Preprint Cambridge Centre for Computational Chemical Engineering ISSN 1473 – 4273

An ontology framework for information modeling and management of eco-industrial parks

Li Zhou [2], Chuan Zhang [4], Iftekhar A. Karimi [2], Markus Kraft [1,3]

released: 25 September 2017

[1] Department of Chemical Engineering and Biotechnology
University of Cambridge
West Site, Philippa Fawcett Drive
Cambridge, CB3 0AS
United Kingdom
E-mail: mk306@cam.ac.uk

[2] Department of Chemical and Biomolecular Engineering
National University of Singapore
4 Engineering Drive 4
Singapore 117585

[3] School of Chemical and Biological Engineering
Nanyang Technological University
62 Nanyang Drive
Singapore 637459

[4] School of Mechanical and Aerospace Engineering
Nanyang Technological University
50 Nanyang Avenue
Singapore 639798

Preprint No. 189

Keywords: eco-industrial park, knowledge base, ontology

Edited by
Computational Modelling Group
Department of Chemical Engineering and Biotechnology
University of Cambridge
West Site, Philippa Fawcett Drive
Cambridge, CB3 0AS
United Kingdom

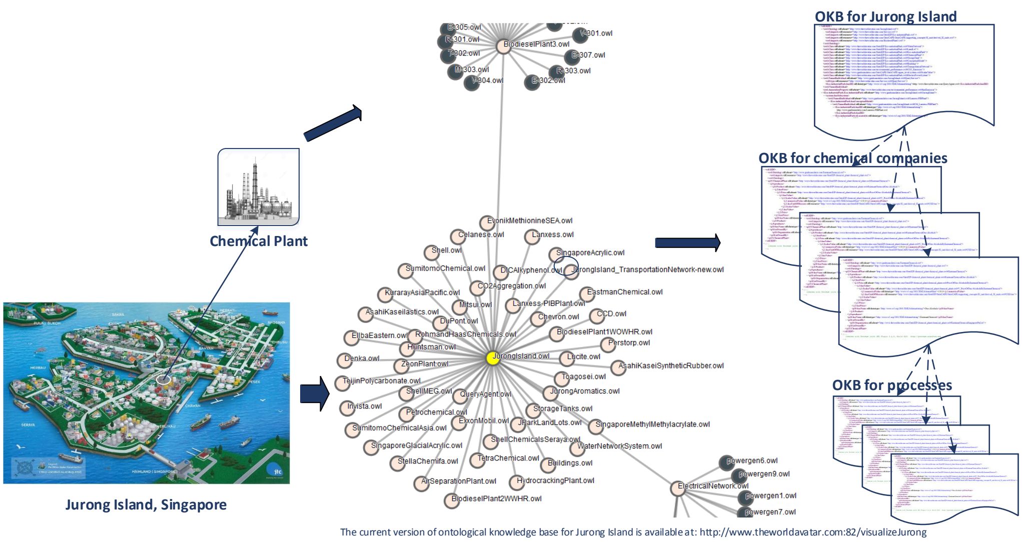
Fax: + 44 (0)1223 334796
E-Mail: c4e@cam.ac.uk
World Wide Web: `http://como.ceb.cam.ac.uk/`

Highlights

- A skeletal ontology is proposed for eco-industrial parks;
- The ontology is used to create an ontological knowledge base for Jurong Island in Singapore;
- A decentralized information management system is established;

Abstract

In this paper, we develop a skeletal ontology for eco-industrial parks. A top-down conceptual framework including five operating levels (unit operations, processes, plants, industrial resource networks and eco-industrial parks) is employed to guide the design of the ontology structure. The detailed ontological representation of each level is realized through adapting and extending OntoCAPE, an ontology of the chemical engineering domain. Based on the proposed ontology, a framework for distributed information management is proposed for eco-industrial parks. As an example, this ontology is used to create a knowledge base for Jurong Island, an industrial park in Singapore. Its potential use in supporting process modeling and optimization are also discussed in the paper.



Contents

1 Introduction

An eco-industrial park (EIP) is a cluster of businesses in a close proximity collaborate with each other and the local community to efficiently share resources and reduce waste and pollution. Setting up EIPs is an effective way towards environmental preservation and resource conservation, which are two of the great challenges that the world is facing today. Numerous research works have been carried out in the past decades, and a number of mathematical programming methodologies have been proposed for the design and optimization of EIPs. Thorough review works can be found in literatures [12, 24]. Currently, the reported optimization approaches are mainly dedicated to the optimal design of single styled networks, such as water network integration [30, 31, 41], energy network synthesis [9, 38, 44], and material network integration [15, 21, 40]. Symbiosis relation exists not only within single-styled resource networks, but also among different types of networks and even cross domain boundaries. In order to reach an optimum symbiotic relation among industries, all resources need to be taken into consideration simultaneously. Also, variability of resource supplies should be addressed in more realistic models because of the inherent uncertainties. A substantial amount of supporting information which covers not only data, but also specific knowledge about the EIP members is required in order to understand the complexity of these issues. Given that an EIP consists of a large amount of interacting industries and organizations, the required supporting information has the following features:

1) Big volume: with the successful implementation of sensors, the data generated by the represented entities is ever-growing. These data need to be stored and analyzed in order to recognize patterns, trends as well as system behavior;

2) Distributed storage: knowledge about the individual EIP member is stored and maintained locally. These information needs to be collected and shared among the relevant organizations;

3) Syntax heterogeneity. Engineering knowledge, whether general domain knowledge or specific evolving knowledge, is usually represented and stored in a diversity of information media, which includes not only text documents in natural language, but also mathematical models, tables and diagrams, structured worksheets, linked text files, and so on. Information of different format needs to be integrated in order to capture different facets of a system;

4) Semantic heterogeneity. Typically, knowledge about the specific engineering design processes is known implicitly to the participating designers, not to mention that the domain knowledge is even more specific and usually segregated into 'domain silos'. Consensual knowledge representation is needed to facilitate the communication across disciplinary boundaries and to create joint understanding and meaning.

Accompanying the aforementioned challenges are the opportunities brought by the ongoing trend of Industry 4.0 and Internet of Things (IoT) [46]. In the future scenario of Industry 4.0, a global network will be built to connect the machinery, factories, and warehousing facilities of industrial businesses as Cyber-Physical Systems (CPS). These CPS will facilitate the connection and control of the technical components intelligently by sharing information that trigger actions. The CPS will take the form of smart machines, smart factories, smart supply chains, smart storage facilities, smart grids and many more. The future scenario of Industry 4.0 is shown in Fig. 1. It can be seen that the prerequisite of realizing Industry 4.0 is to create a virtual representation of the physical world and to establish a communication framework among the dependent entities.

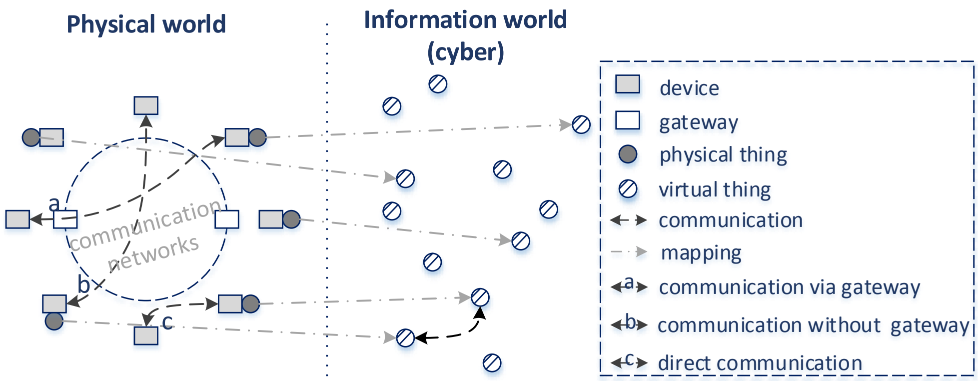


Figure 1: *Technical overview of the IoT. [23]*

In this context, we present a formal representation of different concepts capturing the EIP features. Such formal representation is achieved with the help of ontology. A skeletal ontology is built by adapting and extending OntoCAPE, an ontology for the chemical engineering domain [33]. It is constructed based on a conceptualization framework including five operational levels (unit operations, processes, plants, industrial networks, and eco-industrial parks). The ontology is made up of several parts including *eco_industrial_park*, *resource_network*, *transportation_network*, *electrical_power_system*, and *plant*, as well as a few other modules adapted from OntoCAPE's modules, namely, *chemical_process_system* and *unit_operation*. The potential application of such ontological representation in EIP information management is also discussed in this paper.

The remaining parts of this paper is organized as follows. Section 2 gives a concise literature review about the existing works regarding to the ontology development for engineering domains. Section 3 introduces a hierarchical modeling scheme for the information representation of EIP system. Section 4 presents the proposed ontology for EIP. Section 5 presents the establishment of a decentralized information management system by applying the proposed ontology, followed by conclusions in Section 6.

