

Discovery, Integration and Aggregation of Sensor Data Using the Semantic Web

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1 Introduction

From 2020 onwards all member states of the european union (EU) should provide sensor data to the infrastructure for spatial information in Europe (INSPIRE) in order to comply with annex II and III of the INSPIRE directive (INSPIRE, 2015). For this a number of sensor web enablement (SWE) standards are required to be used (INSPIRE, 2014). The sensor web is a relatively new development and there are still many questions on how to structure it. This thesis aims to develop a method to publish and link sensor metadata on the semantic web to improve the discovery, integration and aggregation of sensor data.

1.1 Background

In 2008 the open geospatial consortium (OGC) introduced a new set of standards called sensor web enablement (SWE). These standards make it possible to connect sensors to the internet and retrieve data in a uniform way. This allows users or applications to retrieve sensor data through standard protocols, regardless of the type of observations or the sensor's manufacturer (Botts et al., 2008). Among other standards SWE includes the observations and measurements (O&M) which is a model for encoding sensor data, the sensor modelling language (SensorML) which is a model for describing sensor metadata and the sensor observation service (SOS) which is a service for retrieving sensor data (Botts et al., 2007). O&M has also been adopted by the international organisation for standardisation (ISO) under ISO 19156:2011 (ISO, 2011).

Recently OGC has defined the role which their standards could play in smart city developments (Percivall, 2015). Smart cities can be defined as "enhanced city systems which use data and technology to achieve integrated management and interoperability" (Moir et al., 2014, p. 18). Research on smart cities has shown a great potential for using sensor data in urban areas. Often this is presented in the context of the internet of things (IoT) (Zanella et al., 2014; Wang et al., 2015a). The IoT can be described as "the pervasive presence around us of a variety of *things* or *objects* ... [which] are able to interact with each other and cooperate with their neighbors to reach common goals" (Atzori et al., 2010, p. 2787).

Parallel to the development of the sensor web other research has focused on the semantic web, as proposed by Berners-Lee et al. (2001). This is a response to the traditional way of using the web, where information is only available for humans to read. The semantic web is an extension of the internet which contains meaningful data that machines can understand as well. Rather than publishing documents on the internet the semantic web contains linked data using the resource description framework (RDF), also known as the 'web of data' (Bizer et al.,

2009). Data in RDF can be queried using the sparql protocol and rdf query language (SPARQL) at so called SPARQL endpoints. Originally, the semantic web intended to add metadata on the internet (Lassila and Swick, 1999). However, today it is being used for linking any kind of data from one source to another in a meaningful way (Cambridge Semantics, 2015).

Sheth et al. (2008) proposes to use semantic web technologies in the sensor web. This so-called semantic sensor web (SSW) builds on standards by OGC and the world wide web consortium (W3C) "to provide enhanced descriptions and meaning to sensor data" (Sheth et al., 2008, p.78). W3C responded to this development by creating a standard ontology for sensor data on the semantic web (Compton et al., 2012).

1.2 Problem statement

Finding sensor data that can be retrieved using open standards is not easy. The implementation of the sensor web is still in an early stage. At the moment there are only a limited number of SOS implementations available on the web and they contain a limited amount of data. In the Netherlands the SOS by the Dutch national institute for public health and the environment (RIVM) is one of the first ones to be developed. It has only recently been launched and contains data on air quality. A number of other organisations still use a custom application program interface (API) to retrieve data from sensors connected to the internet. It has been researched to what extent a catalogue service could be useful for discovering sensor data: the sensor instance registry (SIR) (Jirka and Nüst, 2010) and the sensor observable registry (SOR) (Jirka and Bröring, 2009). Catalogue services have already been available for example for the web map service (WMS), web feature service (WFS) or web coverage service (WCS) (Nebert et al., 2007). However, for discovering the sensor data sources used in this paper no register or catalogue service has been implemented. Atkinson et al. (2015) also argues that catalogue services have a number of major disadvantages. It places a very high burden on the client to not only know where to find the catalogue service, but also to have knowledge on all kinds of other factors (e.g. its organisation, access protocol, response format and response content) (Atkinson et al., 2015, p.128). The authors suggest that linked data is therefore a much better solution for discovering sensor data.

It has been argued that one of the challenges of using sensor data is the difficulty of integrating data from different sources to perform data fusion (Corcho and Garcia-Castro, 2010; Ji et al., 2014; Wang et al., 2015b). Data fusion is "a data processing technique that associates, combines, aggregates, and integrates data from different sources" (Wang et al., 2015a, p. 2). Even if the sources comply with the SWE standards it is challenging, since the data can be of a different scale, both in time and space. Spatio-temporal irregularities are a fundamental property of sensor data (Ganesan et al., 2004).

