EMO: An Ontology for Supporting the Management of Epidemic

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***Abstract*—In order to improve the coverage of concepts in epidemic management, this paper constructs an epidemic management ontology EMO to help manage and analyse epidemic data. First, based on the ISO/IEC 5087 city data model series of standards and TOVE method, EMO is constructed using Protégé. Secondly, the data types and their relationships required in the epidemic management use cases are defined. Finally, the instance data help to verify the ability of EMO to represent the city epidemic management data. Results show that EMO provides a clear, accurate and unified definition of epidemic management data, improves the efficiency of data sharing and integration, and reduces the difficulty of developing epidemic management tools.**

Keywords—ontology, epidemic management, data interoperability, semantic web

I. Introduction

As early as August 2007, the World Health Organization (WHO) warned in its annual report that the world is experiencing the fastest and widest spread of disease in history [1]. Since the beginning of the 21st century, the occurrence frequency of all kinds of global new and re-emerging infectious diseases has been on the rise. The COVID-19 epidemic that emerged at the end of 2019 and spread around the world, as well as various secondary and derived problems brought about by it, have had huge impacts and has created challenges in the construction of emergency management systems and capacity enhancement of governments around the world [2-4]. This has had a huge negative impact on the public's health, and on national and global economies. On 30 January 2020, WHO announced that the outbreak of Covid-19 has constituted a public health emergency of international concern, with the aim of mobilizing more international resources to respond to the epidemic [5].

In response to this challenge, various Standards Development Organizations (SDOs) have developed guidance documents that define methods, processes and checklists for how cities should respond. Yet none of them address the critical issue of defining a shared data model for epidemics that both minimizes the time it takes to develop information systems and improves data interoperability. In a survey of epidemic management data models, 16 epidemic-related Vocabularies/Ontologies (V/Os) were reviewed. The analysis shows that they cover a large portion of the concepts underlying the epidemic management domain. However, there are still some gaps in the coverage. SDOs need to do additional effort to get a consensus on what the standard V/Os should be [6].

In this paper we identify the types of data that epidemic management use cases require, and define a shared data model, Epidemic Management Ontology (EMO). It mainly focuses on information that other city services would request or need from epidemic domain, for representing this data such that it supports interoperability and integration across local and global epidemic management information systems.

II. Requirements

Ontology is one of the main theories and methods for semantic description and expression, focusing on unified and explicit conceptualization and formal expression of conceptual semantic relations [7]. Ontology can provide a set of unified expression of vocabularies and their relationships that are independent of the data source, hence solving the sharing and integration of multi-sourced data.

The approach taken to develop EMO is based on the ontology design and evaluation methodology TOVE defined by Grüninger & Fox [8]. The methodology begins with the documenting of a set of use cases that identify the different users of the ontology and how they would use it. Based on these use cases, a set of Competency Questions, i.e., questions that the ontology must be "competent" to support the answering of, are extracted. Gao et al. specifies eleven use cases and competency questions upon which the design of EMO is based [9]. The use case topics are:

1) Disease Tracing-Epidemiology: The public health department collects case-related information and analyzes

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the source of infection, close contacts, risk areas, etc., and uses tools to predict the development trend of the epidemic and the effect of epidemic prevention measures.

2) Contact Tracing: Citizens can inquire about new confirmed cases in a certain area and whether there are confirmed cases in public transportation they take.

3) Testing: Citizens make an appointment for testing through the system and query the test results online. The public health department can also review the testing results, testing time and vaccination site and find positive patients in time.

4) Infection Prevention for Medical Personnel: Ensure the health of medical personnel who directly contact patients and avoid nosocomial infection. Coordinate and redeploy medical personnel to assist areas with serious epidemic.

5) Vaccination Management: Public health department promotes the vaccine and notifies citizens when they meet the vaccination requirements.

6) Vaccine Efficacy Management: Public health department tracks the vaccinated people and whether they have experienced Adverse Events Following Immunization. This information helps to study the efficacy and side effects of vaccines.

7) Vaccine Distribution Management: Different types of vaccines obtained from multiple sources need to be distributed according to the changes of supply and demand to ensure the balance between supply and demand and reasonable distribution.

8) Transportation Management During Epidemic: During the epidemic, the government may need to control and record public transport and travel, and coordinate and ensure the transportation of emergency supplies and the commuting of medical personnel.

9) Mental Health Management: The mental health of people who feel anxiety, fear or worry due to epidemics should be concerned.