2 Ontology engineering and ontologies in engineering domain: existing works

Ontology engineering is an advanced technique for computer-based information modeling and management, which aims to conceptualize the physical world in a formal and explicit manner [20]. The term "formal" refers to the fact that the knowledge encoded can be readily processed by machines, while the term "explicit" implies that the type of concepts used, and the constraints on their use are explicitly defined; that imposes common agreement on the preciseness of semantics ensuring data and information sharing. In other words, an ontology provides a backbone for knowledge systematization. In the past decade, ontology engineering has evolved into a scientific field of its own with applications in knowledge representation, information integration and so on [33].

According to the "subject of conceptualization", ontologies can be classified into several categories, including top-level ontologies, domain ontologies, task ontologies and application ontologies [18]. Top-level ontologies define general-purpose concepts that are independent of any particular domain or problem. A domain ontology captures the general knowledge of a domain of expertise, which is relevant to a wide range of tasks and applications. Therefore, it is universally applicable (highly reusable) within the respective domain. A task ontology (or method ontology) reflects general problem-solving methods that are applicable in different domains of expertise. It can be seen that the re-usability of domain ontology and task ontology has complementary objectives. An application ontology provides the required concepts for a particular application.

A set of ontology languages have been created in order to implement ontologies in a computer-processable form. Among which, web-based ontology languages (also known as ontology markup languages) are the most recent. It is intended for publishing and sharing ontologies in the World Wide Web. web-based ontology languages are based on the existing markup languages: XML (eXtensible Markup Language) and RDF (Resource Description Format). XML is specially designed to store and transport data with the contextual information tagged. RDF is a scheme developed based on XML syntax. It encodes semantics in sets of triples (subject-predicate-object), and uses IRI (Internationalized Resource Identifier) to specify information resources. A sample code of RDF is shown in Fig. 2.

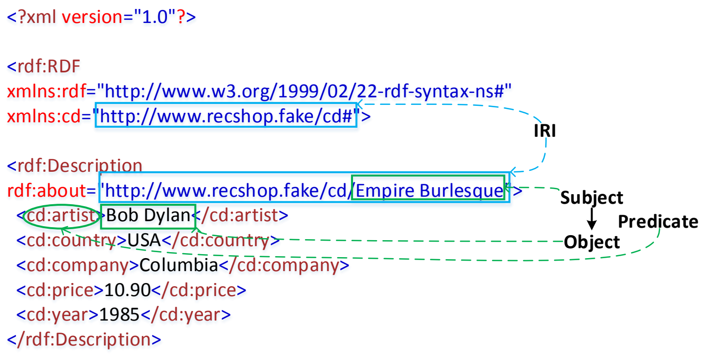


Figure 2: *Encoding information of a CD named Empire Burlesque in triples (Subject-Predicate-Object) and identifying the resources with Internationalized Resource Identifiers (IRIs). (the original code is taken from W3 schools [1])*

Ontology technology has received great attention in the past decade as an advanced knowledge modeling and information management technique [16]. Numerous works have been reported for the development of ontology, especially in engineering domains.

Domain ontologies for chemical industry

Mizoguchi et al. [35, 36] developed a Plant Ontology, which contains two sub-ontologies, Domain Ontology and Task Ontology. The Domain Ontology models plant entities with unchanging characteristics and appearances, such as plant equipments, materials, and properties of materials, while the Task Ontology comprises of description for the plant components whose properties are context-dependent. Subsequently, a Functional Ontology [25] was developed as a complementary ontology to the Plant Ontology. The Functional Ontology describes engineering constituents from different perspective of views (structural, functional, behavioral) and defines relations between the decomposed aspects. The combination of these two ontologies enables the modeling of equipments, materials and operating activities in industrial plants as well as their functions. Batres et al.[10, 11] developed an ontological framework, referred to as multi-dimensional formalism (MDF), which specifies formal descriptions of knowledge about plants, processes and products. MDF is an assemble of several interconnected sub-ontologies that arrange information, activities and tools of the plant, process and product from the perspective of structure, behaviour and operation.

Subsequently, a large-scale ontology called OntoCAPE was developed for chemical process engineering [33, 37], taking into consideration the major engineering activities in this domain (the design, construction, and operations of chemical plants). It covers conceptualization for most of the processes of engineering activities during the life cycle. Among the reported ontologies for chemical process engineering domain, OntoCAPE is currently the most (re)usable ontology available to support software development. It has been field-tested in a number of software projects [13, 43].

Domain ontologies for electrical power system

Kucuk et al. [29] presented an ontology for electrical power quality (PQ) data, called PQONT, which provides a shared vocabulary for system problem detection of governmental and industrial institutions. It was utilized to support a multilingual natural language based interface that allows flexible querying of the PQ data. Another domain ontology for wind energy (WONT) was also reported and a semi-automatic process was proposed to construct the ontology by making use of the existing Web resources [28]. Later on, these two ontologies were extended with weighted attributes, and a high-level domain ontology for electrical energy was built [27].

Domain ontologies for transportation system

Lorenz et al. [32] published an ontology for transportation systems. A public transportation ontology dedicated for user travel planning was also reported [22]. Recently, a domain ontology for intelligent transportation systems was represented [19], which served as a basis of semantic information to a semantic service that allows easy extension.

In spite of many ontological frameworks reported for certain engineering domains and applications, the ontology-based representation and applications for large-scale EIPs has never been achieved before. Although the existing engineering ontologies cover quite a lot of the engineering activities in an EIP, they cannot be directly reused to represent the system as they vary in respect to their internal structures. A consistent and comprehensive ontology framework need to be built to capture and integrate the individual knowledge items emerging in the engineering projects of different domains. However, it has to be underlined that such ontology development is never a one-off job due to the following reasons: a) knowledge can always be approached from different perspectives depending on different applications, leading to different ontology structures; b) human being's cognition of the world keeps evolving. As a consequence, the ontology shall keep evolving as well. In this sense, the proposed ontology in this paper is not intended as a final framework. On the contrary, we treat it as a preliminary trial for such ontological innovations in EIP information management. Moreover, in this work, we are mainly concerned with the the chemical engineering activity related information. Thus, the proposed ontology is mainly focusing on chemical engineering concepts. The detailed structure of such ontology framework will be discussed in Section 3 and Section 4.

3 Hierarchical framework for information modelling of EIP

This section introduces a conceptual framework to guide the EIP information modeling. A conceptual framework is yet another level of abstraction of ontology. It describes the perspective based on which the ontology is constructed, the content of the ontology, as well as the links between the ontology modules. The conceptual framework is shown in Fig. 3. It provides a way to organize the entities in the EIP [39, 45, 47].

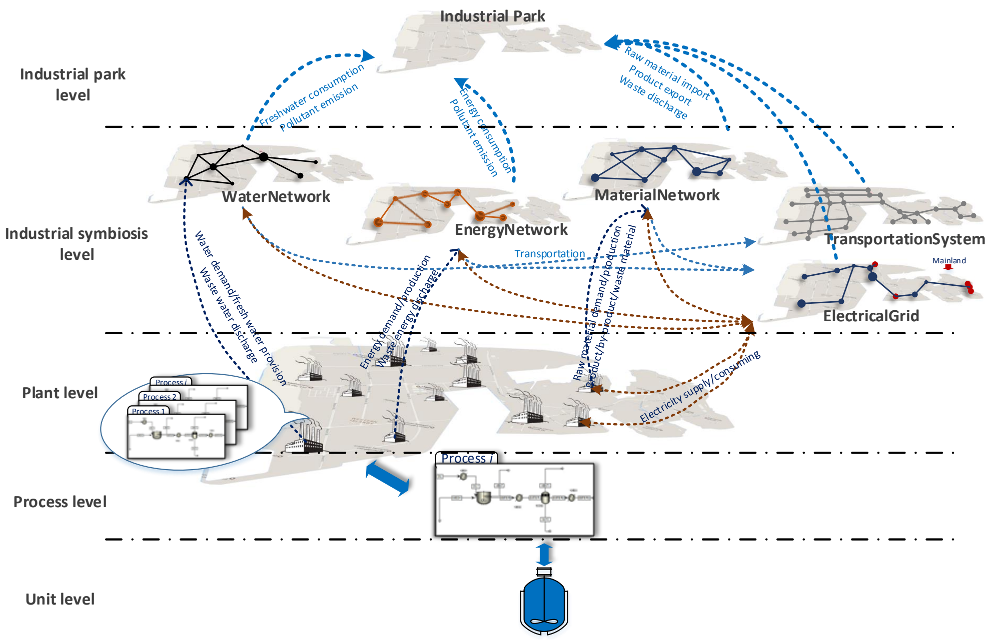


Figure 3: *A hierarchical framework for information modeling and management in EIPs. [47]*

At the topmost layer is the representation of the overall industrial park. It gives a general description for the EIP as a whole. For instance, its geographic location, overall resource (water, energy, and material) consumption, waste (water, energy, and material) as well as pollutant emission etc. Potential applications of such information might be for the EIP governors to query the general operation state of the EIP. One possible detailed ontological modeling of the park layer is given in Section 4.1.

