A Solid Waste Ontology for Global City Indicators (ISO 37120)

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1. Introduction

The evaluation of system performance requires extensive measurements so that one may compare systems based on the common indicators or metrics. This; however, has become increasingly difficult when the systems are cities that develop their own custom metrics. To address this issue, the *ISO37120:2014 Sustainable cities and communities — Indicators for city services and quality of life,* was developed to standardize the evaluation of cities. It contains 100 city indicators spread across 17 themes, The PolisGnosis (Fox, 2017) aims to automate the transversal and longitudinal analysis of city performance based on indicators defined in ISO37120:2014. This would allow cities to diagnose the principal causes of their ill-performing indicators.

As a part of the PolisGnosis project, this work aims to develop and ultimately implement an ontology to represent the definintions of indicators for the ISO37120:2104, Section 16, Solid Waste theme. This section contains 10 city indicators spanning waste generation per capita, waste processing and disposal methods (ISO, 2014).

Following the methodology defined by Gruninger & Fox (1994), section 2 defines a set of competency questions, that the ontology should support the answering of. Section 3 reviews the literature for ontologies that can be reused. Section 4 defines the solid waste ontology, spanning the concepts necessary to answer the competency questions. Section 5 demonstrates the solid waste ontology by defining each of the 10 solid waste city indicators. Finally, section 6, evaluates the solid waste ontology based on its ability to answer the competency questions.

2. Indicator Definitions and Competency Questions

This section reviews the definitions of ISO37120:2014 Solid Waste indicators, and for each indicator specifies a set of competency questions. The purpose of developing competency questions is to identify the key concepts and properties required in the solid waste ontology (Grüninger & Fox, 1994).

Competency questions fall into four categories (Fox, 2015):

- **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):** Questions about a value or relationship that can be deduced from the instantiation.

2.1 ISO 37120 Solid Waste Indicators

2.1.1 Percentage of City Population with Regular Solid Waste Collection (Residential)

"The percentage of city population with regular solid waste collection shall be calculated as the number of people within the city that are served by solid waste collection (numerator) divided by the total city population (denominator). The result shall then be multiplied by 100 and expressed as a percentage.

The number of households in the city serviced with regular solid waste collection shall first be determined. The number of households being serviced by the regular solid waste collection service shall then be multiplied by the current average household size for that city to determine the number of persons serviced with regular solid waste collection.

Regular solid waste collection shall be defined as having the solid waste picked up from the household, transported and dropped at a proper treatment facility (recycling or landfill sites) on at least a weekly basis or every two weeks. If the solid waste is collected in any moving vehicle by persons that have not constituted a legally established entity, the house shall not be considered as a household serviced with a solid waste collection service."

Competency Questions:

1. (F) For which city is this indicator calculated?
2. (D) What is the total number of households in the city of interest?
3. (D) What is the total population of the city?
4. (D) Is the waste being collected from a residential building?
5. (F) How frequent is the regular solid waste collection (RSWC) for the household?
6. (D) Is the disposal site a legal entity?
7. (D) Is the waste collection service provider a legal entity?
8. (D) What is the average household size for the city of interest?
9. (D) How many households have access to RSWC are in the city?

2.1.2 Total Collected Municipal Solid Waster per Capita

The total collected municipal solid waste per capita shall be expressed as the total municipal solid waste produced in the municipality per person. This indicator shall be calculated as the total amount of solid waste (household and commercial) generated in tonnes (numerator) divided by the total city population (denominator). The result shall be expressed as the total municipal solid waste collected per capita in tonnes.

Municipal waste shall refer to waste collected by or on behalf of municipalities.

The data shall only refer to the waste flows managed under the responsibility of the local administration including waste collected on behalf of the local authority by private companies or regional associations founded for that purpose.

Municipal waste should include waste originating from:

- *households;*
- *commerce and trade, small businesses, office buildings and institutions (e.g. schools, hospitals, government buildings).*

The definition should also include:

- *bulky waste (e.g. white goods, old furniture, mattresses);*

- *garden waste, leaves, grass clippings, street sweepings, the content of litter containers, and market cleansing waste, if managed as waste;*
- *waste from selected municipal services, i.e. waste from park and garden maintenance, waste from street cleaning services (e.g. street sweepings, the content of litter containers, market cleansing waste), if managed as waste.*

The definition shall exclude:

- *waste from municipal sewage network and treatment;*
- *municipal construction and demolition waste."*

Competency Questions:

1. (F) Which type of building are the wastes being collected from?
2. (F) How many tons of solid waste are being collected from the building?
3. (F) Which types of solid waste are being collected from the building?
4. (F) Which types of non-solid-waste are being collected from the building?
5. (F) What is the total tonnage of residential solid municipal waste of that city?
6. (F) What is the total tonnage of commercial solid municipal waste of that city?
7. (F) What is the total tonnage of institutional solid municipal waste of that city?
8. (D) What is the total tonnage of all solid waste collected in that city?
9. (D) Is the waste collection service provider a legal entity?
10. (F) Which type of waste is being collected?

2.1.3 Percentage of the City's Solid Waste that is Recycled

"The percentage of the city's solid waste that is recycled shall be calculated as the total amount of the city's solid waste that is recycled in tonnes (numerator) divided by the total amount of solid waste produced in the city in tonnes (denominator). The result shall then be multiplied by 100 and expressed as a percentage.

Recycled materials shall denote those materials diverted from the waste stream, recovered, and processed into new products following local government permits and regulations (International Solid Waste Association, ISWA [23]).

Hazardous waste that is produced in the city and is recycled shall be reported separately"

From this indicator (ISO 37120: 16.3) to 2.1.8 (ISO 37120: 16.8), most of the competency questions can be reused, as these indicators focus primarily on the processing type of the solid waste collected in a city.

Competency Questions:

1. (F) What is the total tonnage of the recycled solid waste at the city of interest?
2. (D) What is the total tonnage of all solid waste collected in that city?
3. (F) Which recycling plant processed this waste?
4. (F) Is the collected solid waste hazardous?
5. (CD) What standard does the recycled product comply?
6. (F) Which type of building are the wastes being collected from?
7. (F) Which type of waste is being collected?

2.1.4 Percentage of the City's Solid Waste that is Disposed of in a Sanitary Landfill

"The percentage of the city's solid waste that is disposed of in a sanitary landfill shall be calculated as the amount of the city's solid waste that is disposed of in a sanitary landfill in tonnes (numerator) divided by the total amount of solid waste produced in the city in tonnes (denominator). The result shall then be multiplied by 100 and expressed as a percentage.

Sanitary landfill shall refer to a carefully designed structure which uses a clay liner or a synthetic liner in order to isolate solid waste from the surrounding environment. This isolation is accomplished with a bottom liner and daily covering of soil."

Competency Questions:

1. (F) What is the total tonnage of the SW disposed at a sanitary landfill at the city of interest?
2. (F) What type of liner does the landfill use?
3. (F) Has the landfill being covered on a daily basis?
4. (F) Who is the plant owner?
5. (D) Is the sanitary landfill site a legal entity?
6. (F) Which type of building are the wastes being collected from?
7. (F) Which type of waste is being collected?
8. (F) Has the landfill being certified by local authorities?

2.1.5 Percentage of the City's Solid Waste that is Disposed of in an Incinerator

"The percentage of the city's solid waste that is disposed of in an incinerator shall be calculated as the total amount of the city's solid waste that is disposed of in an incinerator in tonnes (numerator) divided by the total amount of solid waste produced in the city in tonnes (denominator). The result shall then be multiplied by 100 and expressed as a percentage.

An incinerator shall refer to a unit or facility used to burn waste, often referred to as an incineration plant."

The competency question regarding the definition of the incinerator is not asked for this indicator, as the definition of an incinerator describes a generic industrial incinerator. It would be ideal to reuse an established ontology that has already modeled the taxonomy of a waste processing system as modeling a comprehensive waste processing system from scratch is beyond the scope of this project.

Competency Questions:

1. (F) What is the total tonnage of SW disposed in an incinerator at city of interest?
2. (F) Who is the plant owner?
3. (F) Which type of building are the wastes being collected from?
4. (F) Which type of waste is being collected?
5. (D) Is the incinerator plant a legal entity?

2.1.6 Percentage of the City's Solid Waste that is Burned Openly

"The percentage of the city's solid waste that is burned openly shall be calculated as the amount of the city's solid waste that is burned in tonnes (numerator) divided by the total amount of solid waste produced in the city in tonnes (denominator). The result shall then be multiplied by 100 and expressed as a percentage.

Burned openly shall refer to the combustion of solid waste in an open dump or open space."

Competency Questions:

1. (F) What is the total tonnage of SW being burned openly at the city of interest?
2. (F) Who owns the site?
3. (F) Which type of building are the wastes being collected from?
4. (F) Which type of waste is being collected?
5. (D) Is the burning site a legal entity?

2.1.7 Percentage of the City's Solid Waste that is Disposed of in an Open Dump

"The percentage of the city's solid waste that is disposed of in an open dump shall be calculated as the amount of the city's solid waste that is disposed of in an open dump in tonnes (numerator) divided by the total amount of solid waste produced in the city in tonnes (denominator). The result shall then be multiplied by 100 and expressed as a percentage.

Open dump shall refer to an uncovered space or hole where solid waste is disposed of without further treatment."

Competency Questions:

1. (F) What is the total tonnage of SW being dumped openly at the city?
2. (F) Who owns the site?
3. (F) Which type of building are the wastes being collected from?
4. (F) Which type of waste is being collected?
5. (D) Is the dumping site a legal entity?

2.1.8 Percentage of the City's Solid Waste that is Disposed of by Other Means

"The percentage of the city's solid waste that is disposed of by other means shall be calculated as the total amount of the city's solid waste that is disposed of by other means in tonnes (numerator) divided by the total amount of solid waste produced in the city in tonnes (denominator).

The result shall then be multiplied by 100 and expressed as a percentage. Other means shall refer to methods of disposal by means other than the ones indicated in 16.3 (recycling), 16.4 (sanitary landfill), 16.5 (incinerator), 16.6 (burned openly), and 16.7 (open dump)."

Though not specified in the definition, it is still good practice to identify the waste processing method implemented by the local authority should it lies outside of the conventional processing method enlisted by ISO 37120.

Competency Questions:

1. (F) What is the total tonnage of SW been disposed with other method?
2. (F) How has the SW been disposed?
3. (F) Which type of building are the wastes being collected from?
4. (F) Which type of waste is being collected?
5. (F) Who owns the site?

2.1.9 Hazardous Waste Generation per Capita (Tonnes)

"The hazardous waste generation per capita shall be calculated as the annual total amount of hazardous waste in tonnes (numerator) divided by total city population (denominator). The result shall be expressed as total hazardous waste generated per capita in tonnes.

Hazardous waste generated in the city includes hazardous waste collected under national or municipal hazardous waste directives or regulations, and in accordance with the city's monitoring and information systems. Hazardous waste is usually accepted at landfills, hazardous waste treatment facilities (including incinerators) and wastewater treatment facilities located in the boundaries of the city. This indicator also covers those hazardous wastes exported for disposal.

Hazardous waste shall refer to any substance intended for disposal, which can be harmful to people, plants, animals or the environment. A waste shall be defined as hazardous if it shows one or more of the

following characteristics: toxicity, flammability, corrosivity or reactivity. They can be in any form - liquids, solids, gases (in containers), or sludge and are produced by manufacturing processes, the chemical industry, the petroleum industry and other industrial sectors. Examples include acids, alkalis, solvents, medical waste, resins, sludge and heavy metals.

Hazardous wastes are those substances that require special technologically advanced methods of disposal to render them harmless or less dangerous to humans and the environment. Hazardous waste must be treated, stored, and disposed of properly at designated sites. Most hazardous wastes are eventually disposed in landfills, surface impoundments (which eventually become landfills), land application units, or by deep well injection."

Competency Questions:

1. (F) What is the total tonnage of hazardous waste produced by the city of interest?
2. (F) What is the total tonnage of hazardous waste being exported by the city?
3. (F) To where was the hazardous waste to exported to?
4. (F) What type of hazard does the collected waste impose?
5. (F) How is the hazard waste processed?
6. (F) From which type of building are the wastes being collected?
7. (F) Which type of waste is being collected?
8. (D) Is the treatment plant for hazardous waste a legal entity?

2.1.10 Percentage of the City's Hazardous Waste that is Recycled

"The percentage of the city's hazardous waste that is recycled shall be calculated as the total amount of hazardous waste that is recycled in tonnes (numerator) divided by the total amount of hazardous waste that is generated in tonnes (denominator). The result shall then be multiplied by 100 and expressed as a percentage.

Recycled hazardous waste (or hazardous recyclables) shall refer to hazardous waste that is used, reused, or reclaimed."

Competency Questions:

1. (F) What is the total tonnage of the recycled hazardous waste at the city of interest?
2. (F) What is the total tonnage of hazardous waste recycled in the city?
3. (F) Which type of building are the wastes being collected from?
4. (F) Which type of waste is being collected?
5. (D) Is the plant of recycled a legal entity?

3. Review of Relevant Ontologies

The first two indicators focus on waste collection statistics with city properties. The second indicator went into details on which type of waste can be categorised as solid waste, though not included in the computation. Most indicators provided detailed definitions on how the waste are processed. Based on these observations, the type of information being queried by the indicators and competency questions were categorised into four main sections: waste, city properties, processing methods, and statistics. For each main section, a number of existing ontologies were reviewed. Before presenting these four areas, relevant classes and properties in the GCI Foundation ontology are reviewed (Fox, 2013; 2015).

3.1 GCI Foundation Ontology

The Global City Indicator (GCI) Ontology provides the foundation ontology structure for calculating indicator ratios, uniquely identify place names, validation, provenance, etc. This ontology is essential in designing ontology for ISO 37120 indicators, and is the core ontology for this project (Fox, 2013; 2015). Competency questions referring to location, measurement, and legality can all be covered by this ontology. For example, the Geonames ontology addresses the competency questions about geographical locations where the indicator is calculated; the measurement ontology serves as the link between the population size and the actual value of that measurement. The components of the GCI Foundation Ontology are shown in Figure 1.

