An Environmental Ontology for Global City Indicators (ISO 37120)

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1 Introduction

The international standard ISO 37120, published in 2014, defines over 100 city indicators to be used globally by cities to measure and compare their performance. They cover 17 themes, including education, environment, health, safety, finance, and shelter.

The goal of the PolisGnosis project (Fox, 2015) is to automate the analysis of city performance as defined by these indicators based on data published on the Semantic Web. The PolisGnosis has developed a set of ontologies (Global City Indicator Ontologies) that are able to represent both the definition of ISO and other indicators and the data cities use to derive their indicator values.

This paper describes the ontologies developed to represent environmental theme indicators. It builds on the GCI Foundation ontology (Fox, 2013) for representing the city indicators meta-data, as well as other relevant existing ontologies, such as the W3C sensor ontology.

We begin by defining the environmental theme indicators and the competency questions that the ontologies must answer. We then review existing indicators and ontologies relevant to the environmental theme and determine whether they can be reused in our ontologies. Next, we define a set of environment related ontologies or microtheories which we then use to define each of the ISO37120 Environment theme indicators. Finally, we evaluate our ontologies by their competency questions.

2 Indicators and their Competency Requirements

In this section, we define the environmental theme indicators listed in ISO 37120. A set of competency questions will be outlined for each of these indicators, which our environmental ontology will answer. The competency questions thus represent the knowledge requirements of the ontology. Note that the GCI foundation ontology addresses the measurement theory, statistics, provenance, validity and trust questions, which are therefore excluded here.

The four categories of competency questions to be defined are:

- **Factual (F):** Questions that ask what the value of some property is.
- **Consistency – Definitional (CD):** Questions that determine whether the instantiation of an indicator by a city is consistent with the ISO 37120 definition.
- **Consistency – Internal (CI):** Questions that determine whether different parts of the instantiation are consistent with each other.
- **Deduced (D):** A value or relationship that can be deduced from the instantiation.

2.1 ISO 37120 Environmental Indicators

2.1.1 Fine particulate matter (PM2.5) concentration (ISO37120-8.1)

The definition of fine particulate matter concentration, as stated in ISO 37120, is:

"Fine particulate matter (PM2.5) concentration shall be calculated as the total mass of collected particles that are 2.5 microns or less in diameter (numerator) divided by the volume of air sampled (denominator). The result shall be expressed as the concentration of PM2.5 in micrograms per standard cubic meter (µg/m^3).

The method for measurement shall involve the use of an air sampler which draws ambient air at a constant flow rate into a specially shaped inlet where the suspended particulate matter is inertially separated into one or more size fractions within the PM2.5 size range. The 24-hour (daily) measurements of PM2.5 concentrations are forwarded to a database where yearly summaries for each monitoring stations are computed.

NOTE Since data for PM2.5 is not readily available, levels are often calculated on the basis of PM10 emission and this is reported as a separate indicator."

Competency Questions

1. (F) What is the location of the sensor for sample X?
2. (F) What is the reading of sensor X at time Y?
3. (F) What is the mass of particles in sample X?
4. (F) What is the volume of air in sample X?
5. (D) How many samples were taken at location X over period Y?
6. (D) What is the average fine particulate matter concentration over period Y?
7. (F) What is a sample composed of?
8. (F) Where are the samples stored?

2.1.2 Particulate matter (PM10) concentration (ISO37120-8.2)

The definition of particulate matter concentration, as stated in ISO 37120, is:

"Particulate matter (PM10) concentration shall be calculated as the total mass of collected particles in the PM10 size range (numerator) divided by the volume or air sampled (denominator). The result shall be expressed as the concentration of PM10 in micrograms per standard cubic meter (µg/m^3).

The method for measurement shall involve the use of an air sampler which draws ambient air at constant flow rate into a specially shaped inlet where the suspended particulate matter is inertially separated into one or more size fractions within the PM10 size range. The 24-hour (daily) measurements of PM10 concentrations are forwarded to a database where yearly summaries for each monitoring stations are computed.

NOTE Particulate matter is a mixture of microscopic solids and liquid droplets suspended in the air. These particulates are

made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (such as fragments of pollen or mould spores). Coarse particles are greater than 2.5 microns and less or equal to 10 microns in diameter and are defined as "respirable particulate matter" or PM10. Sources of coarse particles include crushing or grinding operations, and dust from paved or unpaved roads."

Competency Questions

1. (F) What is the location of the sensor for sample X?
2. (F) What is the reading of sensor X at time Y?
3. (F) What is the mass of particles in sample X?
4. (F) What is the volume of air in sample X?
5. (D) How many samples were taken at location X over period Y?
6. (D) What is the average fine particulate matter concentration over period Y?
7. (F) What is a sample composed of?
8. (F) Where are the samples stored?

2.1.3 Greenhouse gas emissions measured in tonnes per capita (ISO37120-8.3)

The definition of greenhouse gas emissions measurement, as stated in ISO 37120, is:

"The greenhouse gas emissions measured in tonnes per capita shall be measured as the total amount of greenhouse gases in tonnes (equivalent carbon dioxide units) generated over a calendar year by all activities within the city, including indirect emissions outside city boundaries (numerator) divided by the current city population (denominator). The result shall be expressed as the total greenhouse gas emissions per capita in tonnes.

The total aggregate tonnage (expressed as equivalent carbon dioxide units of greenhouse gas) of greenhouse gas emissions shall be calculated for all activities within the city for the preceding 12 months.

The Global Protocol for Community-Scale GHG Emissions (GPC), (2012 Accounting and Reporting Standard) refers to a multi-stakeholder consensus-based protocol for developing international recognized and accepted community-scale greenhouse gas accounting and reporting. This protocol defines the basic emissions sources and categories within sectors for a community-scale GHG inventory, in order to standardize GHG inventories between communities and within a community over time. The protocol provides accounting methodologies and step-by-step guidance on data collection, quantification, and reporting recommendations for each source of emissions.

Both emissions sources and sector categorizations reflect the unique nature of cities and their primary emissions sources. These include emissions from: 1) Stationary units, 2) Mobile units, 3) Waste, and 4) Industrial process and product use sectors. For further specifications, refer to the full GPC methodology. Local governments shall be expected to provide information (i.e. quantified emissions) for each of these emission sources.

In order to address the issue of inter-city sources of emissions that transcend more than one jurisdictional body, the GPC integrates the GHG Protocol Scope definitions, as follows:

Scope 2 emissions: Energy-related indirect emissions that result as a consequence of consumption of grid-supplied electricity, heating, and/or cooling, within the community's geopolitical boundary.

Scope 3 emissions: All other indirect emissions that occur as a result of activities within the community's geopolitical boundary.

For step-by-step guidance on data and accounting collection, see Section 3 of the GPC. http://www.ghgprotocol.org/files/ghgp/GPC%20v9%2020120320.pdf

NOTE Greenhouse gases (GHGs) are gases in the atmosphere that absorb infrared radiation that would otherwise escape to space; thereby contributing to rising surface temperatures. There are six major GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The warming potential for these gases varies from several years to decades to centuries.

Users may also consult the ISO 14064 series on Greenhouse Gases for further guidance."

Competency Questions

1. (F) What is the type of sensor used for sample X?
2. (F) What are the components of green house gases?
3. (F) Which greenhouse gas does sample X measure?
4. (F) For each component, what is the amount?
5. (F) What is the location of the sensor for sample X?
6. (F) What is the reading of sample X at time Y?
7. (D) What is the total amount of greenhouse gases during time Y?
8. (CD) Is the total amount of greenhouse gases measured in tonnes?
9. (F) What is the population of the city?
10. (D) What is the total aggregate tonnage of greenhouse gas emissions for all activities within the city for the preceding 12 months?

2.1.4 NO_2 (nitrogen dioxide) concentration (ISO37120-8.4)

The definition of nitrogen dioxide concentration, as stated in ISO 37120, is:

"NO_2 concentration shall be calculated as the sum of daily concentrations for a whole year (numerator) divided by 365 days (denominator). The result shall be expressed as the annual average for daily NO_2 concentrations throughout a 24 hour period from all monitoring stations within the city.

NOTE If the local air quality monitoring station measures NO_2 in parts per billion, the following conversion ratio to μg/m^3 can be used: 1 ppb = 1.88 μg/m^3. The conversion assumes an ambient pressure of 1 atmosphere and a temperature of 25 degrees ˚C. The general equation is μg/m^3 = (ppb)*(12.187)*(M) / (273.15 + ˚C) where M is the molecular weight of the gaseous pollutant. An atmospheric pressure of 1 atmosphere is assumed.

Users of this standard should also note the frequency of NO_2 exposures. Peak exposure is determined by calculating the number of times the hourly mean exceeded 200 μg/m^3 in a calendar year. Long-term exposure is determined by calculating the number of times the daily mean exceeded 40 μg/m^3 of NO_2 in a calendar year.

Data sources: Hourly average concentrations are measured by monitoring equipment and reported to Air Quality monitoring authority (i.e. City Environment Office, National Environment Office, etc.)

Competency Questions

1. (F) What is the type of sensor used for sample X?
2. (F) What is the location of the sensor for sample X?
3. (F) What is the reading of sample X at time Y?
4. (D) What is the hourly average concentration of NO2?
5. (D) What is the daily average concentration of NO_2?
6. (CD) What unit is the NO_2 concentration measured in?
7. (D) How many times did the hourly mean exceeded 200 μg/m^3?
8. (D) How many times did the daily mean exceed 40 μg/m^3?

2.1.5 SO_2 (sulphur dioxide) concentration (ISO37120-8.5)

The definition of sulphur dioxide concentration, as stated in ISO 37120, is:

"SO_2 concentration shall be calculated as the sum of daily concentration for the whole year (numerator) divided by 365 days. The result shall be determined by averaging the hourly concentrations throughout a 24 hour period from all monitoring stations within the city.

Users of this standard should also note the frequency of SO_2 exposures. Peak exposure is determined by calculating the number of times the 10 minute mean exceeded 500 µg/m^3 of SO_s in a calendar year. Long-term exposure is determined by calculating the number of times the daily mean exceeded 20 µg/m^3 of SO_2 in a calendar year.

NOTE If the local air quality monitoring station measures SO_2 in parts per billion, the following conversion ratio to µg/m^3: 1 ppb = 2.62 µg/m^3 shall be used. The conversion assumes an ambient pressure of 1 atmosphere and a temperature of 25 degrees ˚C. The general equation is µg/m^3 = (ppb)*(12.187)*(M) / (273.15 + ˚C) where M is the molecular weight of the gaseous pollutant. An atmospheric pressure of 1 atmosphere is assumed.

Data sources: Hourly average concentrations are measured by monitoring equipment and reported to Air Quality monitoring authority (i.e. City Environment Office, National Environment Office, etc.)

Competency Questions

Questions for this indicator are the same as the questions for the previous indicator, but for SO_2 instead of NO_2.

2.1.6 O_3 (Ozone) concentration (ISO37120-8.6)

The definition of ozone concentration, as stated in ISO 37120, is:

"O_3 (ozone) concentration shall be calculated as the sum of daily concentration for the whole year (numerator) divided by 365 days (denominator). The result shall be expressed as the annual average for daily O_3 (ozone) concentration in µg/m^3. O_3 is normally monitored at 8-hour intervals. To determine the 24 hour average daily concentration, the three 8 hour concentrations shall be determined and averaged over a 24 hour period at all monitoring stations within the city's boundaries.

NOTE If the local air quality monitoring station measures O_3 in parts per billion, the following conversion ratio to µg/m^3 shall be used: 1 ppb = 2.00 µg/m^3. The conversion assumes an ambient pressure of 1 atmosphere and a temperature of 25 degrees ˚C. The general equation is µg/m^3 = (ppb)*(12.187)*(M) / (273.15 + ˚C) where M is the molecular weight of the gaseous pollutant. An atmospheric pressure of 1 atmosphere is assumed.

Long-term exposure shall be determined by the number of days when the daily average concentration over an 8 hour exposure exceeds 100 µg/m^3. Long-term exposure shall be noted.

Competency Questions

Questions for this indicator are the same as the questions for the previous indicator, but for $O_{3.}$

2.1.7 Noise Pollution (ISO37120-8.7)

The definition of noise pollution measurement, as stated in ISO 37120, is:

"Noise pollution shall be calculated by mapping the noise level L_{den} (day-evening-night) likely to cause annoyance as given in ISO 1966-2:1987, identifying the areas of the city where L_{den} is greater than 55 dB(A) and estimating the population of those areas as a percentage of the total city population. The result shall be expressed as the percentage of the population affected by noise pollution.

Users of this standard should note that noise pollution can also be recorded as L_n (night) and when exceeding 50 dB(A) is likely to cause sleep deprivation.

NOTE Another useful indicator of the noise levels in a city is the degree of annoyance as specified in ISO/TS 15666:2003.

Data sources: Average concentrations are measured by monitoring equipment and reported to Air Quality monitoring authority (i.e. City Environment Office, National Environment Office, etc.)

Competency Questions

1. (F) What is the type of sensor used for sample X?
2. (F) What is the location of the sensor for sample X?
3. (F) What is the population of the area covered by sensor X?
4. (F) What is the reading of sample X at time Y?
5. (F) What is the population of the city?
6. (D) What is the noise level L_{den} in area X?
7. (D) What is the percentage of the population affected by noise pollution?
8. (D) Does L_n exceed 50 dB(A)?

2.1.8 Percentage change in number of native species (ISO37120-8.8)

The definition of percentage change in number of native species, as stated in ISO 37120, is:

"The percentage change in number of native species shall be calculated as the total net change in species (numerator) divided by the total number of species from the 5 taxonomic groups from most recent survey (denominator). The result shall then be multiplied by 100 and expressed as a percentage.

The net change in species shall be calculated as the number of new species within the city from the three core taxonomic groups and the city's selection of an additional two taxonomic groups (as a result of re-introduction, rediscovery, new species found, etc.) subtracted by the number of species that have become extirpated or locally extinct within the city.

The three core taxonomic groups shall refer to vascular plants, birds and butterflies. Additional taxonomic groups that cities should select can include the following: mammals, insects, bryophytes, fungi, amphibians, reptiles, freshwater fish, molluscs, dragonflies, carabid beetles, spiders, hard corals, marine fish, seagrasses, sponges, etc. A full list can be found in the User's Manual for the City Biodiversity Index.

Data sources: Possible sources of data include government agencies in charge of biodiversity, city municipalities, urban planning agencies, city forestry departments, biodiversity centres, nature groups, universities, etc."