The second layer from top-down represents the core engineering sub-systems in an EIP. It mainly includes resource networks (water network, energy network and material network), and their supporting engineering systems, i.e. electrical power system and transportation system. The network participants and their roles in the network (whether it's a source, or a sink or both) are specified. Knowledge contained in this layer is useful for industrial resource network formulation and optimization.

Connectivity among the network participants is described on the third layer, which is a collection of the plants reside in the EIP. A plant is represented as a group of manufacturing processes. Plant level information, such as plant ownership, location, raw material requirement, product/by-product specification and waste emission are specified. Such information might benefit the digitalization of chemical plants towards smart plant.

The fourth layer holds description about the manufacturing processes, covering mathematical models that captures the parametric behavior of the process, its economical and environmental performance, which might facilitate the production process automation.

The fifth layer reflects knowledge of the unit operations, including the machinery design parameters, operational conditions, mathematical models that describe the parametric behavior, economical and environmental performance of the unit, as well as their physical connections which reflects the material/energy interdependence.

Finally, it has to be underlined that there is no single correct manner for the ontological representation of a system. The above described systems could be approached from various perspectives at various detail levels. In other words, what properties we describe and how we describe them highly depend on the application requirement. In the next section, we present an ontological representation for EIP that can fulfill the need of our current application requirement, i.e. to support the establishment of a decentralized information management system for EIP. Although we strived to construct the ontology to be as comprehensive and versatile as possible, it is certain that the ontology will need to be extended, with moderate efforts, when it comes to new application requirements.

4 Ontology for eco-industrial park – OntoEIP

4.1 The overall ontology structure

Based on the hierarchical structure proposed in the last section, this section will introduce the detailed ontological representation of each level. The ontologies were developed in Protégé, which is a standard ontology editor for ontology-based intelligent systems [2]. The overall structure of OntoEIP is shown in Fig. 4, it can be seen that the overall ontology is modularized into several modules representing different domain of expertise, namely chemical industry, electrical power system, and transportation network. The modularization is based on the central concepts defined in the module *eco-industrial_park*, including *Eco-industrialPark*, *IndustrialSymbiosis*, *ChemicalPlant*, *ElectricPowerSystem* and *TransportationNetwork*, which is shown in Fig. 5. The descriptions of the relevant concepts are listed in Table. 1.

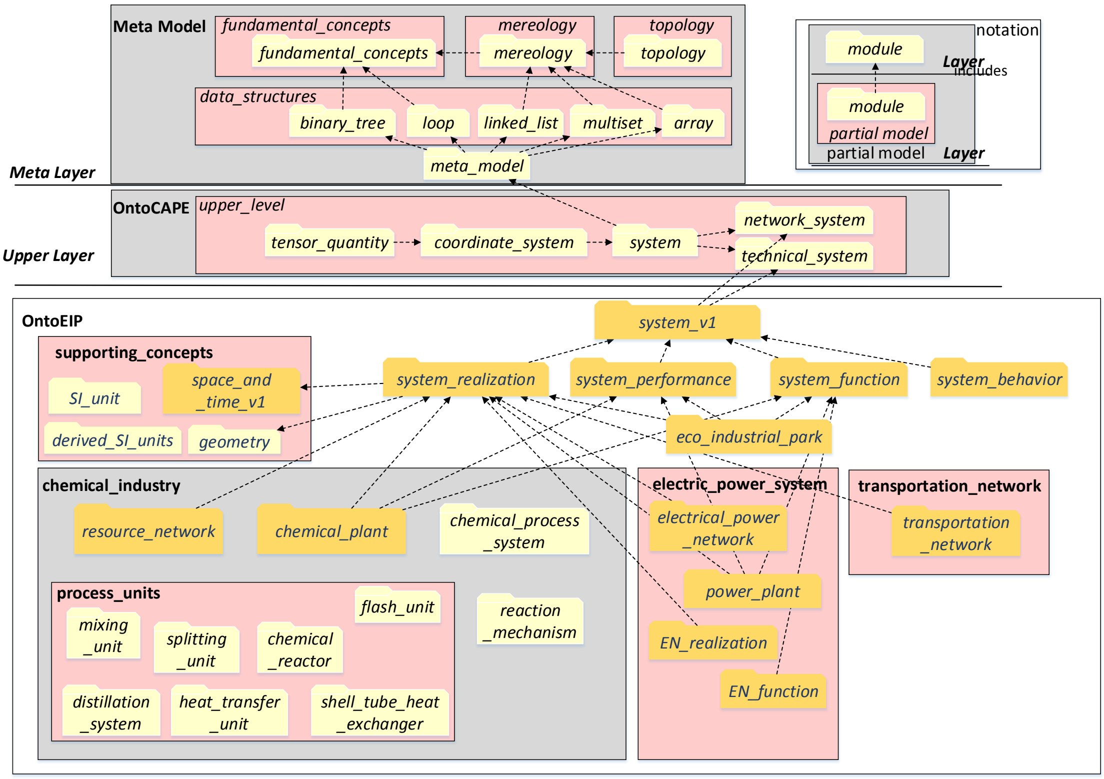


Figure 4: *The structure of OntoEIP extended and adapted from OntoCAPE [33].*

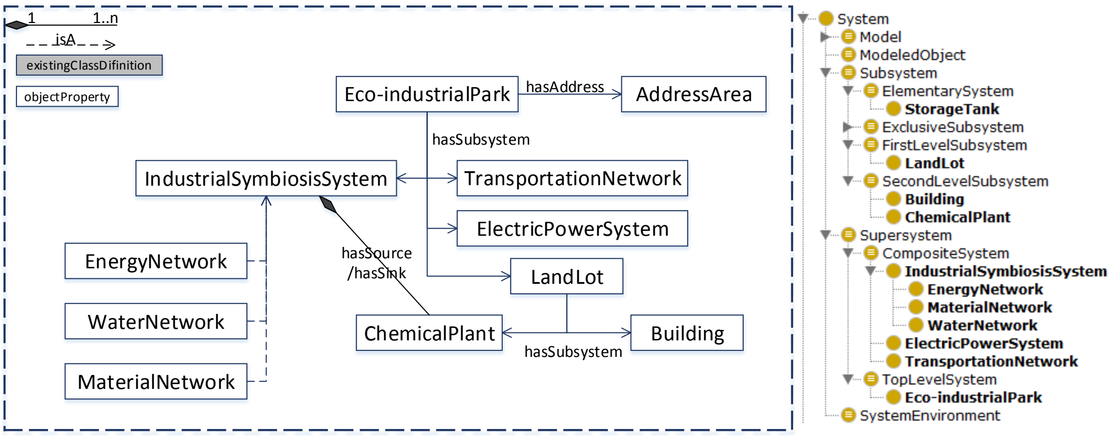


Figure 5: *Representation of an eco-industrial park and its class hierarchy in Protégé [2].*

Table 1: *The relevant eco-industrial park concepts.*

Classes	Definition
IndustrialSymbiosis	Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products [14].
Eco-industrialPark	An *Eco-industrialPark* refers to the concrete realization of the industrial symbiosis. [14]
WaterNetwork	A *WaterNetwork* is also known as water distribution system. It represents a type of industrial symbiosis where industry entities collaborate with each other via the exchange of water streams. [12, 31]
EnergyNetwork	An *EnergyNetwork* is an industrial symbiosis system realized via the exchange of energy streams. [12]
MaterialNetwork	A *MaterialNetwork* can also be presented as material distribution network, or supply chain. It reflects the connection among industries that share materials with each other. [12]
ElectricPowerSystem	An *ElectricPowerSystem* is a network of electrical components deployed to supply, transfer, and use electric power.
TransportationNetwork	A *TransportationNetwork* is a realization of a spatial network, describing a structure which permits either vehicular movement or flow of some commodity.
ChemicalPlant	A *ChemicalPlant* is an industrial plant that uses specialized equipment, units, and technology to transform feedstock chemicals into chemical products (usually on a large scale).

Furthermore, by following the design principle of OntoCAPE, the proposed ontology describes EIP as a whole from four perspectives, namely system realization, system performance, system function, and system behavior. Each as a partial module groups a subset of components (classes, relationships, and constraints) that reflect a particular aspect of the modeled system (Fig. 6). System realization represents the realization aspect of a system, reflecting the physical constitution of a technical system. Generally, it has mostly constant properties that gives static description of a system, such as geographical location, mechanical properties, and geometry. System performance is employed for the evaluation and benchmarking of a technical system. The concept represents a performance measure for the evaluation. Evaluation in the perspective of economics and environment are considered at current stage. System function introduces concepts that reflect the desired behavior of a technical system, while system behavior describes how a system behaves under certain conditions. Surrogate model is employed to capture the behavioral characteristics of a system. Table 2 gives the notions defined for the description of such system features.