10) Emergency Medical Resource Management: Public health department needs to allocate medical resources during epidemic and monitor bed usage and decide whether to build cabin hospitals.

11) Stakeholder Collaboration/Volunteer Management: Epidemic management and prevention require multi-departmental coordination and sometimes coordination with external stakeholders.

III. Overview of EMO

The specification of EMO will provide precise and unambiguous definitions and representations of epidemic management related data for cross-city service sharing. This necessitates a thorough comprehension of the terms used to describe the data and their relationships. This ensures that data is interpreted and used consistently across software systems that were built separately. Improved data consistency will make it easier to share data among different epidemic management information systems. Ontology is used to construct a common data model, associate essential concepts in the field of epidemic management, fully explore the value of data, achieve efficient data usage, and promote collaboration efficiency, all of which can increase the added value of data. This helps public health authorities make scientific decisions and effectively reduce the difficulty of epidemic control and medical resource coordination. On the other hand, the open publication of epidemic data can also reduce public anxiety and panic about the epidemic.

EMO reuses portions of the ISO/IEC 5087 series of standards for the representation and exchange of city data [10-12]. These standards use Web Ontology Language to offer machine-readable definitions. ISO/IEC 5087 series defines a city data model with three levels of abstraction. Part 1 of 5087 series focuses on general concepts such as Agent and Time as a basis for other levels. Part 2 focuses on city-wide concepts, which includes concepts that can be read and updated by multiple city services such as City, Organization and Contact. Service level spans concepts commonly associated with a particular service but still share with other services. Part 3 focuses on one of the city services: transportation planning.

EMO is composed of eleven concept patterns. Fig.1 depicts the eleven concept patterns and the relations that link them.

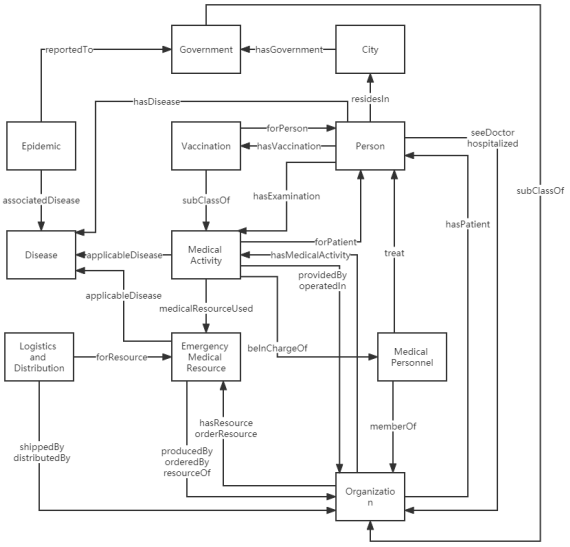

Fig. 1. The patterns of EMO and linking between different patterns (simplified).

A pattern is made up of classes that are related by the topic and interconnected by properties. Epidemic pattern describes infected cases. The type of infectious disease, symptoms corresponding to the case are described in Disease pattern. The case's demographic and epidemiological information are defined in Person pattern. Person pattern is connected to Vaccination pattern when being vaccinated. Vaccination is a subclass of medical activity. Medical activities are usually carried out for a certain disease of a certain person by medical personnel in a medical organization. So Medical activity pattern is directly connected to Person pattern, Disease pattern, Medical personnel pattern and Organization pattern. The Medical personnel pattern defines medical staff who are connected to the Organization pattern due to their working relationship and they treat and are responsible for some patients. Hospital, as a subclass of organization, is place where patients treat diseases and medical personnel carry out medical activities. Since medical resources are consumed in the process of medical activities, these two patterns are also related.

Information about shipment and distribution of medical resources is recorded in Logistics and distribution pattern. As an important kind of organization, the government is defined separately in the Government pattern. Government departments, especially public health departments, are responsible for formulating epidemic prevention measures in epidemic management. City pattern defines the area for epidemic management. Cities are governed by government.

IV. Patterns of EMO

In the remainder of this section, we define eleven patterns in the domain of epidemic management. We first list the competency questions that the pattern is designed to support the answering of, followed by a description of the pattern.

A. Epidemic Pattern

Epidemics are major infectious disease outbreaks. They can occur suddenly and may cause serious damage to public health. Epidemic pattern addresses the following competency questions:

1) What areas experienced clusters/outbreaks during time period p?