A question that comes to mind is to what extent the semantic web could be a better solution for publishing sensor data than using a SOS. The geoweb has some very good qualities, such as very structured approaches in which (sensor) data can be retrieved using well defined services. This is different from for example web pages where content can be completely unstructured. The response of a SOS also contains some semantics about sensor data. There can be x-links inside the extensible markup language (XML) with uniform resource identifier (URI)s that point to semantic definitions of objects. Still, the semantic web could be beneficial for the geoweb as it is machine understandable which could be useful for automatic integration and aggregation. It also contains links to other relevant data which could make discovering sensor data more easy.

1.3 Scientific relevance

Sensor data ties together many different fields of research. On the one hand there is research on how to create the most efficient sensor networks that uses the least amount of power to transfer the observed data over long distances. This involves academic fields such as mathematics, physics and electrical engineering. On the other hand there is research that uses sensor data to gain insights into real world phenomenon. This involves academic fields such as geography, environmental studies and urbanism. In order to connect these scientific fields, research has been focused on the use of computer science and standardisation for transferring sensor data over the internet.

In the future more sensor data is expected to be produced. Both experts and non-experts will be involved in this development. Experts will produce more data because of European legislation (INSPIRE). Non-experts will be involved more often via smart cities and IoT developments where users or consumer electronics produce sensor data as well. This vast amount of data could be very useful for academic research, provided researchers are able to find the data they need online and are able to integrate and aggregate data from heterogeneous sources. Publishing sensor metadata on the semantic web could make it easier to find what you need through related data on the internet. A SOR or SIR is only useful for users if it is already known in advance where to find a specific catalogue service, as content inside the service cannot be linked to from other parts of the web. It is also dependent on whether client applications are capable of having extensive knowledge on how the catalogue services function.

1.4 Research question

This thesis aims to develop a method that uses the semantic web to improve sensor data discovery as well as the integration and aggregation of sensor data from heterogeneous sources. The following question will be answered in this research: *How can the semantic web improve the discovery, integration and aggregation of distributed sensor data?*

2 Related work

A number of research topics are relevant for this thesis: how to use existing standards for publishing sensor data to the semantic web, developing ontologies that are suitable for many different kinds of sensor data and how to aggregate sensor data based on features-of-interest and time. This chapter discusses the recent relevant literature on these topics.

2.1 Sensor data catalogue service

The SOR is "a web service interface for managing the definitions of phenomena measured by sensors as well as exploring semantic relationships between these phenomena" (Jirka and Bröring, 2009, p. vi). This is a web service developed by OGC to enable semantic reasoning on sensor networks, especially concerning phenomenon definitions. This should make it easier to discover sensors that observe a certain phenomenon and to interpret sensor data.

Another web service interface specification by OGC is SIR. SIR is aimed at "managing the metadata and status information of sensors" (Jirka and Nüst, 2010, p. xii). The goal of this web service is to close the gap between metadata models based on SensorML, which is used in SWE, and the metadata model used in OGC catalogue services. Furthermore, it provides functionalities to discover sensors, to harvest sensor metadata from a SOS, to handle status information about sensors and to link SIR instances to OGC catalogue services.

2.2 Semantic sensor data middleware

Henson et al. (2009) and Pschorr (2013) suggest adding semantic annotations to a SOS which they call semantically enabled sos (Sem-SOS). In Sem-SOS the raw sensor data goes through a process of semantic annotating before it can be requested with a SOS service. The retrieved data is still an XML document, but with embedded semantic terminology as defined in an ontology model. The data retrieved from Sem-SOS is therefore semantically enriched.

Janowicz et al. (2013) has specified a method that uses a representational state transfer (REST)ful proxy as a façade for SOS. When a specific URI is requested the so-called semantic enablement layer (SEL) translates this to a SOS request, fetches the data and translates the results back to RDF. In this method the sensor data is converted to RDF on-the-fly. This allows the data to be interpreted by both humans and machines.

Atkinson et al. (2015) have identified that "distributed heterogeneous data sources are a necessary reality in the case of widespread phenomena with multiple stakeholder perspectives" (Atkinson et al., 2015, p.129). Therefore, they propose that methods should be developed to move away from the traditional dataset centric approaches and towards using linked data for cataloguing. This has the potential to bring together data and knowledge from different areas of research about the same (or similar) features-of-interest. It is also argued that using both linked data services and data-specific services could ease the transition into the linked data world.

