, such as the WGS84, GeoSPARQL or Time Ontology mentioned above. WGS84 and GeoSPARQL provide us with spatial classes and datatypes as well as topological relationships between geometry objects using RCC8 operators set [26] (Figure 1). Time Ontology introduces a set of classes and properties describing time periods (Instant, Interval) and time duration as well as topological temporal operators (Allen’s operators [1]). Allen’s operators play analogous role in the description of “topological” time relationships between time periods like the RCC8 operators in space [7].

The domain specific vocabulary contains classes and datatypes as well as properties which are not disciplinary-neutral. Ontologies used for defining the taxonomy for spatial management include the domains of spatial development, cadastre, natural environment, transportation, infrastructure, cultural heritage, etc. There are several examples of modelling “time-aware” representations for various domains [5, 16, 17, 31].

In our example, the TBox component of domain ontologies includes the following classes: “LandLot”, “LandUseUnit”, “LandCoverUnit”, “PlanningZone”, “CadastralBuilding” (building as an object in a cadastre register), subtree of “Road” classes such as “Driveway”, “Road”, “PublicRoad”, “LocalRoad”, “CollectorRoad”, “ArterialRoad”, subtree of infrastructure structures and facilities, including “PipeLine”, “ElectricPower Line”, etc.

The instances of these classes are characterized by properties: “hasOwner” (“LandLot”), “landUseType” (“LandUseUnit”), “landCoverForm” (“LandCoverUnit”), “categoryOfRoad”, “technicalClassOfRoad” (“Road”), “buildingFunction” (“CadastralBuilding”). There are many problems which should be solved using domain specific language, e.g., property “hasAccessToPublicRoad” (rdfs:domain “LandLot”,

Figure 4: Temporal named graphs



rdfs:range "PublicRoad") refers to situation, when some "LandLot" is adjacent to "PublicRoad" (RCC8 EC relationship), but additionally for this lot a formal decision on permission for preparing a gate opening this land lot for this road was issued. Taxonomic ontology should allow to note such fact. However, the criteria as to when a given land lot meets the conditions for issuing such a permission shall not be a part of such ontology. In our system these circumstances are the subject of knowledge base modelling, where rules define the criteria when a land lot might have access to a public road and what category of public roads we need to make it possible.

When we consider heterogeneous spatial data resources, even in the form of Linked Data, as a source of information for spatial planning procedures we shall keep in mind the need of the harmonisation of such data. This process could be similar to the procedure discussed in our article about the integration of SDI data from different application schemas [32]. Another problem appears when the source data lacks temporal description and the reference to the time context only results from our knowledge about the moment when the data was obtained. In this situation we can look at the RDF Datasets and named graphs as structures giving us the opportunity to order the data originating from different moments in containers referring to specified points in time.

2.3 Detecting changes in space in source data

Finding out the changes of a development state or a natural resources state can be made by comparing two RDF graphs representing different moments. Here we should make some assumptions. RDF graphs should use the same vocabularies and conform to analogues relationships, in other words, they should conform to the same model of representation. With such an assumption, changes can be discovered by checking if the graphs are isomorphic [33].

If such two named graphs are isomorphic, we can say that in the assumed domain of discourse we did not discover changes. On the contrary, when we discover differences, we can say that the discussed area of space was reshaped.

Discovering dissimilarities between graphs is not trivial. It seems to be analogous to the "diff" system, used to compare text files in managing changes and updates in a source code. Such system has a special format of a "diff" document, recording insertions and deletions (used for updating applications by so-called "patches"). The idea of a file comparing and expressing disparities in "diff" files is the basis for each versioning system, known as the version (or revision) control system (VCS, RCS). There are many tools for such purpose, e.g., CVS, Subversion, GIT, etc. What is interesting in this context is that all of them provide us with some way of registering history.