2) If the citizen tested positive, what comorbidities do they have?

3) Who were exposed to the citizen x in the location l during time period p?

Epidemic is the core concept of this pattern (Fig.2). Linked to it are the concepts of Case, which identifies the presence of an infectious case at a location and time; Cluster, which represents the presence of two or more cases at same location and time, without a known link; and Outbreak, which denotes two or more cases at the same location and time, with a reasonably established epidemiological link.

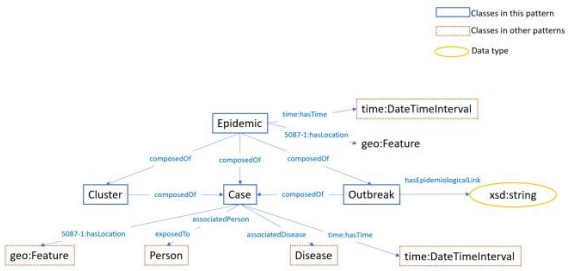

Fig. 2. Core concepts and properties in epidemic pattern.

B. Disease Pattern

Diseases are medical conditions that may have specific signs and symptoms. Infectious diseases are one of the main types of diseases. Disease pattern describes the types and characteristics of infectious diseases, related symptoms and signs, as well as the patient's specific illness record and clinical manifestations. Disease pattern addresses the following competency questions:

1) For a patient y that tested positive, what were their symptoms and when did they appear?

2) What is the common symptom of the affected citizen at time t and location l?

3) What are the possible disease outcomes based on symptom s?

Disease, InfectiousDisease and Symptom are core concepts to describe the specific information about the disease, such as the official name of the disease, common symptoms and period of communicability (Fig.3). DiseaseDescription describes a patient's condition, including the time of infection, the stage and related test, etc.

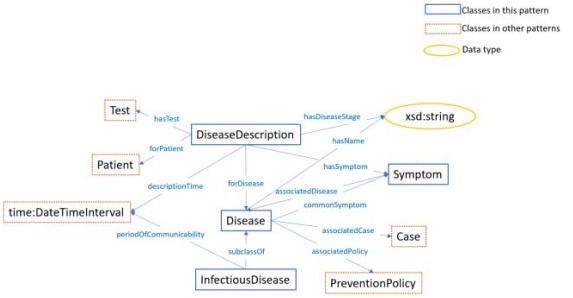

Fig. 3. Core concepts and properties in disease pattern.

C. Person Pattern

A Person may be both a host of a Disease and also a source of infection. It is the decisions and actions that people make that affect the speed and scope of the spread of disease. The Person concept extends ISO/IEC 5087-1:Person to include [11], by identifying the various roles a Person may play in the context of a public health emergency. This pattern addresses the following competency questions:

1) Where has the citizen x been to during time period p?

2) Has the citizen x taken the public vehicle recently? If so, what was the vehicle number, when and where did the citizen x get on and off the vehicle, and where did they sit in the vehicle?

3) Whether these patients with similar symptoms had visited the same place during time period p?

4) What symptoms did citizen x have when confirmed?

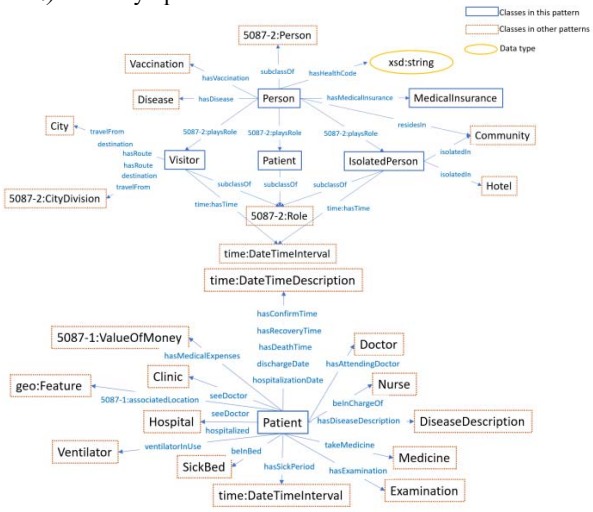

Fig. 4. Core concepts and properties in person pattern.

In Fig.4, Patient, Visitor and IsolatedPerson are roles of Person. Patients are the object of being monitored and being treated. The location, time, medical resources used and medical activities experienced by the patient are defined and represented. Visitors' routes and itineraries are recorded so

that different quarantine policies can be implemented according to the risk level. IsolatedPerson represents people for which additional quarantine conditions apply.