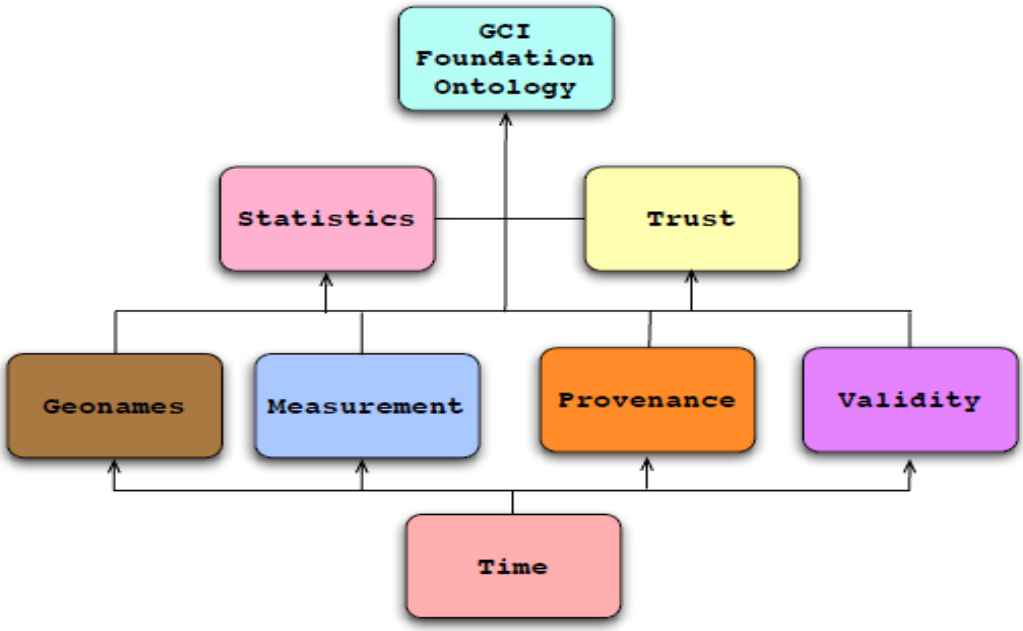

Figure 1 GCI Foundation Ontology Major Sub-ontologies

Relevant Competency Question(s):

- For which city is this indicator calculated?
- What is the average household size of the city of interest?
- How frequent is the regular solid waste collection (RSWC) for the household?
- How many households have access to RSWC in the city?
- What is the total number of households in the city of interest?
- How many tons of solid waste are being collected from the building?
- What is the total tonnage of ____ waste collected in that city?
- What is the total tonnage of recycled ____ solid waste at the city of interest?
- What is the total tonnage of the SW disposed at ____ (method of process) at the city of interest?
- What is the total tonnage of hazardous waste being exported by the city?
- Who owns the site?
- Is the site a legal entity?

GCI Shelter Ontology

ISO 37120 defines that the total population served with Regular Solid Waste Collection (RSWC) of a city is calculated as the number of households served with RSWC multiplied by the average household size of the city. The GCI Shelter Indicator Ontology (Wang & Fox, 2015) has defined classes such as Household and Average_household_size and its measure for a city; however, the household definition from the GCI Shelter ontology needs to be extended as it does not consider the taxonomy of the building type the household is located in. As stated in ISO 37120 solid waste indicators, the type of building the waste is collected from has to be categorised. Therefore, we will extend this sub-ontology with building types to suit our purpose. The structure of household sub-ontology is shown in Figure 2 along with the relevant competency questions. The Household pattern combines elements of the Shelter and Foundation ontologies. The Foundation ontology provides the unit of measure, and the shelter ontology provides the concepts of households. The Household ontology will define the component of the household population questioned in the competency questions regarding to households.

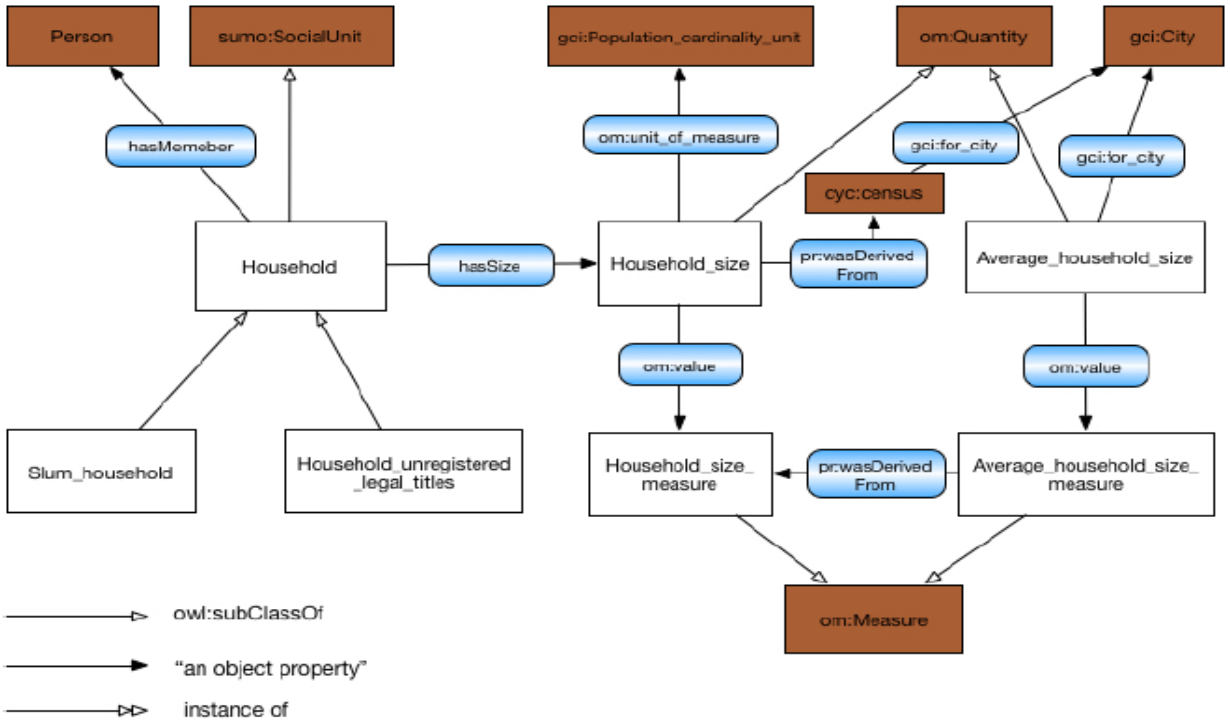

Figure 2 Household Sub-Ontology of GCI Shelter

Relevant Competency Question(s):

- What is the current average household size of the city of interest?
- How frequent is the regular solid waste collection (RSWC) for the household?
- What is the average household size for the city of interest?
- How many households that have access to RSWC are in that city?
- What is the total number of households in the city of interest?

GCI Telecommunication and Service Ontology

The first two indicators of ISO 37120 solid waste described solid waste collection as a service, where the collection agency is the service provider and the households being the service consumer. It has also limited the service frequency that disqualify collections that is less frequent than once per two weeks. This means that the basis of solid waste collection should be established on a model of service.

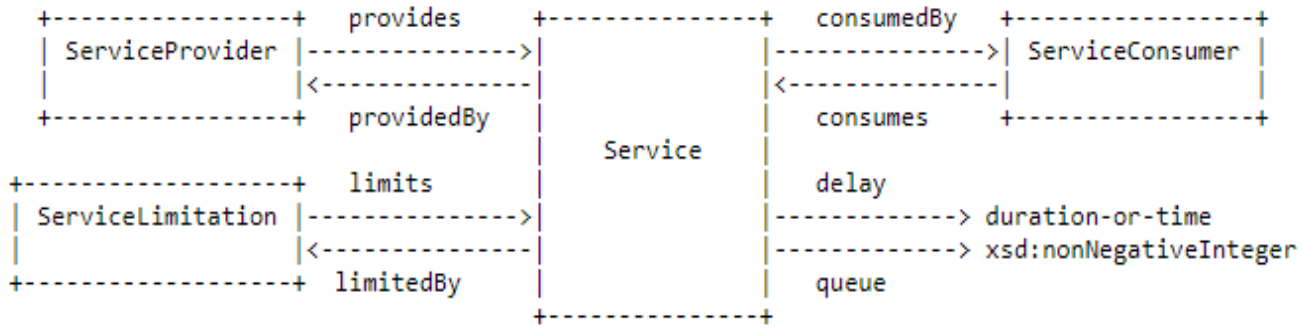

Figure 3 Service Ontology

The GCI Telecommunication and Innovation Ontology (Forde & Fox, 2015), contains a Service class, which is an extension of the Voß's Service Ontology Voß (2013). The classes to be reused from GCI Telecommunication and Innovation Ontology is shown in Table 1. By using the Service ontology, we will be able to define solid waste collection as a service consumed by households across a city, and thereby linking the service providing entity with the household.

Relevant Competency Question(s):

- How frequent is the regular solid waste collection (RSWC) for the household?
- Is the waste collection service provider a legal entity?

Table 1 Service and ServiceConsumer Classes from GCI Telecommunication and Service Ontology

Class	Property	Value Restriction
gcit:Service	gcit:providedBy	some gcit:ServiceProvider
	gcit:limitedBy	some gcit:ServiceLimitation
	gcit:consumedBy	some gcit:ServiceConsumer
	so:delay	some xsd:time
	so:queue	exactly 1 xsd:nonNegativeInteger
gcit:ServiceConsumer	gcit:residentOf	exactly 1 gci:City
	gcit:purchases	min 1 gcit:Service
	so:consumes	min 1 gcit:Service
	owl:equivalentClass	gcit:ServiceUser

3.2 Waste Ontology

The ISO37120 solid waste indicators focuses on how a city treats six categories of solid wastes. Thus, a large portion of the ontology will focus on how solid waste is processed.

The Waste Management Ontology (WMS) represents a waste management system for municipal solid waste disposal and processing (Ramasami, et al, 2015). With minor extension, the waste_type class can be used to categorize waste and thereby determine whether the waste collected from the building satisfies the definition of solid waste provided by ISO 37120 solid waste indicators.

The WMS ontology also contains location_type and Waste_disposal_methods class that can be used to track where a particular batch of waste was collected and how it was treated. Sufficient object and data properties were also defined in this ontology to represent the relation between each class. The class taxonomy and its partial properties are listed in Figure 4.

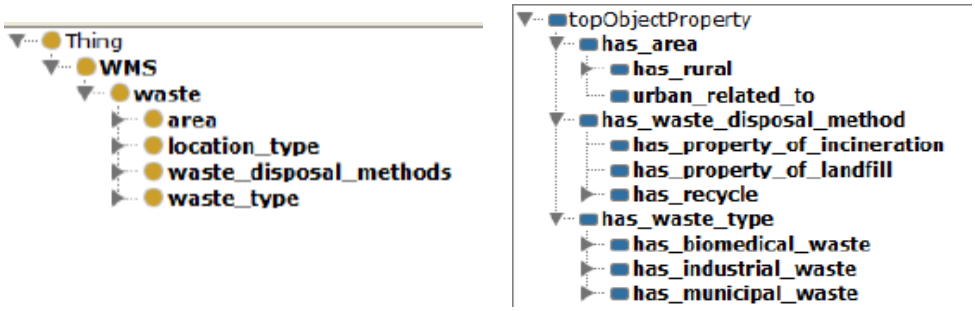

Figure 4 WMS Class Taxonomy

However, there are several issues with this ontology. The first letter of the class names should have been capitalized; the property name should follow the format 'hasArea' instead of 'has_area'; the 'waste' class is incorrectly built as area nor should waste type be subclasses of waste. Lastly, the source did not include a URL for the ontology mentioned; therefore, we will be taking reference of this ontology and be building our version of WMS ontology with the aforementioned issues solved.

Kultsova, et.al. (2016) developed a comprehensive waste ontology for an intelligent decision support waste management system. This ontology categorizes waste based on its physical properties, chemical compositions and hazard level. Based on the waste definition provided in ISO37120, most part of this ontology can be incorporated into the GCI solid waste ontology project. The Origin class enables us to trace the waste source back to household by making household as a subclass of Origin. The Substance class describes the physical state of the waste. Though this ontology contains a class that defines the toxicity and processability of the waste, they do not follow the definition provided by the ISO37120 indicators. Therefore, a modified version of this ontology can be used to describe the waste model for the GCI solid waste. This waste management ontology is depicted in Figure 5.

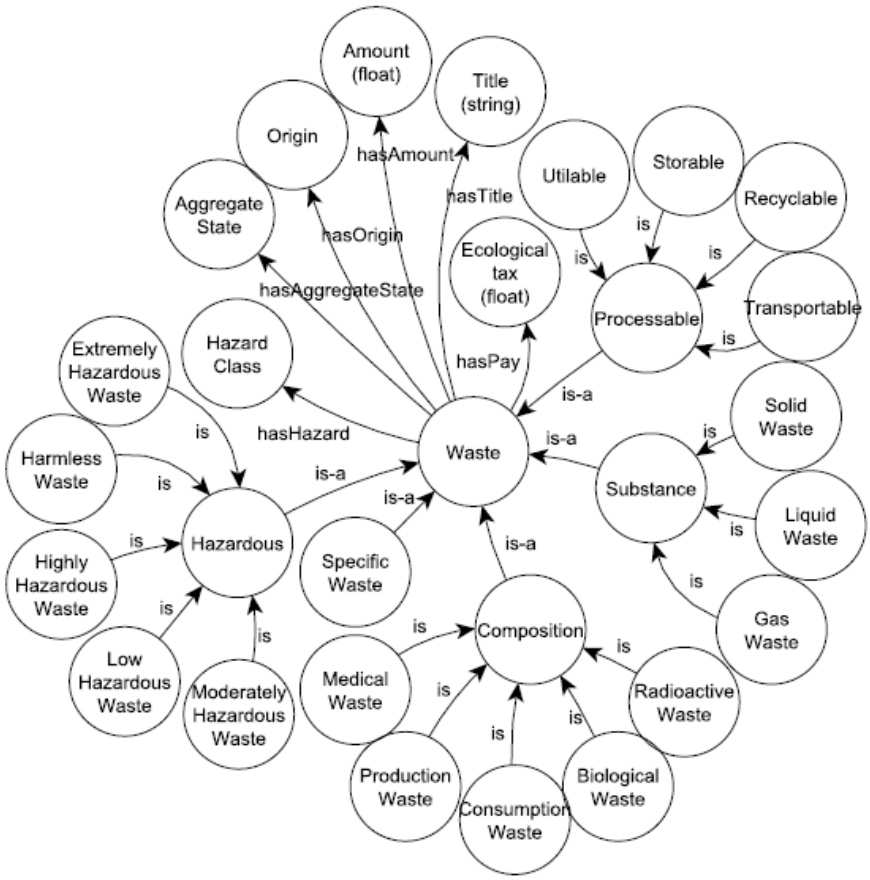

Figure 5 Ontology-Based Waste Management Decision Support System

OntoWM, another waste management ontology was developed by Ahmad et al (year), and reviewed in Mohammad (2018). This ontology was proposed as an auxiliary to the SmartBin system, which aimed to improve the efficiency of the waste collection process.