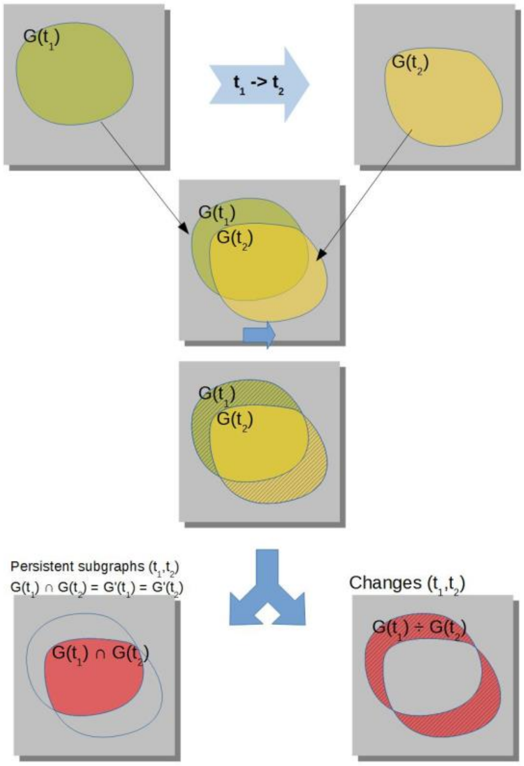
However, the differences in a source code concern strictly the variations of string chains with the line of code as a unit. Discovering the differences between graphs should provide us with an answer to the questions how the meaning of content represented by graphs changed.

Graphs are to be reduced to a form in which serialization methods do not impact the meaning. Such process is known as canonicalization, and it results in a graph in the N-Triples format.

Differences between graphs are recorded in the Delta ontology (an ontology for the distribution of differences between RDF graphs) [3].

Another problem concerns the uniqueness of identity of objects in compared graphs. While we can be confident that the identifier of an object is unique, we can treat the "diff" result as "strong", which means that it is "context free". For example, if we use the IRIs for every object that is repeated in more than one graph we can assume that the comparison result is "strong". We can assume this in other situations, too. If we know the original identification system, which explicitly distinguishes objects – such system is implemented in each register, like a cadastral system – we can use it to discover that some objects in separate graphs are the same, even their IRIs differ. Another way to ensure a common identity of objects in different graphs is to analyse their properties. For example, if given two spatial objects are of the same type and have identical geometry we can treat them as two representations of the same object.

Figure 5: Detecting changes by comparing graphs.

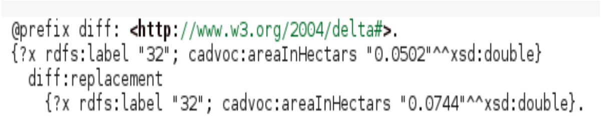


The problem appears when we cannot find a trustful and common identification system. In such a situation the information about changes is "context-sensitive", or "weak".

Taking into account the above objections, if the snapshot named graphs differ, we can say that some events or processes changed the shape of development (Figure 5). The differences can be reflected by the appearing or the disappearing of objects or they can affect the mutual relationships between them. In accordance with the criteria of isomorphism of graphs [33] we can consider the following questions:

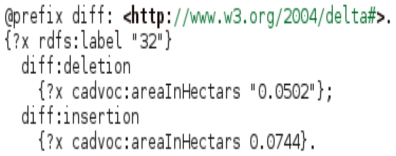
- Do all nodes from an earlier snapshot occur in a later one and are they are identical, and vice versa,
- Do all literals in an earlier graph have their equivalents in a later one, and vice versa,
- Do all triples from an earlier graph have their equivalents on the same predicates in a later one and are they identical to them.

The results of the comparison are recorded in the "diff" graph, using Delta ontology. Below we present an example of such "diff" in a Notation-3 serialization:



```
@prefix diff: <http://www.w3.org/2004/delta#>.
{?x rdfs:label "32"; cadvoc:areaInHectars "0.0502"^^xsd:double}
  diff:replacement
    {?x rdfs:label "32"; cadvoc:areaInHectars "0.0744"^^xsd:double}.
```

Another way to express such change is:



```
@prefix diff: <http://www.w3.org/2004/delta#>.
{?x rdfs:label "32"}
  diff:deletion
    {?x cadvoc:areaInHectars "0.0502"};
  diff:insertion
    {?x cadvoc:areaInHectars 0.0744}.
```

The predicates diff:replacement, diff:deletion, diff:insertion are the crucial structures which are used in further procedure for interpreting changes.