2.3 Sensor data ontologies

Semantic sensor network ontology

W3C has developed an ontology for sensors and observations called the semantic sensor network ontology (SSNO). This ontology aims to address semantic interoperability on top of the syntactic operability that the SWE standards provide. To accommodate different definitions of the same concepts the broadest definitions have been used. Depending on the interpretation these can be further defined with subconcepts. The SSNO is based on the stimulus-sensor-observation pattern, describing the relations between a sensor, a stimulus and observations (figure 1). Sensors are defined as "physical objects ... that observe, transforming incoming stimuli ... into another, often digital, representation", stimuli are defined as "changes or states ... in an environment that a sensor can detect and use to measure a property" and observations are defined as "contexts for interpreting incoming stimuli and fixing parameters such as time and location" (Compton et al., 2012, p 28). The ontology can be used to model sensor networks from four different perspectives (sensor, observation, system, and feature & property), which have been discussed together with additional relevant concepts.

Observation capability metadata model

Hu et al. (2014) have reviewed a number of metadata models (including SensorML and SSNO) for the use of earth observation (including remote sensing). They argue that all of the current metadata models are not sufficient for sensor data discovery. This conclusion is based on an evaluation of six criteria. Three steps have been identified in the process of obtaining relevant sensor data for earth observation, which have been used to derive criteria for their evaluation framework. These steps are sensor filtration, sensor optimisation and sensor dispatch. The filtration of sensors should result in a set of sensors that meets the requirements of the application: it should measure the right phenomenon, be active, be inside the spatial and temporal range, and have a certain sample interval. In sensor optimisation the selected sensors should be combined to complement or enhance each other. To do this, the observation quality, coverage and application is relevant. In the last step - sensor dispatch - the data should be retrieved,

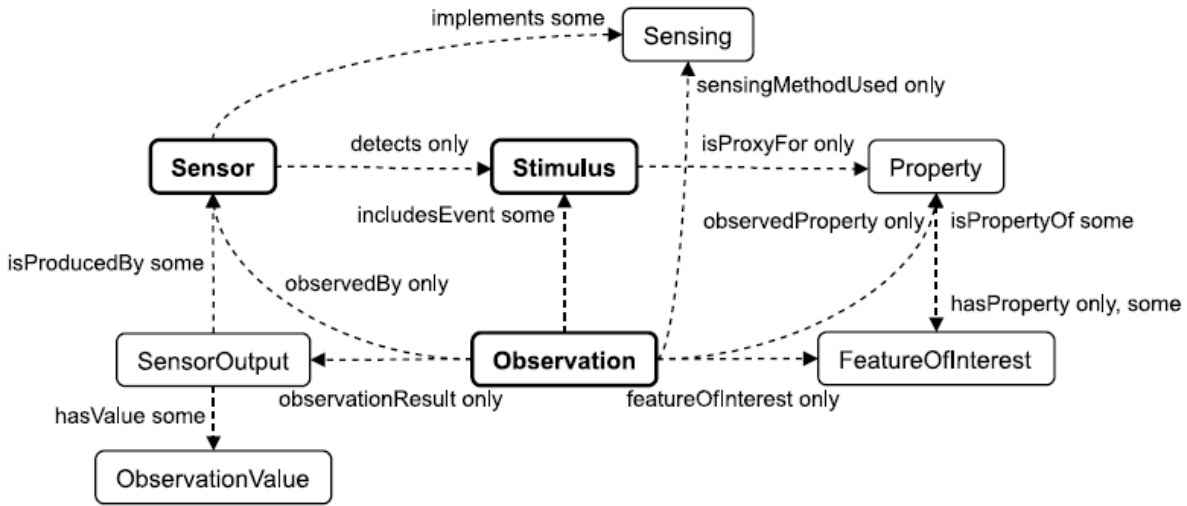


Figure 1: The stimulus-sensor-observation pattern (Compton et al., 2012, p. 28)

stored transmitted. In every evaluated model sensors can describe in different ways or only partially, which affects the outcome of the sensor dispatch.

Therefore, a metadata model is proposed that “reuses and extends the existing sensor observation-related metadata standards” (Hu et al., 2014, p. 10546). It is composed of five modules: observation breadth, observation depth, observation frequency, observation quality and observation data. They should be derived from metadata elements described using the Dublin Core metadata element set. These five modules can then be formalized following the SensorML schema which can be queried by users via a ‘Unified Sensor Capability Description Model-based Engine’.

Om-lite & sam-lite ontologies

Cox (2015b) has been working on a new semantic ontology based on O&M. Previous efforts, such as the SSNO have been using pre-existing ontologies and frameworks. However, there are already many linked data ontologies that could be useful for describing observation metadata, such as space and time concepts. Also, the SSNO does not take sampling features into account. The proposed om-lite ontology defines the concepts from O&M regarding observations, while the sam-lite defines the sampling feature concepts. The author also provides a mapping of the SSNO to om-lite.