Consequently, this ontology focused on the collection and transportation of waste, which can be used to define waste collection service provider. It also elaborated the organization taxonomy of the waste

collection agency, which can be used to identify the ownership of the service provider and whether the service provider is government approved. A graphical illustration of OntoWM is shown in Figure 6.

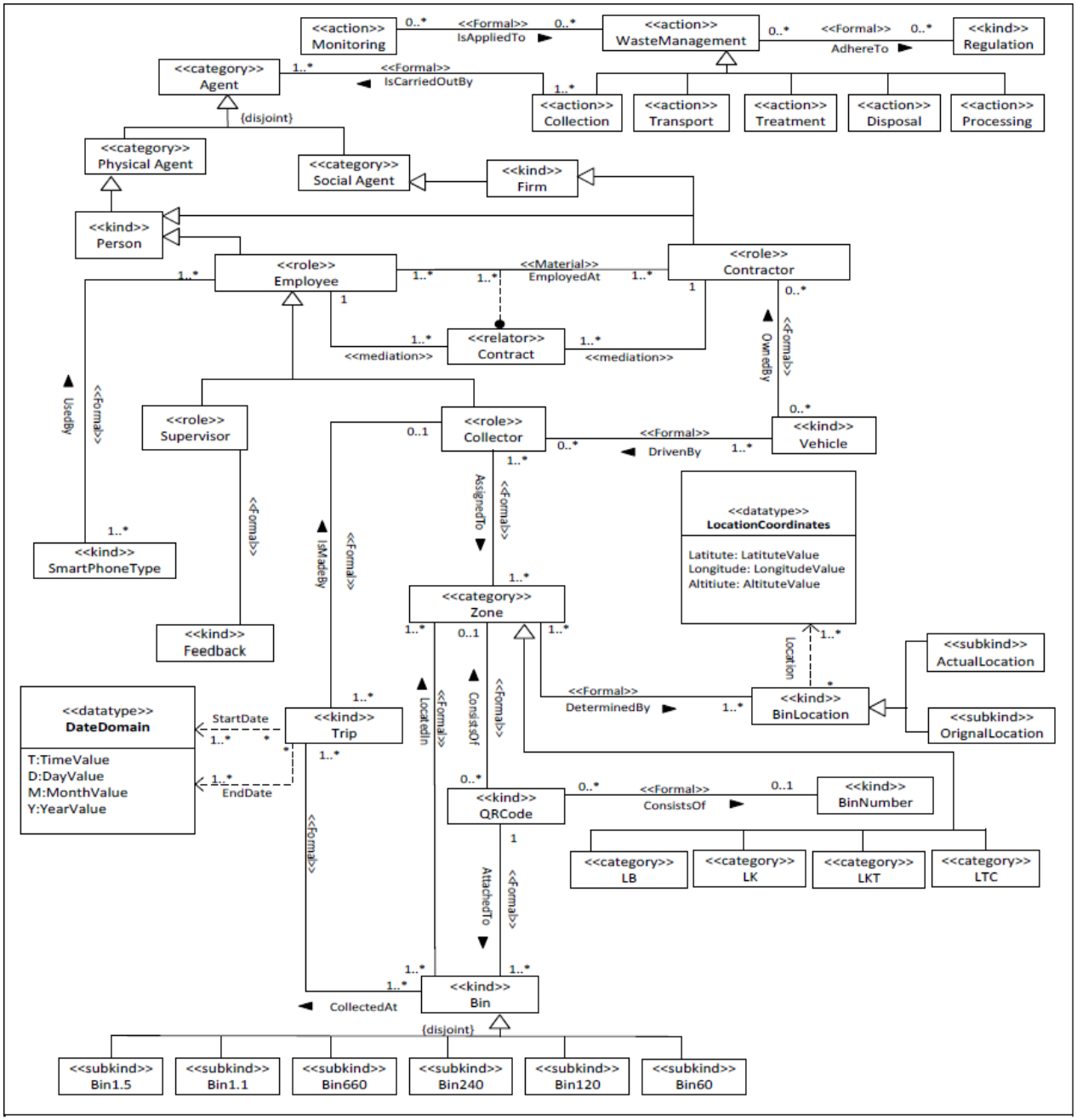

Figure 6 Taxonomy of OntoWM

An ontology focusing on processing engineering for waste management was proposed by Muñoz et al. (2013). This ontology organizes waste treatment data for potential greener waste processing in factories, plants, and other types of industrial sites. An overview of this ontology is shown in Figure 7.

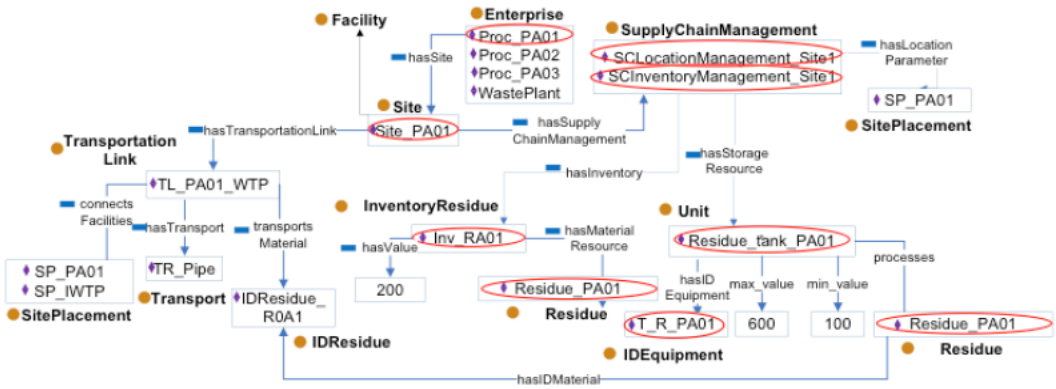

Figure 7 Taxonomy of OntoWM

This formalizes the engineering of waste processing in a step-by-step approach. This may be useful in gathering and organizing data collected from specific equipment, but might not be suitable for defining waste processing on a higher level. Therefore, this ontology is not relevant for our purposes.

The ontologies introduced above are able to define a taxonomy for waste, waste collection provider, and the processing entity but lacks an overall structure that correlates the three components together. For this purpose, another ontology model proposed by Pohjola, et al. (2002) was reviewed. This ontology provides a taxonomy that relates waste, collection, and production. However, the ISO37120 indicators do not require nor need to know how the waste was generated, which corresponds to the ResidualProduction class in this ontology, this ontology can still be modified to construct a system that includes the generation, collection, and processing of solid waste. The taxonomy of the formalized waste management system is shown in Figure 8. Any waste related competency questions will be able to answered by the waste ontologies.

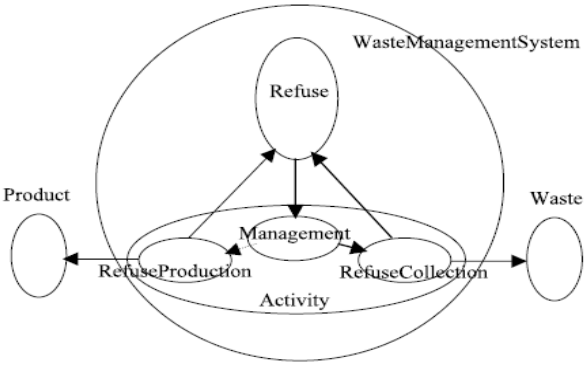

Figure 8 Ontology based waste management model

Relevant Competency Question(s):

- Which types of solid waste are being collected from the building?
- Which types of non-solid-waste are being collected from the building?
- Is SOME waste collection/disposal site provider a legal entity?
- What is the total tonnage of SOME TYPE of waste recycled in that city?
- What is the total tonnage of the hazard waste exported from that city?
- What is the total tonnage of SOME TYPE of waste of that city?
- What type of liner does the landfill use?
- Has the landfill been covered on a daily basis?
- What waste disposal (combustion) method is being used by the plant?
- How are those SW been disposed?
- To where was the hazardous waste to exported to?
- What type of hazard does the collected waste impose?
- Which type of waste is being collected?
- How is the hazard waste processed?

3.3 Transportation Ontology

A transportation ontology is needed for two reasons. First, though not required by the indicators, being able to track the waste on transport is required by law. For example, according to Canadian regulations, the local waste management program must submit movement documents before shipping any hazardous waste. This implies that for any models that wish to include transporting hazardous waste must also be able to track the entity that produced the waste.

Second, to fully define the classes required for exported wastes, adding a transportation ontology would help differentiate the export class with the other waste processing methods.

GCI Transportation Ontology contains a GCI Trip class that can help to specify sender's location (Yousif & Fox, 2018), receiver's location, and the time of which the batch is sent and received. We will not be using the entire class; the properties to be reused are listed in Table 2. This ontology can answer any competency question regarding to the whereabout of the exported solid waste.

Table 2 GCI Trip from GCI Transportation Ontology

Class	Property	Value Restriction
GCI_Trip	rdfs:subClassOf	GCITransportationOntologyThing
	trip:startLoc*	exactly 1 icontact:Address
	trip:endLoc*	exactly 1 icontact:Address
	dateOfDeparture	exactly 1 time:DateTimeDescription
	dateOfArrival	exactly 1 time:DateTimeDescription

*Trip ontology should also be implemented to use this class.

Relevant Competency Question(s):

- To where was the hazardous waste to exported to?

3.4 Organization Ontology

The municipal services for waste collection and processing can be represented as an organization with members, goals, and a series of activities. The Organization ontology satisfies this taxonomy and provides authority for representing the empowerment of individuals. Figure 9 depicts the Organization ontology (Fox, et. al. 1998). By modeling service entities like organizations, we can establish the ownership class to identify whether the

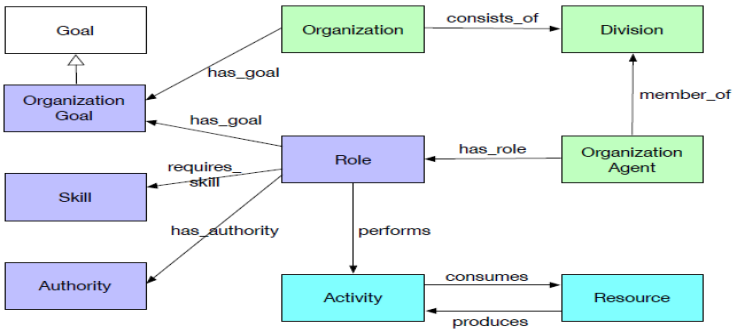

Figure 9 Organization Ontology

Relevant Competency Question(s):

- Who is the plant owner?

service is privately owned or municipal funded, and thereby linking the service provider and the owner of the service provider.

3.5 Building Ontology

The ISO37120 solid waste core indicators refer to the type of building with solid waste collection such as commercial, institutional, and residential. For example, the 1st indicator restricts that only residential buildings are qualified for analysis, which excludes all solid wastes generated by factories and labs. Due to this reason, a building ontology, capable of distinguishing different categories of buildings, is needed.

In GCI Recreation ontology, Abdulai & Fox (2017) extended a building ontology from COSMO ontology (Cassidy, 2020). The COSMO building class includes basic definitions of a building, while the GCI Recreation ontology added a few more physical properties to the COSMO building. Neither of which provided the building ontology to distinguish the function of a building. Therefore, in the GCI Solid Waste ontology, the GCI Recreation Ontology is extended to identify the function and purpose of the building. The building ontology will be used to link household with the building providing the building type so that our ontology is able to distinguish the service user from residential building and other types of buildings.

Table 3 COSMO and GCI Recreation Building Ontologies

Class	Property	Value Restriction
cosmo:Building	owl: subClassOf	cosmo:FixedStructure
	owl: subClassOf	cosmo: HumanShelterConstruct
gcir:Building	owl: subClassOf	cosmo:Building
	cosmo: isOwnedBy	some cosmo: IntelligentAgent
	gcir: numberOfLevels	exactly 1 xsd: positiveinteger
	gcir: numberOfRecRooms	exactly 1 xsd: positiveinteger
	cosmo: contains	some gcir: BuildingLevel
	gci: for_city	exactly 1 gci: City

Relevant Competency Question(s) to this Section:

- Which types of solid waste are being collected from the building?
- Which types of non-solid-waste are being collected from the building?
- Is the waste being collected from a residential building?

3.6 Environment Ontology

The ISO 37120 Solid Waste Indicators refer to methods for waste processing. This requires that we define each waste processing method and would also require a side-track study into how each method is defined; what are the fundamental requirements for those methods; and their interactions with the waste management system. Defining a standalone waste processing ontology model is out of the scope of this project; therefore, it is ideal that we use an external ontology to help us define the waste processing techniques.

The Environment Ontology (ENVO), developed by (Buttigieg, et al. 2013; 2016), comprise a collection of definitions for environmental processes and ecological systems, and is ideal for defining some of the

common waste processing methods like incineration, and landfill. A partial taxonomy of ENVO is shown in Figure 10.

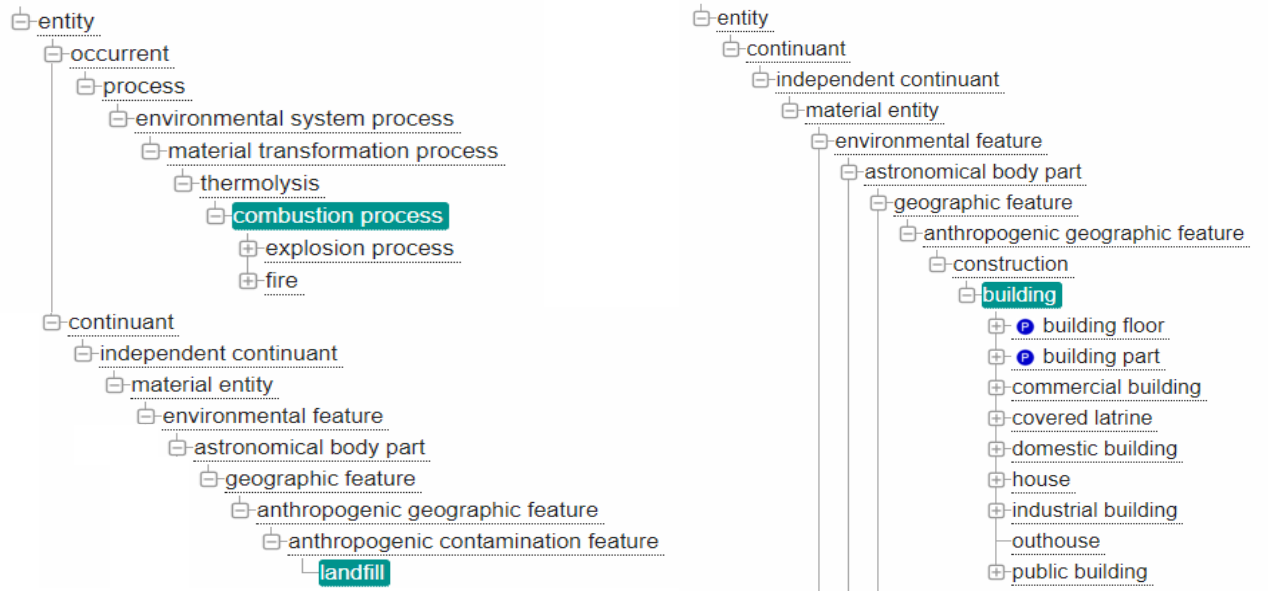

Figure 10 Environment Ontology

It is worth noting that some of the indicators considers only the wastes collected from specific types of buildings. Therefore, bottom classes of aforementioned residential and commercial buildings must also be defined. ENVO also defined commercial and residential buildings which we can use to distinguish those bottom classes in our model. ENVO ontology can provide the definitions of some of the waste processing methods listed by the ISO37120 Solid Waste indicators.