There are several tools which can be used in graphs comparison procedure.[35] Our team is testing the RDFLib compare.py module [27, 28].

3 Interpretion of the nature of changes

The crucial problem is how to interpret the differences detected in a state, represented in distinct graphs [34]. Interpretation should provide us with an answer to the questions what kind of changes we found (process or events), what is the type of the detected process, or, respectively, event, in accordance with the categories associated with our domain of discourse, and how such a process impacts the state of objects which are the bearers of them.

However, the TBox defining terminology for RDF datasets conforms to issues from the discussed domain, but the expressiveness of these ontologies is weak. They lack criteria necessary to perform inference procedures using reasoners. Such criteria have the form of logical rules, defining conditions that should be fulfilled in order an object to belong to the tested class ("to be of given type").

Such description makes it possible to discover new facts, like membership in specialized classes, and providing additional information about object properties and relationships. New facts do not mean new resources – we still remain in the area of obtained source data. Nevertheless, we can obtain new knowledge about the nature of these resources.

For example, if we revealed differences between snapshots, inference could answer the question what type of changes we observe.

To recognize such issues as the nature of changes and their impact on objects we need an ontology which can provide us with appropriate categories, a description of space, time, substance of objects, their behaviour in accordance with their nature (are they material or immaterial, concrete or abstract) and structure (are they cumulative / dissective or not) [9].

The idea to use one of the existing formal ontologies (known also as foundational or upper ontologies) [21] results from the fact that they are well-designed for specific purposes: to be templates for domain ontologies or to play the role of cross-mapping hubs. The term "formal ontology" is used by E. Husserl [14] to distinguish ontologies dealing with general domain-neutral categories from domain ontologies [9]. There are several formal ontologies: BFO, DOLCE [8], GFO [13], and others. [24] Each of them presents its own bias [20]. We chose BFO, which seems to be well-suited for the description of real world spatial problems.

Formal ontologies could be used as templates for domain ontologies by extending neutral categories into domain specific concepts, useful for interpreting “raw” RDF graphs [15].

3.1 Spatiotemporal issues in BFO

Almost all formal ontologies distinguish between objects, which are persistent over time, called “endurants” or “happening” at the time (running, flowing), called the “perdurants”. These categories, in BFO, are called respectively: “continuants” and “occurents”. [15]

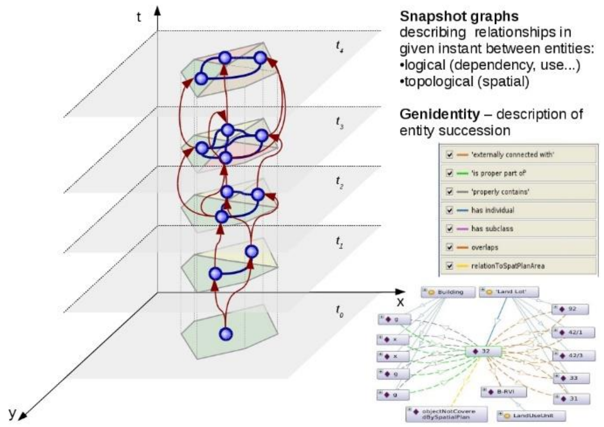
Continuants include physical objects, for example: building, road, etc... But they can also be abstract objects that do not exist physically, like a lot or an administrative unit. Occurents are events or processes, but in BFO, temporal and spatiotemporal regions, too.

BFO creates separate ontologies for continuants and occurents: respectively SNAP and SPAN ontologies. SNAP ontology is a snapshot of the state of reality, SPAN models objects which “span” over some period of time. BFO requires additional ontologies (trans-ontologies) which reconcile these areas in a coherent framework.

The SNAP-SNAP ontology allows for the reasoning involving comparisons of states at different times (snapshots). The main task is to discover changes, qualitative, substantial, spatial and locational [9].