Cox (2015b) describes how the PROV ontology (Lebo et al., 2013) can be directly used inside om-lite. The PROV ontology is “concerned with the production and transformation of Entities through time-bounded Activities, under the influence or control of Agents” (Cox, 2015b, p. 12). This is a very convenient ontology for modelling real world entities, such as sensors, observation processes and sampling processes. Many other ontologies could be implemented in combination with om-lite and sam-lite, depending on the kind of observations that are being modelled and the data publisher’s preference.

2.4 Sensor data aggregation

Sensor data aggregation can be performed for two purposes: to reduce the energy constraint of sensor networks (Korteweg et al., 2007) or to sample a feature-of-interest in space and/or time (INSPIRE, 2014). Sampling is performed when a feature-of-interest is not accessible, in which case “observations are made on a subset of the complete feature, with the intention that

the sample represents the whole" (Cox, 2015a). Stasch et al. (2011a) proposes a web processing service (WPS) that retrieves sensor data from a SOS service in order to aggregate it based on features-of-interest. The approach by Stasch et al. (2011b) is similar, but takes sensor data as input that is already published on the semantic web.

Ganesan et al. (2004) stresses that spatio-temporal irregularities are fundamental to sensor networks. Irregular sampling can have a potentially large influence on the accuracy of the aggregated outcome. For example, averaging sensor data from a feature-of-interest that is being sampled densely in some parts and more sparsely in other parts could lead to inaccurate results. To counter this the values of the densely sampled area should have a lower weight than the values from the sparsely sampled area. The same holds true for temporal irregularities (Ganesan et al., 2004). Also, Stasch et al. (2014) argue that in order for automatic aggregation to work there needs to be semantics on which kind of aggregation methods are appropriate for a specific kind of sensor data. Not all kinds of aggregation are meaningful (e.g. taking the sum of temperature values). This requires a formalisation of expert knowledge which they call semantic reference systems.

2.5 Discussion

Sem-SOS (Henson et al., 2009; Pschorr, 2013) as well as SEL (Janowicz et al., 2013) focus on combining the sensor web with the semantic web, but do not address the integration and aggregation of sensor data. Similarly, Atkinson et al. (2015) proposes to expose sensor data to the semantic web in order to find other kinds of related data about the same feature-of-interest. Data that is collected from another area of research for example. Atkinson et al. (2015) do not mention the integration of sensor data from heterogeneous sources either. Stasch et al. (2011b) and Stasch et al. (2011a) suggest interesting methods for aggregating sensor data based on features-of-interest. However, also these studies use sensor data from a only single source into account. Moreover, Corcho and Garcia-Castro (2010) and Ji et al. (2014) argue that methods for integration and fusion of sensor data on the semantic web is still an area for future research. Data fusion is "a data processing technique that associates, combines, aggregates, and integrates data from different sources" (Wang et al., 2015a, p. 2).

Jirka and Nüst (2010) and Jirka and Bröring (2009) present methods for including SOS services in an OGC catalogue service using SOR and SIR. Making sensor metadata available in a catalogue service will improve the discovery. However, discovery through the semantic web is likely to be more effective, since links can be created towards the sensor data from many different sources of related information. Another advantage is that links can be created by everybody that publishes linked data on the web, allowing sensor data to be used for implementations that were not identified beforehand by the publisher. Also, the semantic web will be easier to access, while the catalogue service can only be accessed on at a certain uniform resource locator (URL) which has to be known to potential users. This thesis therefore focuses on the discovery, integration and aggregation of sensor data using the semantic web.

The idea by Jones et al. (2014) of delivering data to users through a service with which they are already familiar is very appealing, because it would enable sensor data to be immediately used in any existing geographical information system (GIS). This is also suggested by Atkinson et al. (2015) to ease the transition to the linked data world. However, current research has mainly been concerned with static geographic data, not with (aggregated) sensor data. Therefore, this thesis aims to provide the service for integrating and aggregating sensor data as a WPS.

3 Research objectives

3.1 Research question

The main question this thesis will try to answer is:

How can the semantic sensor web improve the discovery, integration and aggregation of distributed sensor data?

To answer the main question a number of sub-questions need to be answered:

- How can sensor metadata be retrieved from a SOS and automatically published on the semantic web?
- How can metadata on the semantic web be linked to relevant features-of-interest using existing vocabularies?
- How can incoming links be automatically generated from DBPedia?
- How can aggregation methods be represented on the semantic web to formalise expert knowledge and prevent meaningless aggregation?
- To what extent can already existing standards for retrieving geographic data be used for a service that supplies integrated and aggregated sensor data?

3.2 Objectives

This thesis explores a method to store metadata of sensors on the semantic web, and to link it to real world features-of-interest and to appropriate methods for aggregation. This should improve the discovery of sensor data through links to other related data on the internet.