Competency Questions

1. (F) How many different species are present in the city?
2. (F) What are the taxonomic groups in the city?
3. (F) What are the species present in the city?
4. (F) What are the new species in the city?
5. (D) What is the number of new species within the city?
6. (F) Which species have become extirpated or locally extinct within the city?
7. (D) What is the number of species that have become extirpated or locally extinct within the city?
8. (CD) Are the species within the three core taxonomic groups or the city's selection of an additional two taxonomic groups?
9. (D) What is the total net change in species?

2.2 Ontology Requirements

The introduction of the ISO 37120 standards has allowed for global standardization of how we measure city performance. To be able to achieve automated, replicable, and globally comparable measurements, these standards and their supporting information must be represented in a machine readable format that truly engulfs the concepts beyond their English definitions. This is the basis for the GCI ontologies.

For the environmental indicators theme, we define these concepts or microtheories based on the 8 indicators and their competency questions, as outlined in the previous section. The first 6 indicators cover different types of air pollution, the 7th covers noise pollution, and the last covers biological species.

With the exception of the last, all our indicators are measured by automatic sensors. Each reading is a measure of a certain quantity, and is measured in a certain unit.

Based on this, to be able to describe all of these indicators completely, we need to define the following microtheories:

1- Pollution
2- Species
3- Sensors

3 Background

3.1 City Indicators

There are many environmental indicators used around the world to help cities measure the state of the environment. In line with the pressure-state-response model developed by the OECD[1], these indicators fall into three subsets. The first subset, referred to as "state" indicators, is the collection of ecological indicators which can include physical, biological and chemical measures, such as temperature, or the number of breeding bird pairs in an area. The second subset, referred to as "pressure" indicators, is the collection of indicators that measure human activities or anthropogenic pressures, such as greenhouse gas emissions. The third subset track societal responses to environmental issues, such as the number of people serviced by sewage treatment. All these indicators can vary from very specific measures used in technical research, to very general and simple measures used daily by the general public, such as UV index.

In Canada, for example, Canadian Environmental Sustainability Indicators[2] (CESI) measure the progress of the Federal Sustainable Development Strategy, report to Canadians on the state of the environment, and describe Canada's progress on key environmental sustainability issues. Some CESIs are concerned with greenhouse gas emissions, air quality, air pollutant emissions, freshwater quality in Canadian rivers, water quantity in Canadian rivers, extent of Canada's wetlands, and the status of major fish stocks, among many others.

3.2 Environmental Standards

Environmental standards are put in place by agencies around the world to ensure a certain quality of environmental measures. These can vary in geographical constraints, with some standards being enforced locally, regionally, nationally, or globally.

In Canada, for example, Canada-wide Standards[3] (CWS) flow from a political commitment by federal, provincial and territorial Ministers to address key environmental protection and health

[1] The OECD Environmental Indicators documentation can be found at https://www.oecd.org/env/indicators-modelling-outlooks/24993546.pdf
[2] CESIs can be found on the Environment and Climate Change Canada website at https://www.ec.gc.ca/indicateurs-indicators/
[3] CWSs can be found on the Environment and Climate Change Canada website at http://www.ec.gc.ca/lcpe-cepa/

risk issues that require concerted action across Canada. CWSs can include qualitative or quantitative standards, guidelines, objectives and criteria for protecting the environment and reducing risks to human health. CWSs include standards for benzene, dioxins, mercury, particulate matter, ozone, and petroleum hydrocarbons.

In Europe, the European Commission[4] has an exclusive right to propose new environmental policy, as well as a responsibility to ensure the implementation of environmental rules. The EU is considered to have the most extensive environmental laws of any international organisation. The EU's environmental legislation addresses issues such as acid rain, ozone layer, air quality, noise pollution, waste and water pollution, and sustainable energy. It is estimated to amount to well over 500 directives, regulations and decisions.

Globally, the ISO 14000 Environmental management[5] family of standards provides tools for companies and organizations of all kinds to manage their environmental responsibilities. It provides a framework for environmental management systems (EMS), focuses on specific approaches such as audits and communications, and addresses environmental challenges such as climate change.

3.3 Ontologies

Before we build our ontology, we look for existing ontologies that are related to any of the microtheories above, and assess the degree to which they answer our competency questions. The ontologies we found that contain concepts and properties related to the competency questions include:

1- Law and Environment Ontology (http://leo.informea.org/)
2- NASA Climate Ontology (https://cds.nccs.nasa.gov/tools-services/ontology/)
3- AIR_POLLUTION_Onto (http://dl.ifip.org/db/conf/ifip12/aiai2009/Oprea09.pdf)
4- BioTop (http://www2.imbi.uni-freiburg.de/ontology/biotop/)
5- EnvO (http://environmentontology.org/)
6- W3C Semantic Sensor Network Ontology (http://www.w3.org/2005/Incubator/ssn/ssnx/ssn)

Law and Environment Ontology (http://leo.informea.org/)

According to their website, "LEO provides an agreed to semantic standard for any institution or organization that collects and manages data, information and knowledge in the field of Environmental Law and Governance". This is more of a taxonomy, as it provides a hierarchy of environmental terms along with their definitions and links to related laws. It is not written in .owl or any other ontology format.

[4] The European Commission's environmental standards can be found at http://ec.europa.eu/environment
[5] The ISO 14000 Environmental management family of standards can be found at http://www.iso.org/iso/iso14000

LEO is very broad, with a hierarchy of definitions including all terms related to land, water, air, pollution, biodiversity, chemicals, etc. However, it focuses more on the law aspect of environmental data collection, and is especially designed for MEA (Multilateral Environmental Agreements) and International Environmental Law.

As depicted in Figure 1, the LEO is divided into the following sections: Air and Climate, Land, Water, Biodiversity, and Chemicals and Wastes. The sections that are most relevant to us are Air and Climate, and Biodiversity.

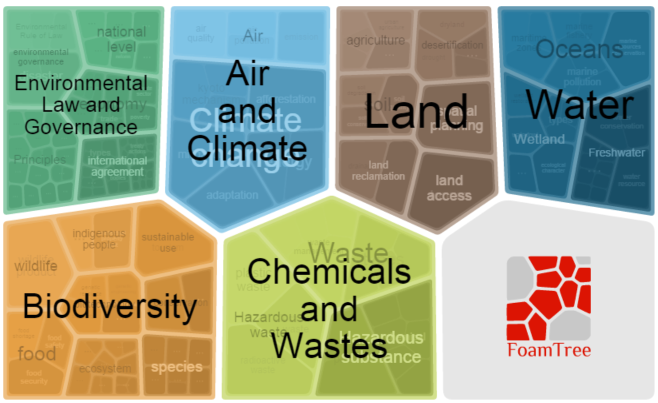

Figure 1: Main components of LEO

AIR_POLLUTION_Onto (http://dl.ifip.org/db/conf/ifip12/aiai2009/Oprea09.pdf)

This ontology focuses on air pollution (which are 6 out of the 8 ISO37120 environmental indicators). The primary focus of this ontology is to link pollutants with meteorological factors. Thus, it divides its classes into pollutants, pollutant sources, and meteorological factors.

The ontology focuses on some of the same pollutants that are in the ISO 37120 standard, including SO2, NO2, CO2, PM2.5, and PM10. It does not, however, include the other greenhouse gases or ozone. Also, it does not include sensors or data collection methods.

This ontology is outlined in the referenced PDF file, but is not available as an OWL file. The following figure, available from the PDF file, show some relevant classes used in this ontology. The relevant classes will be recreated in our ontology.

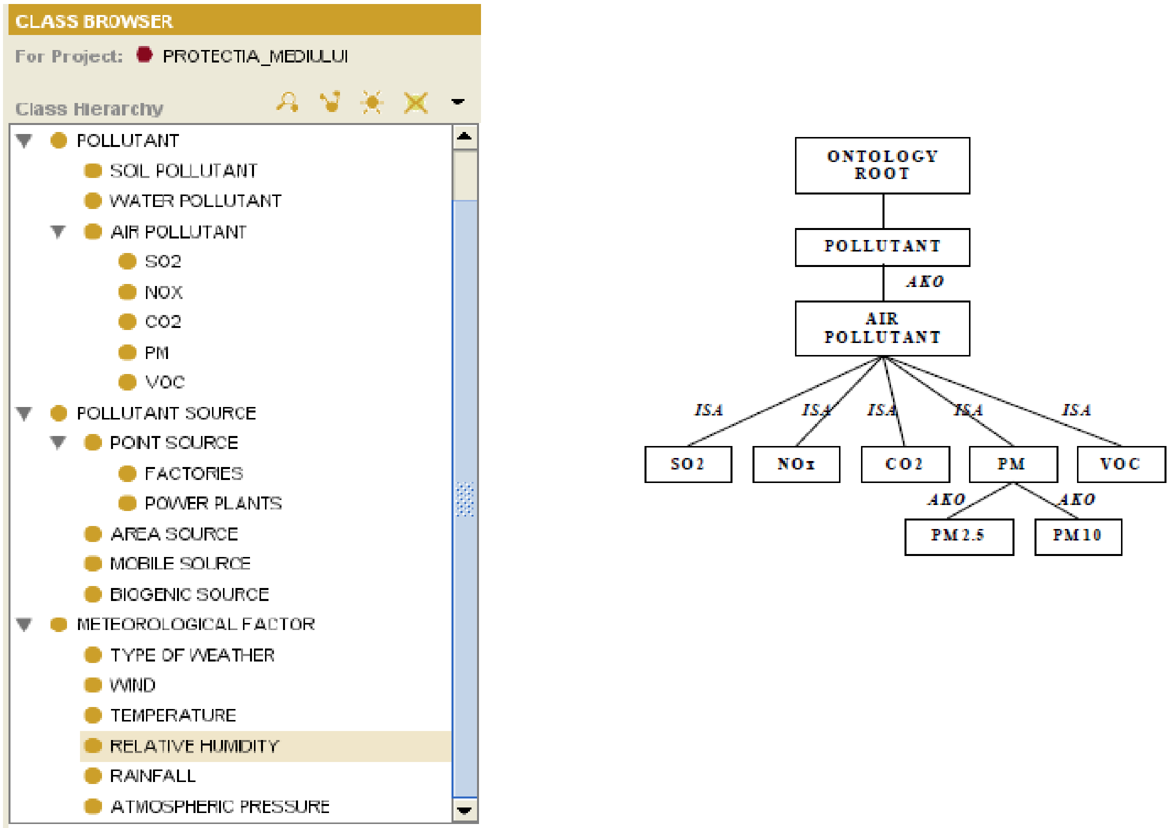

Figure 2: AIR_POLLUTION_Onto classes

EnvO (http://environmentontology.org/)

EnvO is a community ontology that "provides a controlled, structured vocabulary that is designed to support the annotation of any organism or biological sample with environment descriptors."

EnvO is a very broad ontology, which divides its classes into biomes, environmental features, and environmental material. Examples of the three are forests, ponds, and water, respectively. Thus, this ontology attempts to describe the environment as a whole.

W3C Semantic Sensor Network Ontology (http://www.w3.org/2005/Incubator/ssn/ssnx/ssn)

This is a broad ontology that describes the capabilities of different sensors, their measurement processes and the resultant observations. It provides a foundation for other ontologies to use for their sensor information. The following diagram illustrates the classes and their relationships in this ontology.

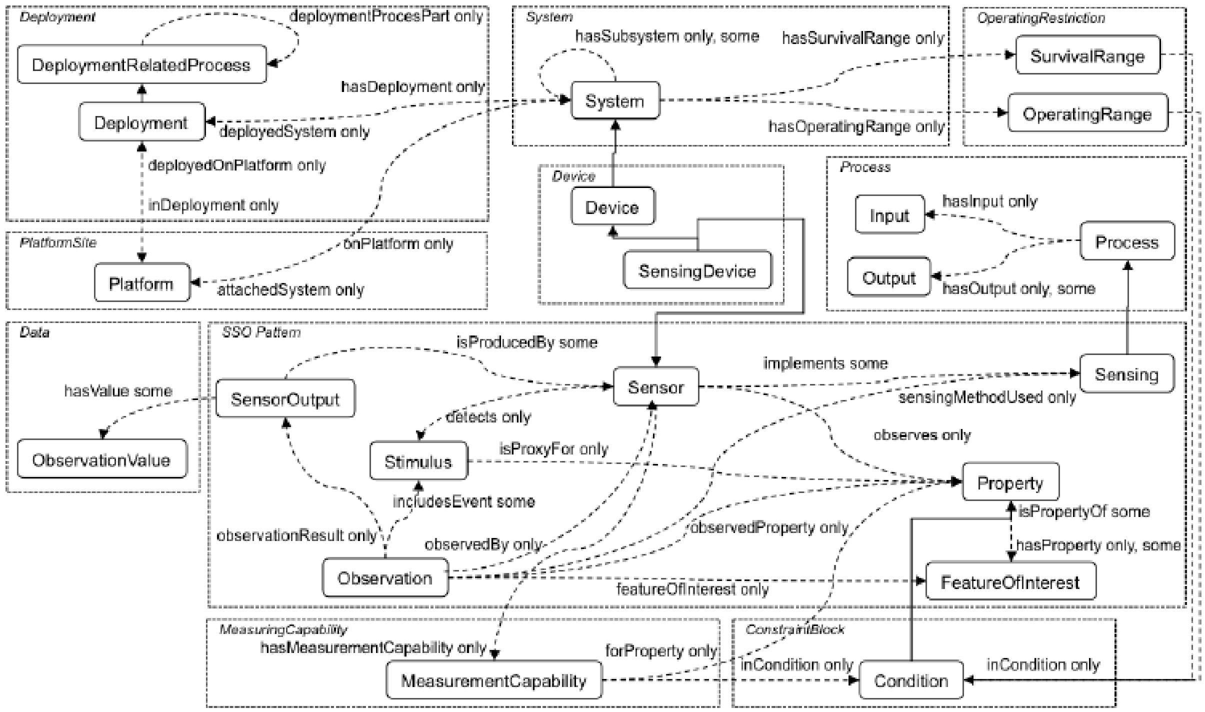

Figure 3: SSN Ontology

Relevant to our project, the SSN ontology defines classes for sensing devices and their outputs, and relates them via the property 'isProducedBy'. These classes will be imported and used in our ontology to relate our pollutants to their sensors. The prefix 'ssn' will be used where needed.

3.4 Global City Indicator Foundation Ontology

To develop an environmental ontology that can represent the definition of each environmental indicator and answer the corresponding competency questions, we first build on the Global City Indicator Foundation Ontology[6]. The GCI Foundation Ontology integrates and extends the following existing ontologies, depicted in Figure 4.