Because SNAP ontologies look like snapshots, it is important to show the dependencies and consequences of the mutual preceding and succession of objects. It is provided using structure of so called genidentity. [9] (Figure 6)

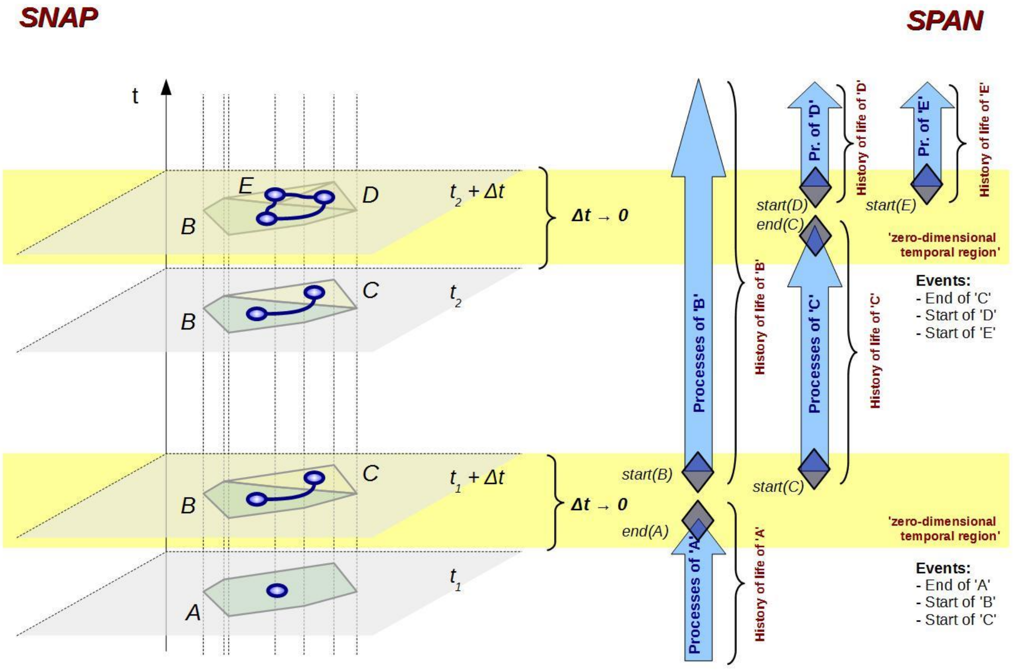
Figure 6: Role of “genidentity” in building relationships between objects in different snapshots.



The most typical entity in SPAN ontology is a process. Characteristics of the process is described by the 'process profile', which is a subclass of the process. 'Process profile' could describe the rate of change of an entity's state caused by a process. 'History of life' is a subclass of the process class, too. It directly describes the changes of the continuant.

Another classes represent space and time in a 4-dimesional manner [8, 9]. The SNAP-SPAN trans-ontology combines issues of persistent objects and processes.(Figure 7) [9]

Figure 7: Relations between SNAP and SPAN ontologies.



3.2 Building domain ontologies as an implementation of a formal ontology template

The domain ontologies for knowledge bases reflect a division similar to that which was presented in subsection 2.2 for taxonomic ontologies used as RDF graphs TBox. In most cases we could find a congruent class hierarchy and corresponding properties.

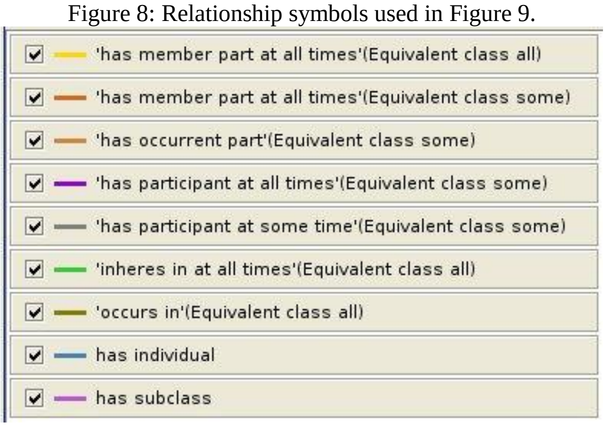
However, the knowledge base domain ontologies are constructed using different approach. Firstly, all class hierarchies are anchored to formal ontology roots. At this point a distinction between continuants and occurents is made. [15]

Secondly, the disparity lies in the depth of a hierarchy. The structures of subclasses are deeper and more branched, giving more detailed specialisation and reflecting precise distinctions between subtypes of objects belonging to one general kind.