3.7 GovStat Ontology

The GCI Foundation ontology has incorporated the GovStat (GS) ontology to utilize its definitions for measurement data manipulation (Fox, 2018), as most ISO37120 indicators require summing over a population, not only for the cardinality of the

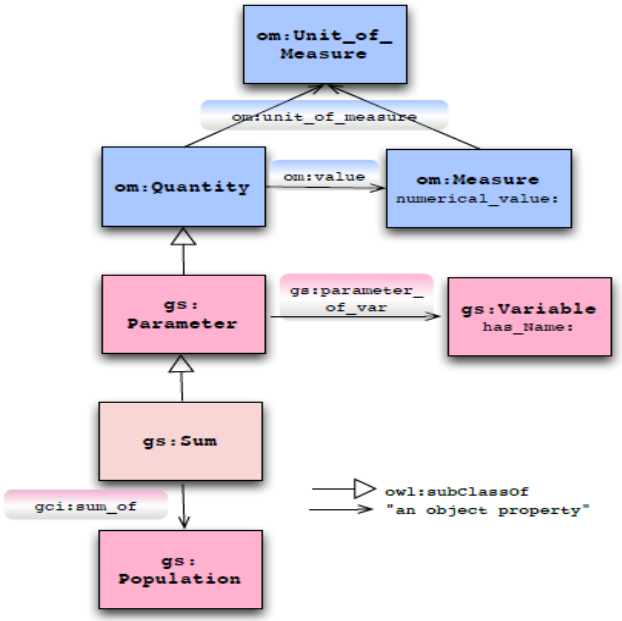

Figure 11 Taxonomy of Quantity and Measure in GovStat

Relevant Competency Question(s) to this Section:

- How frequent is the RSWC for the household?
- What is the average household size for the city of interest?
- What is the total number of residential building in the city?
- How many households in that city have access to regular SWC?

population, but also for a particular measurement. Some definitions from GS must be reused to establish those linkage between GCI Foundation, Measurement Ontology (OM), and our model for GCI Solid Waste. Figure 11, depicts how GS can be used to link with om:Quantity, which would act as the master class for most of our indicator classes. The GovStat ontology should be able to answer competency questions regarding the values of populations or indicators.

3.8 Additional Vocabularies

The National Cancer Institute Thesaurus (NCIT) (Zhang, 2020) and Ontology for MIRNA Target (OMIT) (Balhoff, 2020) provides a wide range of common properties and class that can be utilised in the ISO 37120 Solid Waste ontology. For instance, the 'Physical State' can be used to define the class to contain the physical form of the waste, which would help to address competency questions asking which categories a waste belongs to. The figure below depicts some of the classes available in NCIT.

NCIT: http://purl.obolibrary.org/obo/ncit.owl

OMIT: http://purl.obolibrary.org/obo/omit.owl

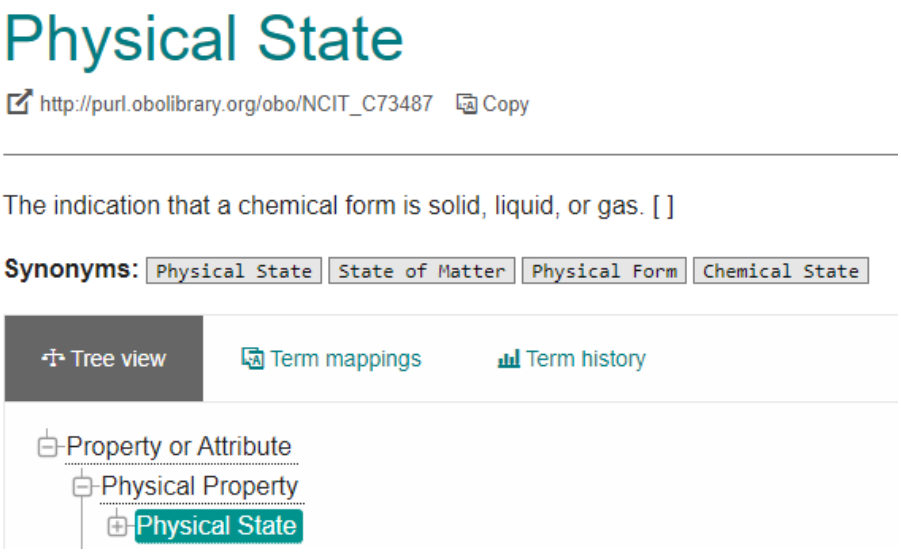

Figure 6 NCIT Vocabularies

Relevant Competency Question(s) to this Section:

- Which types of solid waste are being collected from the building?
- Which types of non-solid-waste are being collected from the building?
- What is the total tonnage of SOME TYPE of waste recycled in that city?
- What is the total tonnage of SOME TYPE of waste of that city?

4 GCI Solid Waste Ontology

In this section we introduce the GCI Solid Waste Ontology. Based on the CQs introduced in section 2, and the review of the literature in section 3, we reuse several of the identified ontologies, and extend them where needed to address the CQs.

4.1 Municipal Entities

The ISO 37120 Solid Waste has mentioned a couple key municipal entities such as household, solid waste collection service provider, and processing sites. Surrounding these entities, a number of competency questions were pointed:

- Who owns the site?
- Is the site a legal entity?
- What is the current average household size of the city of interest?
- What is the total number of households in the city of interest?
- Is the waste collection service provider a legal entity?
- Which types of solid waste are being collected from the building?
- Which types of non-solid-waste are being collected from the building?
- Is SOME waste collection/disposal site provider a legal entity?
- Who is the plant owner?
- Is the waste being collected from a residential building?
- How frequent is the RSWC for the household?
- What is the total number of residential building in the city?
- How many households in that city have access to regular SWC?

First, we provide definitions for municipal services and entities such as building, service provider, organization owners, etc. Any existing types of organizations, personnel, and their location of operation will be defined under this section. The concepts are shown in Table 4. Each type of waste processing site is defined in this section. They are all subsumed by waste processing site, but are distinguished by their waste processing method. Following is a description of the object properties:

- collects: the type of waste that is collected
- hasDisposalLocation: denotes the dumping site associated with the waste collector
- isLegal: is the entity approved by legal authority or not
- process: act of turning one object into other form
- hasProcessingMethod: the method used in resource conversion operations
- hasProcessingStandard: the guidelines followed in the resource conversion operation
- produce: act of generating one object by the act performing entity

Table 4 Definitions of Municipal Entities		
Class	**Property**	**Value Restriction**
WasteCollectionProvider	rdfs:subClassOf	org:Organization
	rdfs:subClassOf	gcii:ServiceProvider
	org:hasOwner	exactly 1 Owner
	collects	only Waste
	hasDisposalLocation	exactly 1 WasteProcessingSite
	isLegal	exactly 1 xsd:boolean
	ic:hasAddress	exactly 1 ic:Address
	gcii:provides	only WasteCollectionService
WasteProcessingSite	rdfs:subClassOf	org:Organization
	rdfs:subClassOf	gcii:ServiceProvider
	org:hasOwner	exactly 1 Owner
	process	only Waste
	isLegal	exactly 1 xsd:boolean
	hasProcessingMethod	exactly 1 WasteProcessingMethod
	hasProcessingStandard	exactly 1 ProcessingStandard
	ic:hasAddress	exactly 1 Address
LandfillSite	rdfs:subClassOf	WasteProcessingSite
	hasProcessingMethod	only Landfill
RecyclingSite	rdfs:subClassOf	WasteProcessingSite
	hasProcessingMethod	only Recycle
	produce	only RecycledProduct
IncinerationSite	rdfs:subClassOf	WasteProcessingSite
	hasProcessingMethod	only Incineration
OutdoorIncinerationSite	rdfs:subClassOf	WasteProcessingSite
	hasProcessingMethod	only BurnedOpenly
OutdoorDumpingSite	rdfs:subClassOf	WasteProcessingSite
	hasProcessingMethod	only DumpedOpenly
OtherProcessingSites	rdfs:subClassOf	WasteProcessingSite
	hasProcessingMethod	only (OtherMethod or Exported)
WasteCollectionService	rdfs:subClassOf	gcii:Service
	hasServiceInterval	exactly 1 ot:interval

The Building ontology from the GCI Recreation ontology provided a basic definition of what a building should be. To configure the definition of the building class for the GCI Solid Waste, it should have a solid waste collection provider. This links the building with the waste classes and therefore the household. The household is also linked to the building class by the livesIn property imported from the GCI Telecommunication and Innovation ontology.

The ISO 37120 Solid Waste indicators requires the ontology to query on the functionalities of the building, the type of ownership of the service provider and the processing site. To address these requirements, the following properties are defined.

- hasTeanant: the entity that take residence in the building
- hasOwnershipStatus: describing whether the entity is municipal or private property
- hasServiceProvider: the identity of the entity currently servicing the subject

Class	Property	Value Restriction
Building	rdfs:subClassOf	gcir: Building
	hasServiceProvider	exactly 1 WasteCollectionProvider
	gci:locatedIn	exactly 1 gci:City
	ic:hasAddress	exactly 1 ic:Address
	hasTenant	Some Tenant
ResidentialBuilding	rdfs:subClassOf	Building
	hasTeanant	only Household
	rdfs:subClassOf	envo:ResidentialBuilding
ConstructionSite	rdfs:subClassOf	gcir:OutdoorSpace
	hasTeanant	only {NoTenant}
PublicArea	rdfs:subClassOf	gcir:OutdoorSpace
	isAccessedBy	only gcir:Public
Garden	rdfs:subClassOf	gcir:WoodedArea
	org:isOwnedBy	exactly 1 Household
CommercialBuilding	rdfs:subClassOf	Building
	hasTenant	only Organization
	rdfs:subClassOf	envo:CommercialBuilding
Owner	rdfs:subClassOf	org:OrganizationAgent
	hasOwnershipStatus	exactly 1 xsd:String

Extending from the Household ontology from the GCI Shelter, a number of properties are added to link the Household with the Waste class. To distinguish the type of the building the waste is collected from, as mentioned above, a household is associated with the Building class via livesIn property where the functionality of the building can be queried.

The Solid Waste Household class extends the GCI Shelter Household to include the production of waste. It is also distinguished from HouseholdWithSolidWasteCollection to filter out the households that produce waste, but do not have access to regular solid waste collection.

Class	Property	Value Restriction
Household	rdfs:subClassOf	gcis:Household
	rdfs:subClassOf	gcii:ServiceConsumer
	gcis:livesIn	exactly 1 gcisw:ResidentialBuilding
	produce	only Waste
HouseHoldWith SolidWasteCollectionConsumer	rdfs:subClassOf	gcis:Household
	rdfs:subClassOf	gcii:ServiceConsumer
	gcis:livesIn	exactly 1 ResidentialBuilding
	produce	only Waste
	gcii:consume	only WasteCollectionService
	hasServiceProvider	exactly 1 WasteCollectionProvider

4.2 Solid Waste

The ISO 37120 document provides guidelines at to the types of waste that can be categorized as solid waste. Under its definition, the waste must also be collected by a legal entity on behalf of the local municipality; therefore, it must be processed by the waste systems define above. Hazardous waste was also appeared extensively in the ISO 37120 solid waste indicators. By definition, it must be processed which renders them less harmful before being disposed or recycled. To better comply with the indicators, each instance of the '*Waste*' class would represent an identifiable amount of waste collected by a legal, municipal waste collection service provider. The Waste classes will address the following competency questions:

- What is the total tonnage of hazardous waste being exported by the city?
- Which types of solid waste are being collected from the building?
- Which types of non-solid-waste are being collected from the building?
- What is the total tonnage of SOME TYPE of waste recycled in that city?
- What is the total tonnage of the hazard waste exported from that city?
- What is the total tonnage of SOME TYPE of waste of that city?
- What type of hazard does the collected waste impose?
- Which type of waste is being collected?
- How is the hazard waste processed?

The unit of the measurement for the amount of waste collected is being restricted by tonne. The Waste classes are shown in Table 5. The following properties are introduced:

- collectedBy: entity obtained by another entity
- collectedFrom: the location the entity was collected from
- producedBy: the origin of the entity that was produced
- processedBy: refers to the other entity that the current entity is manipulated by.
- hasProcessingDate: the datetime the entity was processed on
- hasCollectionDate: the datetime the entity was collected on
- hasWasteType: the categorization of the waste by its content?
- hasWeight: the weight associated to the entity
- hasHazardType: the hazard the entity is subjecting to its surroundings
- hasPhysicalForm: the state of matter the entity is in
- composedOf: subjects that the entity is constructed of or included in.
- isOverWeight: a Boolean flag describes if the entity has excessive amount of weight

Table 5 Waste Definitions

Class	Property	Value Restriction
Waste	collectedBy	only WasteCollectionProvider

	collectedFrom	only Building
	processedBy	only WasteProcessingSite
	hasCollectionDate	exactly 1 ot:interval
	hasProcessingDate	exactly 1 ot:interval
	hasWeight	exactly 1 WasteTonnage
	isOverWeight	exactly 1 xsd:boolean
	hasPhysicalForm	exactly 1 WastePhysicalState
HazardWaste	rdfs:subClassOf	Waste
	isComposedOf	some Material
	isHazardous	exactly 1 xsd:boolean
ResidentialWaste	rdfs:subClassOf	Waste
	collectedFrom	only ResidentialBuilding
CommercialWaste	rdfs:subClassOf	Waste
	collectedFrom	only CommercialBuilding
BulkyWaste	rdfs:subClassOf	Waste
	isOverWeight	only True
GardenWaste	rdfs:subClassOf	Waste
	collectedFrom	only Garden
SewageWaste	rdfs:subClassOf	Waste
	rdfs:subClassOf	envo:Sewage
ConstructionWaste	rdfs:subClassOf	Waste
	collectedFrom	only ConstructionSite
MunicipalServiceWaste	rdfs:subClassOf	Waste
	collectedFrom	only PublicArea

Other than the waste type mentioned in the ISO 37120, hazard state, form and type are also defined as they were mentioned in the indicator requirements for the hazardous waste. Hazard state refers to whether the waste is hazardous or not; hazardous form would describe the physical state of the waste, i.e. liquid or solid; and hazard type describes the hazard this particular waste may induce to its surroundings.