- Time (Hobbs & Pan, 2006).
- Measurement (Rijgersberg et al., 2011)
- Statistics (Pattuelli, 2009).
- Validity (Fox & Huang, 2005).
- Trust (Huang & Fox, 2006).
- Placenames (www.geonames.org).

[6] The GCI Foundation ontology can be found at http://ontology.eil.utoronto.ca/GCI/GCI-Foundation.owl along with its documentation at http://ontology.eil.utoronto.ca/GCI/GCI-Foundation.html. We will use the prefix "gci" where needed.

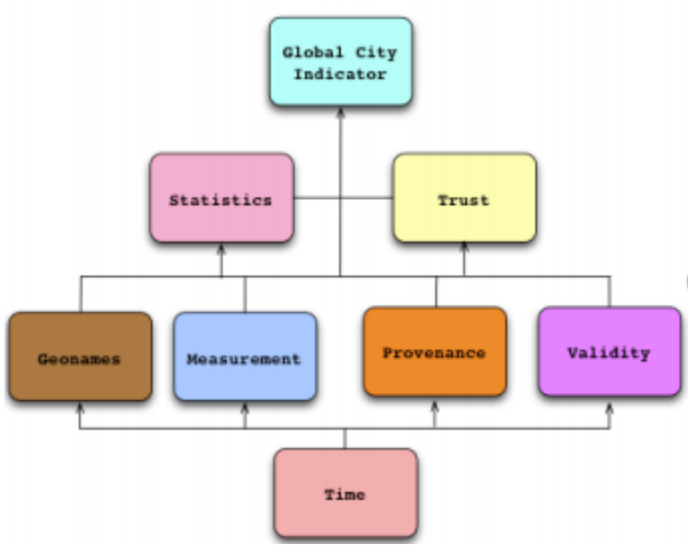

Figure 4: GCI Foundation Ontology Components

This covers the meta data for all indicators, and serves as a foundation for all indicator themes. To completely represent an indicator theme, each ontology builds on this foundation and adds to it all information relevant to the specific theme.

4 Architecture of the Global City Indicator Ontology

Figure 5 depicts the organization of files used to define the ISO 37120 ontology we are developing. Only four of the indicator themes are depicted here due to space limitations. At the highest level, i.e., ISO 37120 Ontology level, the ISO 37120 module[7] contains the globally unique identifier (IRI) for each ISO 37120 indicator. For example, the IRI for the NO2

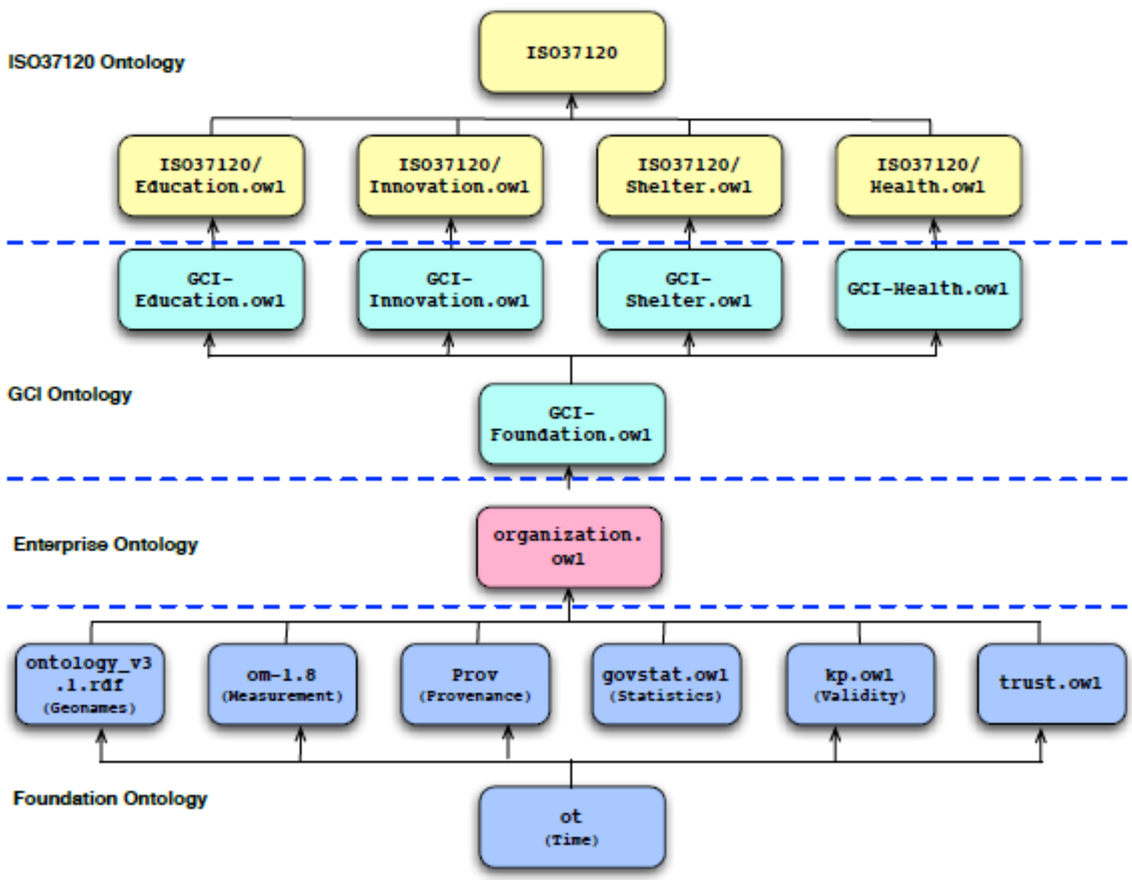

Figure 5: ISO 37120 Ontology Modules

For each category of indicators in the ISO 37120 specification, (e.g. Environment), there is a separate file that provides the definition of each indicator in that category. For example, ISO37120/Environment.owl[8] provides a complete OWL definition for all eight of the indicators in the ISO 37120 specification.

The GCI Ontology level provides the category specific ontologies required to define each category's indicators. For example, to define the ISO 37120 Environment indicators, we need an environmental ontology covering concepts such as pollution, sensors, species, etc.

[7] The ISO 37120 module is available at http://ontology.eil.utoronto.ca/GCI/37120.owl.
[8] http://ontology.eil.utoronto.ca/GCI/ISO37120/Environment.owl.

GCI-Environment.owl[9] provides the classes used by ISO37120/Environment.owl.

All of the category specific indicator ontologies rely about the GCI Foundation ontology for more generic concepts such as population counts and ratios, meta-information, etc.

The Enterprise Ontology level contains Enterprise Modelling ontologies. In this figure we only show the Organization Ontology file[10] (Fox et al., 1998), which is one of the TOVE Enterprise Modelling ontologies (Fox & Grüninger, 1998). In addition to the Organization ontology, TOVE has ontologies spanning:

- Activities and States (Gruninger & Fox, 1994)
- Resources (Fadel et al., 1994; Fadel, 1994).
- Quality Measurement (Kim & Fox, 1994).
- Activity-Based Costing (Tham et al., 1994).
- Product (Lin et al., 1997).
- Product Requirements (Lin et al., 1996).
- Human Resources (Fazel-Zarandi & Fox, 2012).

Finally, the Foundation Ontology (Fox, 2013) level provides very basic ontologies that were selected as the foundation for the GCI-Foundation.owl ontology. We review here the basic structure of a ratio indicator, as defined in the GCI Foundation ontology, and upon which the environmental indicators are based.

At the core of the Foundation ontology is the OM measurement ontology (Rijgersberg et al., 2011). The purpose of a measurement ontology is to provide the underlying semantics of a number, such as what is being measured and the unit of measurement. The importance of grounding an indicator in a measurement ontology is to assure that the numbers are comparable. Note that this does mean that they are measuring the same thing, but that the actual measures are of the same type, e.g., the units for NO2 are consistently in $\mu g/m^3$.

Figure 7 depicts the basic classes of the OM ontology used to represent an indicator. There are three main classes in OM: a 'Quantity' that denotes what is being measured, e.g., diameter of a ball; a 'Unit of Measure' that denotes how the quantity is measured, e.g., centimeters; and a 'Measure' that denotes the value of the measurement which is linked to the both 'Quantity' and 'Unit of Measure'. For example, NO2_Concentration is a subclass of 'Quantity' that has a value that is a subclass of 'Measure' whose units are 'micrograms_per_cubic_metre' that is a subclass of 'Unit of Measure'.

[9] The GCI Environmental ontology can be found at http://ontology.eil.utoronto.ca/GCI/Environment/GCI-Environment.owl along with its documentation at http://ontology.eil.utoronto.ca/GCI/Environment/index.html. We will use the prefix "gcien" where needed.

[10] The Organization ontology can be found at http://ontology.eil.utoronto.ca/organization.owl along with its documentation at http://ontology.eil.utoronto.ca/organization.html. We will use the prefix "org" where needed.

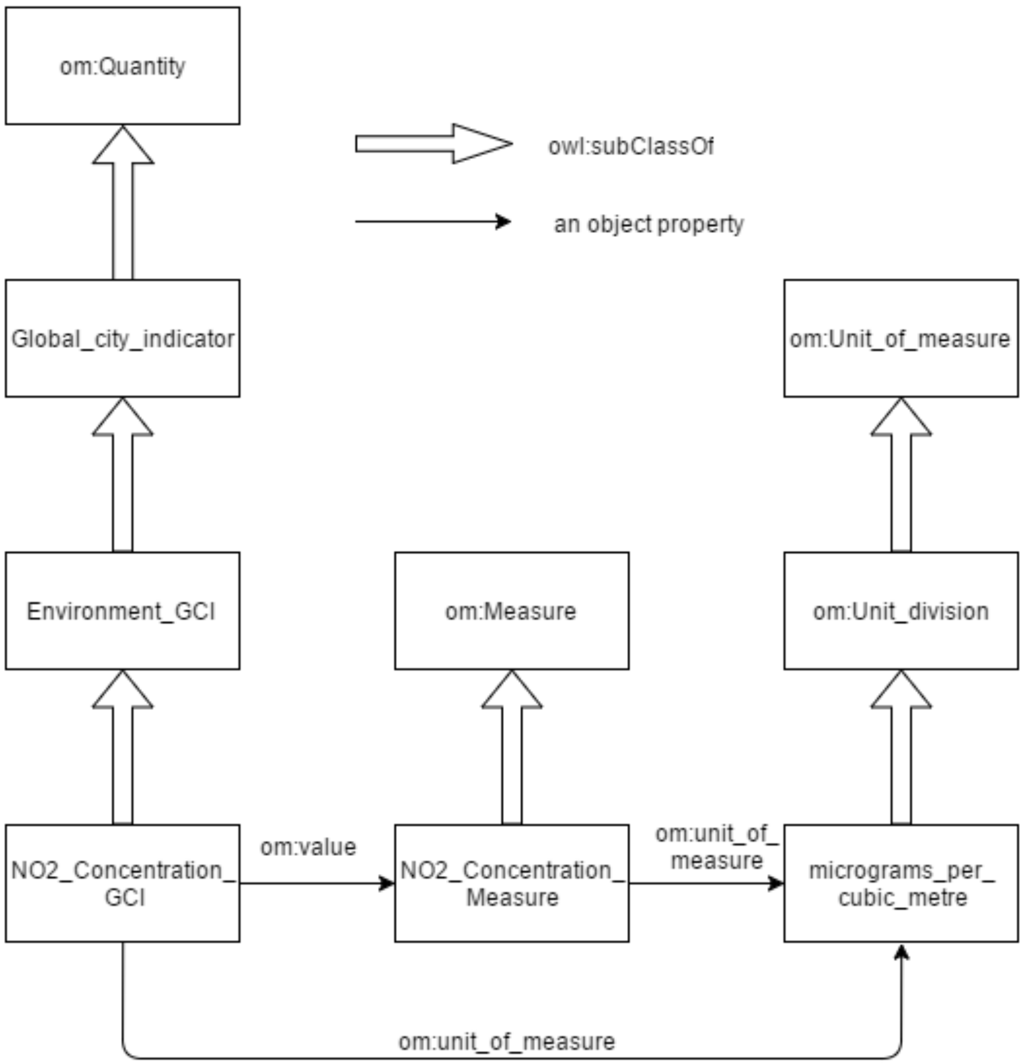

Figure 6: Measurement Ontology

Each indicator of the eight environmental theme indicators is a ratio of a certain numerator to a certain denominator. Each numerator or denominator may be defined by a certain related class. For example, the numerator for the NO2 concentration indicator is the yearly sum of NO2 concentrations (Yearly_Sum_NO2), which is defined by the individual measures of NO2 concentrations (NO2_Concentration) over the year. A ratio indicator has a unit of measure depending on the indicator. Each indicator is measured for a specific year, using property ‘for_year’, and for a specific city, using the property ‘for_city’. Figure 8 illustrates this structure, which will be used in the indicator definitions that follow.

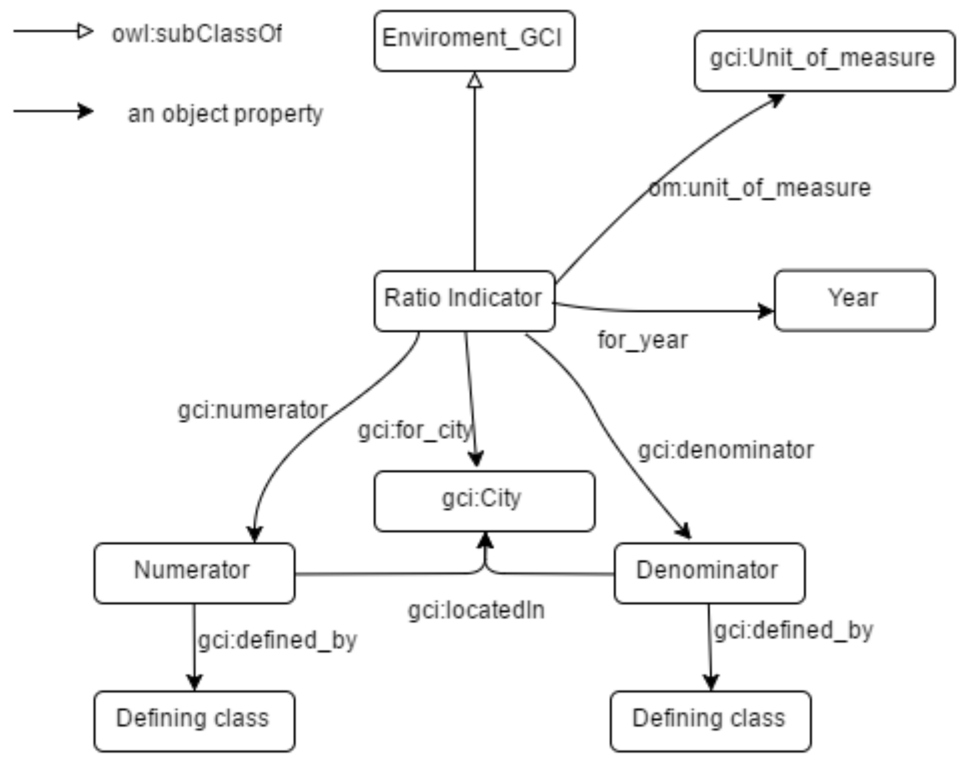

Figure 7: Foundation Ontology ratio definition

5 GCI Environmental Ontology

In order to represent the definitions of the ISO 37120 environmental indicators and answer their competency questions, we need to define all information not included in the GCI Foundation ontology. These include microtheories of pollution, sensors, and species. These three microtheories are represented in their separate ontologies.