Thirdly, there is a way of defining specialised classes performed by restrictions on properties and encoding logic rules used as classification criteria.

This example concerns the description of the behaviour of entities represented by the so-called "land cover" ("LandCoverUnit" class) which is useful for analysing environmental changes. The analysed subject is focused on "Forest" entities and the deforestation processes affecting them. Similar problems were discussed with reference to the deforestation process in Amazonia using the Linked Brazilian Amazon Rainforest Data [18, 22].

Figure 8: Relationship symbols used in Figure 9.

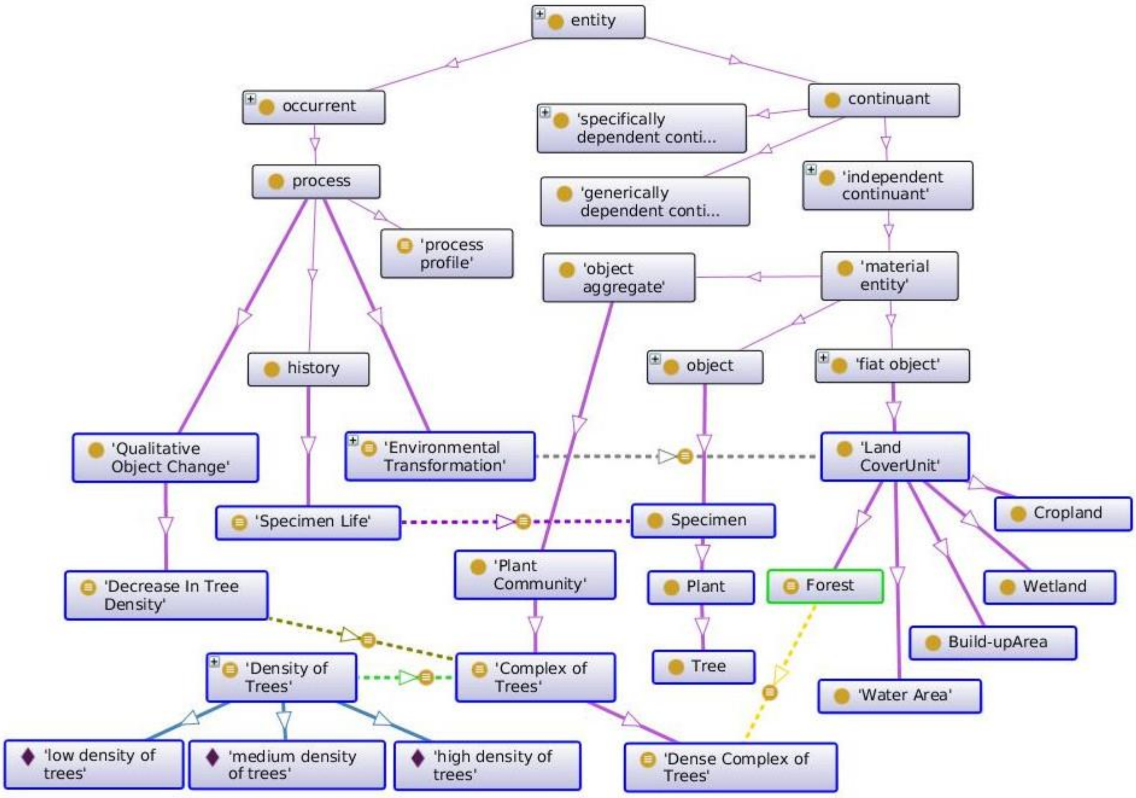


☑ — 'has member part at all times'(Equivalent class all)
☑ — 'has member part at all times'(Equivalent class some)
☑ — 'has occurrent part'(Equivalent class some)
☑ — 'has participant at all times'(Equivalent class some)
☑ — 'has participant at some time'(Equivalent class some)
☑ — 'inheres in at all times'(Equivalent class all)
☑ — 'occurs in'(Equivalent class all)
☑ — has individual
☑ — has subclass

Class "Forest" belongs to a branch of "continuant" subclasses (Figure 9). From the environmental point of view, it is a floral complex, formed by a number of characteristic floral and faunal communities, creating together a forest biocoenosis. Considering the class "Forest" as a subclass of "LandCoverUnit" we can describe forest, to put it simply, as an area with "high density of trees".