To improve the integration of sensor data a middleware architecture will be developed that can return sensor data for features-of-interest from different sources. The sensor data can be returned raw or aggregated. Only appropriate methods of aggregation are offered for each kind of observations, based on a formalisation of expert knowledge on the semantic web. The service can be accessed as a WPS.

3.3 Scope

The focus of this thesis is to explore the role of the semantic web in discovering, integrating and aggregating sensor data from heterogeneous sources. Therefore, accepted OGC and ISO standards will be, such as SOS, SensorML and O&M. The om-lite and sam-lite ontologies will be used in combination with geoSPARQL. An in-depth analysis of different (upcoming) standards lies outside the scope of this research.

4 Methods

4.1 Sensor observation service

There are a number of different requests that can be made to retrieve sensor (meta)data from a SOS: GetCapabilities, DescribeSensor and GetObservation. These requests can be made as a hypertext transfer protocol (HTTP) GET request or a HTTP POST request. The response is an XML document using the O&M (for GetObservation) or SensorML (for DescribeSensor).

4.2 Resource description framework

Publishing static geographic data on the semantic web requires a conversion of Shapefile to RDF. First the Shapefile is loaded into a Postgres database with the Postgis extension. After that a Python script retrieves the records from the database. Attributes of the records will be mapped to classes from predefined ontologies. Then the script creates an RDF graph and serialises it to a certain RDF language. This is written to a file. The final step is to publish the RDF on the web and create a SPARQL endpoint to query the data (Missier, 2015).

In RDF data is stored in so-called 'triples'. These triples are structured as: subject, predicate and object (Berners-Lee et al. (2001)). The subject and the object are things and the predicate is the relation between these two things. Three types of data can make up these triples. The first type is an international resource identifier (IRI). This is a reference to a resource and can be used for all positions of the triple. A URL is an example of an IRI, but IRIs can also refer to resources without stating where a location or how it can be accessed. It is a generalisation of a URI, also allowing non-ASCII characters. The second type of data is a literal. A literal is a value which is not an IRI, such as strings, numbers or dates. These values can only be used as object in a triple. Sometimes it's useful to refer to things without assigning them with a global identifier. The third type is the blank node and can be used as a subject or object without using an IRI or literal (Manola et al., 2014).

There are a number of different languages for writing down these triples (serialisation), such as XML (Gandon and Schreiber, 2014), N3 (Berners-Lee and Connolly, 2011) and Turtle (Beckett et al., 2014).

The sensor metadata is also being published on the semantic web. To do this an XML document is automatically retrieved from a SOS by a Python script. This script then extracts the relevant data from the XML and maps it to an ontology. It outputs an RDF file that will be published online. When new sources of sensor data are added the RDF documents will be updated.

4.3 Ontology mapping

The unified modeling language (UML) diagram (figure 2) describes different components of a SOS. The SOS has a number of metadata attributes such as the service provider's details (including contact information), its spatial and temporal extent (spatialFilter & temporalFilter) and the capabilities to query a subset of this extent. It receives data from a sensor which makes observations. An observation can be defined as "an action whose result is an estimate of the value of some property of the feature-of-interest, obtained using a specified procedure" (Cox, 2015a). The sensor is placed at a sampling point. The sampling point is part of a sampling features which intends to resemble the feature-of-interest. In the case of air quality the feature-of-interest is the bubble of air surrounding the sensor, therefore the sampling point equals the feature-of-interest (INSPIRE, 2014). The design is that an observation of the sampling feature describes the feature-of-interest through measuring one of its properties. The measurement procedure is described by a short string of text, input and output parameters and the units of measurement of the output. The relation between feature-of-interest and administrative units is added to improve the discovery of sensor data on the semantic web.

To publish data on the semantic web ontologies are required to specify the different classes and their relations. An ontology for static geographic data has to be connected to an ontology for sensor metadata. From the UML diagram in figure 2 the classes Observation, Process, ObservedProperty and FeatureOfInterest can be mapped to classes belonging to web ontology language (OWL) for observations (Cox, 2015c). SamplingFeature and Sampling point can be mapped to classes from OWL for sampling features Cox (2015d). GeoSPARQL can be used for the administrativeUnits class (Perry and Herring, 2011) and the PROV ontology for the sen-