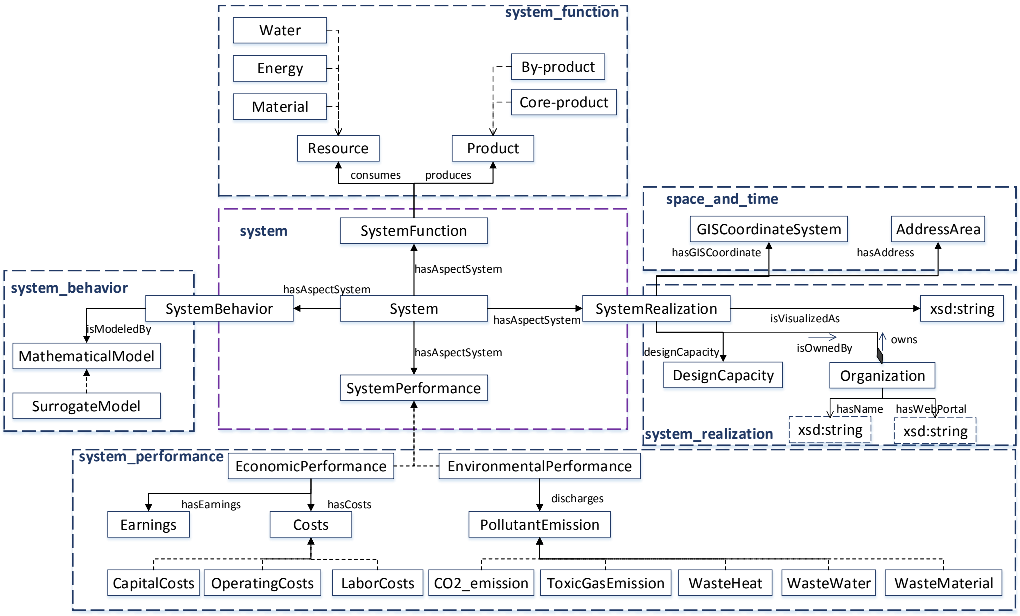


Figure 6: *The concepts describing the common feature of a system.*

Table 2: *Concepts that reflect the generic system features.*

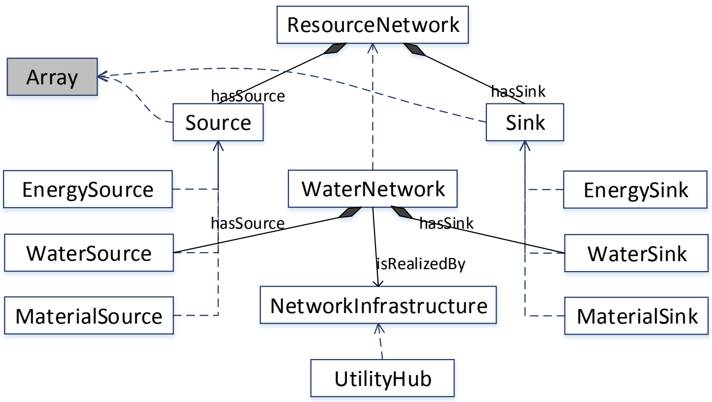
Classes	Definition
Organization	An *Organization* is a group of people, companies, or countries, which is set up for a particular purpose [34].
DesignCapacity	*Capacity* denotes the maximum amount of product that a factory, company, machine etc. is designed to produce or deal with. [?]
AddressArea	An *AddressArea* represents the geographic location on the Earth's surface where a system resides, it provides the connection to the road network. [32]
GeographicCoordinateSystem	A *GeographicCoordinateSystem* is a coordinate system used in geography that enables every location on Earth to be specified by a set of numbers, letters or symbols. A common choice of coordinates is latitude, longitude and elevation. [6]
ProjectedCoordinateSystem	A *ProjectedCoordinateSystem* is defined on a flat, two-dimensional surface. It has constant lengths, angles, and areas across the two dimensions. [8]
Cost	Cost describes all kinds of costs that may arise with respect to producing a product.
CapitalCost	*CapitalCost* are fixed, one-time expenses incurred on the purchase of land, buildings, construction, and equipment used in the production of goods or in the rendering of services. [3]

OperatingCost	*OperatingCost* are the expenses which are related to the operation of a business, or to the operation of a device, component, piece of equipment or facility. [4]
LaborCost	*LaborCost* denotes the expenses which are related to manpower for the operation of a business or a system.
Earnings	*Earnings* denotes the net benefits of a corporation's operation. [5]
Price	*Price* denotes the currency per unit weight of a product. [7]
PollutantEmission	*PollutantEmission* represents the pollutant (liquid or gaseous) discharged from a system to the environment.
Resource	*Resource* denotes natural, or commercial resources that could be used to produce certain type of products.
Product	*Product* denotes for an economic goods or service.

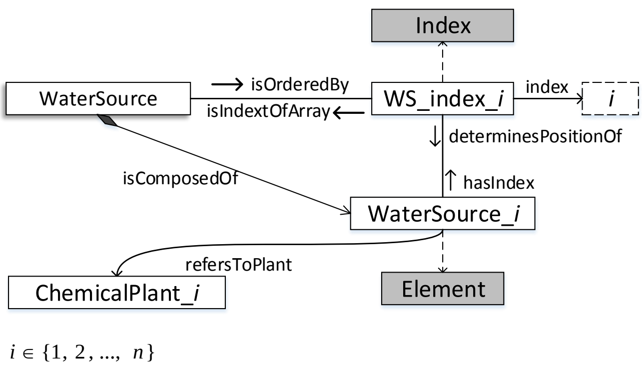
4.2 Ontological representation of chemical industry

For the process level, and unit level ontology, they are already well established in OntoCAPE, thus this study mainly focuses on ontologies at resource network level, and plant level and industrial park level. The term industrial symbiosis defined by Chertow [14] is used to represent the resource sharing networks. It was defined as "engaging separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, and water". Based on the exchanged resources, industrial symbiosis can be classified into water network, energy network and material network [12]. Other important concepts are electric power system and transportation network. The former represents the grid that provides power to the industrial park, while the latter refers to the road network.

Industrial symbiosis is the key feature of an EIP. It allows multiple independently operating plants to share common resources and utilities. A symbiotic network refers to the resource exchanging network among a number of industrial plants which are geographically closely located [30]. Through the network, the waste, by-products and/or products (in material or energy form) produced from one plant could be utilized in another as feedstock. Generally, three types of industrial symbiotic system have been largely investigated, namely, water network, energy network and material network. For description of symbiotic system, two concepts are important, *Source* and *Sink*. The former represents the plant from which a certain type of resource is available, whereas the latter represents the plant that consumes the resource [30]. The representation of a resource exchange network is given in Fig. 7a. The main components are the participating companies, which can be sources, or sinks, or even both. Fig. 7b gives an exemplary representation of a set of chemical plant that serve as water sources. The design and operation of the resource exchange network is determined by information of its participating plants, such as their geographic location, specifications for the desired resources, and characteristics of the available resources. Such information is described in plant ontology, as stated in the previous section, which is illustrated in Fig. 8a. In particular, physical locations (noted as *AddressArea*) are rather important, as it determines the physical distance between two plants, which further affects the transportation cost when resource sharing occurs. The detailed description of the plants' physical location is held by another module, namely transportation ontology. Such cross-reference would not influence the integrity of the overall ontology. On the contrary, it can enhance a structuralized knowledge management which will be discussed in detail later. The key concepts defined in the *industrial_symbiosis* module are listed in Table 3.