5.1 Pollution Ontology

This section describes the pollution ontology found at:
http://ontology.eil.utoronto.ca/GCI/Environment/Pollution.owl

Seven of our eight environmental theme indicators are related to pollution. Each of the seven is concerned with a specific type of pollutant. For example, the fourth indicator is concerned with the air pollutant NO2. We review its competency questions:

1. (F) What is the type of sensor used for sample X?
2. (F) What is the location of the sensor for sample X?
3. (F) What is the reading of sample X at time Y?
4. (D) What is the hourly average concentration of NO2?
5. (D) What is the daily average concentration of NO2?
6. (CD) What unit is the NO2 concentration measured in?
7. (D) How many times did the hourly mean exceed 200 µg/m3?
8. (D) How many times did the daily mean exceed 40 µg/m3?

To answer any of these questions, we need to first define which pollutant we are measuring. Therefore, we first need an ontology that represents the different types of pollutants.

Reviewing our ontologies in section 3.3, we see that the ontology AIR_POLLUTION_Onto contains some classes we can reuse, namely Air Pollutant and its subclasses: SO2, NO2, CO2, PM2.5, and PM10. Since AIR_POLLUTION_Onto is not available as an owl file, we must recreate these classes, and add others that we need.

As described in Figure 6, pollutants are divided into three subclasses: air pollution, water pollution, and noise pollution. Air pollution is divided into five subclasses: particulate matter, nitrogen dioxide, sulphur dioxide, ozone, and greenhouse gases. Particulate matter is divided into two subclasses, PM2.5 and PM10. Greenhouse gases are divided into six subclasses: N2O, HFCs, PFCs, CH4, CO2, and SF6.

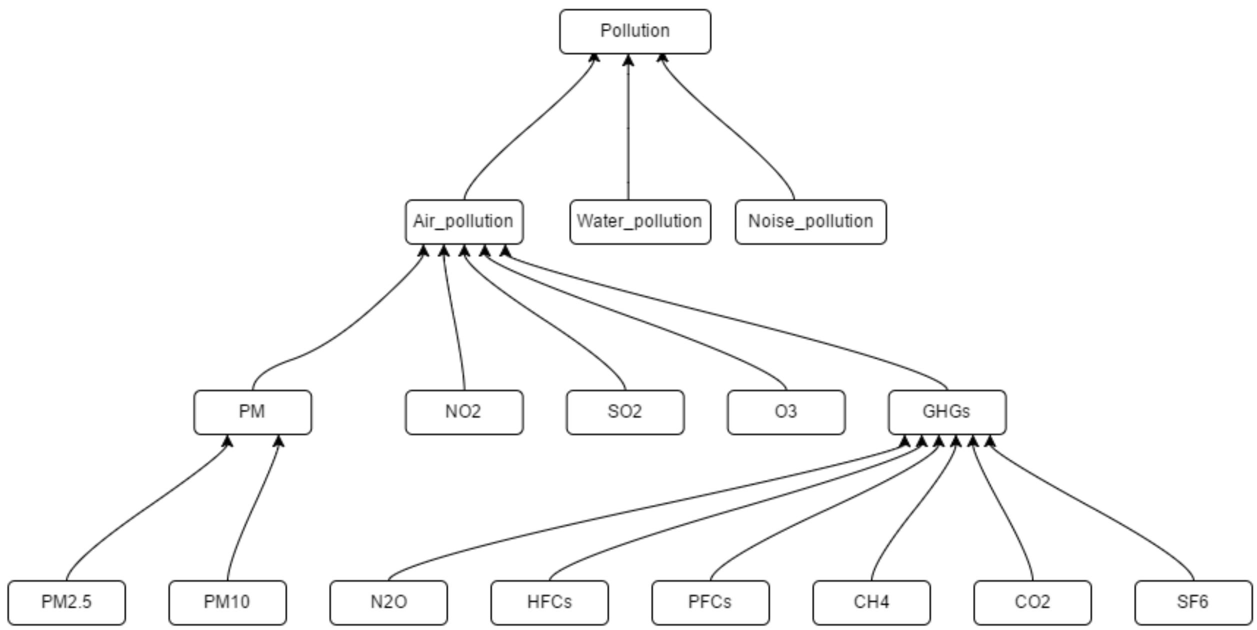

Figure 8: Pollution Taxonomy

This ontology represents pollutants and pollutant concentrations. The respective classes are related by the attribute "measures".

The ontology imports the GCI Foundation ontology to express the units of measure of each pollutant concentration. The GCI Foundation ontology uses the Ontology of Units of Measure[11] to give a foundation for measurements and their units. It divides measurements into a quantity, such as length, and a unit of measure, such as meters. A unit of measure has a scale classified as interval or ratio, and whether the number is the composition of dimensions, such as velocity being composed of speed and direction. It also defines whether it has a starting point, such as absolute zero on the Kelvin scale.

We also relate each measurement of pollution concentration to the sensor it is measured by, using the property "is_produced_by" and the class "Sensing_device", both imported from the W3C Sensor Ontology.

The following tables define the classes and properties in the pollution ontology.

Class	Property	Value Restriction
Pollution_concentration	owl:subClassOf	om:Quantity
	measures	exactly 1 Pollution
	temporal_average	some Pollution_average

[11] The Ontology of Units of Measure (OM) can be found at http://www.wurvoc.org/vocabularies/om-1.6/. We will use the prefix "om" where needed.

	ssn:is_produced_by	exactly 1 ssn:Sensing_device
Pollution_average	has_periodicity	exactly 1 gci:interval

We can measure the hourly, daily, monthly, or any other average for any pollutant. This is defined by the class "Pollution_average", which can have a periodicity of any interval, such as hour, day, or month.

Class	**Property**	**Value Restriction**
Air_pollution_concentration	owl:subClassOf	Pollution_concentration
	measures	exactly 1 Air_pollution

Class	**Property**	**Value Restriction**
Noise_pollution_concentration	owl:subClassOf	Pollution_concentration
	measures	Noise_pollution
	om:unit_of_measure	value gci:decibel

Class	**Property**	**Value Restriction**
NO2_concentration	owl:subClassOf	air_pollution_concentration
	measures	exactly 1 NO2
	om:unit_of_measure	value gci:microgram_per_cubic_metre

Class	**Property**	**Value Restriction**
SO2_concentration	owl:subClassOf	air_pollution_concentration
	measures	exactly 1 SO2
	om:unit_of_measure	value gci:microgram_per_cubic_metre

Class	**Property**	**Value Restriction**
O3_concentration	owl:subClassOf	air_pollution_concentration
	measures	exactly 1 O3
	om:unit_of_measure	value gci:microgram_per_cubic_metre

For PM2.5 and PM10, the definition of the concentration is based on the mass of particles divided by the volume of air sampled. Therefore, we define classes for mass and volume as well, and relate them to the concentration using the numerator and denominator properties defined in the foundation ontology.

Class	**Property**	**Value Restriction**
PM2.5_concentration	owl:subClassOf	air_pollution_concentration
	measures	exactly 1 PM2.5
	om:unit_of_measure	value gci:microgram_per_cubic_metre
	gci:numerator	exactly 1 PM2.5_Mass
	gci:denominator	exactly 1 PM2.5_Volume
PM2.5_Mass	owl:subClassOf	om:Mass

	om:unit_of_measure	value gci:microgram
PM2.5_Volume	owl:subClassOf	om:Volume
	om:unit_of_measure	value om:cubic_metre

Class	**Property**	**Value Restriction**
PM10_concentration	owl:subClassOf	air_pollution_concentration
	measures	exactly 1 PM10
	om:unit_of_measure	value gci:microgram_per_cubic_metre
	gci:numerator	exactly 1 PM10_Mass
	gci:denominator	exactly 1 PM10_Volume
PM10_Mass	owl:subClassOf	om:Mass
	om:unit_of_measure	value gci:microgram
PM10_Volume	owl:subClassOf	om:Volume
	om:unit_of_measure	value om:cubic_metre

For the greenhouse gases, we define classes for each type separately as follows.

Class	**Property**	**Value Restriction**
N2O_concentration	owl:subClassOf	GHGs_concentration
	measures	exactly 1 N2O
	om:unit_of_measure	value om:tonne

Class	**Property**	**Value Restriction**
CO2_concentration	owl:subClassOf	GHGs_concentration
	measures	exactly 1 CO2
	om:unit_of_measure	value om:tonne

Class	**Property**	**Value Restriction**
SF6_concentration	owl:subClassOf	GHGs_concentration
	measures	exactly 1 SF6
	om:unit_of_measure	value om:tonne

Class	**Property**	**Value Restriction**
CH4_concentration	owl:subClassOf	GHGs_concentration
	measures	exactly 1 CH4
	om:unit_of_measure	value om:tonne

Class	**Property**	**Value Restriction**
HFCs_concentration	owl:subClassOf	GHGs_concentration
	measures	exactly 1 HFCs
	om:unit_of_measure	value om:tonne

Class	Property	Value Restriction
PFCs_concentration	owl:subClassOf	GHGs_concentration
	measures	exactly 1 PFCs
	om:unit_of_measure	value om:tonne

5.2 Sensor Ontology

This section describes the sensor ontology found at:
http://ontology.eil.utoronto.ca/GCI/Environment/Sensors.owl

Some of our competency questions are concerned with the sensors used to measure the environmental indicators. For example, for greenhouse gases:

1. (F) What is the type of sensor used for sample X?

   and

7. (F) What is the location of the sensor for sample X?

To identify the sensor used in each measurement, we need to define the class for sensors and the property that relates the measurement with the sensor. These are imported from the W3C Semantic Sensor Network Ontology reviewed in Section 3.3 as follows.

Class	Property	Value Restriction
ssn:Sensing_Device	owl:subClassOf	ssn:PhysicalObject
	measures	some om:Quantity
	gci:haslocation	exactly 1 gci:Geocoordinates

where ssn is the prefix for the W3C Sensor Ontology.

To differentiate between the types of pollutants, we define additional classes for each type of sensor as follows.

Class	Property	Value Restriction
PM2.5_Sensing_device	owl:subClassOf	ssn:Sensing_device
PM10_Sensing_device	owl:subClassOf	ssn:Sensing_device
NO2_Sensing_device	owl:subClassOf	ssn:Sensing_device
O3_Sensing_device	owl:subClassOf	ssn:Sensing_device
SO2_Sensing_device	owl:subClassOf	ssn:Sensing_device
N2O_Sensing_device	owl:subClassOf	ssn:Sensing_device

CO2_Sensing_device	owl:subClassOf	ssn:Sensing_device
SF6_Sensing_device	owl:subClassOf	ssn:Sensing_device
CH4_Sensing_device	owl:subClassOf	ssn:Sensing_device
PFCs_Sensing_device	owl:subClassOf	ssn:Sensing_device
HFCs_Sensing_device	owl:subClassOf	ssn:Sensing_device
Noise_Sensing_device	owl:subClassOf	ssn:Sensing_device

5.3 Species Ontology

This section describes the species ontology found at:
http://ontology.eil.utoronto.ca/GCI/Environment/Species.owl

This ontology is needed to answer the competency questions of the eight environmental theme indicator:

1. (F) How many different species are present in the city?
2. (F) What are the taxonomic groups in the city?
3. (F) What are the species present in the city?
4. (F) What are the new species in the city?
5. (D) What is the number of new species within the city?
6. (F) Which species have become extirpated or locally extinct within the city?
7. (D) What is the number of species that have become extirpated or locally extinct within the city?
8. (CD) Are the species within the three core taxonomic groups or the city's selection of an additional two taxonomic groups?
9. (D) What is the total net change in species?

The questions refer to the taxonomic groups defined in the User's Manual for the City Biodiversity Index[12]. To represent these taxonomic groups, we create a class for each of them as follows.

Class	**Property**	**Value Restriction**
TaxonomicGroup	owl:subClassOf	owl:Thing
CoreTaxonomicGroup	owl:subClassOf	TaxonomicGroup
OptionalTaxonomicGroup	owl:subClassOf	TaxonomicGroup
VascularPlants	owl:subClassOf	CoreTaxonomicGroup
Birds	owl:subClassOf	CoreTaxonomicGroup
Butterflies	owl:subClassOf	CoreTaxonomicGroup
Mammals	owl:subClassOf	OptionalTaxonomicGroup
Insects	owl:subClassOf	OptionalTaxonomicGroup
Bryophytes	owl:subClassOf	OptionalTaxonomicGroup

[12] The User's Manual for City Biodiversity Index can be found at https://www.cbd.int/authorities/doc/User's%20Manual-for-the-City-Biodiversity-Index18April2012.pdf

Fungi	owl:subClassOf	OptionalTaxonomicGroup
Amphibians	owl:subClassOf	OptionalTaxonomicGroup
Reptiles	owl:subClassOf	OptionalTaxonomicGroup
FreshwaterFish	owl:subClassOf	OptionalTaxonomicGroup
Molluscs	owl:subClassOf	OptionalTaxonomicGroup
Dragonflies	owl:subClassOf	OptionalTaxonomicGroup
CarabidBeetles	owl:subClassOf	OptionalTaxonomicGroup
Spiders	owl:subClassOf	OptionalTaxonomicGroup
HardCorals	owl:subClassOf	OptionalTaxonomicGroup
MarineFish	owl:subClassOf	OptionalTaxonomicGroup
Seagrasses	owl:subClassOf	OptionalTaxonomicGroup
Sponges	owl:subClassOf	OptionalTaxonomicGroup

Each species is a subclass of a taxonomic group.