D. Medical Personnel Pattern

Medical activities affect the effectiveness of epidemic management. This pattern addresses the following competency questions:

1) Which medical personnel in the hospital h are temporarily redeployed from other regions?

2) Who is the epidemic prevention worker for location l at time t?

3) Are there any medical personnel currently infected with disease d in the hospital h? If so, how many?

In Fig. 5, MedicalWorker is an occupation that is responsible for helping patients improve their physical and mental health. Doctor, Nurse, Paramedic and Ambulance driver are common medical jobs, but they have different tasks. Some staff are not medical personnel, but participate in epidemic prevention, such as disinfecting public places. They are collectively referred to as EpidemicPreventionWorker. OnDuty and ScheduledOnDuty are concepts used to describe the start and end time of the medical personnel on duty.

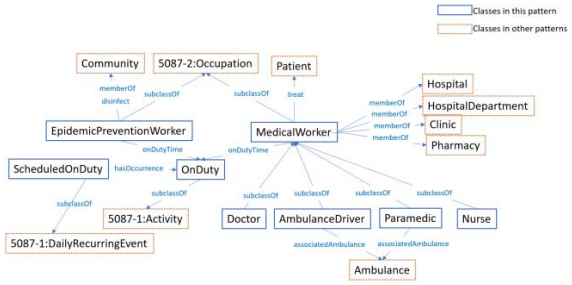

Fig. 5. Core concepts and properties in medical personnel pattern.

E. Emergency Medical Resource Pattern

Medical resources often capture the important preconditions and effects of the medical activity. Distribution and use of medical resources affect medical treatment and prevention behaviour. This pattern addresses the following competency questions:

1) What is the available hospital capacity in area a at time t of acute care beds, ICU beds, Ventilators, etc.?

2) What types and number of medical resources does the hospital h lack at time t?

3) What is the inventory of resource x at distribution centre y?

4) How many medical resources of type e are consumed on average in a day during time period p at location l?

When an epidemic occurs, medical resources such as vaccines and testing reagents are often in high demand (Fig.6). Scarce medical resources should be allocated reasonably to ensure that people can use them fairly. Bed usage also needs to be monitored dynamically to ensure that it does not exceed the hospital's capacity. Ambulances are needed to transport patients when there is an epidemic happens or when people make emergency calls. Medical resources are usually generated by manufacturers and owned and used by medical organizations. And LivingResource has been added to represent that patients, medical personnel, isolated people and others also need some necessary living resources.

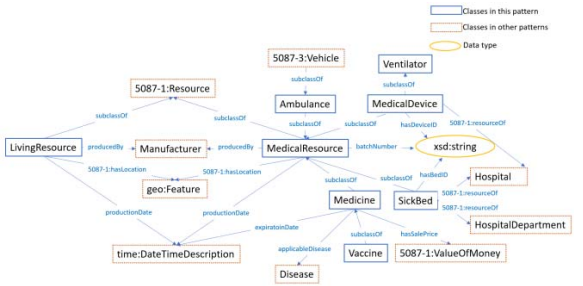

Fig. 6. Core concepts and properties in emergency medical resource pattern.

F. Medical Activity Pattern

A medical activity brings together medical resources at some location at some time to achieve some outcome. Medical activities span prevention, diagnosis, treatment, and recovery. Medical activities also include services for the sale of medical items such as medicines. This pattern addresses the following competency questions:

1) Which hospitals provide testing for the disease d in the area a at time t?

2) Where, when and what was the result of citizen x's last epidemic test for disease d?

3) When can a citizen make an appointment for testing of disease d at hospital h?

4) What was the reason for obtaining test for disease d of citizen x?

In Fig.7, Medical activity is carried out by medical personnel, often occur in medical organizations, and consumes medical resources. Patients who are being treated receive some physical examinations to help doctors better understand the patient's current health status and symptoms. Infection may cause pathological changes in other parts of the body or organs of the patient. This may require doctors and experts from different departments or fields to make a Consultation for the patients. When people feel unwell, they can make an appointment with a doctor for examination. Information of transporting the patient is recorded in AmbulancePickup. Test has been introduced to help describe information of each test. People who take the test care about their results and medical organizations also care if they detect infected patients.