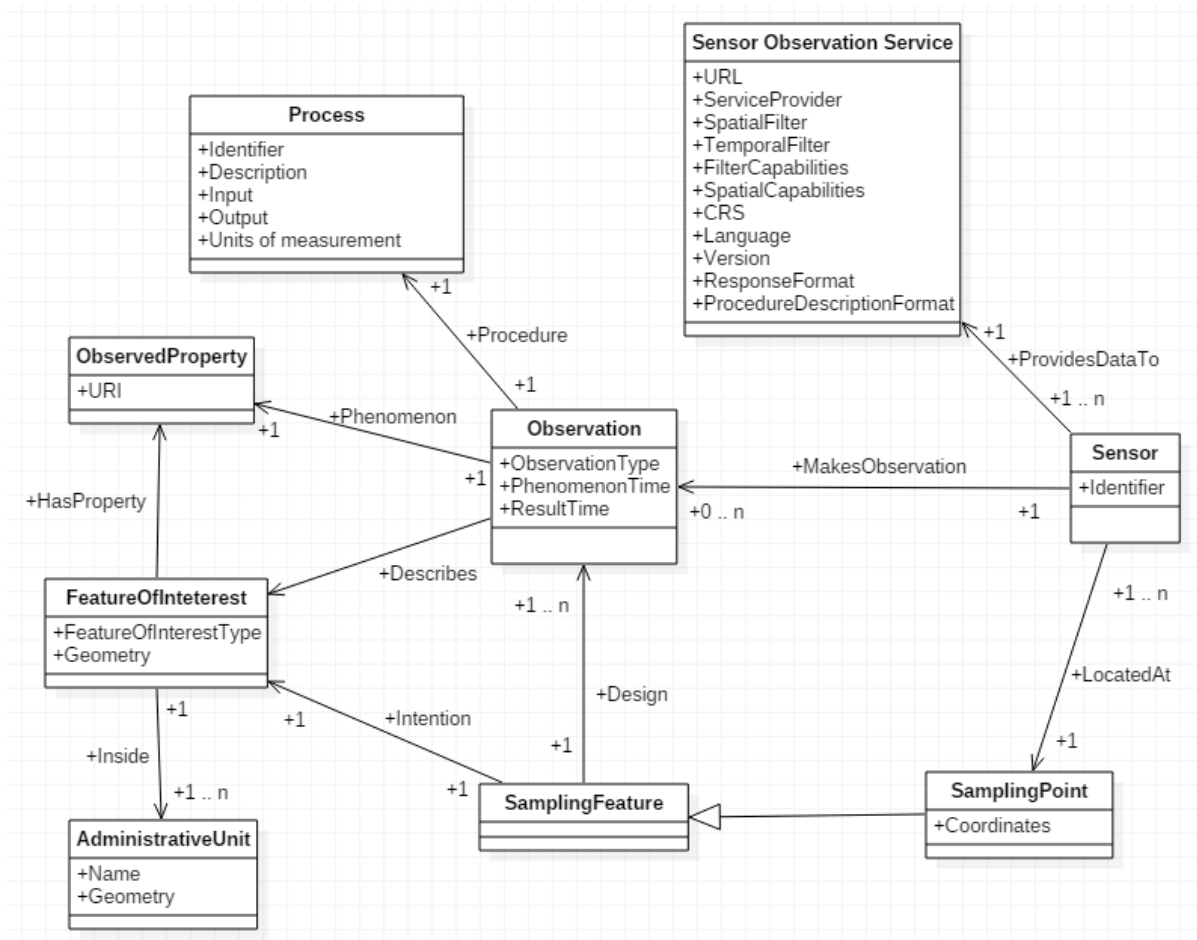


Figure 2: UML diagram of sensor observations service

sensor and sensor observation service classes (W3C Semantic Sensor Network Incubator Group, 2011).

4.4 Sensor data aggregation

There are many different ways to aggregate sensor data, for example by taking the minimum value, the maximum value, the average value, the sum, etc. In order to determine which method of aggregation is applicable for a specific kind of sensor data the sensor metadata will contain links to appropriate aggregation methods. However, which methods are appropriate should be based on expert knowledge. Therefore, this requires a literature analysis.

5 Planning

This chapter provides an overview of the deadlines for the thesis, ranging from the start of the thesis on November tenth, 2015 to the final deadline on June twentieth, 2016. Based on these deadlines a planning has been made, which breaks down the total workload into twelve parts. A GANTT chart is presented as a graphical presentation of the thesis planning (figure 3).

For the planning of the thesis a number of deadlines are important. At five moments in time the status of the thesis has to be presented and at three of these moments it is required to hand in a report. The five deadlines are referred to as P1 to P5 in the graduation manual.