We then need to represent the change in species, ie: addition of a new species or extinction of an existing species. We create a class for a SpeciesEvent, which contains all the information about that event. To represent these events, we import the Event Ontology[13] and expand on it as follows.

Class	**Property**	**Value Restriction**
SpeciesEvent	owl:subClassOf	event:Event
	for_species	some TaxonomicGroup
	event:place	exactly 1 geo:SpatialThing
	event:time	exactly 1 time:TemporalEntity
	reason	some xsd:string
SpeciesIntroduction	owl:subClassOf	SpeciesEvent
SpeciesExtinction	owl:subClassOf	SpeciesEvent

6 ISO 37120 Environmental Indicators Ontology

Now that we have defined the pollution, sensors, species, and foundation ontologies, we have all the classes and properties necessary to represent the definitions of the ISO 37120 Environmental indicators. In this section, we represent the eight Environmental theme indicators. The OWL definitions can be found at http://ontology.eil.utoronto.ca/GCI/ISO37120/Environment.owl.

[13] The Event Ontology can be found at http://motools.sourceforge.net/event/event.html

6.1 Fine particulate matter (PM2.5) concentration (ISO37120:8.1)

The following diagram shows a partial definition of ISO37120:8.1. Some subClassOf links have been omitted due to space limitations.

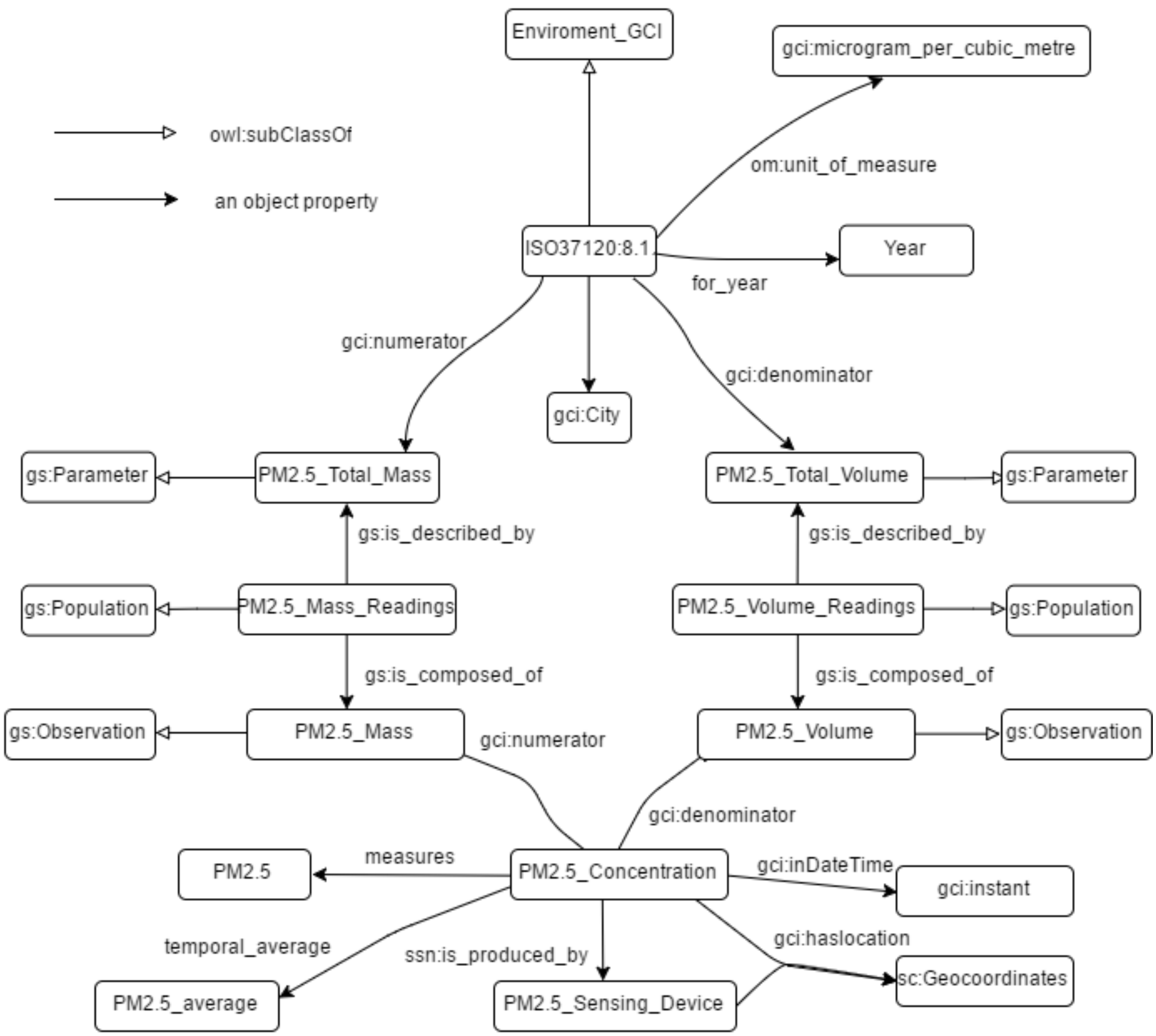

Figure 10 uses the Foundation ontology to provide the scaffolding for indicator 8.1. The PM2.5 indicator is a ratio that has the numerator of total mass of particulate matter of size 2.5 microns or less, and denominator of the total volume of the air sampled.

The total mass of particulate matter is derived from the individual measurements of mass each day. Similarly, the total volume of air sampled is derived from the individual measurements of volume each day. To represent this in our ontology, we build on the structure defined in the

GovStat Ontology[14]. The total mass and total volume are defined as subclasses of the "gs:Parameter" class. In the GovStat Ontology, every parameter is related to a population of measurements by the property "gs:is_described_by". In our case, the population is a collection of PM2.5 mass readings. The population measure is also related to the observations, or individual measurements, by the property "gs:is_composed_of".

PM2.5_Total_Mass is also a subclass of om:Quantity, and PM2.5_Mass is also a subclass of om:Mass. These links have been omitted from the graph for clarity.

To represent each measurement completely, we relate it to a time stamp and a location stamp. We also include the URI for the database where the measurements are stored.

Class	**Property**	**Value Restriction**
PM2.5_Total_Mass	owl:subClassOf	gs:Parameter, om:Quantity
PM2.5_Total_Volume	owl:subClassOf	gs:Parameter, om:Quantity
PM2.5_Mass_Readings	owl:subClassOf	gs:Population
	gs:is_described_by	exactly 1 PM2.5_Total_Mass
	gs:is_composed_of	some PM2.5_Mass
PM2.5_Volume_Readings	owl:subClassOf	gs:Population
	gs:is_described_by	exactly 1 PM2.5_Total_Volume
	gs:is_composed_of	some PM2.5_Volume
PM2.5_Mass	owl:subClassOf	gs:Observation, om:Mass
	databaseURI	some xsd:string
PM2.5_Volume	owl:subClassOf	gs:Observation, om:Volume
	databaseURI	some xsd:string

Class	**Property**	**Value Restriction**
PM2.5_concentration	ssn:is_produced_by	PM2.5_Sensing device
	gci:haslocation	exactly 1 sc:Geocoordinates
	gci:inDateTime	exactly 1 gci:instant
	databaseURI	some xsd:string

6.2 Fine particulate matter (PM10) concentration (ISO37120:8.2)

Similarly to PM2.5, the 8.2 indicator is determined by the ratio of the mass of PM10 particles to the volume of air sampled. Figure 10 illustrates the definition, and the tables that follow define the new classes and properties.

[14] The GovStat Ontology can be found at ontology.eil.utoronto.ca/govstat.owl. The prefix gs will be used where needed.

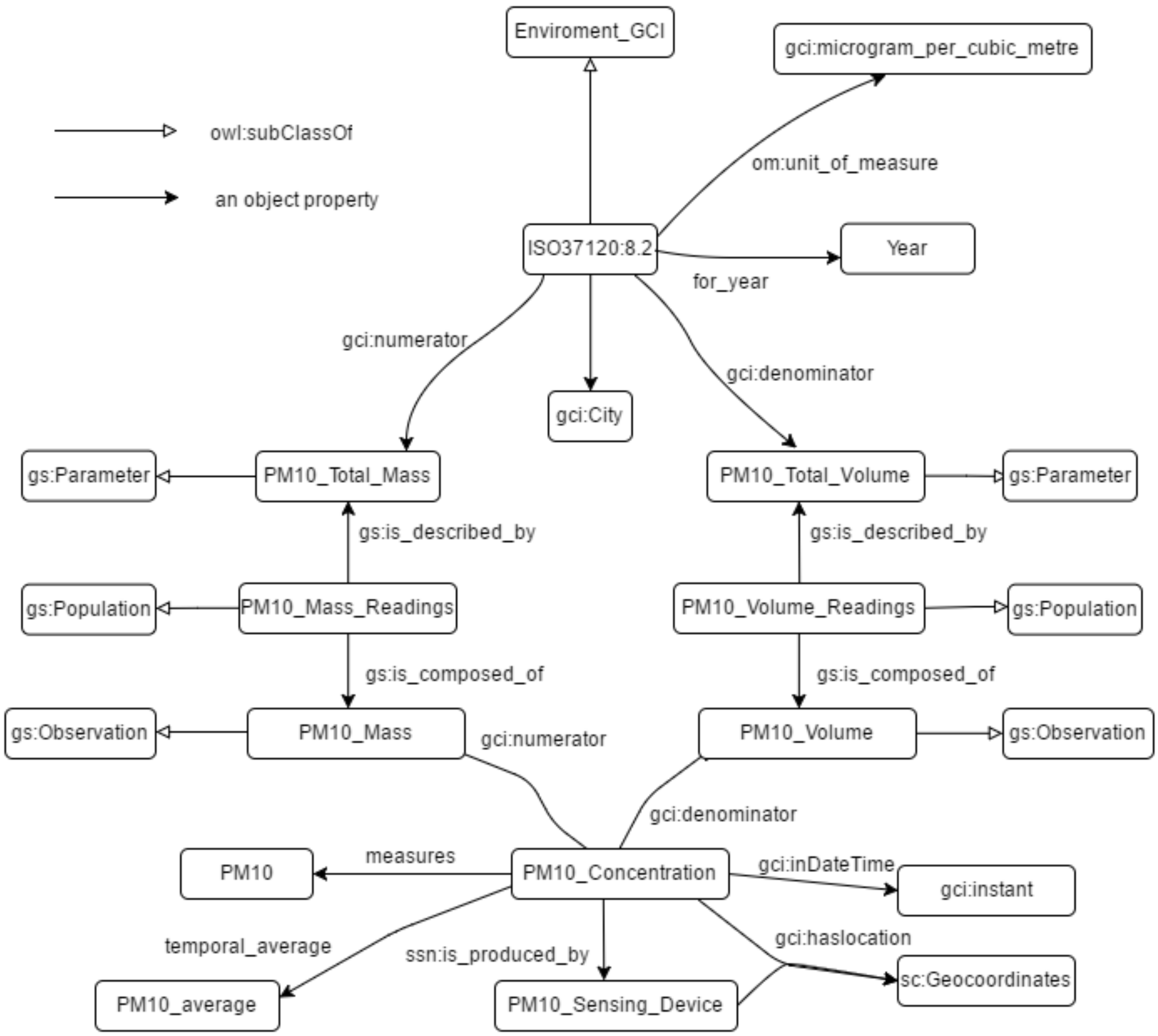

Figure 9: Indicator 8.2 Definition

Class	Property	Value Restriction
PM10_Total_Mass	owl:subClassOf	gs:Parameter, om:Quantity
PM10_Total_Volume	owl:subClassOf	gs:Parameter, om:Quantity
PM10_Mass_Readings	owl:subClassOf	gs:Population
	gs:is_described_by	exactly 1 PM10_Total_Mass
	gs:is_composed_of	some PM10_Mass
PM10_Volume_Readings	owl:subClassOf	gs:Population
	gs:is_described_by	exactly 1 PM10_Total_Volume
	gs:is_composed_of	somg PM10_Volume
PM10_Mass	owl:subClassOf	gs:Observation, om:Mass
	databaseURI	some xsd:string
PM10_Volume	owl:subClassOf	gs:Observation, om:Volume

	databaseURI	some xsd:string

Class	**Property**	**Value Restriction**
PM10_concentration	ssn:is_produced_by	PM10_Sensing device
	gci:haslocation	exactly 1 sc:Geocoordinates
	gci:inDateTime	exactly 1 gci:instant
	databaseURI	some xsd:string

6.3 Greenhouse gas emissions measured in tonnes per capita (ISO37120:8.3)

The definition of this indicator involves the addition of all measurements of greenhouse gases over the year as the numerator, and the population of the city as the denominator. This requires the addition of new classes to define the yearly sum of GHGs as well as the city population, as shown below.

Unlike particulate matter definitions above, the separate GHG measurements do not consist of a numerator and a denominator, but consist of a single measurement in tonnes. These measurements are aggregated to form the population subclass 'GHGs_readings'. The sum of these readings form the parameter subclass 'Yearly_Sum_GHGs'. In turn, this sum is divided by the city population to result in the final indicator.

