An Ontology-based Approach to Modelling Spatial Interdependency of Critical Infrastructure

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Abstract

Critical infrastructures are providing flows of services, the disruption of which are seriously affecting society's functioning and well-being. There is an emerging trend of interdependencies within and between infrastructure systems becoming more coupled, making them prone to 'domino effects'. While interdependencies within an infrastructure system may be represented as flows of networks, the representation of interdependencies between systems has been a challenge. Until now, most of the existing works have not modelled spatial interdependencies. This project aims to clearly define spatial interdependencies of critical infrastructures or systems and build the framework for knowledge of infrastructures and their interdependencies. Based on this framework, a tool will be developed to represent interdependencies of different systems. Once a formal consistent representation exists, ontology-driven information systems (ODIS) provide interfaces to answer what-if questions (query languages), to automate or semi-automate inferential reasoning. This ODIS can be used to connect to the existing geospatial database and support different applications (e.g. urban planning, spatial analysis).

Keywords and phrases Ontology, Spatial interdependency, Infrastructure

1 Introduction

Critical infrastructures (CIs) constitute a technological skeleton of our society by producing and distributing the basic necessities for human beings, such as water, food, energy, transportation, communication, etc. CIs are not standalone but interdependent at multiple levels to enhance the overall performance of the society and the well-being of human beings.

Recent worldwide events such as the Hurricane Sandy in North-eastern US and the Kaohsiung gas explosions have highlighted that interdependencies among CIs made the system vulnerable to cascading failures, thus amplifying the impact of the initial failures into catastrophic proportions. Furthermore, urbanization has increased the complexity of the CIs as well as the interdependencies among the systems, which again emphasizes the need for reaching an evolving understanding of the interdependencies among CIs. Over the last decade, interdependencies of different forms have been identified and categorized [6]. Based on their manner of affecting the system, the interdependencies can be further classified into two types:

- Flow interdependencies, where two systems are interconnected through material and/or information flows (SCHDA systems), such as power or control information;
- Non-flow interdependencies include spatial interdependencies that reflect geographic relationship among different systems, and logical interdependencies represent the relationship of two systems without any direct flow or geographic connection. Figure 1 shows the spatial interdependency among different systems in Jurong Island of Singapore. A bunch of pipes, which may belong to different industrial sections and is carrying different types of chemicals, are geographically in close proximity to each other. A failure of one, for

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example, a leakage on one of the pipes that transports explosive or corrosive chemical, may lead to cascade failure to the others, as it is very likely that an explosion to one of the pipes will damage all the other adjacent pipes.