This leads us to identifying the attributes responsible for the description of the dynamics of processes. Category "DensityOfTrees", which is the "determinable universal", has three instances (tropes): "HighDensityOfTrees",

Figure 9: Domain ontology – Forest class and its relationships to dependent objects classes, quality objects and processes (BFO – thin borders, domain ontology classes – thick). Relationship symbols are explained in Figure 8.



“MediumDensityOfTrees”, and “LowDensityOfTrees”. These tropes depend on the cardinality of individual objects, i.e. 'trees' that collect over some area, which is used to evaluate the tree density. In such a relationship we can bind individual specimens with the form of “land cover”.

Continuants are bearers of occurents. The change of the state of spatial objects is the result of processes. This dependence represents cause-and-effect relationship.

The rate of change is described by an occurent 'ProcessProfile', and in this example it refers to the pace of deforestation. This allows us to specify the mode and strength of the impact of the occurent on the state of the continuant Figure 9.

3.3 Associating taxonomic ontologies with axiomatic ontologies derived from formal ontologies

To get added value from simultaneously using RDF datasets coding snapshots and axiomatic ontologies we should to combine three elements:

- real data from a spatiotemporal ABox,
- information about changes detected by testing differences between named graphs of snapshots,
- a rich logic model contained in axiomatic domain ontologies.

Taxonomic ontologies recording spatial data in RDF graphs have poor expressiveness. That is why possibility of interpretation of such data is limited. We can change this situation by injecting expressiveness of axiomatic domain ontologies into assertions representing real data.

We should bear in mind that vocabularies defining data models for RDF graphs and axiomatic domain ontologies derived from formal ontologies describe the same domain of discourse. As we have presented, we can find conceptual similarities on the highest level of the class and property hierarchies, (e.g., we can find pairs of analogues categories like land lots, buildings, land cover units, roads, pipelines etc..). However, they describe reality in a different manner. What is more, when we immerse deeper into a detailed specialisation of the class hierarchy the degree of disparities between these two kinds of ontologies will increase.

Taxonomic ontologies, used as vocabularies for RDF graphs, define a simple hierarchy of types and general relationships between objects of a particular type. We can learn from those data whether it is a lot, a land use unit, a land cover unit or a building, as well as if a given lot is adjacent to another, if this building is within the boundaries of a lot. Additionally, these datasets store information about the geometry or the area of objects. Therefore, such data give basic quantitative and qualitative properties describing objects and basic information about mutual relationships between them, including functional, topological, and dependency relationships.

As a result of studying differences between snapshots we receive a “diff graph” using simple Delta ontology. It gives us