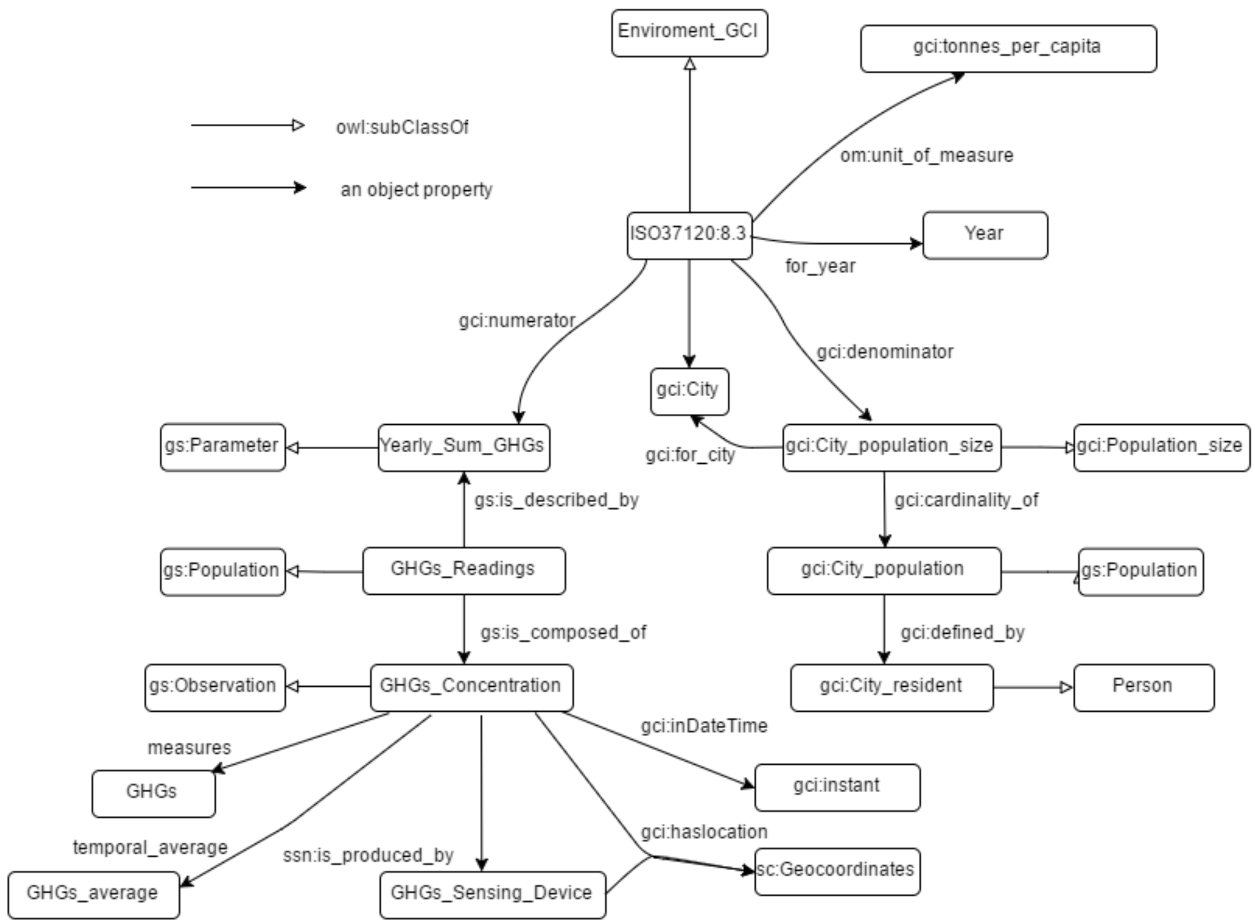

Figure 10: Indicator 8.3 Definition

Class	**Property**	**Value Restriction**
Yearly_Sum_GHGs	owl:subClassOf	gs:Parameter
GHGs_Readings	owl:subClassOf	gs:Population
	gs:is_described_by	exactly 1 Yearly_Sum_GHGs
	gs:is_composed_of	some GHGs_Concentration
GHGs_Concentration	owl:subClassOf	gs:Observation

Again, to represent each measurement completely, we relate it to a timestamp and a location stamp. We also include the URI for the database where the measurements are stored.

Class	**Property**	**Value Restriction**
GHG_concentration	ssn:is_produced_by	GHG_Sensing device
	gci:haslocation	exactly 1 sc:Geocoordinates
	gci:inDateTime	exactly 1 gci:instant
	databaseURI	some xsd:string

To represent the current population of the city, we use the class for 'City_population_size', defined in the GCI Foundation ontology, as follows.

Class	**Property**	**Value Restriction**

gci:City_population_size	owl:subClassOf	gci:Population_size
	gci:cardinality_of	gci:City_population
	om:unit_of_measure	gs:decokilopc
	gci:for_city	exactly 1 city
gci:City_population	owl:subClassOf	gs:Population
	gci:defined_by	gci:City_resident

6.4 NO_2 (nitrogen dioxide) concentration (ISO37120:8.4)

The definition of the nitrogen dioxide indicator is the total sum of NO_2 concentrations over a year, divided by the number of days in a year. Unlike the definition of GHGs, the yearly sum here is the addition of *daily averages* for a year.

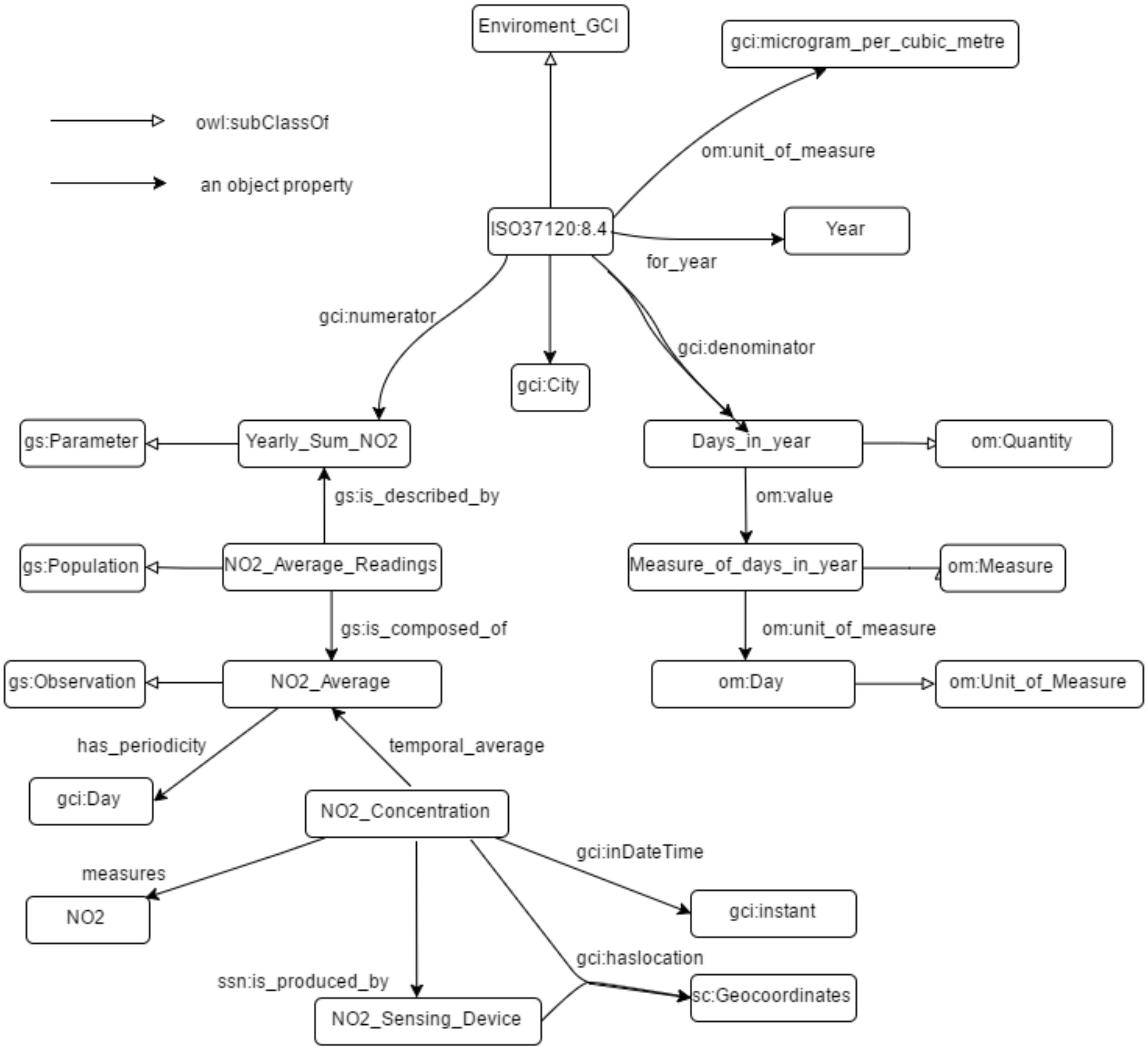

Figure 11: Indicator 8.4 Definition

To represent this definition, we define the classes as follows.

Class	Property	Value Restriction
Yearly_Sum_NO2	owl:subClassOf	gs:Parameter
NO2_Average_Readings	owl:subClassOf	gs:Population
	gs:is_described_by	exactly 1 Yearly_Sum_NO2
	gs:is_composed_of	some NO2_Average
NO2_Average	owl:subClassOf	gs:Observation
	has_periodicity	om:Day

The average is calculated daily as specified in the indicator definition. Thus, the periodicity of the average is specified as 'Day'.

We must also add the measure for number of days in a year. This must follow the measurement ontology quantity-measure-unit scheme as shown below.

Class	Property	Value Restriction
Days_in_year	owl:subClassOf	om:Quantity
	om:value	Measure_of_days_in_year
Measure_of_days_in_year	owl:subClassOf	om:Measure
	om:unit_of_measure	om:Day

We also add the time and location stamp to each concentration measurement as follows, and include the URI for the database where the measurements are stored

Class	Property	Value Restriction
NO2_concentration	ssn:is_produced_by	NO2_Sensing device
	gci:haslocation	exactly 1 sc:Geocoordinates
	gci:inDateTime	exactly 1 gci:instant
	temporal_average	some NO2_average
	databaseURI	some xsd:string

6.5 SO_s (sulphur dioxide) concentration (ISO37120:8.5)

This definition is very similar to NO_s. The figure illustrates the definition of the indicator and the tables describe the new classes and properties.

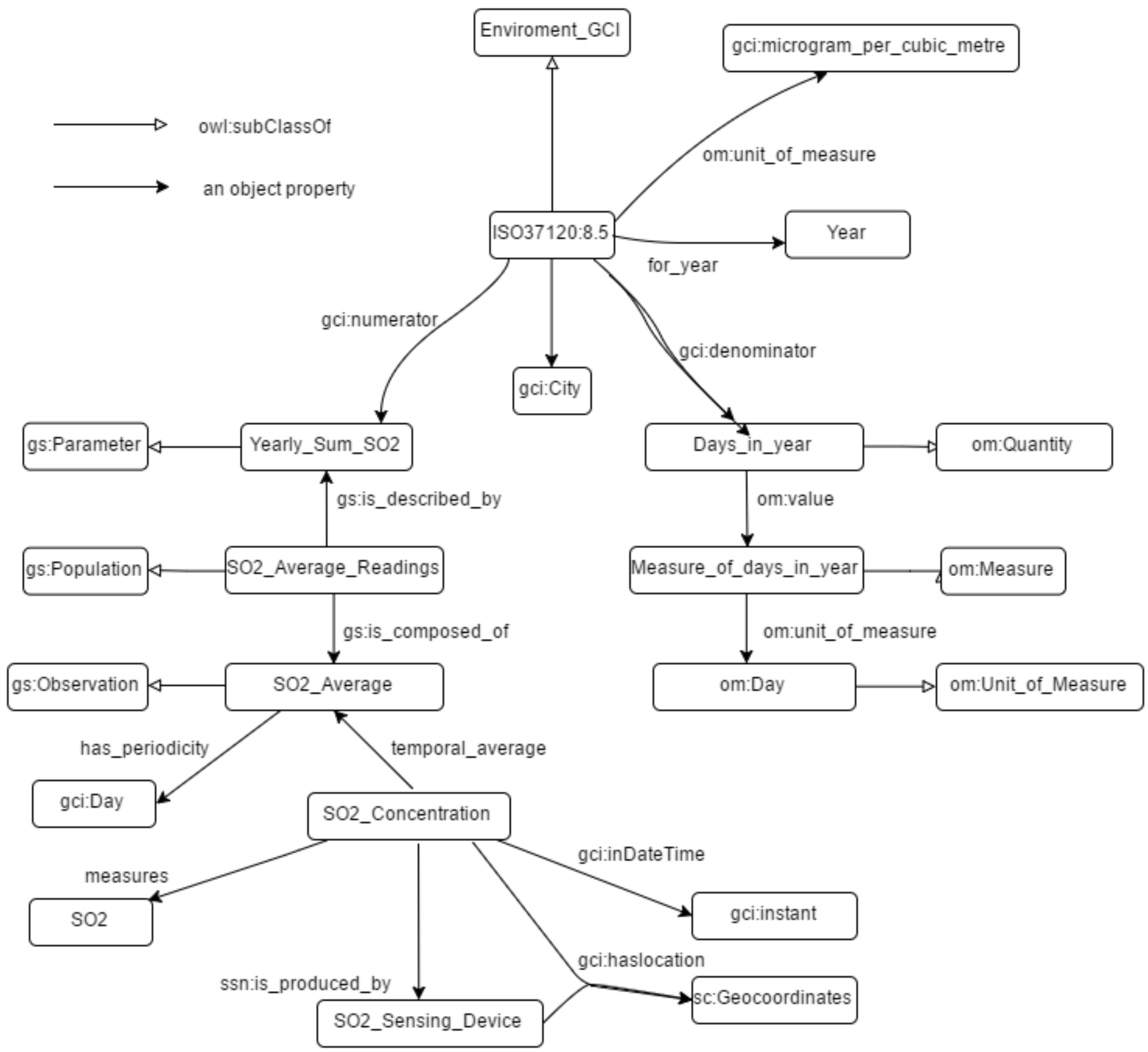

Figure 12: Indicator 8.5 Definition

Class	Property	Value Restriction
Yearly_Sum_SO2	owl:subClassOf	gs:Parameter
SO2_Average_Readings	owl:subClassOf	gs:Population
	gs:is_described_by	exactly 1 Yearly_Sum_SO2
	gs:is_composed_of	some SO2_Average
SO2_Average	owl:subClassOf	gs:Observation
	has_periodicity	gci:Day

Class	Property	Value Restriction

SO2_concentration	ssn:is_produced_by	SO2_Sensing device
	gci:haslocation	exactly 1 sc:Geocoordinates
	gci:inDateTime	exactly 1 gci:instant
	temporal_average	some SO2_average
	databaseURI	some xsd:string

6.6 O_3 (Ozone) concentration (ISO37120:8.6)

This definition is also very similar to NO_s and SOs. The definition is illustrated below followed by the description of new classes and properties.