Thesis Planning

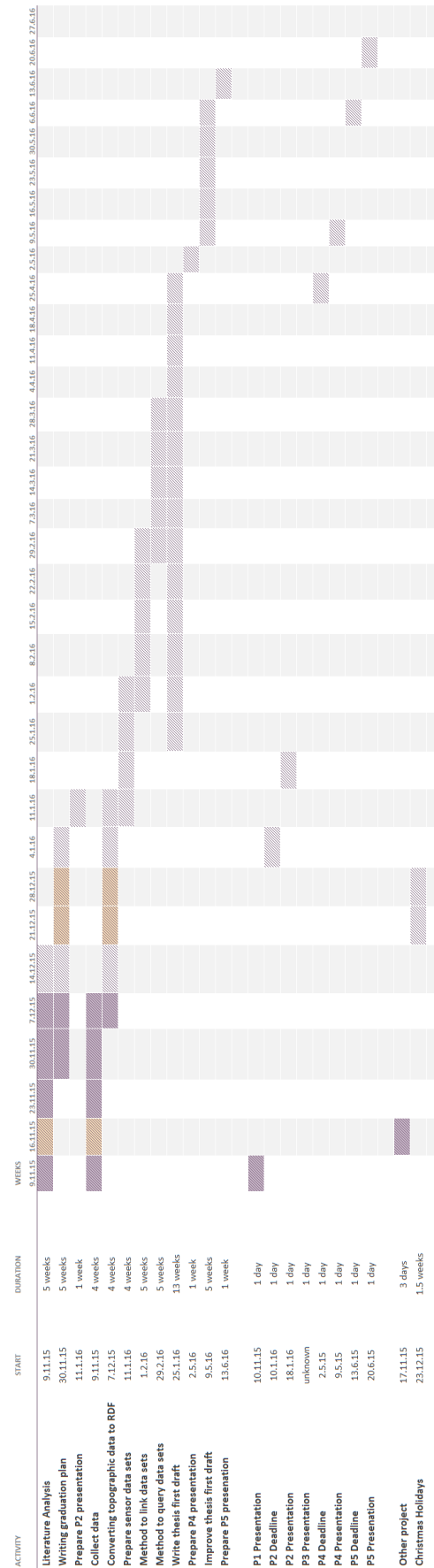


Figure 3: GANTT chart showing the planning of the thesis

P1 took place on November tenth, 2015. The general idea for the thesis was presented here and a number of students and staff was present to provide feedback. This document is part of the deliverables for P2. At P2 the research proposal for the thesis needs to be handed in. This contains the research question, its relevance, a literature analysis of related work, a description of the methods, a planning and an overview of the tools and data that will be used. The research proposal is due January eleventh, 2016. The P2 presentation is scheduled on January eighteenth, 2016. Preliminary results are presented at P3, for which the date is still unknown. The P4 deadline is on May second, 2016. This is the deadline for handing in the first draft of the thesis report. It should also be presented on May seventh, 2016. The final deadline (P5) is on the thirteenth of June, 2016. The thesis outcomes will be presented on June twentieth, 2016.

6 Tools and Data

The methods that will be researched in this thesis are also going to be tested in a prototype application. Creating a prototype requires data and software tools. This chapter briefly describes the tools and data that will be used.

6.1 Data

The data can be divided into static geographic data and sensor data. For static data the topographic data sets from the Dutch central agency for statistics (CBS) and the Dutch cadaster will be used. Shapefiles of Dutch neighbourhoods (wijken, figure 4) have been downloaded from <http://www.cbs.nl/nl-NL/menu/themas/dossiers/nederland-regionaal/publicaties/geografische-data/archief/2015/wijk-en-buurtkaart-2014-art.htm>.

The dataset of Dutch provinces (provincies, figure 6) and municipalities (gemeenten, figure 5) has been downloaded from <https://www.pdok.nl/nl/producten/pdok-downloads/basis-registratie-kadaster/bestuurlijke-grenzen-actueel>. It was very difficult to obtain data of administrative boundaries of Belgium (even from the INSPIRE data portal). Therefore, all data for Belgium was retrieved from <http://www.gadm.org/>.

Air quality sensor data will be used from the RIVM (<http://inspire.rivm.nl/sos/>) and from the Belgian interregional environment agency (IRCEL-CELINE) (<http://sos.irceline.be/>). Both of these organisations have a SOS where data can be retrieved according to the SWE standards. They provide three kinds of sensor data: particulate matter (PM_{10}), nitrogen dioxide (NO_2) and ozone (O_3).

To store the static geographic data a spatial database will be created. A Postgres database will be used for this with the Postgis extension. With the plugin 'PostGIS 2.0 Shapefile and DBF loader' the downloaded shapefiles can be imported into the database.