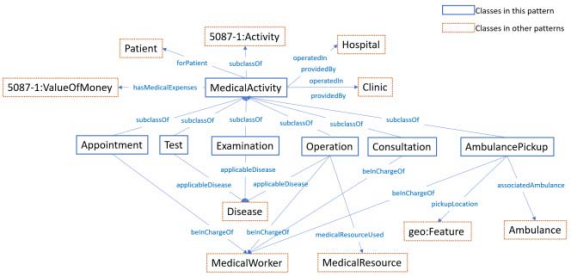

Fig. 7. Core concepts and properties in medical activity pattern.

G. Vaccination Pattern

Vaccine is an important medical resource to prevent and

control the occurrence of the infectious disease in epidemic management. Class Vaccine has been defined in medical resource pattern. Popularizing the vaccination helps to reduce the reproduction number of the population and restore normal social order and economic activities more quickly. Vaccination pattern addresses the following competency questions:

1) Where has the citizen x been vaccinated against the disease d, and how many doses have they received?

2) How many people in area a have received the nth dose of vaccine for disease d at time t?

3) How many people in age range r have received the nth does of vaccine for disease d at time t?

4) Which hospitals provide vaccination for the disease d in area a at time t?

In Fig.8, Vaccination is commonly used in the vaccination management and vaccine efficacy management use cases. VaccineAvailable is a subclass of 5087-1:Resource that indicates when and where the vaccine will be available [8]. People can make an appointment to be vaccinated. Each person may need more than one dose to be fully vaccinated hence the concepts of Dose and Vial have been added to capture these characteristics.

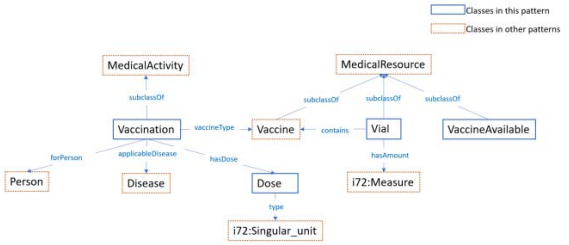

Fig. 8. Core concepts and properties in vaccination pattern.

H. Logistics and Distribution Pattern

Resources managed in logistics and distribution may include tangible goods such as medical materials, equipment, and supplies, as well as food and other living resources. Under the special background of severe epidemic, shortage of medical resources and supplies is common. This pattern addresses the following competency questions:

1) What are the planned shipments of vaccine x that are to be received from manufacturer m during time period t?

2) What is the inventory of vaccine x at location y?

3) What is the planned allocation of vaccine x for location y during time period t?

4) How many vials/doses of vaccine x were delivered to location y during time period t?

In Fig.9, Public health department needs to work with logistics providers to ensure timely delivery of resources. LogisticsProvider is also responsible for individual requirements for shipping items. DistributionSpecification describes the distribution records of supplies, including by whom, to whom, when the distribution plan was generated, etc. ShipSpecification focuses on the transportation records of resources, including transportation address, time, etc. Information when the supplies and resources are produced is described by ProductionSpecification. Some medical organizations order medical resources from the manufacturer for further use or resale. OrderSpecification helps to describe such activities. Resale is recorded in SaleSpecification class.

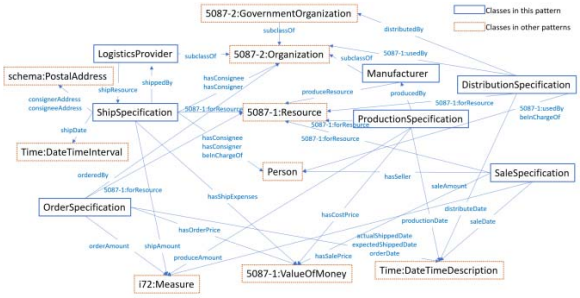

Fig. 9. Core concepts and properties in logistics and distribution pattern.

I. City Pattern

5087-2 city pattern is extended to represent the role of administrative or functional areas in epidemic management [11]. City pattern addresses the following competency questions:

1) How many cumulative confirmed cases of the disease d are there in the area a at time t?

2) How many cumulative deaths of the disease d are there in the area a during time period p?

3) What are the current medium-risk districts in the city c?

4) Which day had the most confirmed new cases of the disease d during time period p in the area a?

For epidemic-related use cases, City pattern is foundational (Fig.10). City, District and Community are used to describe spatial and location information of a patient, a close contact person, a vehicle, a medical organization, etc. The lockdown state of a city or district has an impact on transportation management use case. Two properties hasRiskLevel and hasCaseReport have been added to indicate infected cases and corresponding risk level in a district.