Class	**Property**	**Value Restriction**
WastePhysicalState	rdfs:subClassOf	ncit:PhysicalState
	composedOf	{Solid} or {Gaseous} or {Liquid} or {Sludge}

The table below defines the specific types of hazard wastes mentioned by the ISO 37120 Solid Waste indicators. The hazard wastes are defined as subclasses of HazardWaste and can be differentiated by their components. The user may also define their own Hazard as a subclass of HazardWaste to extend it.

Class	**Property**	**Value Restriction**
ToxicWaste	rdfs:subClassOf	HazardWaste
	composedOf	{chlorine} or {formaldehyde}
FlammableWaste	rdfs:subClassOf	HazardWaste

	composedOf	{gasoline} or {methanol}
CorrosiveWaste	rdfs:subClassOf	HazardWaste
	composedOf	{hydrofluoric acid} or {chloric acid}
ReactiveWaste	rdfs:subClassOf	HazardWaste
	composedOf	{batteries} or {Oxidizer}

4.3 Waste Processing Classes

Waste processing methods were split into 6 major categories according to ISO 37120. In the following each category is represented as a class. The 'WasteProcessingMethod' class is developed based on the aforementioned WMS ontology, with each of the more specific processing method branched out as subclasses. The recording of exported hazardous waste was required by the ISO 37120; thus, the act of export is treated as a method of waste processing. It was also assumed that the act of export occurs only between one waste processing plant and another, since waste cannot be exported from one person's home directly to overseas waste processing plants. The competency questions regarding waste processing method will be addressed by the aforementioned classes:

What type of liner does the landfill use?

- Has the landfill been covered on a daily basis?
- What waste disposal (combustion) method is being used by the plant?
- How are those SW been disposed?
- To where was the hazardous waste to exported to?
- How is the hazard waste processed?

Here we provide the definitions of the new object properties. The definitions of the waste processing classes are shown in Table 6. The WasteProcessingMethod class would hold the same meaning as the 'waste_disposal_method' class from the WMS ontology created by Ramasami, et al (2015). Since no link nor OWL file was provided, we will recreate this class in our ontology.

- requireSite: the type of processing site required for the designated processing method
- hasLinerType: refers to the liners used in the landfill
- consume: act of using a resource
- hasCoverInterval: the time interval between covering of landfill
- hasProcessDescription: detailed description of the operations of resource manipulation
- hasProcessingStandard: the title of the processing standard the processing plant adopted.

Table 6 Definitions of Waste Processing Entities

Class	Property	Value Restriction
WasteProcessingMethod	rdfs:subClassOf	act:Activity
	rdfs:subClassOf	wms:waste_disposal_methods
	performedBy	only WasteProcessingSite
	consume	only Waste

	requireSite	only InPlant or OutdoorOnsite
Recycle	rdfs:subClassOf	WasteProcessingMethod
	produce	only RecycledProduct
	requireSite	only InPlant
Landfill	rdfs:subClassOf	WasteProcessingMethod
	hasLinerType	min 1 Liner
	hasCoverInterval	exactly 1 xsd:DateTimeInterval
	requireSite	only OpenArea
InPlantIncineration	rdfs:subClassOf	WasteProcessingMethod
	rdfs:subClassOf	envo:CombustionProcess
	requireSite	only InPlant
BurnedOpenly	rdfs:subClassOf	WasteProcessingMethod
	rdfs:subClassOf	envo:CombustionProcess
	requireSite	only OpenArea
OpenDump	rdfs:subClassOf	WasteProcessingMethod
	requireSite	only OpenArea
Exported	rdfs:subClassOf	WasteProcessingMethod
	rdfs:subClassOf	gcit:Trip
	trip:startLoc	exactly 1 WasteProcessingPlant
	trip:endLoc	exactly 1 WasteProcessingPlant
OtherMethod	rdfs:subClassOf	WasteProcessingMethod
	hasProcessDescription	exactly 1 xsd:String

Class	**Property**	**Value Restriction**
RecycledProduct	rdfs:subClassOf	schema:Product
	hasProcessingStandard	exactly 1 xsd:String

Recycling plant is different from the rest as it produces product at the end of the processing cycled. The product will comply to some certain processing standard. The definition of the recycled product is shown below.

To distinguish openly burned and incinerated wastes, two classes from the GCI Recreation are extended and used to distinguish processing plants that execute its processing in open and enclosed space.

4.4 Measurement Classes

The final part of the ontology is the units of measure. The ontology reuses GCI foundation measurement classes, which in turn are based on the OM measurement ontology. The classes from this section share

Class	**Property**	**Value Restriction**
InPlant	rdfs:subClassOf	gcir:IndoorSpace
	gci:located_in	only WasteProcessingPlant
OpenArea	rdfs:subClassOf	gcir:OutdoorSpace
	gci:located_in	only WasteProcessingPlant

many competency questions with classes from other main concept groups. As the classes in this section focuses on establishing the concept of their numerical values and units while other sections focus on defining the actual concept of the term. The '*wasteTonnageVar*' is the data property of '*WasteTonnage*,'

which has to be defined using string due to comply with Protégé. The concepts and their definitions for GCI Solid Waste measurement classes are listed in Table 7. Any competency questions about the weight of the waste can be covered by the classes defined in this section. The same can be done for other measurements queried by the competency questions as well.

- What is the total tonnage of SOME TYPE of waste recycled in that city?
- What is the total tonnage of the hazard waste exported from that city?
- What is the total tonnage of SOME TYPE of waste of that city?

Table 7 Waste Measurement Classes		
Class	**Property**	**Value Restriction**
WasteTonnage	rdfs:subClassOf	gci:GCI_Quantity
	om:unit_of_measure	gci:tonne
wasteTonnageVar	rdfs:type	gs:Variable
	gs:has_Name	value “hasWasteTonnage”

5. Definition of ISO 37120 Solid Waste Indicators

In this section we represent the definition of each Solid Waste Indicator using the Solid Waste Ontology defined in the previous section. Once defined, each indicator can be instantiated to represent a specific city’s indicator value, and the data used to derive it, for some interval of time.

5.1 Percentage of City Population with Regular Solid Waste Collection (Residential)

This indicator describes the portion of the population that has access to regular solid waste collection. It has defined that population that has access to solid waste collection service to be the multiplication between the average household size of a city and the number of households that have access to regular solid waste collection.

By this definition, the numerator of this ratio quantity shall be the population with solid waste collection, which itself is a product quantity of average household size and the total number of households; the denominator is the city population size. The ‘*rdfs:label*’ property verbally defines the indicator and is optional.

Class	**Property**	**Value Restriction**
ISO37120_16_1	rdfs:subClassOf	gci: GCIRatioQuantity
	om:numerator	exactly 1 16_1_Population_Served_by_SWC_size
	om:denominator	exactly 1 gci:City_Population_size
	rdfs:label	"Percentage of City Population with Regular Solid Waste Collection (Residential)"
	om:unit_of_measure	value gci:population_ratio_unit
16_1_Population_Served_by_SWC_size	rdfs:subClassOf	gci:Product_Quantity
	om:unit_of_measure	value gci:population_cardinality_unit

	om:term_1	exactly 1 16_1_Total_number_of_Household_with_SWC_size
	om:term_2	exactly 1 (gci:GCI_quantity and om:numerical_value xsd.integer[>=0])
16_1_Total_number_of_Household_with_SWC	rdfs:subClassOf	gci:Population
	gci:defined_by	exactly 1 HouseholdWithSolidWasteCollection
16_1_Total_number_of_Household_with_SWC_size	rdfs:subClassOf	gci:Population_size
	gci:cardinality_of	exactly 1 16_1_Total_number_of_Household_with_SWC

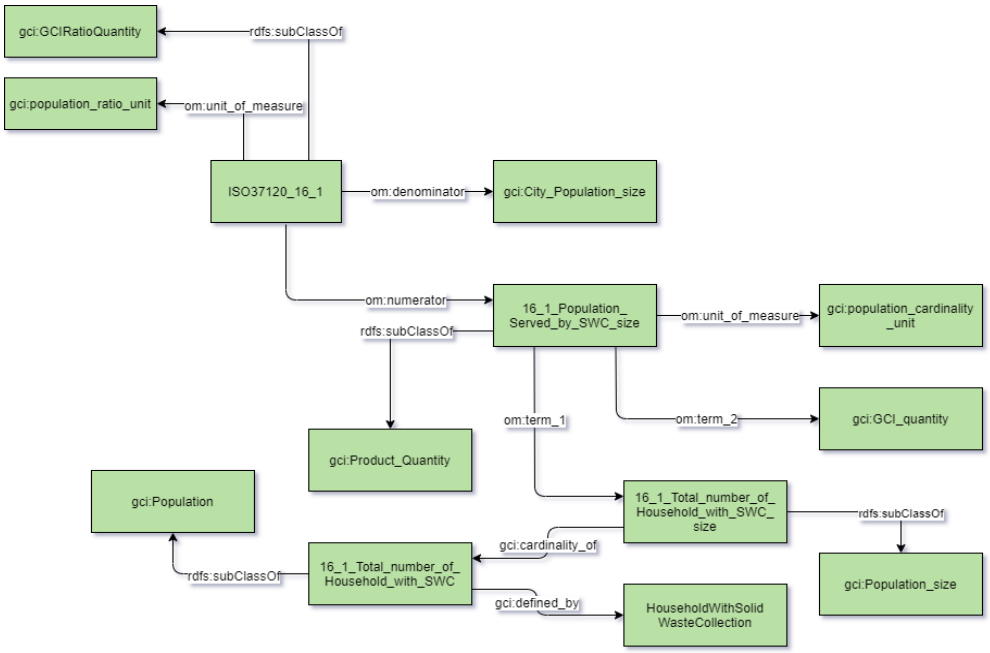

Figure 12 Definition of ISO37120 Indicator 16.1

5.2 Total Collected Municipal Solid Waste per Capita

This indicator measures the municipal solid waste produced per person in a city. It has declared that only wastes that are produced by households and commercial purpose are eligible for consideration. Other waste such as sewage waste, construction waste, bulky waste, garden waste and municipal service waste are exempted from this analysis. It is important to emphasize that the date of the waste instance must be within the date specified by the indicator. This is to ensure that we only compute the waste data for the year and datetime specified by the user.

By defining residential waste tonnage and commercial waste tonnage, a total waste tonnage can be defined as the sum of the aforementioned waste weightings. The numerator of this ratio quantity reuses the '*TotalWasteTonnage'* from the previous indicator; the denominator would be the city population size defined in the GCI Foundation.

Class	Property	Value Restriction
ISO37120_16_2	rdfs:subClassOf	gci: GCIRatioQuantity
	om:numerator	exactly 1 16_2_TotalWasteTonnage
	om:denominator	exactly 1 gci:City_Population_size
	rdfs:label	"Total Collected Municipal Solid Waste per Capita"
16_2_TotalWasteTonnage	rdfs:subClassOf	gs:Sum
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
	gci:sum_of	exactly 1 16_2_MunicipalSolidWasteTonnage
	gs:sum_of_var	value wasteTonnageVar
16_2_MunicipalSolidWasteTonnage	rdfs:subClassOf	gci:Population
	gci:for_city	exactly 1 gci:City
	gci:defined_by	only (ResidentialWaste or CommercialWaste)

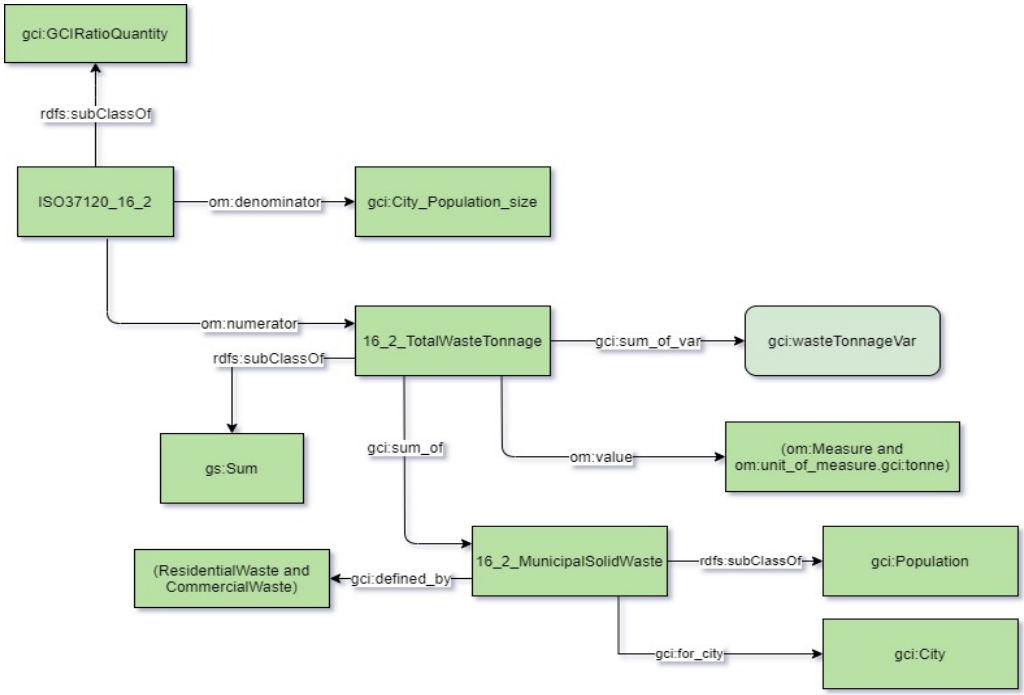

Figure 13 Definition of ISO37120 Indicator 16.2

5.3 Percentage of the City's Solid Waste that is Recycled

This indicator computes the proportion of all of the solid waste recycled in the city. The ISO37120 Solid Waste mentioned that hazardous waste shall not be considered in this indicator. Total waste tonnage from the second indicator can be reused. The ISO37120 16.3 WasteTonnage and its measure counterpart inherit

the OM Quantity and Measure from the WasteTonnage and WasteTonnageMeasure defined in section 4.4. The RecycledWasteTonnage shall be defined by the waste that is being recycled.