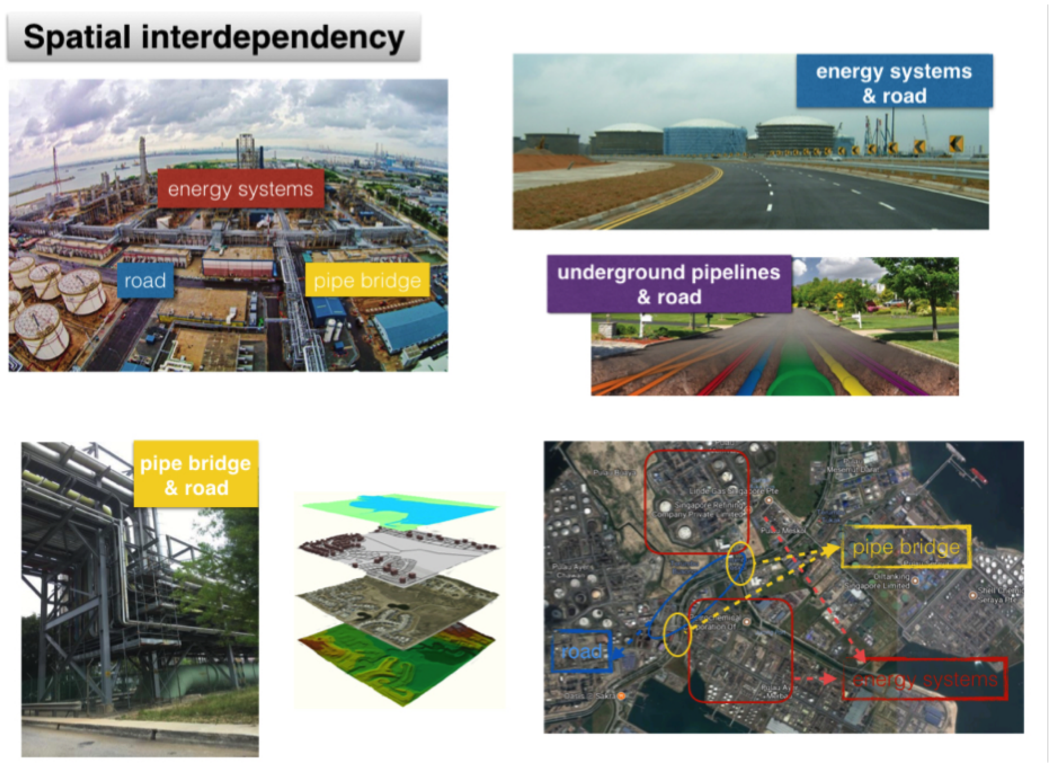


Figure 1 An example of spatial interdependency.

For the past decade, substantial research was carried out, investigating the interdependencies among CIs, mainly focusing on the flow interdependencies. Complex network theory is widely used to capture or analyse failure in the CIs networks through their flow interdependencies [2, 5]. For spatial interdependencies, dedicated studies started in 2014, limited work [1, 3] can be found in the literature, though it is also of great importance to the system analysis. A comprehensive understanding of infrastructure interdependencies for both flow and non-flow correlations at both local and regional scales is a necessary first step towards better preparedness and more effective loss mitigation measures. However, limited work can be found on this subject, especially about the non-flow interdependencies.

Overall, there are two main gaps in the study of interdependencies, (1) the lack of models for non-flow interdependencies, especially spatial and logical interdependencies, (2) the lack of a comprehensive framework to model and simulate all types of interdependencies. The objective of this project is to develop a framework to model and present spatial interdependencies of the CIs. Taking up more challenges, this project has three main sub-objectives:

- A knowledge-based framework for spatial interdependency of CIs should be developed to integrate the knowledge for interdependency representation and data mining in the applications;
- This work needs to connect the existing geospatial database to the knowledge-based framework;

- A knowledge-based application platform aims to provide query and visualization service for users.

2 Ontology-based modelling for spatial interdependency

An ontology-based approach allows computing systems and machines to understand concepts and domains through a common vocabulary that represents the relationships between those concepts. Ontologies not only reflects the understanding of the target world like the human mind, but also can connect data in various concept levels and provide knowledge to analyse big data. Hence, this work is an initial step to understand spatial interdependency of infrastructures. Following Fonseca's five universe paradigm [4], this framework organize ontologies in logical and representation universe (Figure 2). The logical universe is concerned with describing specific subjects and tasks. The subject ontology aims to describe the vocabulary related to CI, includes geographic area ontology defines attributes and subclasses to describe the geographic objects (e.g. point, line and polygon) and critical infrastructure ontology defines attributes and relationships of CI components. The representation universe provides a method ontology to describe the characteristics of interdependency. This work only focuses on the definition of spatial interdependency. This model can be improved to integrate the various interdependencies.

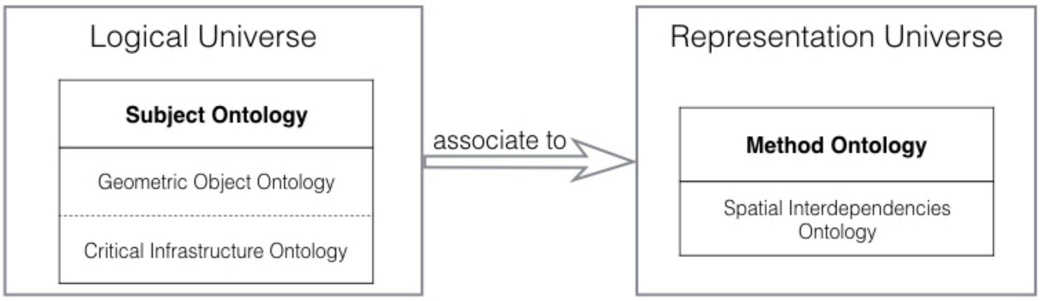


Figure 2 The framework of ontologies for spatial interdependency of CIs.

Most of the existing works pay more attention to the flow interdependency and ignore the importance of spatial interdependency in the complex cities. Hence, this work focuses on the spatial interdependency at the beginning. It aims to define the different types of spatial interdependency that will be implemented with critical infrastructure ontology for presentation. The spatial interdependency includes five types: cross, contain, overlay, touch and intersect (Figure 3). The spatial relations are used to define spatial interdependency.