Figure 10: Associating domain ontologies: taxonomic with axiomatic

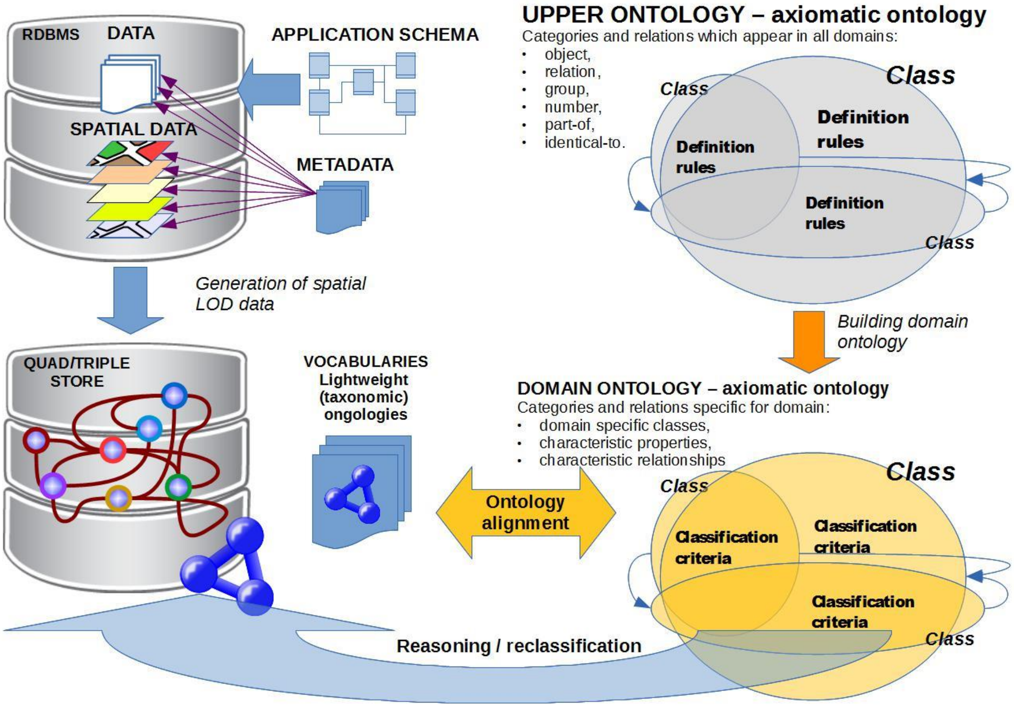
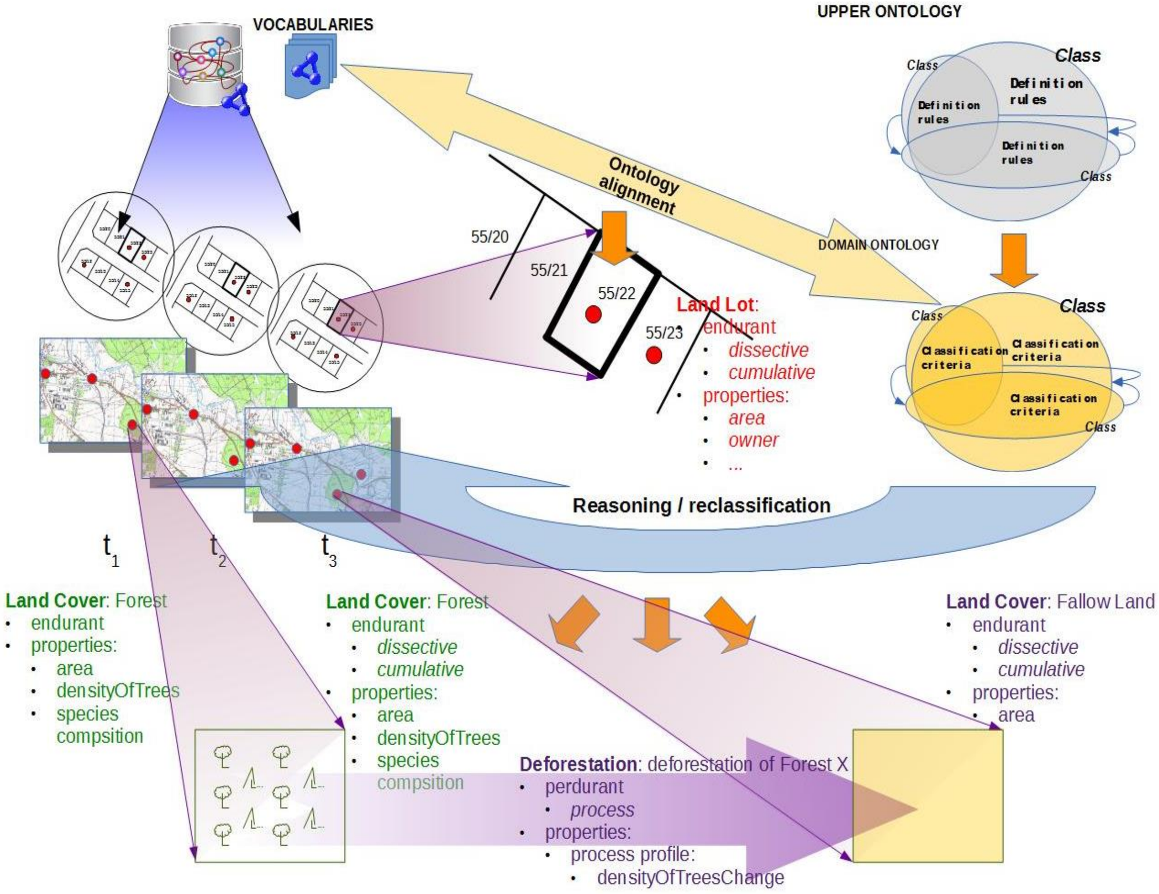


Figure 11: Inference of changes in nature



information about the changed objects and alteration of relations between them.