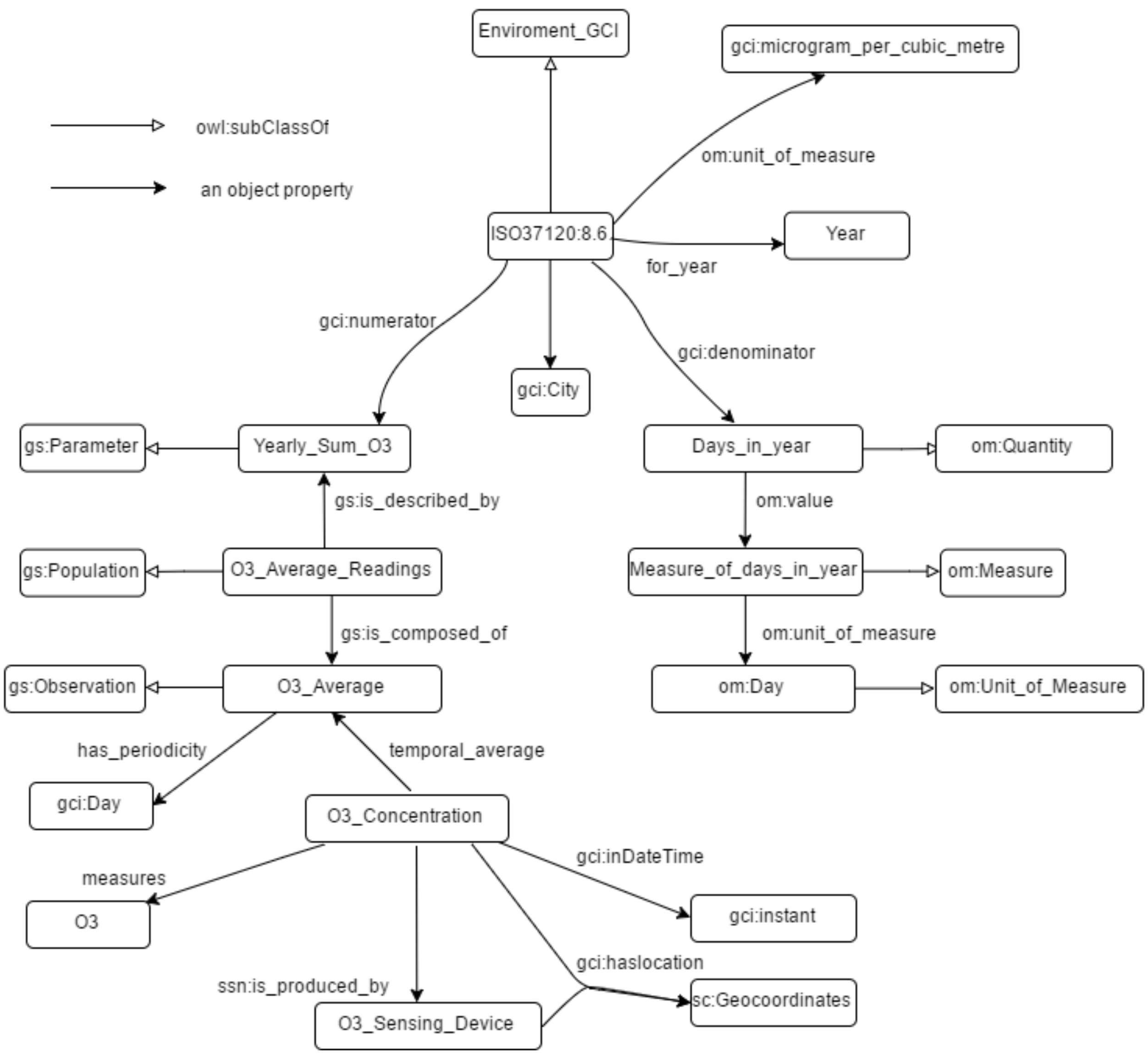

Figure 13: Indicator 8.6 Definition

Class	Property	Value Restriction
Yearly_Sum_O3	owl:subClassOf	gs:Parameter
O3_Average_Readings	owl:subClassOf	gs:Population
	gs:is_described_by	exactly 1 Yearly_Sum_O3
	gs:is_composed_of	some O3_Average
O3_Average	owl:subClassOf	gs:Observation
	has_periodicity	gci:Day

Class	Property	Value Restriction
O3_concentration	ssn:is_produced_by	O3_Sensing device
	gci:haslocation	exactly 1 sc:Geocoordinates
	gci:inDateTime	exactly 1 gci:instant
	temporal_average	some O3_average
	databaseURI	some xsd:string

6.7 Noise Pollution (ISO37120:8.7)

For noise pollution, the definition is the percentage of the population affected by noise pollution. The numerator here is the size of the population living in areas where the noise level is higher than 55 dB. The denominator is the total population of the city.

First, we must define a class for Lden (Level-day-evening-night). This is the average sound level over a 24 hour period, with a penalty of 5 dB added for the evening hours or 19:00 to 22:00, and a penalty of 10 dB added for the nighttime hours of 22:00 to 07:00.

Class	Property	Value Restriction
Lden	day-evening-night	Noise_pollution_concentration
	om:unit_of_measure	gci:decibel

Then, we define the class that represents the part of the population that is affected by Lden being greater than 55 dB.

Class	Property	Value Restriction
LdenHigh_population	owl:subClassOf	gci:Population
	gci:defined_by	Lden
LdenHigh_population_size	owl:subClassOf	gci:Population_size
	gci:cardinality_of	LdenHigh_population

Then, we complete the definition of each measurement by relating it to its sensor, time, and location, and defining its temporal average. We also include the URI for the database where the measurements are stored.

Class	Property	Value Restriction

Noise_pollution_concentration	ssn:is_produced_by	Noise_Sensing device
	gci:haslocation	exactly 1 sc:Geocoordinates
	gci:inDateTime	exactly 1 gci:instant
	temporal_average	some Noise_average
	databaseURI	some xsd:string

The definition is illustrated in figure 15.

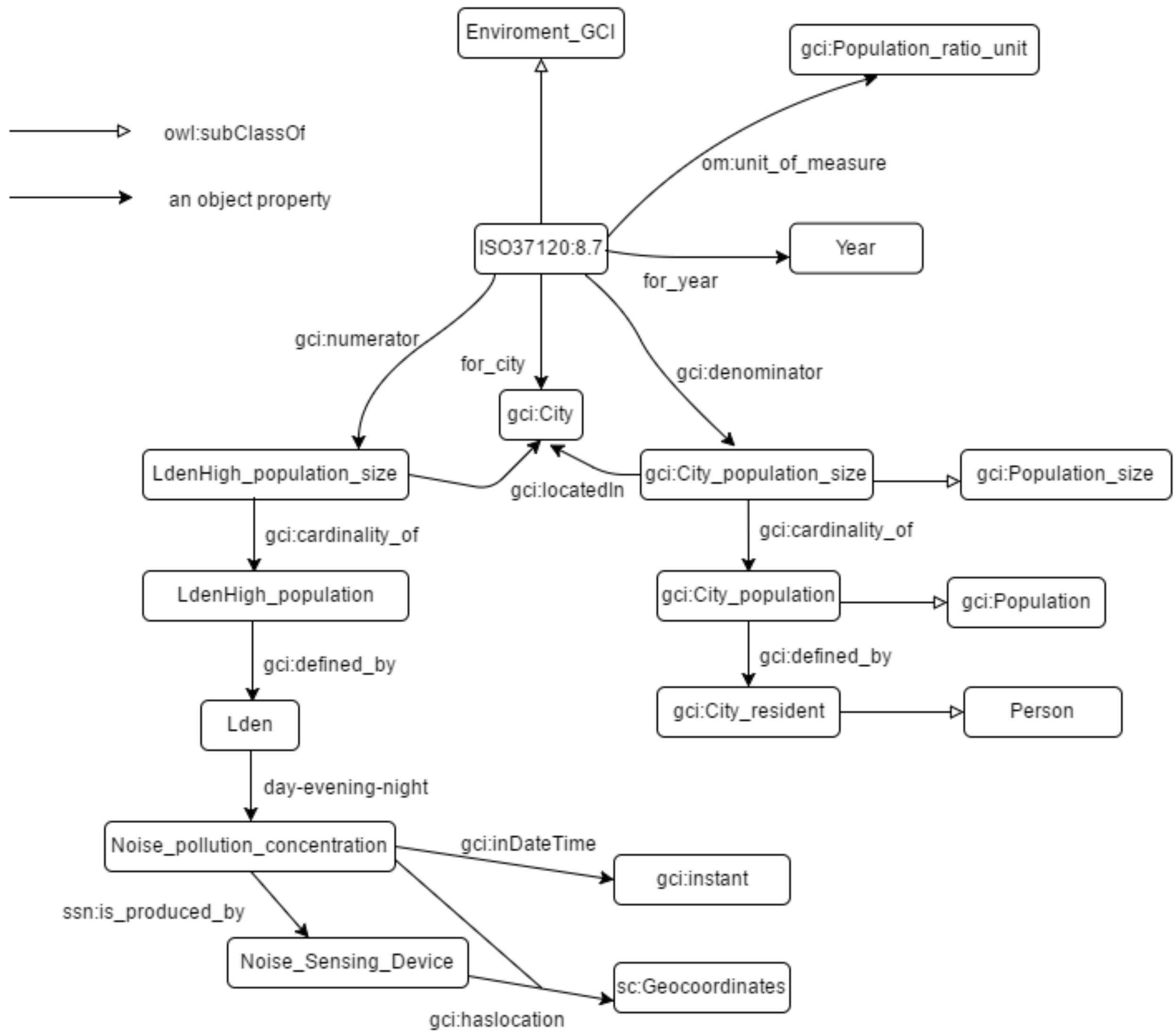

Figure 14: Indicator 8.7 Definition

6.8 Percentage change in number of native species (ISO37120:8.8)

For this indicator, the numerator is defined as the net change in species, while the denominator is defined as the total number of species.

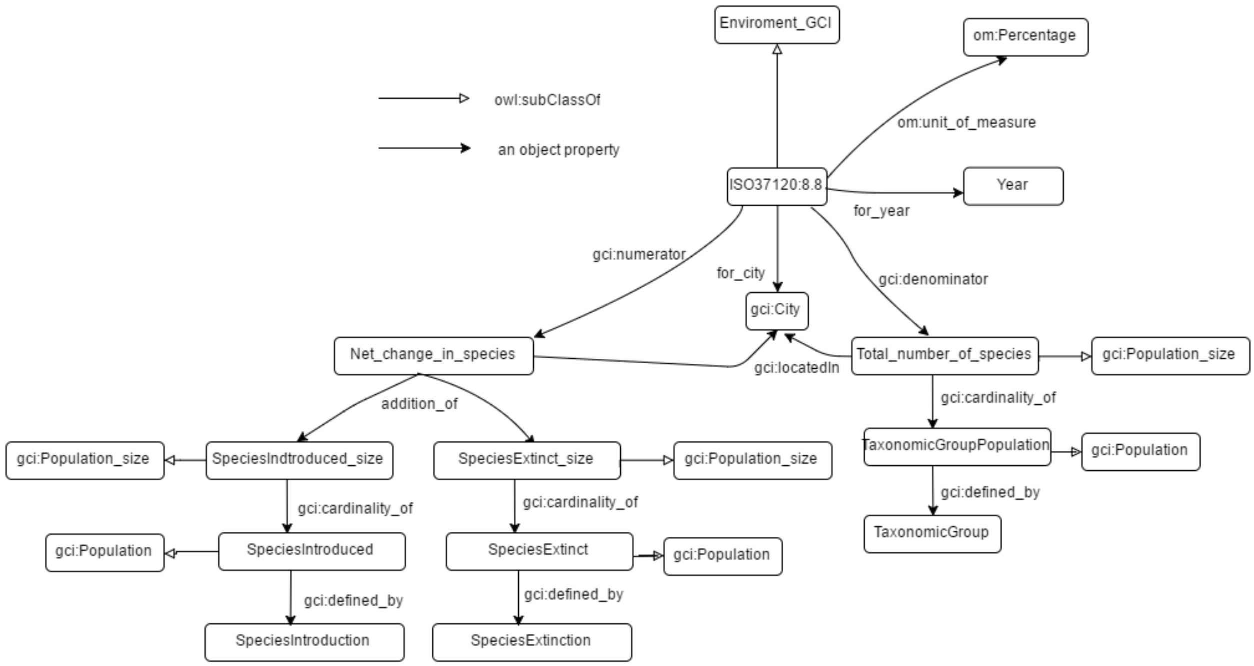

Figure 15: Indicator 8.8 Definition

To define the net change in species, we must be able to represent new additions as well as extinctions. This is achieved by the classes 'SpeciesIntroduction' and 'SpeciesExtinction', which contain all the relevant information about the event. That way, we can identify which species are currently present, and which have gone extinct.

The number of species that are introduced is calculated as the cardinality of the population, 'SpeciesIntroduced'. Similarly, the number of species that are extinct is calculated as the cardinality of the population, 'SpeciesExtinct', as a negative integer. Then, the net change in species is the addition of two cardinalities. The property addition_of denotes the terms whose values need to be added to calculate the net change. The terms also need to be disjoint with each other.

Class	**Property**	**Value Restriction**
SpeciesIntroduced_size	owl:subClassOf	gci:Population_size
	gci:cardinality_of	SpeciesIntroduced
SpeciesIntroduced	owl:subClassOf	gci:Population
	gci:defined_by	SpeciesIntroduction
	owl:disjointWith	SpeciesExtinct

Class	Property	Value Restriction
SpeciesExtinct_size	owl:subClassOf	gci:Population_size
	gci:cardinality_of	SpeciesExtinct
SpeciesExtinct	owl:subClassOf	gci:Population
	gci:defined_by	SpeciesExtinction
	owl:disjointWith	SpeciesIntroduced

Class	Property	Value Restriction
Net_change_in_species	owl:subClassOf	gci:Population_size
	addition_of	Only (SpeciesIntroduced_size and SpeciesExtinct_size)

Class	Property	Value Restriction
Total_number_of_species	owl:subClassOf	gci:Population_size
	gci:cardinality_of	TaxonomicGroupPopulation
TaxonomicGroupPopulation	owl:subClassOf	gci:Population
	gci:defined_by	Taxonomic group

7 Evaluation

In this section we verify that the Environment Indicator ontology answers the competency questions laid out in section 2. We use the data for the year 2013 for the city of Toronto in Ontario, Canada. We choose the ISO37120:8.1 indicator, the indicator for PM2.5 concentration, as an example.

First we define our example instances in the tables below. The first table defines the instances that provide background information on the city of Toronto, while the second table defines instances of concepts related to the 8.1 indicator.