- Intersect: it tests whether the interiors of the geometries intersect. If the two objects have any space in common, they have intersect interdependency.
- Touch: it tests whether two objects touch at their boundaries, but do not intersect in their interiors
- Overlay: if one object lies in the interior of the other object their, these two objects are overlaying.
- Contain: Object A contains object B if and only if no points of B lie in the exterior of A, and at least one point of the interior of B lies in the interior of A. An important subtlety of this definition is that A does not contain its boundary, but A does contain itself.
- Cross: two objects cross if the supplied objects have some, but not all, interior points in common.

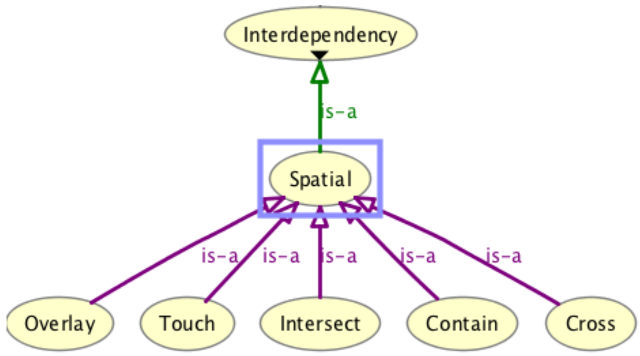


Figure 3 Spatial interdependency ontology.

The critical infrastructure ontology aims to describe the attributes and relationships of CIs. Each CI has specific function and phenomena. Hence, each CI component is a stand-alone system as a subclass in the *CI_components* class. Each CI component can be a separate domain ontology to organize the properties and behaviours. Figure 4 shows the hierarchy of transportation and power grid in the critical infrastructure ontology as the example. The concept "transportation" includes two subclasses, transport types and transport objects. Five types of the public transportation system are defined in the type class, like the bus is a type of public transportation system. The transport object class is elements of the public transportation system. The *hasObjects* relationship is defined to connect *T_Type* and *T_Objects*. For instance, the bus *hasObject* the station. Moreover, the association of different CI components should be defined to organize the interdependencies on the cross-domain in the further step.

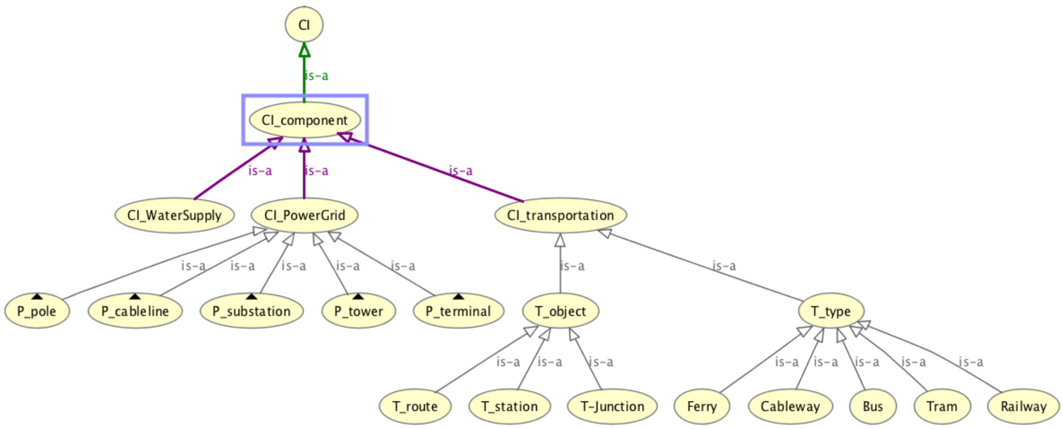
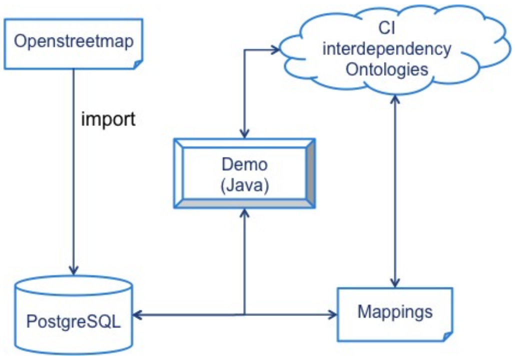


Figure 4 Critical infrastructure ontology.