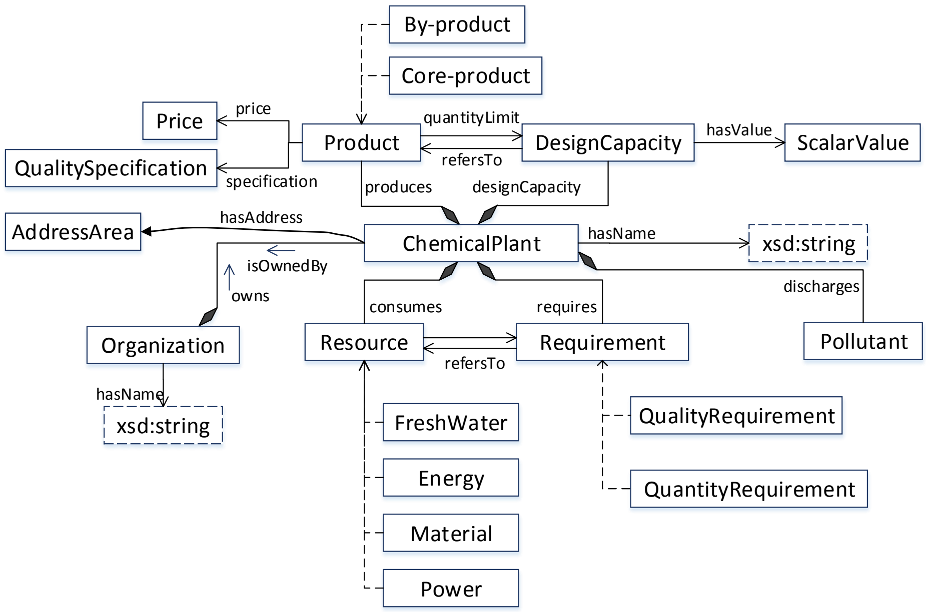


(a) *Representation of resource networks.*

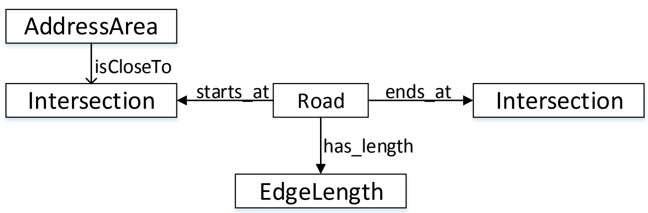


(b) *Exemplary representation of water sources.*

Figure 7: *Representation of a resource network and the corresponding source set.*



(a) *Representing a chemical plant.*



(b) *representing the physical address of a chemical plant.*

Figure 8: *Representation of a chemical plant and its location in the transportation system ontology.*

Table 3: *Relevant terminology for resource network representation.*

Classes	Description
Source	A *Source* represents a place, organization, or process from which a particular resource can be obtained.
Sink	A *Sink* denotes a place, organization, or process that consumes a certain type of resource.
UtilityHub	A *UtilityHub* is a centralized infrastructure that serves as storage tank to help the management of utility distribution.
NetworkInfrastructure	A *NetworkInfrastructure* signifies the infrastructure system that realises the allocation of resource network. It is composed of connections (pipelines) and devices (pumps, utility hub, waste treatment unit etc.).

4.3 Ontological representation of electrical power system

Electrical power system is of great importance to the normal and efficient operation of industrial manufacture systems. An electrical power system is an interconnected network of several major subsystems, including generation subsystem, transmission subsystem, distribution subsystem and utilization subsystem [17]. A generation subsystem includes two main components, namely generator and transformer. The generator is responsible for generating electric power in accordance with the predicted load requirements [42]. Normally, electricity generation from the generator is at a relatively low voltage, typically 20 kV. For the purpose of efficient power transmission, transformers are used for stepping up of the generated voltage to high voltage, extra-high voltage, or even ultra-high voltage. After voltage regulation, the electricity generated from a generation system is transfered to the distribution system via transmission lines. High voltage (HV) transmission lines are used for long distance electric power transmissions (from generation subsystem to distribution subsystem), while low voltage (LV) transmission lines are used for short distance transmissions (from the distribution subsystem to the utilization subsystem). For the modeling of transmission lines, four concepts are important, namely series resistance, series inductance, shunt capacitance, and shunt conductance [17]. Utilization subsystems (Loads) are categorized into industrial, commercial, and residential. Industrial loads refer to manufacture plants and electric-consuming equipments, such as pumps, while residential and commercial loads are the lighting, heating and cooling system in buildings. These concepts are organized into aspect modules, namely function, behavior, realization, as is shown in Fig.9.

It needs to be highlighted that the ontology presented here not only provides a backbone to represent the electrical power system as an individual technical component, but also provides concepts that could link the electrical engineering domain with the chemical engineering domain. For example, a pump, as a technical component (*Machine*) of chemical industry, is also an instance of *IndustrialLoad*. As a result, a pump will be modeled jointly by two ontology modules that describe the pump from the perspective of two different domain of expertise.

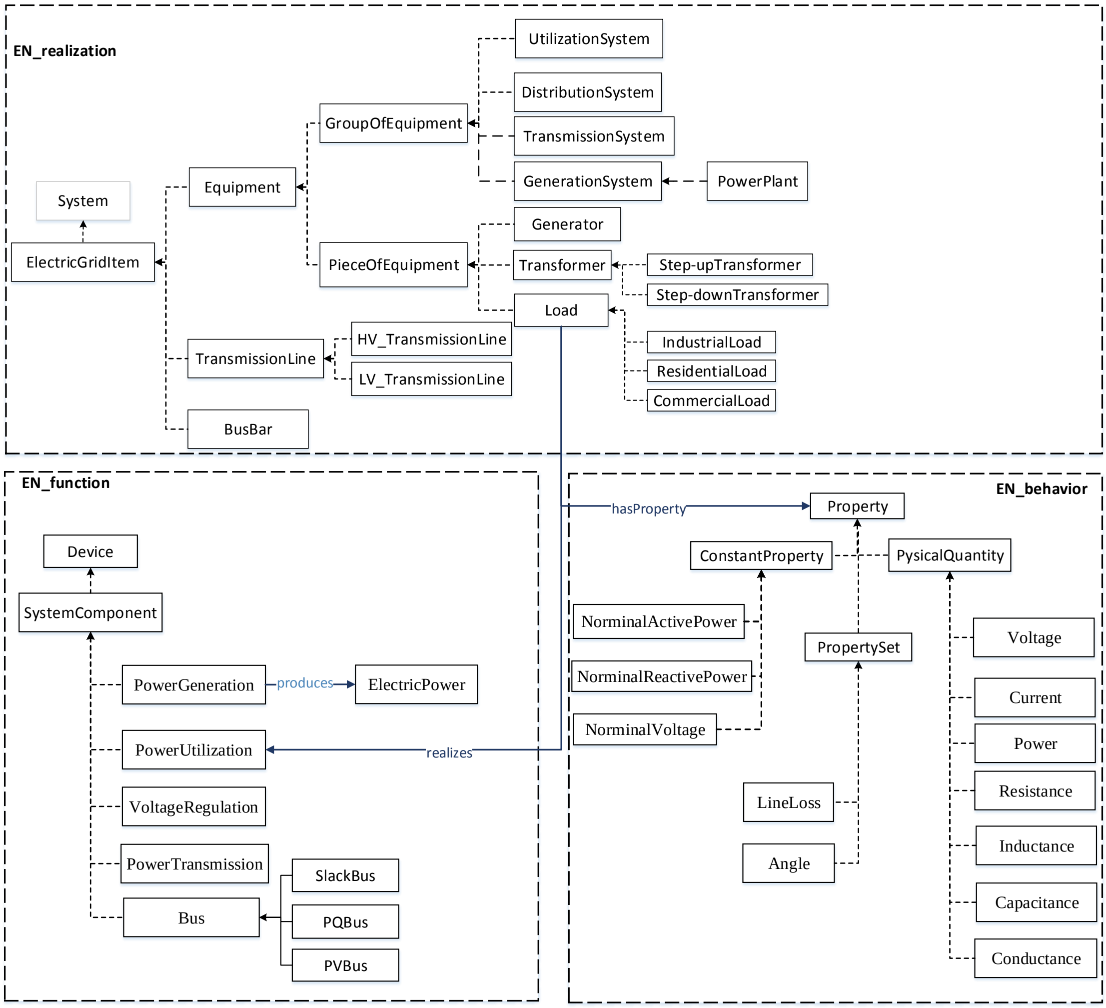


Figure 9: *Taxonomy of the concepts considered in electrical power system ontology.*

5 Ontology enabled decentralized information management system for Jurong Island

In this section, we present a framework for decentralized information management for EIP based on the developed ontology. The idea of constructing such a framework is based on the following two reasons. Firstly, the usefulness of an ontological knowledge model for facilitating collaboration is greatly reduced if the model is placed into a central repository that is disjoint from the original model developer and maintainer [26]. Secondly, it is impractical and inapplicable to handle the EIP information in a centralized manner, as the information of each individual industry organization is usually owned and managed individually, and the key technical details are usually kept confidential to the outsiders.

Fig. 10 shows a schematic representation of the proposed decentralized information management system. It gives how the proposed ontological framework can be utilized to facilitate the establishment of a hierarchical information representation and sharing system for the participants in an eco-industrial park. By applying the proposed ontology, a set of Ontological Knowledge Bases (OKBs) can be generated for the technical components of different operational levels. These OKBs (represented as nodes) are connected through predefined relations indicating the interdependencies among the represented entities.