6.2 Prototype

The methods researched in this thesis will be implemented in a prototype. The prototype will be written in the Python programming language and will use a number of Python packages and libraries:

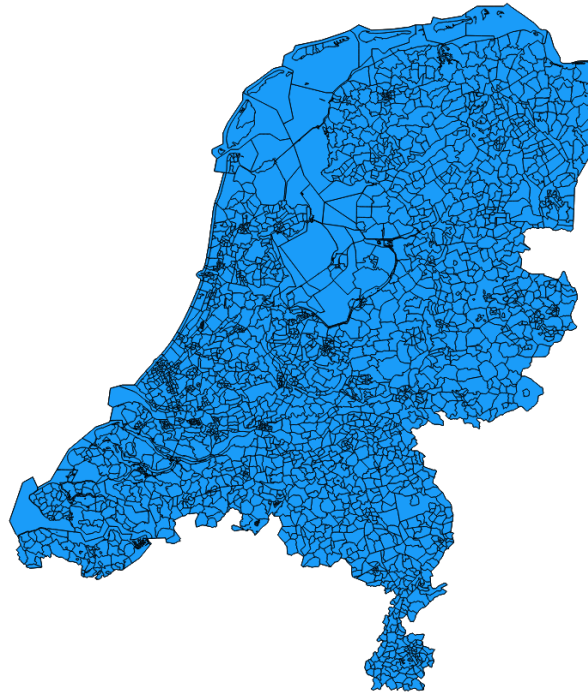


Figure 4: Dataset of neighbourhoods in the Netherlands in 2014 (from CBS)

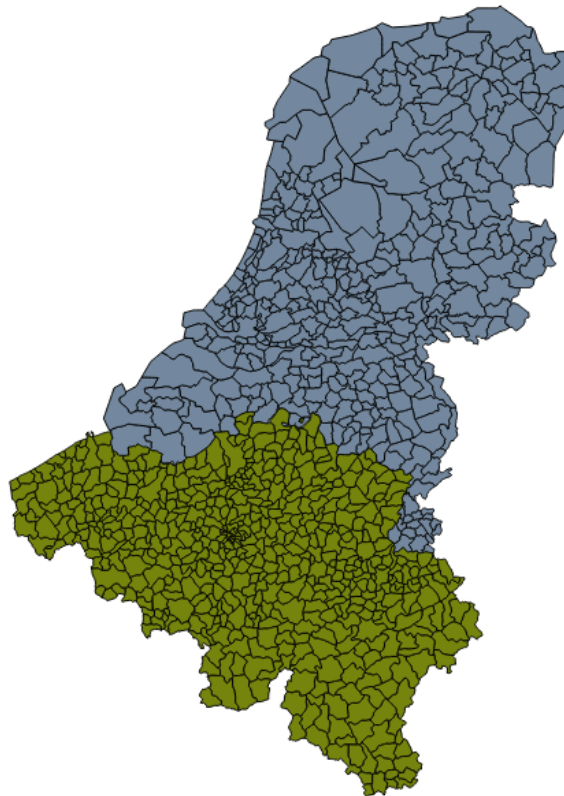


Figure 5: Dataset of municipalities in the Netherlands and Belgium in 2015 (from Dutch cadaster and GADM.org)

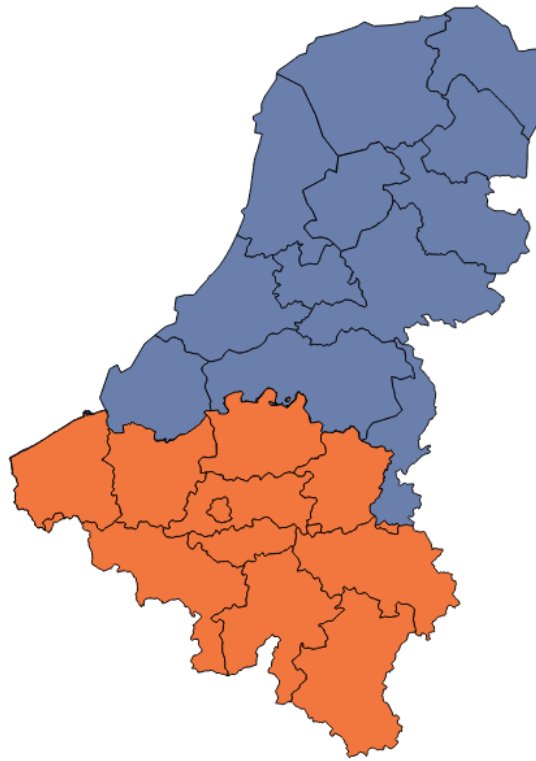


Figure 6: Dataset of provinces in the Netherlands and Belgium in 2015 (from Dutch cadaster and GADM.org)

- Psycopg2 will be used to connect a Python script to a Postgres database.
- Python's Request library will be used for making HTTP POST and GET requests.
- For working with XML Python's xml package will be used.
- To create RDF documents the Python library RDFLib will be used.
- The scripts will be part of a WPS using PyWPS

6.3 Server

The prototyp will be created on a localhost at first. Once finished it could be hosted on the university server. For the localhost the Apache software will be used, since the PyWPS software requires this.

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