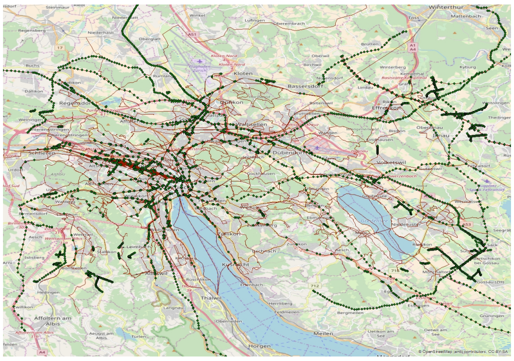
Geometric object ontology describes the geographic information of critical infrastructures. Spatial data is used to represent geographic characteristics of CIs from logical universe to representation universe. Hence, the definition of geometric object ontology begins at the basic attributes of spatial data. The dataset has attributes as the coordinate system, data type, time and so on. The geometric object ontology has three subclasses, point, line and polygon. On the one hand, geometric object ontology connects to the critical infrastructural ontology to describe geometric characteristics of infrastructures. On the other hand, geometric object ontology plays an important role to connect the ontology-based model and the geospatial database. Each object of the geospatial database is an instance of the geometric object ontology.

3 Implementation

The implementation of ontology-based modeling includes three main parts, CI spatial interdependency ontology, spatial database, and application platform (Figure 5a). This work uses the points and lines of Openstreetmap data as data source 5b, which includes information about type of objects (e.g. gas and pipeline) and geospatial information. Zurich is study area in this case study. This work uses geospatial information of Openstreetmap to computer spatial relationship of objects and identify spatial interdependency according to the definition in the CI interdependency ontology. In order to use Openstreetmap data, OSM file is imported to the PostgreSQL database in three tables, includes points, lines and polygons, which are based on the format of Openstreetmap data.



(a) The system structure.



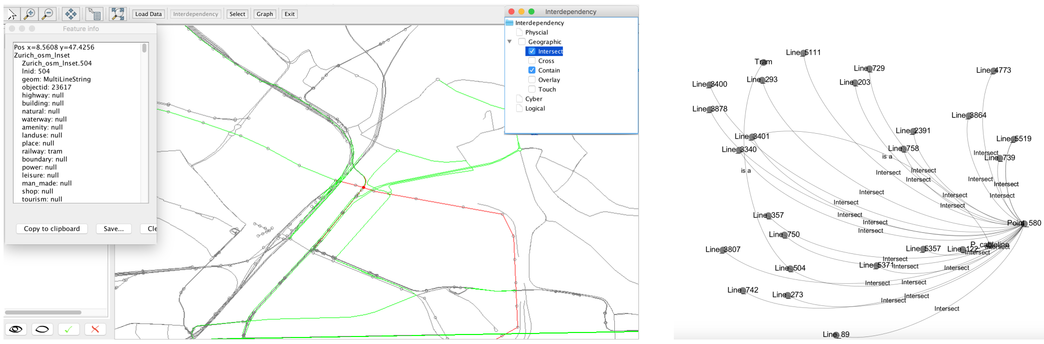
(b) The original data source from Openstreetmap.

Figure 5 System design.

In the case study, the geospatial data of Zurich is imported from PostgreSQL and visualised in the application platform. Figure 6a shows a screenshot of the application platform. The platform provides some basic function of data browser, such as details of geospatial data, zoom in and zoom out. The interdependency window shows the interdependency tree that is extracted information from the CI interdependency ontology. The users can check one or several types of interdependencies at the same time. The selected objects are red in the map, their interdependent objects are green, and the other objects without interdependencies are grey. The graph is generated to display the relationship of selected objects and their interdependent objects. Through the example in the Figure 6b, we can find the selected objects are tram and cable line. And their interdependent objects are displayed in the graph.

4 Conclusion and further work

This work developed a framework to the model spatial interdependency of critical infrastructure. This is a process to transform knowledge from human cognition to computer language. This framework of ontologies does not only provide a model to integrate knowledge of CIs, but also include spatial information. Moreover, the separating ontologies are reusable in different applications. This is only an initial design of ontologies for the research on the CIs



(a) The visualisation of spatial interdependency.

(b) The graph of spatial interdependency.

Figure 6 Demo

interdependencies. The physical, logical and cyber interdependencies should be integrate with spatial interdependency to provide a comprehensive description of interdependency. The application platform should be improved as the web service. The reasoning mechanism of the ontology should be developed to build the interdependencies of different CI components.

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