Axiomatic ontologies give us classification criteria in the form of logic rules: does a given lot meet the conditions for building a house, can we classify some land unit as a forest, can we interpret some detected change as decreasing population density, does some change alter the type of an object, etc.

We arrived at two models describing the same reality and information about how it changes, and now we want to combine them in such a way that we can enrich orderly raw source data by complex definitions in the form of logic rules. (Figure 10)

First, we have to find references between these two models. We can assume that on the top level of domain categories the terminology influencing concepts and predicates is similar because they concern the same domain. Nevertheless, for more specialised classes and properties we should use ontology alignment [19]. We have to find equivalent categories and discover rules of projections between classes and properties when relationships are not direct or obvious. We deal here with different levels of complexity and expressiveness. This is the reason why it could not be simply ontology mapping. [32]

Alignment between terminology of taxonomic and axiomatic structures provides us with detailed characteristics of entities. For example, objects of such classes as "LandLot" or "LandCoverUnit" are both "cumulative" and "dissective". This means that as a result of both a division and a merger of their instances we get objects of the same type. [15]

3.4 Discovering the nature of changes – processes and events

A crucial problem in discovering the nature of changes is to refer the differences classified simply in Delta ontology to process or event classes from axiomatic ontology.

This problem should be split into elementary issues. What processes or events are carried by given continuants ? What continuants, in particular, what state of the continuants, depends on given process or event? These relationships are defined in an axiomatic domain ontology. That is why we should learn which differences from the Delta ontology refer to given objects of a certain type and correspond to a particular class of occurents from the domain ontology.

When we combine the differences with occurents (processes or events), and these with continuants, we can conclude the "history of an object", describing the behaviour of a continuant. This behaviour depends on the nature of an object (is this cumulative, dissective or not).

Then we can find out the pace of change. If we notice that some datatype property from RDF graph snapshots is bound to some occurent and changes in subsequent named graphs, we can detect the pace of the process which BFO calls “process profile”, or conclude that we are dealing with an event.

Subsequently, we can discover that a process leads to an object reclassification. Because of the type and nature of a continuant, as well as the process type and its profile, we can classify the type of change as qualitative, substantial, or spatial / location change.

Referring to the example of land cover changes the natural aspect is essential for the sustainability and the state of this complex. The impact on the natural equilibrium of the ecosystem of “Forest” can cause its gradual fading. We can collect data from monitoring and observe the number of trees on a given area. Decrease in the density of trees causes a reclassification of this object. Subsequently, such decrease could be classified as a process (occurent) of deforestation, resulting in a change of land cover form. It is possible to describe this process by deforestation rate, an instance of class “ProcessProfile”.

The changes of properties are tested against the criteria of classification. Depending on the effects of object changes we can interpret the change as qualitative or substantial. Such procedure provides us with knowledge about the possible effects of the changes resulting in a reclassification of objects. Ontological description makes it possible to use the available reasoning engines for this purpose.

When density of trees reaches a certain value, one can no longer consider this instance of “LandCoverUnit” as a “Forest”. Due to the process of deforestation this land cover unit ultimately becomes fallow land. (Figure 11) [15].

Conclusions

This paper illustrates the potential of the use of RDF Datasets as storing structures for spatial information retrieved from heterogeneous spatial data resources. These structures make it possible to reflect the spatiotemporal contexts of such data and bind them to the rich representation model provided by axiomatic (formal and domain) ontologies.

The whole appeal of spatiotemporal model inherited from formal ontology consists in capturing the process not only in the statistical form, but above all in the cause-and-effect relationship.

Outlook

We can see promising possibilities for future research, e.g., richer description of contexts provided by named Graphs. When treated like common RDF resources they could be described by all possible RDF structures, creating “meta-graphs”. In this way we are provided with a broader possibility of the description of real phenomena, introducing, for example, the multidimensional or the probabilistic context.

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