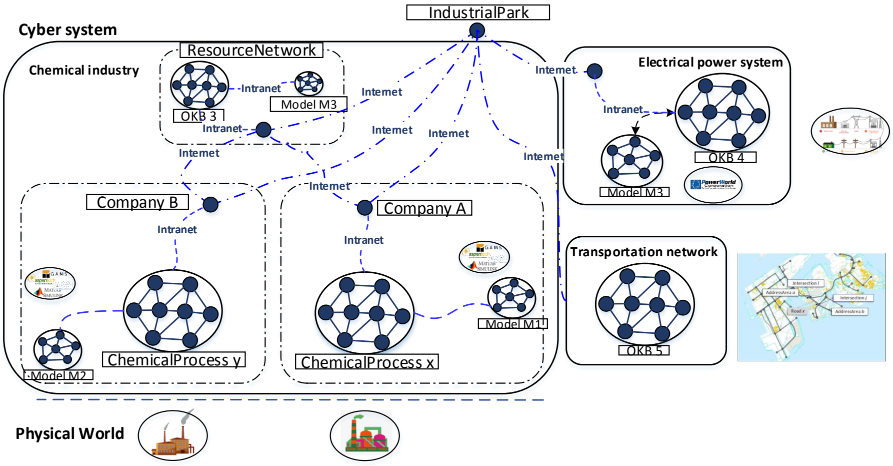


Figure 10: *A schematic representation of the decentralized knowledge management system.*

The proposed method is applied to Jurong Island, which is a 32 km^2 artificial island located to the southwest of Singapore. It is home to more than 100 chemical and power plants. To raise its competitiveness, the Singapore government plans to optimize its resource and energy utilization through collaborative solutions. One important prerequisite to achieve such collaborative benefits is a reliable and efficient information management system. Fig. 11 shows a snapshot of the ontological representation of Jurong Island. As is shown, Jurong Island is of type Eco-industrial Park, and consists of a set of subsystems, including chemical plants, electrical power system, transportation system, water network system and so on. Each subsystem is identified by an IRI, through which the corresponding OKB can be accessed. Fig. 12 gives the ontological representation for a bio-fuel plant. It takes methanol and tripalmitin as raw materials, and produces biodiesel as the main product and glycerol as by-product. It discharges waste steam and CO_2 to the environment. The plant consists of three biodiesel producing processes, whose detailed information is stored in different knowledge bases. One of the knowledge bases is illustrated in Fig. 13, which shows that the process is composed of 25 process units, including heat exchangers, pumps, reactors and so on. Detailed information about these process units is again stored in dedicated knowledge bases. These dedicated knowledge bases for processes and process units may only be accessible for certain group of people with authorizations. Fig. 14 illustrates description for one of the reactors, covering its connectivity with other process components and its properties as a power consuming units. The OKB system developed for Jurong Island is available at `http://www.theworldavatar.com:82/visualizeJurong`. A snapshot of the information management system is shown in Fig. 15. The yellow node sitting at the middle represents Jurong Island, while the pink nodes connected to it represent the subsystems (chemical plants, electrical power system, transportation system, etc.).

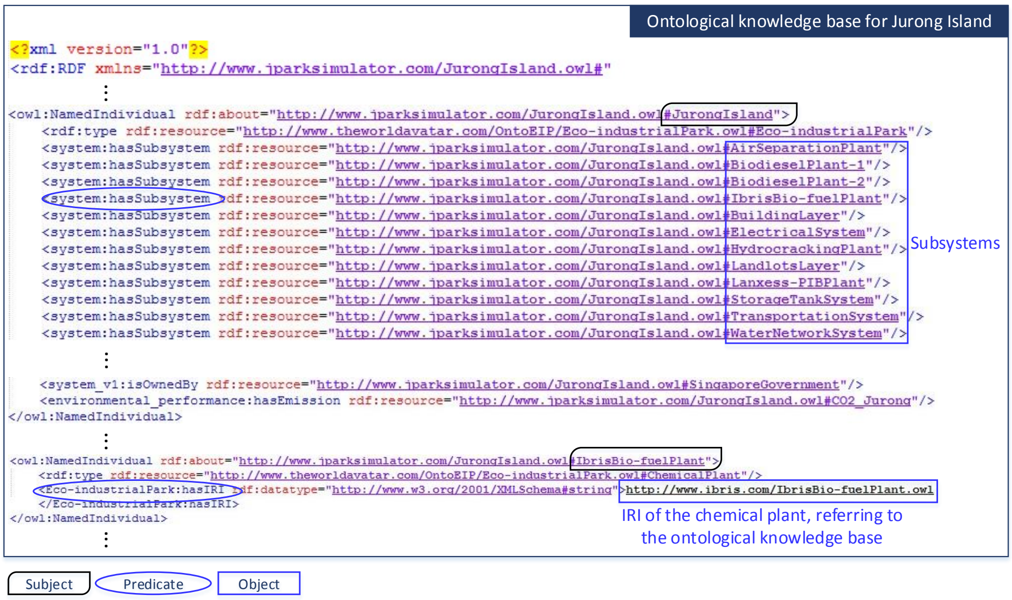


Figure 11: *Ontological representation of Jurong Island, showing the subsystem, including chemical plants, electrical power system, transportation system, water network system and so on.*

Figure 12: *Ontological representation of the Ibris Bio-fuel Plant, showing its physical address, raw material, product, and pollutant emission.*

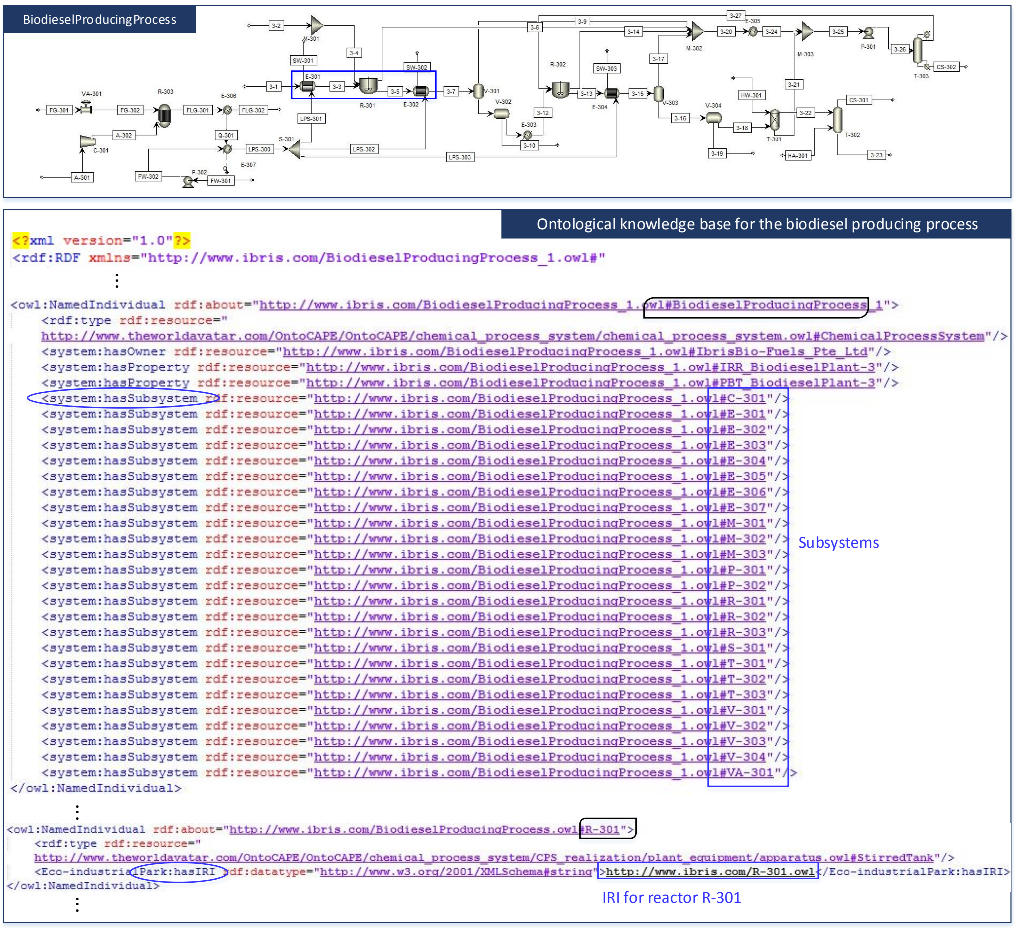


Figure 13: *Ontological representation of a biodiesel producing process, showing the technical components (machines and equipments) that compose the process system.*