The method used to define this indicator is the exact same method used to defined the previous one, except that a recycled waste should be initialized so that '*16_3_RecycledWasteTonnage*' can be defined. Reusing the '*16_2_TotalWasteTonnage*' from section 5.2 as the denominator, the '*ISO37120_16_3*' can then be calculated. The taxonomy of this indicator is shown in Figure 14.

Class	**Property**	**Value Restriction**
ISO37120_16_3	rdfs:subClassOf	gci: GCIRatioQuantity
	om:numerator	exactly 1 16_3_TotalRecycledWasteTonnage
	om:denominator	exactly 1 16_2_TotalWasteTonnage
	rdfs:label	"Percentage of the City's Solid Waste that is Recycled"
	om:unit_of_measure	exactly 1 om:percent
16_3_TotalRecycledWasteTonnage	rdfs:subClassOf	gs:Sum
	gci:sum_of	exactly 1 16_3_RecycledWasteTonnage
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
	gs:sum_of_var	value wasteTonnageVar
16_3_RecycledWasteTonnage	rdfs:subClassOf	gci:Population
	gci:for_city	exactly 1 gci:City
	gci:defined_by	exactly 1 16_3_RecycledWaste
16_3_RecycledWaste	rdfs:subClassOf	Waste
	processedBy	only RecyclingSite

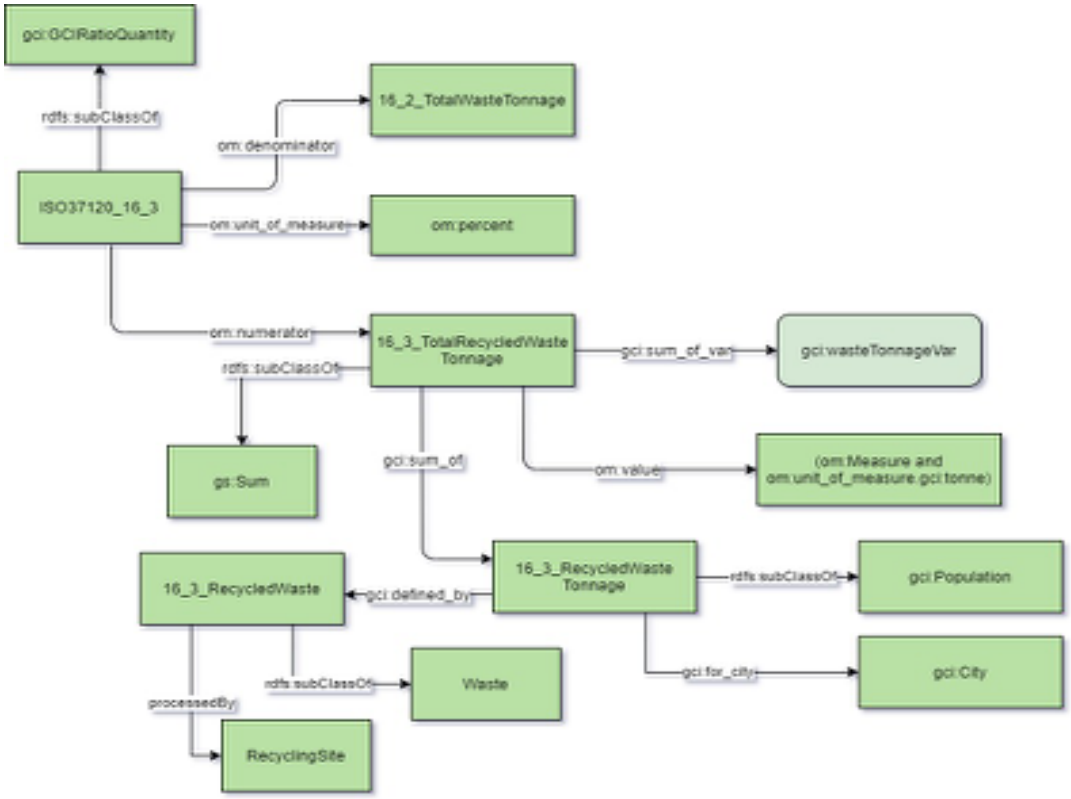

Figure 14 Definition of ISO37120 Indicator 16.3

5.4 Percentage of the City's Solid Waste that is Disposed of in a Sanitary Landfill

Similar to the previous indicator, this indicator evaluates the percentage of solid waste that were disposed in landfill. The indicator defined sanitary landfill as a prominent structure fitted with liners that can either be made from clay or be synthetic. It also requires the landfill to be soil-covered daily. The numerator of this indicator should be the total amount of solid waste disposed in the landfill divided by the total amount of solid waste calculated in the second indicator.

Defining '*16_4_LandfillWaste*' as a subclass of '*Waste*' and use it to define the population class that is the '*16_4_LandfillWasteTonnage*'. To sum over the weight of all waste that are being processed at a landfill site, '*16_4_TotalLandfillWasteTonnage*' was defined and used as the numerator to be divided by the total waste tonnage defined in section 5.2. The taxonomy of this indicator is given in Figure 15.

Class	**Property**	**Value Restriction**
ISO37120_16_4	rdfs:subClassOf	gci: GCIRatioQuantity
	om:numerator	exactly 1 16_4_TotalLandfillWasteTonnage
	om:denominator	exactly 1 16_2_TotalWasteTonnage
	rdfs:label	"Percentage of the City's Solid Waste that is Disposed of in a Sanitary Landfill"
	om:unit_of_measure	only om:percent
16_4_TotalLandfillWasteTonnage	rdfs:subClassOf	gs:Sum
	gci:sum_of	exactly 1 16_4_LandfillWasteTonnage
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
	gs:sum_of_var	value wasteTonnageVar
16_4_LandfillWasteTonnage	rdfs:subClassOf	gci:Population
	gci:for_city	exactly 1 gci:City
	gci:defined_by	exactly 1 16_4_LandfillWaste
16_4_LandfillWaste	rdfs:subClassOf	Waste
	processedBy	only LandfillSite

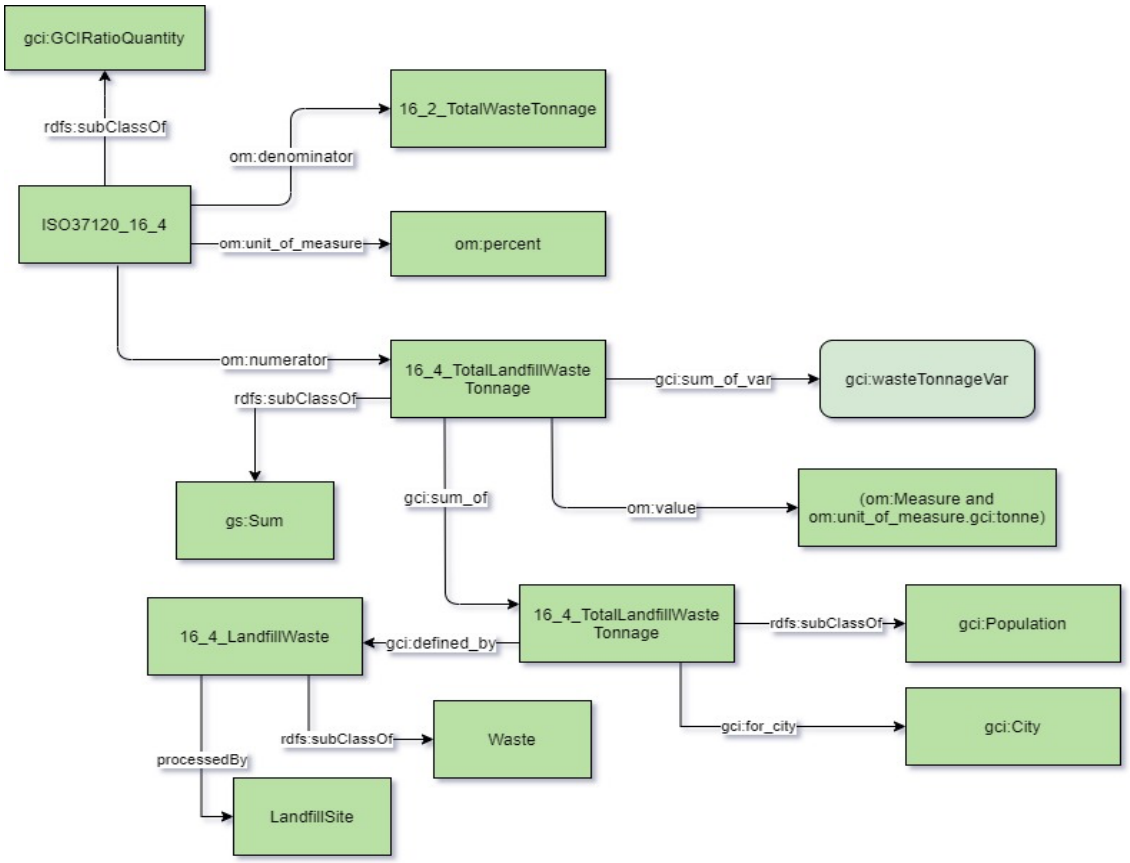

Figure 15 Definition of ISO37120 Indicator 16.4

5.5 Percentage of the City's Solid Waste that is Disposed of in an Incinerator

This indicator calculates the percentage of incinerated solid wastes out of all municipal solid waste in a city. The indicator only provided a broad definition for incineration plant as a facility whose main purpose is to burn waste. The numerator was defined as the total tonnage of incinerated solid waste; and the denominator of this indicator is the total municipal waste tonnage.

In this indicator, simple switch the waste to '16_5_IncineratedWaste' for a new set of population and sum classes. The numerator of this indicator will point to the new sum class.

Class	**Property**	**Value Restriction**
ISO37120_16_5	rdfs:subClassOf	gci: GCIRatioQuantity
	om:numerator	exactly 1 16_5_TotalIncineratedWasteTonnage
	om:denominator	exactly 1 16_2_TotalWasteTonnage
	rdfs:label	"Percentage of the City's Solid Waste that is Disposed of in an Incinerator"
	om:unit_of_measure	only om:percent
16_5_TotalIncineratedWasteTonnage	rdfs:subClassOf	gs:Sum
	gci:sum_of	exactly 1 16_5_IncineratedWasteTonnage
	gci:sum_of_var	value wasteTonnageVar
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
16_5_IncineratedWasteTonnage	rdfs:subClassOf	gci:Population
	gci:for_city	exactly 1 gci:City
	gci:defined_by	exactly 1 16_5_IncinerationWaste
16_5_IncineratedWaste	rdfs:subClassOf	Waste
	processedBy	only IncinerationSite

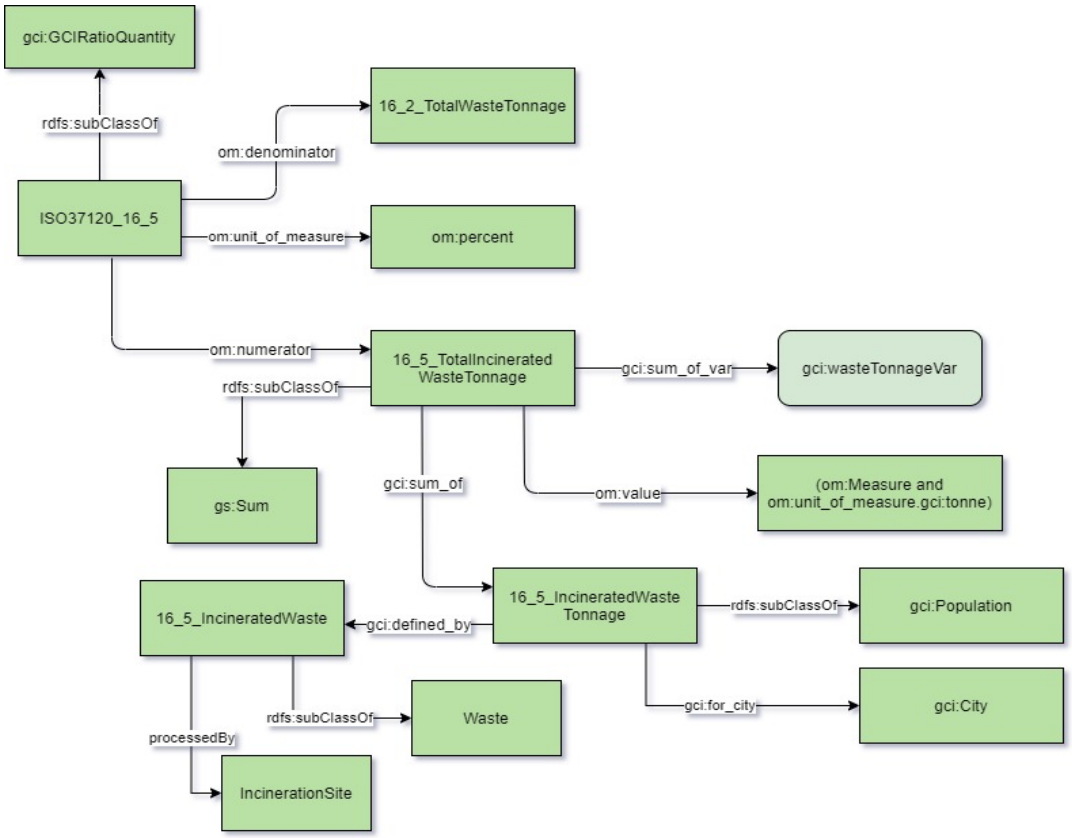

Figure 17 Definition of ISO37120 Indicator 16.5

5.6 Percentage of the City's Solid Waste that is Burned Openly

Closely related to the previous indicator, this indicator computes the percentage of municipal solid waste that is incinerated, but in an open space. The ISO37120 16.5 and 16.6 distinguished incineration plant and outdoor waste burning site only by the fact that one is done inside a plant while the other is not. The numerator of this indicator would be the solid waste incinerated in an outdoor space, divided by the total municipal waste tonnage. Using the exact same method, define a new waste with the condition that is being burned openly.