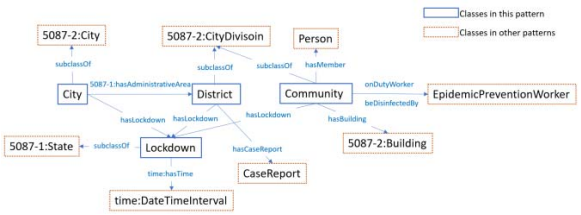

Fig. 10. Core concepts and properties in city pattern.

J. Government Pattern

Government is a decision-maker and promulgator of policies and measures in epidemic management. Different levels of administrative regions have corresponding levels of governments. They need to make objective judgments on the overall situation of epidemics, deploy prevention and control measures, coordinate medical resources and equipment and prevent the spread of the epidemic. The government releases authoritative and real data to people to help them protect themselves. Government pattern addresses the following competency questions:

1) Does the citizen x require referral to public health department for contact tracing?

2) Whether the average number of daily infections in a time period p bounced back after the cessation of the policy z?

3) What is the status of subsidies received by enterprises or individuals affected by the epidemic?

In Fig. 11, PublicHealthDepartment focuses on the evolution of the epidemic, tracking of cases, vaccinations and its efficacy, effect of prevention measures, management of medical personnel and allocation of medical resources. Hospitals report confirmed cases to the public health department. When tracking close contacts and restricting traffic, the transportation department provides necessary assistance. The department of finance will give subsidies for organizations or individuals affected by the epidemic.

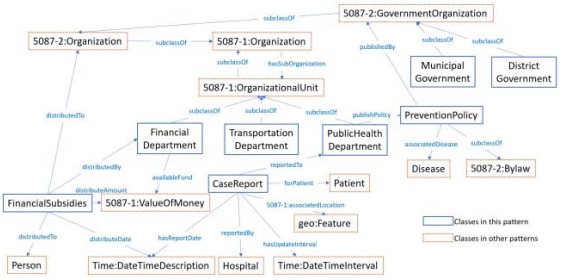

Fig. 11. Core concepts and properties in government pattern.

K. Organization Pattern

Medical organizations are the most important type of organizations in the epidemic management system. Medical organization describes institutions that provide medical services, use medical resources, manage medical personnel, prevent and control epidemic and carry out medical treatment. Organization pattern addresses the following competency questions:

1) How many hospitals are there in the city? And what are they?

2) How many vaccination sites are there in the city?

3) What is the address of a certain hospital?

4) Which pharmacies can citizen buy a certain medical supply such as masks at?

In Fig. 12, Hospitals provides basic medical services such as pre-examination and treatment. HospitalDepartment specializes in treating different types of diseases. Clinic is also a main undertaker of medical activities. Pharmacy is responsible for provisioning medical supplies and resources. Laboratory is the organization to analyze and test the sample and specimen. TestingSite and VaccinationSite may be stationary or mobile. Hotel is also a type of organization that can be used to isolated visitors.

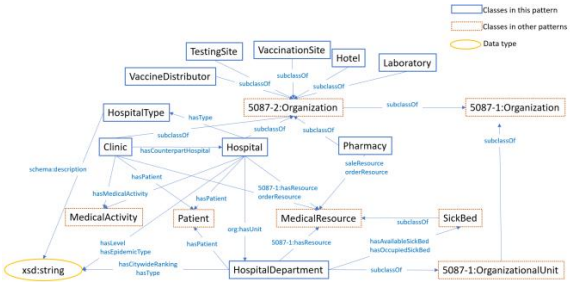

Fig. 12. Core concepts and properties in organization pattern.

V. Evaluation

We define eleven use cases and corresponding competency questions for epidemic management in a technical report. The use cases are drawn from different stakeholders such as public health department and medical organizations and help to evaluate an epidemic management ontology.

In this section we evaluate EMO to verify its ability to represent competency questions in SPARQL based on the evaluation process in TOVE method. The data used to instantiate the EMO ontology and verify its capabilities are test data adapted from some real data in City of Jinan. Due to privacy concerns, most epidemic information has not been made public. Therefore, most of the data instances are based on our understanding of epidemic information rather than city public data. Instances are stored in the graph database.

The following shows how some of the competency questions for Disease tracing and Contact tracing use cases can be answered with SPARQL. The evaluation result proves that EMO is adequate for describing city data relevant to epidemic management.