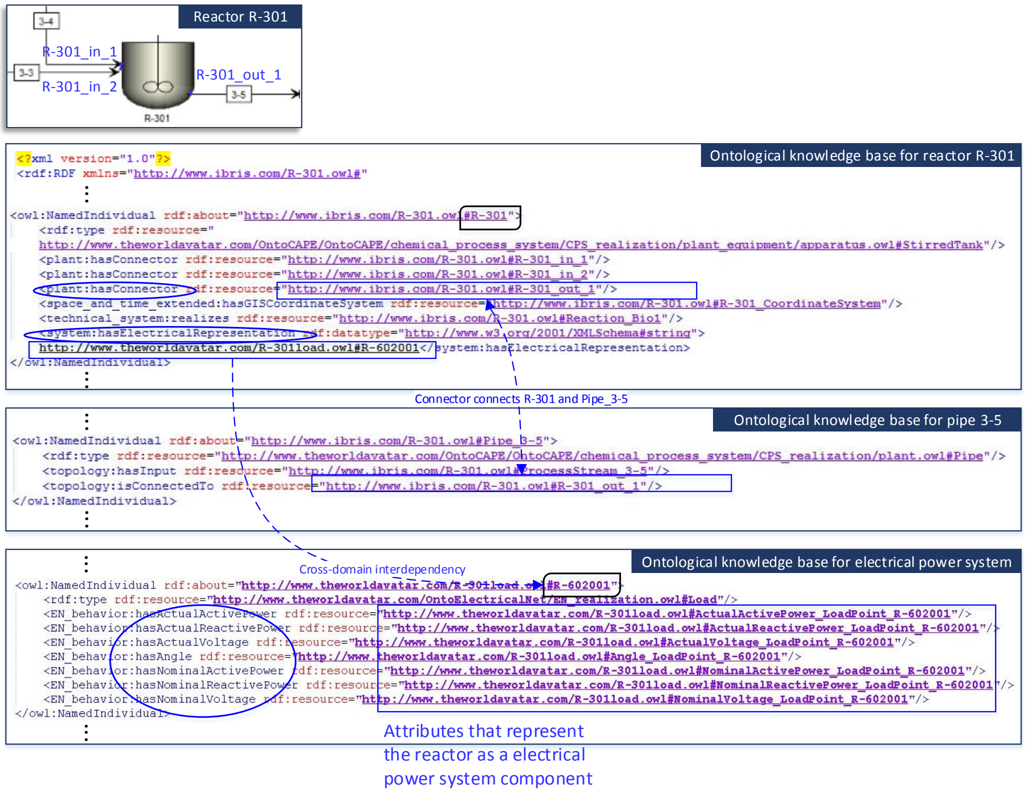


Figure 14: *Ontological representation of the biodiesel reactor R-301 as part of the biodiesel producing process, showing information about the reactor type, physical location, connectivity with other process component, as well as its property from electrical engineering point of view.*

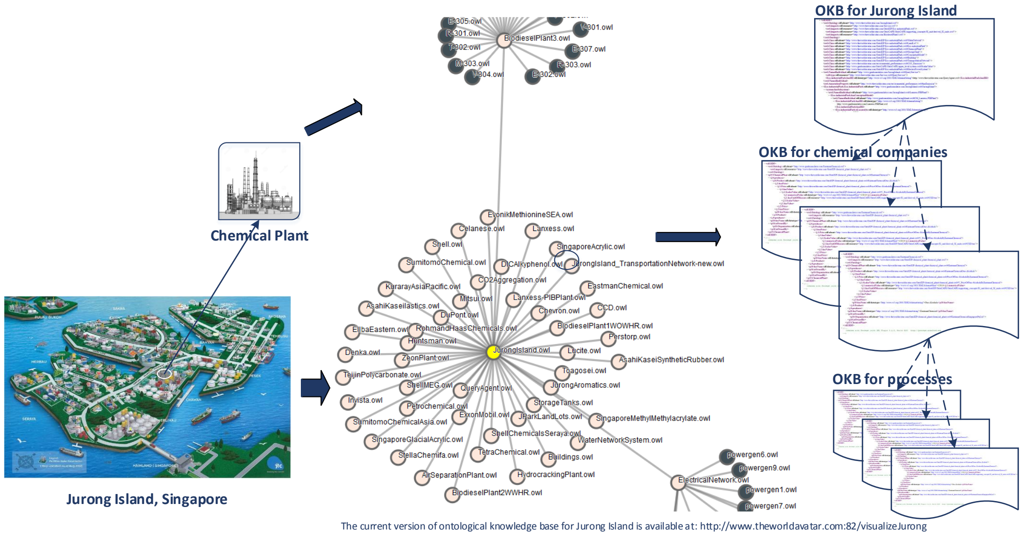


Figure 15: *Structure representation of the ontological knowledge bases (OKBs) built for Jurong Island. Each node refers to an OKB (an owl file) that holds information for an entity. An edge represents the interrelationship between two entities.*

6 Conclusion and future work

This paper presents a skeletal ontology for the information modeling and management of EIPs. The proposed ontology is constructed based on a conceptualization framework including five operational levels (unit operations, processes, plants, industrial networks and eco-industrial parks). EIP level gives general description of the EIP as a whole. Industrial networks targets at the resource network (water network, energy network and material network) in EIP and their supporting engineering systems, namely electrical power system and transportation network. Groups of manufacturing processes are represented in the plant level. Process level holds description about individual manufacturing processes, while unit level reflects knowledge of the unit operations.

Based on such conceptualization framework, the detailed serialization of ontological modeling of EIP is also achieved. The ontology consists of several parts including eco-industrial park, resource network, chemical plant, transportation network, electrical power system as well as several other modules adapted from OntoCAPEs modules (namely, chemical process system, unit operation). The developed ontology describes EIP from four perspectives, system realization, system performance, system function, and system behavior. The core concepts associated with each aspect are also elaborated in the paper. The benefit of such ontological modeling is shown through the establishment of a decentralized information management system for large scale EIP. With the help of the system, data from disparate databases can be integrated, and the reusability of information as well as the efficiency of information sharing is increased. The proposed methodology is applied to Jurong Island in Singapore, a set of ontological knowledge bases is developed for the represented entities.

The potential benefit of such a system can be further unleashed through the continuous iterative development of the ontology and construction of agents. Although we strive to develop a comprehensive and versatile ontological representation for EIPs that can support as many applications as possible, yet it is already clear that the ontology needs to be improved, with moderate efforts, for other applications. On top of the OKB, agents with different capabilities is going to be developed to carry out desired activities, such as system self-diagnostic, self-prediction, self-configuration and so on.

In short, we deem ontology as a powerful tool for EIP knowledge management, particularly in the future scenario of Industry 4.0 and Internet of Things (IoT). The capabilities ontology has in reconciling data heterogeneity and promoting knowledge share make it an indispensable ingredient on the road map towards future smart eco-industrial park. We believe much more potentials regarding to the EIP optimal operation could be unleashed given the growing data availability and machine computational power. We hope this work could appeal to more collaborative efforts towards the future smart EIP.

7 Acknowledgements

This project is funded by the National Research Foundation (NRF), Prime Ministers Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme.

References

[1] Xml rdf, 2016. URL https://www.w3schools.com/xml/xml_rdf.asp. Date accessed: 11.09.2017.

[2] A free, open-source ontology editor and framework for building intelligent systems, 2016. URL http://protege.stanford.edu/. Date accessed: 18.06.2017.

[3] Capital cost, 2017. URL https://en.wikipedia.org/wiki/Capital_cost. Date accessed: 07.07.2017.

[4] Operating cost, 2017. URL https://en.wikipedia.org/wiki/Operating_cost. Date accessed: 07.07.2017.

[5] Earnings, 2017. URL https://en.wikipedia.org/wiki/Earnings. Date accessed: 07.07.2017.

[6] What are geographic coordinate systems?, 2017. URL http://desktop.arcgis.com/en/arcmap/10.3/guide-books/map-projections/about-geographic-coordinate-systems.htm. Date accessed: 07.07.2017.

[7] Price, 2017. URL https://en.wikipedia.org/wiki/Price. Date accessed: 07.07.2017.

[8] What are projected coordinate systems?, 2017. URL http://desktop.arcgis.com/en/arcmap/10.3/guide-books/map-projections/about-projected-coordinate-systems.htm. Date accessed: 07.07.2017.

[9] H. Afshari, R. Farel, and Q. Peng. Improving the resilience of energy flow exchanges in eco-industrial parks: Optimization under uncertainty. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*, 3 (2):021002, 2017.

[10] R. Batres and Y. Naka. Process plant ontologies based on a multi-dimensional framework. In *AIChE symposium series*, number ISBN No: 0-8169-0826. AIChE Symposium Series, 2000.

[11] R. Batres, A. Aoyama, and Y. Naka. A life-cycle approach for model reuse and exchange. *Computers & Chemical Engineering*, 26(4):487–498, 2002. doi:10.1016/S0098-1354(01)00794-3.

[12] M. Boix, L. Montastruc, C. Azzaro-Pantel, and S. Domenech. Optimization methods applied to the design of eco-industrial parks: a literature review. *Journal of Cleaner Production*, 87:303–317, 2015. doi:10.1016/j.jclepro.2014.09.032.

[13] S. C. Brandt, J. Morbach, M. Miatidis, M. Theißen, M. Jarke, and W. Marquardt. An ontology-based approach to knowledge management in design processes. *Computers & Chemical Engineering*, 32(1):320–342, 2008. doi:10.1016/j.compchemeng.2007.04.013.

[14] M. R. Chertow. Industrial symbiosis: literature and taxonomy. *Annual review of energy and the environment*, 25(1):313–337, 2000. doi:10.1146/annurev.energy.25.1.313.