Class	Property	Value Restriction
ISO37120_16_6	rdfs:subClassOf	gci: GCIRatioQuantity
	om:numerator	exactly 1 16_6_TotalOpenlyBurnedWasteTonnage
	om:denominator	exactly 1 16_2_TotalWasteTonnage
	rdfs:label	"Percentage of the City's Solid Waste that is Disposed of in an Incinerator"
	om:unit_of_measure	only om:percent
	rdfs:subClassOf	gs:Sum

16_6_TotalOpenlyBurnedWasteTonnage	gci:sum_of	exactly 1 16_6_OpenlyBurnedWasteTonnage
	gci:sum_of_var	value wasteTonnageVar
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
16_6_OpenlyBurnedWasteTonnage	rdfs:subClassOf	gci:Population
	gci:defined_by	exactly 1 16_6_OpenlyBurnedWaste
	gci:for_city	exactly 1 gci:City
16_6_OpenlyBurnedWaste	rdfs:subClassOf	Waste
	processedBy	only OutdoorIncinerationSite

'*16_6_TotalOpenlyBurnedWasteTonnage*', which is then used as the numerator of this indicator.

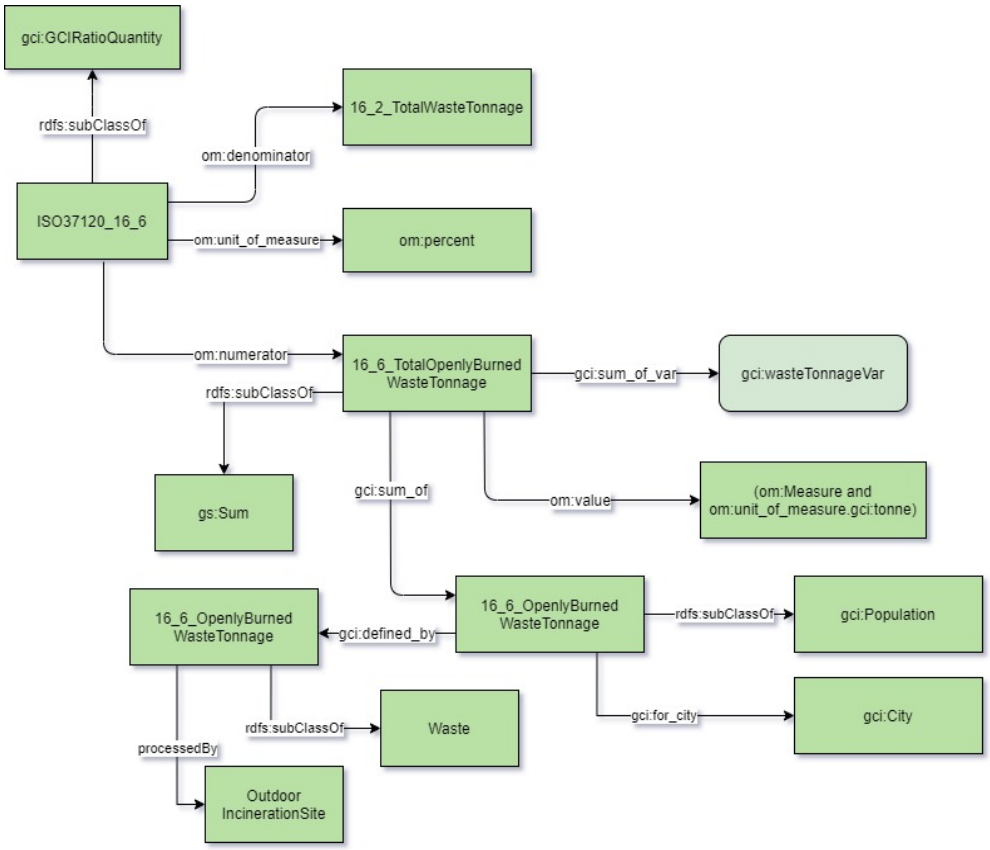

Figure 17 Definition of ISO37120 Indicator 16.6

5.7 Percentage of the City's Solid Waste that is Disposed of in an Open Dump

This indicator calculates the percentage of solid waste that are being dumping in an outdoor, open, and uncovered space. The numerator of this indicator is the total tonnage of openly dumped waste; the denominator of this indicator is the total tonnage of municipal solid waste generated in the city. The method used to define this indicator is the exact same method used for the previous indicator with the exception that the classes are now based on '*16_7_OpenlyDumpedWaste*'.

Class	Property	Value Restriction
ISO37120_16_7	rdfs:subClassOf	gci: GCIRatioQuantity
	om:numerator	exactly 1 16_7_TotalOpenlyDumpedWasteTonnage
	om:denominator	exactly 1 16_2_TotalWasteTonnage
	rdfs:label	"Percentage of the City's Solid Waste that is Disposed of in an Open Dump"
	om:unit_of_measure	only om:percent
16_7_TotalOpenlyDumpedWasteTonnage	rdfs:subClassOf	gs:Sum
	gci:sum_of	exactly 1 16_7_OpenlyDumpedWasteTonnage

	gci:sum_of_var	value wasteTonnageVar
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
16_7_OpenlyDumpedWasteTonnage	rdfs:subClassOf	gci:Population
	gci:for_city	exactly 1 gci:City
	gci:defined_by	exactly 1 16_7_OpenlyDumpedWaste
16_7_OpenlyDumpedWaste	rdfs:subClassOf	Waste
	processedBy	only OutdoorDumpingSite

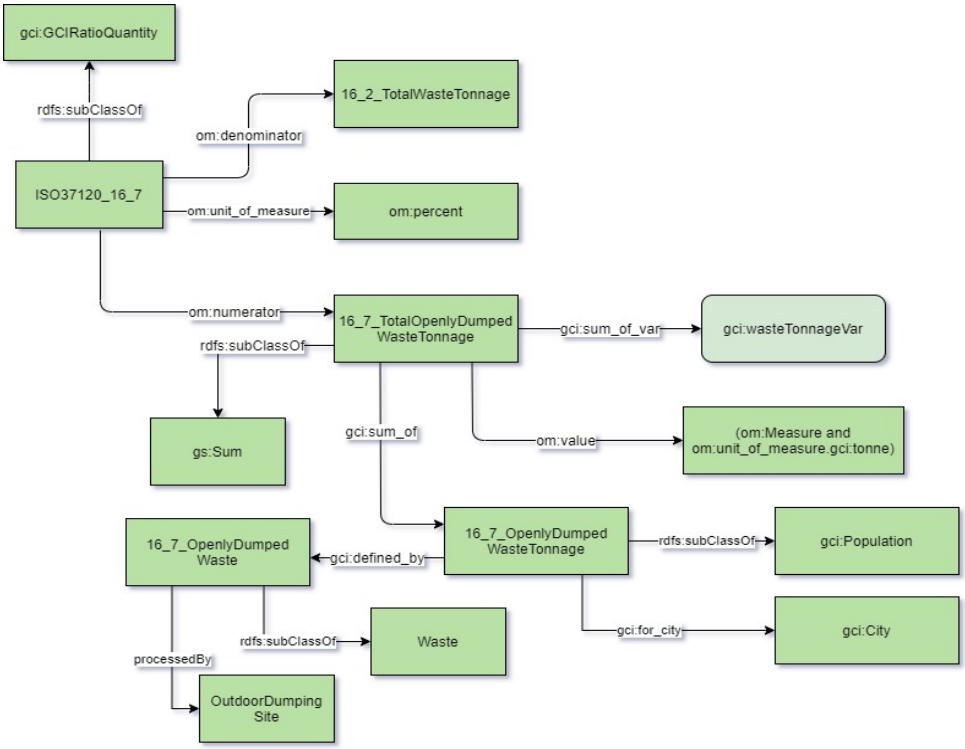

Figure 18 Definition of ISO37120 Indicator 16.7

5.8 Percentage of the City's Solid Waste that is Disposed of by Other Means

This indicator calculates the percentage of solid waste that are being processing by methods which are not discussed by any of the previous indicators. The ISO37120 does not require any descriptions for the method other than the tonnage of the processed waste. The numerator of this indicator would be the total tonnage of solid waste processed by other means; the denominator would be the total municipal solid waste generated in the city. The method used to define this indicator is the exact same method used for the previous indicator with the exception that the classes are now based on '*16_8_WasteProcessedByOtherMeans*'.

Class	**Property**	**Value Restriction**
ISO37120_16_8	rdfs:subClassOf	gci: GCIRatioQuantity
	om:numerator	exactly 1 16_8_TotalOtherMethodWasteTonnageMeasure

	om:denominator	exactly 1 16_2_TotalWasteTonnage
	rdfs:label	"Percentage of the City's Solid Waste that is Disposed of by Other Means"
	om:unit_of_measure	only om:percent
16_8_TotalOtherMethodWasteTonnage	rdfs:subClassOf	gs:Sum
	gci:sum_of	exactly 1 16_8_OtherMethodWasteTonnage
	gci:sum_of_var	value wasteTonnageVar
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
16_8_OtherMethodWasteTonnage	rdfs:subClassOf	gci:Population
	gci:for_city	exactly 1 gci:City
	gci:defined_by	exactly 1 16_8_WasteProcessedByOtherMeans
16_8_WasteProcessedByOtherMeans	rdfs:subClassOf	Waste
	processedBy	only 1 OtherProcessingSites

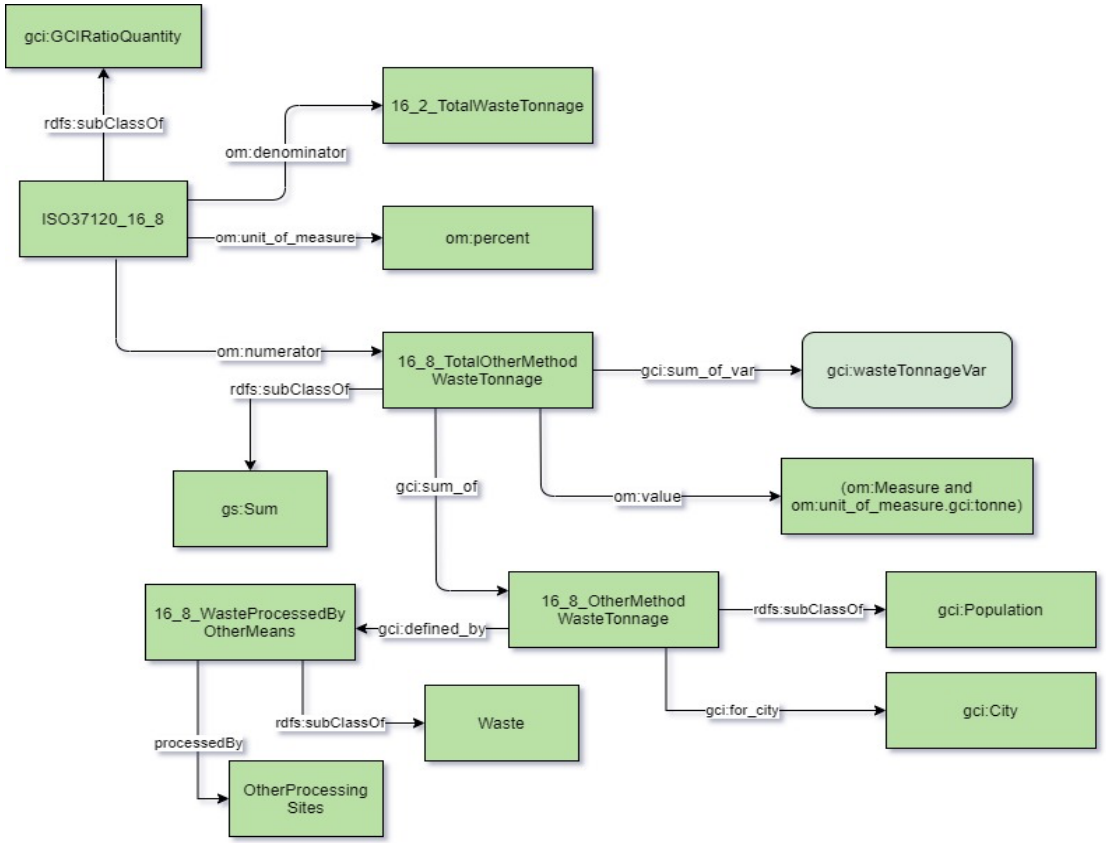

Figure 19 Definition of ISO37120 Indicator 16.8

5.9 Hazardous Waste Generation per Capita (Tonnes)

As mentioned before, required by the ISO 37120, hazard waste must be reported separately from the rest of the solid waste. The hazardous waste is defined as any waste that has one or more hazard types such as toxic and flammable, and can be originated from any types of building. The numerator of this indicator is defined as the total hazardous waste tonnage, divided by the population size of the city.

For this indicator, a '*HazardWaste*' class has already been defined in section 4.2; therefore, only a population and a sum extension classes are needed. The denominator is now the city population size defined in GCI Foundation.