Prefixes are as follows:

- gn: http://sws.geonames.org/
- sc: http://schema.org/
- gci: http://ontology.eil.utoronto.ca/GCI/Foundation/GCI-Foundation.owl#
    - The foundation ontology described in section 4
- pol: http://ontology.eil.utoronto.ca/GCI/Environment/Pollution.owl#
    - The pollution ontology defined in section 5

- sen: http://ontology.eil.utoronto.ca/GCI/Environment/Sensors.owl#
    - The sensors ontology defined in section 5
- ssn: http://purl.oclc.org/NET/ssnx/ssn
    - The W3C Sensor ontology
- om: http://www.wurvoc.org/vocabularies/om-1.8/
    - The measurement ontology
- gs: http://ontology.eil.utoronto.ca/govstat.owl#
    - The govstat ontology described in section 6
- iso: http://ontology.eil.utoronto.ca/ISO37120.owl#
    - URIs for each ISO37120 indicator
- isoen: http://ontology.eil.utoronto.ca/GCI/ISO37120/Environment.owl#
    - The ISO37120 environment indicators definitions defined in section 6

Instance	**Property**	**Value**
gn:6251999	rdfs:label	Canada
	rdfs:type	gn:Feature
	rdfs:type	sc:Country
gn:6093943	rdfs:label	Ontario
	rdfs:type	gn:Feature
	rdfs:type	sc:Province
gn:6167865	rdfs:label	Toronto
	rdfs:type	gn:Feature
	rdfs:type	sc:City

Instance	**Property**	**Value**
8.1_ex	rdfs:type	iso:8.1
(instance of 8.4)	gci:numerator	8.1_ex_PM2.5_Total_Mass
	gci:denominator	8.1_ex_PM2.5_Total_Volume
	for_year	2013
	gci:for_city	gn:6167865
8.1_ex_value	rdfs:type	om:Measure
(the value of 8.1)	om:numerical_value	8.42
	om:unit_of_measure	gci:microgram_per_cubic_metre
8.1_ex_PM2.5_Total_Mass	rdfs:type	isoen:PM2.5_Total_Mass
(numerator of 8.1)	om:value	8.1_ex_PM2.5_Total_Mass_value
8.1_ex_PM2.5_Total_Mass_value	rdfs:type	om:Measure
	om:numerical_valu	0.04945

(value of numerator of 8.1)	e	
	om:unit_of_measure	gci:microgram
8.1_ex_PM2.5_Mass_Readings *(population of 8.1 numerator)*	rdfs:type	isoen:PM2.5_Mass_Readings
	gs:is_described_by	8.1_ex_PM2.5_Total_Mass_value
	gs:is_composed_of	8.1_ex1_PM2.5_Mass, 8.1_ex2_PM2.5_Mass, 8.1_ex3_PM2.5_Mass
8.1_ex1_PM2.5_Mass *(observation of 8.1 numerator)*	rdfs:type	pol:PM2.5_Mass
	om:value	8.1_ex1_PM2.5_Mass_value
	databaseURI	http://www.airqualityontario.com/history/
8.1_ex1_PM2.5_Mass_value *(value of observation of 8.1 numerator)*	rdfs:type	om:Measure
	om:numerical_value	0.01542
	om:unit_of_measure	gci:microgram
8.1_ex2_PM2.5_Mass	rdfs:type	pol:PM2.5_Mass
	om:value	8.1_ex2_PM2.5_Mass_value
	databaseURI	http://www.airqualityontario.com/history/
8.1_ex2_PM2.5_Mass_value	rdfs:type	om:Measure
	om:numerical_value	0.01751
	om:unit_of_measure	gci:microgram
8.1_ex3_PM2.5_Mass	rdfs:type	pol:PM2.5_Mass
	om:value	8.1_ex3_PM2.5_Mass_value
	databaseURI	http://www.airqualityontario.com/history/
8.1_ex3_PM2.5_Mass_value	rdfs:type	om:Measure
	om:numerical_value	0.01652
	om:unit_of_measure	gci:microgram
8.1_ex_PM2.5_Total_Volume *(denominator of 8.1)*	rdfs:type	isoen:PM2.5_Total_Volume
	om:value	8.1_ex_PM2.5_Total_Volume_value
8.1_ex_PM2.5_Total_Volume_value *(value of denominator of 8.1)*	rdfs:type	om:Measure
	om:numerical_value	0.00587
	om:unit_of_measure	gci:cubic_metre
8.1_ex_PM2.5_Volume_Reading	rdfs:type	isoen:PM2.5_ Volume _Readings

s *(population of 8.1 denominator)*	gs:is_described_by	8.1_ex_PM2.5_Total_ Volume _value
	gs:is_composed_of	8.1_ex1_PM2.5_ Volume, 8.1_ex2_PM2.5_ Volume, 8.1_ex3_PM2.5_ Volume
8.1_ex1_PM2.5_ Volume *(observation of 8.1 denominator)*	rdfs:type	pol:PM2.5_ Volume
	om:value	8.1_ex1_PM2.5_ Volume _value
	databaseURI	http://www.airqualityontario.com/history/
8.1_ex1_PM2.5_ Volume _value *(value of observation of 8.1 denominator)*	rdfs:type	om:Measure
	om:numerical_value	0.0021
	om:unit_of_measure	gci: cubic_metre
8.1_ex2_PM2.5_ Volume	rdfs:type	pol:PM2.5_ Volume
	om:value	8.1_ex2_PM2.5_ Volume _value
	databaseURI	http://www.airqualityontario.com/history/
8.1_ex2_PM2.5_ Volume _value	rdfs:type	om:Measure
	om:numerical_value	0.00188
	om:unit_of_measure	gci: cubic_metre
8.1_ex3_PM2.5_ Volume	rdfs:type	pol:PM2.5_ Volume
	om:value	8.1_ex3_PM2.5_ Volume _value
	databaseURI	http://www.airqualityontario.com/history/
8.1_ex3_PM2.5_ Volume _value	rdfs:type	om:Measure
	om:numerical_value	0.00189
	om:unit_of_measure	gci:cubic_metre
8.1_ex1_PM2.5_Concentration	rdfs:type	pol:PM2.5_Concentration
	gci:numerator	8.1_ex1_PM2.5_ Mass
	gci:denominator	8.1_ex1_PM2.5_ Volume
	om:value	8.1_ex1_PM2.5_ Concentration _value
	pol:temporal_average	pol:PM2.5_average
	ssn:is_produced_by	8.1_ex1_PM2.5_Sensing_Device
	gci:inDateTime	8.1_ex1_instant
	gci:haslocation	8.1_ex1_geocoordinates
	databaseURI	http://www.airqualityontario.com/history/
8.1_ex1_PM2.5_ Concentration	rdfs:type	om:Measure

_value	om:numerical_value	7.34
	om:unit_of_measure	gci:microgram_per_cubic_metre
8.1_ex1_PM2.5_Sensing_Device	rdfs:type	sen:PM2.5_Sensing_Device
	gci:haslocation	8.1_ex1_geocoordinates
8.1_ex1_instant	rdfs:type	gci:instant
	gci:inXSDDateTime	2013-01-01T02:00:00
8.1_ex1_geocoordinates	rdfs:type	sc:Geocoordinates
	sc:address	184 College St, Toronto, ON
	sc:postalCode	M5S3E4
8.1_ex2_PM2.5_Concentration	rdfs:type	pol:PM2.5_Concentration
	gci:numerator	8.1_ex2_PM2.5_ Mass
	gci:denominator	8.1_ex2_PM2.5_ Volume
	om:value	8.1_ex2_PM2.5_ Concentration _value
	pol:temporal_average	pol:PM2.5_average
	ssn:is_produced_by	8.1_ex1_PM2.5_Sensing_Device
	gci:inDateTime	8.1_ex2_instant
	gci:haslocation	8.1_ex2_geocoordinates
	databaseURI	http://www.airqualityontario.com/history/
8.1_ex2_PM2.5_ Concentration _value	rdfs:type	om:Measure
	om:numerical_value	9.31
	om:unit_of_measure	gci:microgram_per_cubic_metre
8.1_ex2_instant	rdfs:type	gci:instant
	gci:inXSDDateTime	2013-01-02T02:00:00
8.1_ex2_geocoordinates	rdfs:type	sc:Geocoordinates
	sc:address	184 College St, Toronto, ON
	sc:postalCode	M5S3E4
8.1_ex3_PM2.5_Concentration	rdfs:type	pol:PM2.5_Concentration
	gci:numerator	8.1_ex3_PM2.5_ Mass
	gci:denominator	8.1_ex3_PM2.5_ Volume
	om:value	8.1_ex3_PM2.5_ Concentration _value
	pol:temporal_average	pol:PM2.5_average
	ssn:is_produced_by	8.1_ex3_PM2.5_Sensing_Device
	gci:inDateTime	8.1_ex3_instant
	gci:haslocation	8.1_ex3_geocoordinates
	databaseURI	http://www.airqualityontario.com/history/

8.1_ex3_PM2.5_ Concentration _value	rdfs:type	om:Measure
	om:numerical_value	8.74
	om:unit_of_measure	gci:microgram_per_cubic_metre
8.1_ex3_PM2.5_Sensing_Device	rdfs:type	sen:PM2.5_Sensing_Device
	gci:haslocation	8.1_ex3_geocoordinates
8.1_ex3_instant	rdfs:type	gci:instant
	gci:inXSDDateTime	2013-01-03T02:00:00
8.1_ex3_geocoordinates	rdfs:type	sc:Geocoordinates
	sc:address	900 Bay St, Toronto, ON
	sc:postalCode	M7A1C2

Next, we answer the competency questions for indicator 8.1 using SPARQL queries as follows.

1. What is the location of the sensor for sample X?

```
SELECT ?location ?postal WHERE
  { ?sc:Geocoordinates sc:address ?location.
    ?sc:Geocoordinates sc:postalCode ?postal.
    ?sen:PM2.5_Sensing_Device gci:haslocation ?sc:Geocoordinate.
    :8.1_ex1_PM2.5_Concentration ? ssn:is_produced_by ?sen:PM2.5_Sensing_Device }
```

   Answer: 184 College St, Toronto, ON M5S3E4

2. What is the reading of sensor X at time Y?

```
SELECT ?reading ?unit WHERE
 { ?om:Measure om:numerical_value ?reading.
   ?om:Measure om:unit_of_measure ?unit.
   ?pol:PM2.5_Concentration om:value ?om:Measure.
   ?pol:PM2.5_Concentration ssn:is_produced_by 8.1_ex1_PM2.5_Sensing_Device.
   ?pol:PM2.5_Concentration gci:inDateTime gci:instant.
   ?gci:instant gci:inXSDDateTime:2013-01-01T02:00:00 }
```

   Answer: 7.34 microgram_per_cubic_metre

3. What is the mass of particles in sample X?

```
SELECT ?mass ?unit WHERE
 { ?om:Measure om:numerical_value ?mass.
```

```
   ?om:Measure om:unit_of_measure ?unit.
   ?pol:PM2.5_Mass om:value ?om:Measure.
   :8.1_ex1_PM2.5_Concentration gci:numerator ?pol:PM2.5_Mass }
```

Answer: 0.01542 microgram

4. What is the volume of air in sample X?

```
SELECT ?volume ?unit WHERE
  { ?om:Measure om:numerical_value ?volume.
   ?om:Measure om:unit_of_measure ?unit.
   ?pol:PM2.5_Volume om:value ?om:Measure.
   :8.1_ex1_PM2.5_Concentration gci:denominator ?pol:PM2.5_Volume }
```

Answer: 0.0021 cubic metre

5. How many samples were taken at location X over period Y?

```
SELECT (COUNT ?samples AS ?num) WHERE
  { ?samples a pol:PM2.5_Concentration.
    ?pol:PM2.5_Concentration gci:haslocation sc:Geocoordinates.
    ?sc:Geocoordinates sc:postalCode :M5S3E4.
    ?pol:PM2.5_Concentration gci:inDateTime gci:instant.
    ?gci:instant gci:inXSDDateTime ?dateTime.
    FILTER (?dateTime >= "2013-01-01T00:00:00"^^xsd:dateTime &&
            ?dateTime <= "2013-01-03T00:00:00"^^xsd:dateTime) }
```

Answer: 2

6. What is the average fine particulate matter concentration over period Y?

```
SELECT (AVG(?concentration) AS ?avg) WHERE
  { ?om:Measure om:numerical_value ?concentration.
   ?pol:PM2.5_Concentration om:value ?om:Measure.
   ?pol:PM2.5_Concentration gci:inDateTime gci:instant.
   ?gci:instant gci:inXSDDateTime ?dateTime.
    FILTER (?dateTime >= "2013-01-01T00:00:00"^^xsd:dateTime &&
            ?dateTime <= "2013-01-04T00:00:00"^^xsd:dateTime) }
```

Answer: 8.42

7. What is a sample composed of?

```
SELECT ?observation ?numericalvalue ?unit WHERE
  { ?observation a pol:PM2.5_Mass.
    :8.1_ex_PM2.5_Mass_Readings gs:is_composed_of ?observation.
    ?observation om:value ?value.
    ?value om:numerical_value ?numericalvalue.
    ?value om:unit_of_measure ?unit}
```

Answer: 8.1_ex1_PM2.5_Mass 0.01542 microgram
8.1_ex2_PM2.5_Mass 0.01751 microgram
8.1_ex3_PM2.5_Mass 0.01652 microgram

8. Where are the samples stored?

```
SELECT ?database WHERE
  { 8.1_ex1_PM2.5_Concentration databaseURI ?database}
```

Answer: http://www.airqualityontario.com/history/

8 Conclusions

This research defines an ontology for the representation of ISO37120 Environmental theme indicator definitions. To do so, we first define three ontologies to represent all relevant information relating to pollution, sensors, and species. This allows the automation of the analysis of a city's performance, as represented by these indicators, in order to identify root cause of differences over time and between cities.

In summary, this research makes the following contributions:

1. Defines a pollution ontology, a sensor ontology, and a species ontology.
2. Represents each ISO37120 environmental indicator definition using the GCI Foundation ontology and the three above mentioned ontologies.
3. Enables the publishing of the ISO37120 environmental theme indicator definitions using Semantic Web standards.

9 Acknowledgements

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11 Appendix

The Global City Indicator Foundation ontology can be found in: http://ontology.eil.utoronto.ca/GCI/Foundation/GCI-Foundation.owl.

The Global City Indicator Environment ontology can be found in: http://ontology.eil.utoronto.ca/GCI/Environment/GCI-Environment.owl.

URIs for all of the ISO37120 indicators can be found in: http://ontology.eil.utoronto.ca/ISO37120.owl.

Definitions of the ISO37120 Environment indicators, using the GCI Foundation and Environment ontologies can be found in: http://ontology.eil.utoronto.ca/GCI/ISO37120/Environment.owl.

Representation of the City of Toronto 2013 ISO 37120 Environment values can be found in: http://ontology.eil.utoronto.ca/ISO37120/Toronto/2013/ISO37120_8_2013_TO.owl