[15] E. Cimren, J. Fiksel, M. E. Posner, and K. Sikdar. Material flow optimization in by-product synergy networks. *Journal of Industrial Ecology*, 15(2):315–332, 2011. doi:10.1111/j.1530-9290.2010.00310.x.

[16] J. Davies, R. Studer, and P. Warren. *Semantic Web technologies: trends and research in ontology-based systems*. John Wiley & Sons, 2006. URL `https://books.google.com.sg/books?hl=en&lr=&id=ePCrymWkcl0C`. Date accessed: 21.08.2017.

[17] M. E. El-Hawary. *Introduction to electrical power systems*, volume 50. John Wiley & Sons, 2008. URL `http://ieeexplore.ieee.org.libproxy1.nus.edu.sg/servlet/opac?bknumber=5361023`.

[18] A. Gomez-Perez, M. Fernández-López, and O. Corcho. *Ontological Engineering: with examples from the areas of Knowledge Management, e-Commerce and the Semantic Web.* Springer Science & Business Media, 2006. URL `https://books.google.com.sg/books?hl=en&lr=&id=qR_3BwAAQBAJ&oi=fnd&pg=PA1&dq`. Date accessed: 21.03.2017.

[19] D. Gregor, S. Toral, T. Ariza, F. Barrero, R. Gregor, J. Rodas, and M. Arzamendia. A methodology for structured ontology construction applied to intelligent transportation systems. *Computer Standards & Interfaces*, 47:108–119, 2016. doi:10.1016/j.csi.2015.10.002.

[20] T. R. Gruber. A translation approach to portable ontology specifications. *Knowledge acquisition*, 5(2):199–220, 1993. doi:10.1006/knac.1993.1008.

[21] H. Haslenda and M. Jamaludin. Industry to industry by-products exchange network towards zero waste in palm oil refining processes. *Resources, Conservation and Recycling*, 55(7):713–718, 2011. doi:10.1016/j.resconrec.2011.02.004.

[22] M. Houda, M. Khemaja, K. Oliveira, and M. Abed. A public transportation ontology to support user travel planning. In *2010 Fourth International Conference on Research Challenges in Information Science (RCIS)*, pages 127–136. IEEE, 2010. doi:10.1109/RCIS.2010.5507372.

[23] International Telecommunication Union. Series Y: Global information infrastructure, internet protocol aspects and next-generation networks. *Telecommunication Standardization Sector of ITU*, 2001.

[24] C. A. Kastner, R. Lau, and M. Kraft. Quantitative tools for cultivating symbiosis in industrial parks; a literature review. *Applied Energy*, 155:599–612, 2015. doi:10.1016/j.apenergy.2015.05.037.

[25] Y. Kitamura and R. Mizoguchi. Ontology-based description of functional design knowledge and its use in a functional way server. *Expert Systems with Applications*, 24(2):153–166, 2003. doi:10.1016/S0957-4174(02)00138-0.

[26] S. Kraines, R. Batres, B. Kemper, M. Koyama, and V. Wolowski. Internet-based integrated environmental assessment, part II: Semantic searching based on ontologies and agent systems for knowledge discovery. *Journal of Industrial Ecology*, 10(4): 37–60, 2006. doi:10.1162/jiec.2006.10.4.37.

[27] D. Küçük. A high-level electrical energy ontology with weighted attributes. *Advanced Engineering Informatics*, 29(3):513–522, 2015. doi:10.1016/j.aei.2015.04.002.

[28] D. Küçük and Y. Arslan. Semi-automatic construction of a domain ontology for wind energy using Wikipedia articles. *Renewable Energy*, 62:484–489, 2014. doi:10.1016/j.renene.2013.08.002.

[29] D. Küçük, Ö. Salor, T. İnan, I. Çadırcı, and M. Ermiş. PQONT: A domain ontology for electrical power quality. *Advanced Engineering Informatics*, 24(1):84–95, 2010. doi:10.1016/j.aei.2009.06.009.

[30] Y. T. Leong, J.-Y. Lee, R. R. Tan, J. J. Foo, and I. M. L. Chew. Multi-objective optimization for resource network synthesis in eco-industrial parks using an integrated analytic hierarchy process. *Journal of Cleaner Production*, 143:1268–1283, 2017. doi:10.1016/j.jclepro.2016.11.147.

[31] Z. Liao, J. Wu, B. Jiang, J. Wang, and Y. Yang. Design methodology for flexible multiple plant water networks. *Industrial & engineering chemistry research*, 46(14): 4954–4963, 2007. doi:10.1021/ie061299i.

[32] B. Lorenz, H. J. Ohlbach, and L. Yang. Ontology of transportation networks. 2005.

[33] W. Marquardt, J. Morbach, A. Wiesner, and A. Yang. *OntoCAPE: A re-usable ontology for chemical process engineering*. Springer Science & Business Media, 2009. URL `https://books.google.com.sg/books?hl=en&lr=&id=lSDQhCoJki8C`. Date accessed: 27.05.2017.

[34] M. Mayor. *Longman dictionary of contemporary English*. Pearson Education India, 2009.

[35] R. Mizoguchi. Ontological engineering: foundation of the next generation knowledge processing. In *Web intelligence: Research and development*, pages 44–57. Springer, 2001. doi:10.1007/3-540-45490-X_5.

[36] R. Mizoguchi, K. Kozaki, T. Sano, and Y. Kitamura. Construction and deployment of a plant ontology. In *International Conference on Knowledge Engineering and Knowledge Management*, pages 113–128. Springer, 2000. doi:10.1007/3-540-39967-4_9.

[37] J. Morbach, A. Yang, and W. Marquardt. OntoCAPE - A large-scale ontology for chemical process engineering. *Engineering applications of artificial intelligence*, 20 (2):147–161, 2007. doi:10.1016/j.engappai.2006.06.010.

[38] S. K. Nair, Y. Guo, U. Mukherjee, I. Karimi, and A. Elkamel. Shared and practical approach to conserve utilities in eco-industrial parks. *Computers & Chemical Engineering*, 93:221–233, 2016. doi:10.1016/j.compchemeng.2016.05.003.

[39] M. Pan, J. Sikorski, J. Akroyd, S. Mosbach, R. Lau, and M. Kraft. Design technologies for eco-industrial parks: From unit operations to processes, plants and industrial networks. *Applied Energy*, 175:305–323, 2016. doi:10.1016/j.apenergy.2016.05.019.

[40] R. Tan and K. Aviso. An inverse optimization approach to inducing resource conservation in eco-industrial parks. In *Proceedings of the 11th International Symposium on Process Systems Engineering*, pages 775–778. Elsevier: Singapore, 2012.

[41] B. T. C. Tiu and D. E. Cruz. An MILP model for optimizing water exchanges in eco-industrial parks considering water quality. *Resources, Conservation and Recycling*, 119:89–96, 2017. doi:10.1016/j.resconrec.2016.06.005.

[42] C. Wadhwa. *Electrical power systems*. New Age International, 2006. URL `https://books.google.com.sg/books?hl=en&lr=&id=PqS9nKmWzssC`. Date accessed: 21.08.2017.

[43] A. Yang, B. Braunschweig, E. S. Fraga, Z. Guessoum, W. Marquardt, O. Nadjemi, D. Paen, D. Pinol, P. Roux, S. Sama, M. Serra, and S. I. A multi-agent system to facilitate component-based process modeling and design. *Computers & Chemical Engineering*, 32(10):2290–2305, 2008. doi:10.1016/j.compchemeng.2007.11.005.

[44] C. Zhang, L. Zhou, P. Chhabra, S. S. Garud, K. Aditya, A. Romagnoli, G. Comodi, F. Dal Magro, A. Meneghetti, and M. Kraft. A novel methodology for the design of waste heat recovery network in eco-industrial park using techno-economic analysis and multi-objective optimization. *Applied Energy*, 184:88–102, 2016. doi:10.1016/j.apenergy.2016.10.016.

[45] C. Zhang, A. Romagnoli, L. Zhou, and M. Kraft. Knowledge management of eco-industrial park for efficient energy utilization through ontology-based approach. *Applied Energy*, 2017. doi:10.1016/j.apenergy.2017.03.130.

[46] C. Zhang, L. Zhou, M. Pan, A. Romagnoli, and M. Kraft. Towards intelligent thermal energy management of eco-industrial park through ontology-based approach. *Energy Procedia*, 105:3295–3300, 2017. doi:10.1016/j.egypro.2017.03.745.

[47] L. Zhou, M. Pan, J. J. Sikorski, S. Garud, L. K. Aditya, M. J. Kleinelanghorst, I. A. Karimi, and M. Kraft. Towards an ontological infrastructure for chemical process simulation and optimization in the context of eco-industrial parks. *Applied Energy*, In Press, 2017. doi:10.1016/j.apenergy.2017.05.002.