Class	**Property**	**Value Restriction**
ISO37120_16_9	rdfs:subClassOf	GCIRatioQuantity
	om:numerator	exactly 1 16_9_TotalHazardousWasteTonnage
	om:denominator	exactly 1 gci:City_Population_size
	rdfs:label	"Hazardous Waste Generation per Capita (Tonnes)"
16_9_TotalHazardousWasteTonnage	rdfs:subClassOf	gs:Sum
	gci:sum_of	exactly 1 16_9_HazardousWasteTonnage
	gci:sum_of_var	value wasteTonnageVar
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
16_9_HazardousWasteTonnage	rdfs:subClassOf	gci:Population
	gci:for_city	exactly 1 gci:City
	gci:defined_by	exactly 1 HazardWaste

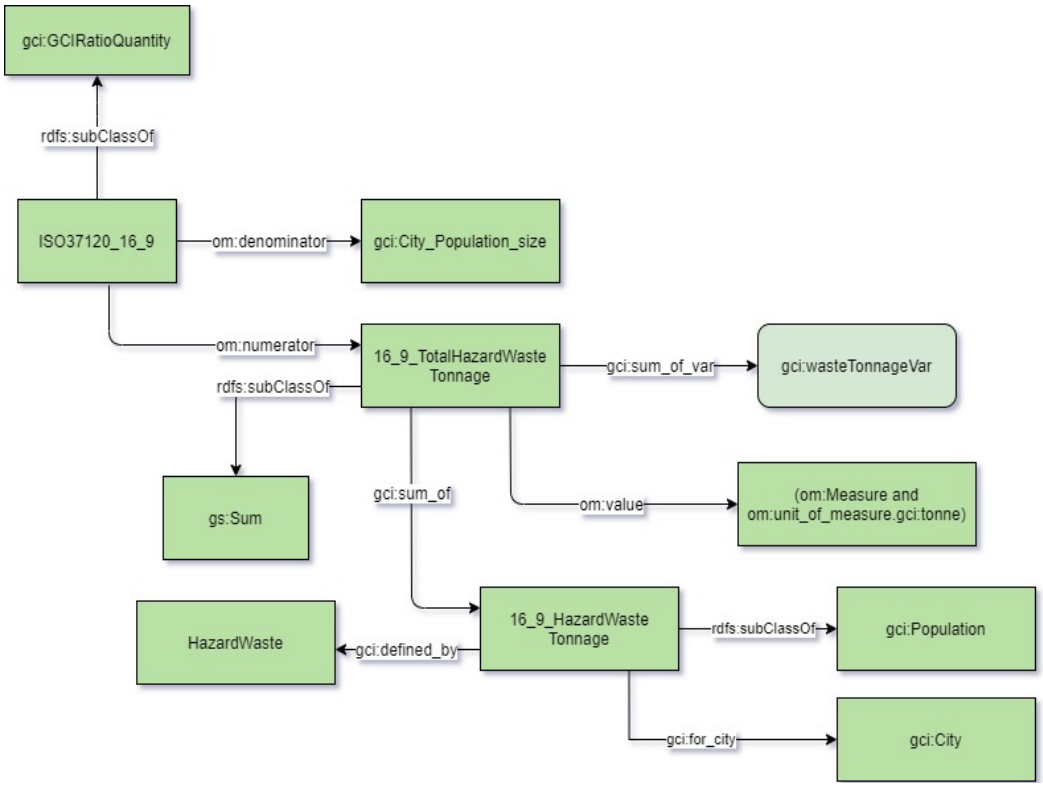

Figure 20 Definition of ISO37120 Indicator 16.9

5.10 Percentage of the City's Hazardous Waste that is Recycled

This indicator reports the proportion of the hazardous waste that is being recycled, out of the total hazardous waste produced in the city. The measurement shall be defined by waste that is both hazardous, and is being recycled. The numerator of this indicator is the total recycled hazard waste tonnage, over the total municipal solid waste tonnage.

A new waste class is needed for this indicator as we now need to further restrict the '*HazardWaste*' defined in section 4.2 to hazardous waste that is also recycled. This can be done by defining '*16_10_RecycledHazardWaste*' as a subclass of '*HazardWaste*' and is processed by any recycling plant. Then, the population and sum classes are created to accumulate all recycled hazardous waste tonnages for the numerator of this indicator. For the denominator, the '*16_9_TotalHazardousWasteTonnage*' from the previous indicator can be reused.

Class	Property	Value Restriction
ISO37120_16_10	rdfs:subClassOf	GCIRatioQuantity
	om:numerator	exactly 1 16_10_TotalRecycledHazardWasteTonnage
	om:denominator	exactly 1 16_9_TotalHazardousWasteTonnage
	rdfs:label	"Percentage of the City's Hazardous Waste that is Recycled"
	om:unit_of_measure	only om:percent

16_10_TotalRecycledHazardWasteTonnage	rdfs:subClassOf	gs:Sum
	gci:sum_of	exactly 1 16_10_RecycledHazardWasteTonnage
	gci:sum_of_var	value wasteTonnageVar
	om:value	exactly 1 (om:Measure and om:unit_of_measure.gci:tonne)
16_10_RecycledHazardWasteTonnage	rdfs:subClassOf	gci:Population
	gci:for_city	exactly 1 gci:City
	gci:defined _by	exactly 1 16_10_RecycledHazardWaste
16_10_RecycledHazardWaste	rdfs:subClassOf	HazardWaste
	processedBy	only RecyclingSite

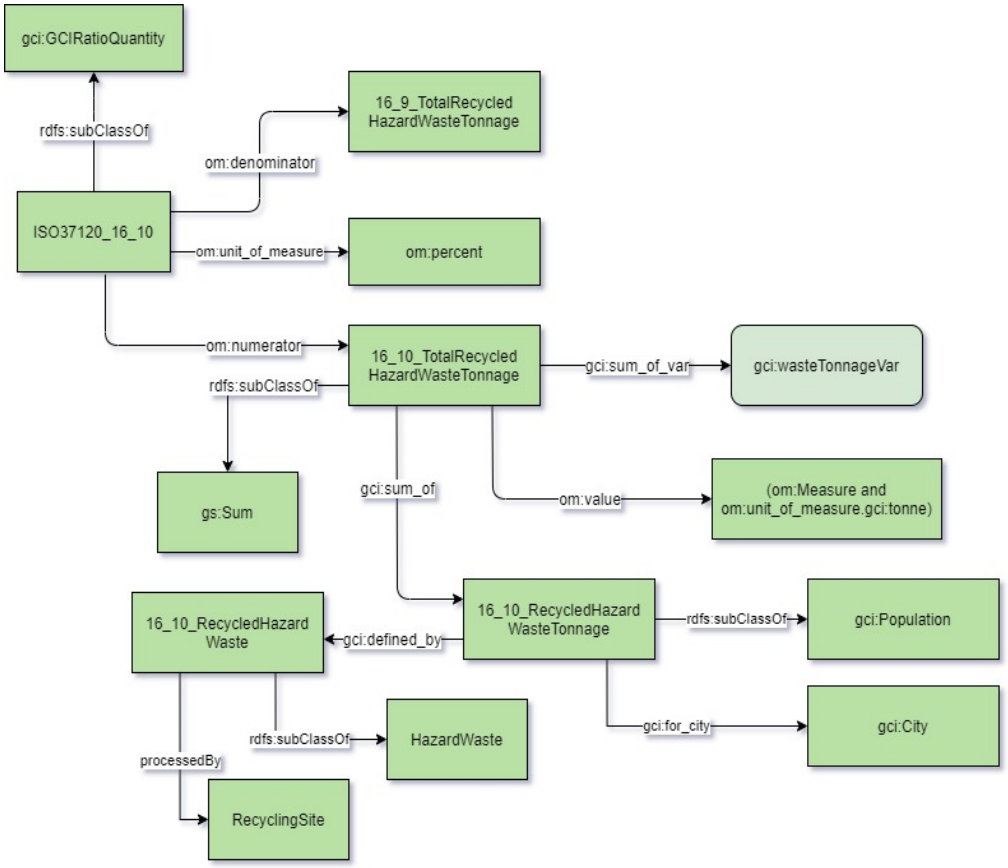

Figure 21 Definition of ISO37120 Indicator 16.10

6. Ontology Evaluation

In this section, we demonstrate the completeness of our ontology model by implementing an example of indicator 16.3. The table below lists the instances in our example for indicator ISO37120 16.3 Percentage of the City's Solid Waste that is Recycled.

Instances	**Properties**	**Values**

Toronto	rdfs:type	gci:City
	rdfs:type	gci:Feature
	rdfs:label	“Toronto”
ISO37120_16_3_ex	rdfs:type	iso37120:16.3
	gci:for_city	Toronto
	gci:nominator	totalRecycledWasteTonnage_1
	gci:demoninator	totalWasteTonnage_1
	om:value	ISO37120_16_3_val
ISO37120_16_3_val	rdfs:type	om:Measure
	om:unit_of_measure	om:percent
	om:numerical_value	12.622
totalRecycledWasteTonnage_1	rdfs:type	gcisw_37120: 16_3_TotalRecycledWasteTonnage
	gs:sum_of	recycledWasteTonnage_1
	om:value	totalRecycledWasteTonnage_val
totalRecycledWasteTonnage_val	rdfs:type	om:Measure
	om:unit_of_measure	gci:tonne
	om:numerical_value	300.5
recycledWasteTonnage_1	rdfs:type	gci:Population
	gci:defined_by	recycledWaste_1
recycledWaste_1	rdfs:type	gcisw_37120:16_3_RecycledWaste
	rdfs:type	gcisw:BulkyWaste
	gcisw:collectedFrom	building_1
	gcisw:processedBy	recyclingPlant_1
	gcisw:isHazardous	False
building_1	rdfs:type	gcir:ResidentialBuilding
	rdfs:label	“BuildingName”
recyclingPlant_1	rdfs:type	gcisw:RecyclingSite
	rdfs:label	“Name of RecyclingSite_1”
totalWasteTonnage_1	rdfs:type	gcisw_37120:16_2_TotalWasteTonnage
	om:value	totalWasteTonnage_val
totalWasteTonnage_val	rdfs:type	om:Measure
	om:unit_of_measure	gci:tonne
	om:numerical_value	2380.8

The ontology is tested by querying for the pre-defined competency questions in Section 2.1.3.

1. (F) What is the total tonnage of the recycled solid waste at the city of interest?

```
SELECT ?city_name ?val
WHERE {
  ?indicator gci:for_city ?city.
  ?city rdfs:label ?city_name.
  ?indicator gci2:numerator ?indicator_param.
  ?indicator_param om:value ?indicator_param_val.
  ?indicator_param_val om:numerical_value ?val
}
```

RETURN:

city_name	val
“Toronto”	"300.5"^^xsd:float

2. (D) What is the total tonnage of all solid waste collected in that city?

```
SELECT ?city_name ?val
WHERE {
  ?indicator gci:for_city ?city.
  ?city rdfs:label ?city_name.
  ?indicator gci2:denominator ?indicator_param.
  ?indicator_param om:value ?indicator_param_val.
  ?indicator_param_val om:numerical_value ?val
}
```

RETURN:

city_name	val
“Toronto”	"2380.7"^^xsd:float

3. (F) Which recycling plant processed this waste?

```
SELECT ?plant_name
WHERE {
  ?indicator gci:for_city ?city.
  ?city rdfs:label ?city_name.
  ?indicator gci2:numerator ?indicator_param.
  ?indicator_param gs:sum_of ?indicator_pop.
  ?indicator_pop gci:defined_by ?waste.
  ?waste gcisw:processedBy ?plant.
  ?plant rdfs:label ?plant_name
}
```

RETURN:

plant_name
"Name of RecyclingSite_1"

4. (F) Is the collected solid waste hazardous?

```
SELECT ?hazardState
WHERE {
  ?indicator gci:for_city ?city.
  ?city rdfs:label ?city_name.
  ?indicator gci2:numerator ?indicator_param.
  ?indicator_param gs:sum_of ?indicator_pop.
  ?indicator_pop gci:defined_by ?waste.
  ?waste gcisw:isHazardous ?hazardState
}
```

RETURN:

hazardState
"No"

5. (CD) What standard does the recycled product comply?

```
SELECT ?standard
WHERE {
  ?indicator gci:for_city ?city.
  ?city rdfs:label ?city_name.
  ?indicator gci2:numerator ?indicator_param.
  ?indicator_param gs:sum_of ?indicator_pop.
  ?indicator_pop gci:defined_by ?waste.
  ?waste gcisw:processedBy ?plant.
  ?plant gcisw:produce ?product.
  ?product gcisw:hasProcessingStandard ?standard
}
```

RETURN:

standard
"ISWA"

6. (F) Which type of building are the wastes being collected from?

```
SELECT ?buildingFunction
WHERE {
  ?indicator gci:for_city ?city.
  ?city rdfs:label ?city_name.
  ?indicator gci2:numerator ?indicator_param.
  ?indicator_param gs:sum_of ?indicator_pop.
  ?indicator_pop gci:defined_by ?waste.
  ?waste gcisw:collectedFrom ?building.
  ?building rdfs:type ?buildingFunction
}
```

RETURN

buildingFunction
gcisw:ResidentialBuilding

7. (F) Which type of waste is being collected?

```
SELECT ?wasteType
WHERE {
  ?indicator gci:for_city ?city.
  ?city rdfs:label ?city_name.
  ?indicator gci2:numerator ?indicator_param.
  ?indicator_param gs:sum_of ?indicator_pop.
  ?indicator_pop gci:defined_by ?waste.
  ?waste rdfs: ?wasteType
}
```

RETURN

wasteType	
gcisw:BulkyWaste	gcisw:RecycledWaste

7. Conclusion

To create a knowledge base for the ISO37120 Solid Waste city performance indicators, we defined a collection of ontological entities mentioned in ISO37120 Solid Waste indicators such as Waste, Waste Collection Agents, and Waste Processing Methods. This model was then implemented in the indicator ontology model, where we defined our numerators and denominators, so that the value of the indicator in question may be derived on a semantic basis. All of the aforementioned models were built in protégé.

In conclusion, this project has completed the following objectives:

- Defined the GCI Solid Waste Ontology model that integrated a wide range of concepts related to solid waste, its collection, and its processing methods.
- Defined ISO37120 Solid Waste Indicator ontology based on the GCI Solid Waste Ontology and GCI Foundation Ontology

- As the result of above points, the definitions of the ISO37120: indicators comply to the Semantic Web standard.
- Created a generalized, standard knowledge base of ISO37120 Solid Waste indicators which enables the unique identification of regional specific knowledge and the data that can be used to derive indicator values.

8. Acknowledgement

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APPENDIX I

Prefixes	Name	URL
ic	iContact	http://ontology.eil.utoronto.ca/tove/icontact#
om	OWL Measure	http://www.wurvoc.org/vocabularies/om[1.8/
act	activity	http://ontology.eil.utoronto.ca/tove/activity#
tr	Trust & Validity	http://ontology.eil.utoronto.ca/trust.owl#
org	Organisation	#http://ontology.eil.utoronto.ca/tove/organization#
trip	Trip	https://enterpriseintegrationlab.github.io/icity/Trip/doc/index-en.html
envo	Environment	http://purl.obolibrary.org/obo/envo.owl
gci	GCI Foundation	http://ontology.eil.utoronto.ca/GCI/Foundation/GCI-Foundation-v2#
gcis	GCI Shelter	http://ontology.eil.utoronto.ca/GCI/Shelters/GCI-Shelters.owl#
gcit	GCI Innov-tele	http://ontology.eil.utoronto.ca/GCI/Innovation/GCI-Innovation.owl#

gcir	GCI Recreation	http://ontology.eil.utoronto.ca/GCI/Recreation/GCI-Recreation.owl#
cosmo	Common Semantic Model	http://micra.com/COSMO/COSMO.owl
gn	Geonames	http://sws.geonames.org/
gs	GovStat	http://ontology.eil.utoronto.ca/govstat.owl#
ot	OWL Time	http://www.w3.org/2006/time
so	Service	http://purl.org/ontology/service
iso37120	ISO 37120	http://ontology.eil.utoronto.ca/ISO37120.owl#
gcisw	GCI Solid Waste	http://ontology.eil.utoronto.ca/GCI/Solidwaste/GCI-Innovation#