1) How many districts are there in a city: measures the representation of the administrative area in a city. We answer this for a specific city Jinan. It will return the number of districts in Jinan.

```
SELECT  count(?district)
WHERE {
?city 5087-1: hasAdministrativeArea ?district.
?city schema:legalName ?name.
FILTER(?name=”Jinan”)}
```

2) What are the current medium-risk districts in a city: measures the representation of risk level of administrative areas in a city. We answer this for a specific city Jinan. It will return instances of districts with medium-risk.

```
SELECT  ?district
WHERE {
?city 5087-1: hasAdministrativeArea ?district.
?city schema:legalName ?name.
?city 5087-1: hasAdministrativeArea ?district.
?district emo:hasRiskLevel ?rl.
FILTER (?rl="medium" &&  ?name=”Jinan”)}
```

3) How many designated hospitals are there in the city? And what are they: measures the representation of hospitals and their types. We answer this for a specific city Jinan. It will return instances of designated hospital.

```
SELECT ?hospital
WHERE {
?city schema:legalName ?name.
?city emo:hasOrganization ?hospital.
?hospital emo:hasPatient ?patient.
?hospital emo:hasType ?type.
```

FILTER(?name=”Jinan” && ?type=”designated”)}

4) What symptoms did citizen x have when confirmed: measures the representation of symptoms of a patient We answer this for a specific patient YingWu. It will return her symptoms when confirmed.

```
SELECT ?symptom
WHERE {
?person schema:givenName ?gname.
?person schema:familyName ?fname.
?person 5087-2:playsRole ?patient.
?patient emo:hasConfirmTime ?time.
?patient emo:hasDiseaseDescription ?disdescrip.
?disdescrip emo:forDisease emo:Covid-19.
?disdescrip emo:descriptionTime ?time.
?disdesctip emo:hasSymptom ?symptom.
FILTER (?gname="Ying" && ?fname=”Wu”)}
```

5) How many ECMOs are distributed to a certain hospital in a certain date: measures the representation of distribution of medical resources. We answer this for a specific hospital, Shandong Provincial Chest Hospital and a specific date, February 8, 2020. It will return the amount of ECMO to be distributed to this hospital.

```
SELECT ?amount
WHERE {
?distrispec emo:distributeContent emo:ECMO.
?distrispec emo:distributeDate ?time.
?distrispec 5087-1used:By ?hospital.
?hospital 5087-1:hasName ?name
FILTER (?time>="2020-02-08T00:00:00"^^xsd:dateTime && ?time<="2020-02-08T23:59:59"^^xsd:dateTime && ?name=” Shandong Provincial Chest Hospital”).}
```

6) Currently, what is the COVID-19 infection rate (number of confirmed cases /population size) in a district of a city: measures the representation of both confirmed cases and population size of a city and their calculations. We answer this for a specific city Jinan and a specific district LixiaDistrict. It will return a number to represent current infection rate of a district.

```
SELECT ((count(distinct ?patient))/MIN(?population))
WHERE {
?city schema:legalName ?cname.
?district 5087-1:hasName ?dname.
?district 5087-1: administrativeAreaOf ?city.
?district 5087-1:hasPopulationSize ?ps.
?ps iso21972:numerical_value ?population.
 {SELECT ?patient
 WHERE {
?person 5087-1:playsRole ?patient.
?patient emo:hasDiseaseDescription ?disdescrip.
?disdescrip emo:forDisease emo:Covid-19.
?patient 5087-1:associatedLocation emo:LixiaDistrict.
?patient emo:hasConfirmTime ?time.
FILTER(?time<=NOW())  }}
FILTER(?cname=”Jinan” && ?dname=” Lixia District”) }
```

VI. Conclusion

Based on the ISO/IEC 5087 series of standards, this work constructs an urban epidemic management ontology EMO using the ontology construction tool protégé and the TOVE method. The data from City of Jinan are adapted and used to validate the ontology. Ontologies and instances are stored in the graph database. Competency questions are expressed and answered using SPARQL language to verify the information retrieval and definition capabilities of the ontology. Finally, EMO makes up for some missing but important concepts in the existing epidemic management related ontologies, and improves the coverage of concepts in the domain of epidemic management. This is conducive to the standardization, sharing and integration of epidemic management data, and improves the efficiency of epidemic data use.

Acknowledgment

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