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An ontology framework towards decentralized information management for eco-industrial parks

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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 uses in supporting process modeling and optimization and facilitating industrial symbiosis are also discussed in the paper.

Key words: eco-industrial park, knowledge base, ontology, process modelling

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1. Introduction

An eco-industrial park (EIP) is a cluster of businesses in close proximity that 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 few 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 literature [1, 2]. Currently, the reported optimization approaches are mainly dedicated to the optimal design of single styled networks, such as water network integration [3, 4, 5], energy network synthesis [6, 7, 8], and material network integration [9, 10, 11]. 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 relationship 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 number 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 and trends as well as system behavior;

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

3) Syntax heterogeneity: engineering knowledge is usually represented and stored in a diverse information media, which include 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 implicitly held by the participating designers and segregated into ‘domain silos’. Consensual knowledge representation is needed to facilitate the communication across disciplinary boundaries and to create joint understanding and meaning.

5) **Privacy:** information is often separately stored by different stakeholders of EIP, thus information sharing, although technically realizable, is often hindered by privacy-related issues. How to identify and solve such potential privacy issues remains another important open question.

Accompanying the aforementioned challenges are the opportunities brought by the ongoing trends of Industry 4.0 and Internet of Things (IoT) [12]. 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: Virtual representation of physical entities in cyberspace. [13]

In this context, we present a formal representation of different concepts that capture the typical features of an EIP. 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 [14]. The term “skeletal” implies that the proposed ontology should be intended as a preliminary trial for ontological innovations in EIP information management instead of an omnipotent and complete version of EIP information modeling. At the current stage, the ontology development mainly focuses on the modeling of chemical engineering activities, such as transportation and electrical engineering. 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*, *chemical_process_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 are organized as follows. Section 2 gives a concise literature review of the existing works in relation to the ontology development for engineering domains, as well as a discussion on research gaps. Section 3 introduces a hierarchical modeling scheme for the information representation of an 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. Existing onotologies in the engineering domain and research gaps

Ontology engineering is a powerful tool for computer-based information modeling and management that aims to conceptualize the physical world in a formal and explicit manner [15]. 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; this 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 [14].

According to the “subject of conceptualization”, ontologies can be classified into several categories, including top-level ontologies, domain ontologies,

task ontologies and application ontologies [16]. 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 these, 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 RDF code is shown in Fig. 2.

```

<?xml version="1.0"?>

<rdf:RDF
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:cd="http://www.recshop.fake/cd#">

  <rdf:Description
    rdf:about="http://www.recshop.fake/cd/Empire Burlesque">
    <cd:artist>Bob Dylan</cd:artist>
    <cd:country>USA</cd:country>
    <cd:company>Columbia</cd:company>
    <cd:price>10.90</cd:price>
    <cd:year>1985</cd:year>
  </rdf:Description>

```

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 [17])

Ontology engineering has received great attention in the past decade as

an advanced knowledge modeling and information management method [18]. Numerous works have been reported for the development of ontology, especially in engineering domains.

Domain ontologies for chemical industry

Mizoguchi et al. [19, 20] developed a Plant Ontology that 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 a description for the plant components whose properties are context-dependent. Subsequently, a Functional Ontology [21] was developed as a complementary ontology to the Plant Ontology. The Functional Ontology describes engineering constituents from different perspectives (structural, functional, behavioral) and defines relations between the decomposed aspects. The combination of these two ontologies enables the modeling of equipment, materials and operating activities in industrial plants as well as their functions. Batres et al. [22, 23] 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 plants, processes, and products from the perspective of structure, behaviour and operation. PRONTO, an ontology developed for product-related information management for supply chain operation, was proposed by Gimenez et al. [24, 25, 26]. It can be utilized to support the construction of a distributed product data management system. Batres et al. [27] proposed a 4-Dimensional data modeling approach to capture the object performance on time-line, as well as a upper ontology based on ISO 15926 for chemical plants which describes general conceptions such as activities, physical quantities, topology. Subsequently, a large-scale ontology called OntoCAPE was developed for chemical process engineering [28, 14], 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. OntoCAPE is widely reused for chemical process system modelling as well as software platform development for process system engineering [29, 30, 31].

Domain ontologies for socio-technical systems

Van Dam et al. [32, 33] proposed an ontology for socio-technical systems

that describes the system from two perspectives, namely, a physical network of technical artefacts and a social network of actors. Relations were defined to connect the physical network and social network. By following the modeling rule, complex socio-technical infrastructure systems were modeled, covering oil refinery supply chains, electrical power systems and public transportation systems. The same research group has employed the developed ontology for intelligent transportation system control [34], efficiency analysis of complex systems [35], planning of inter-modal freight hub locations [36, 37], abnormal situation management of refinery supply chain [38, 39], multi-agent systems for the control of electricity infrastructure [40, 41] and energy and transport infrastructures [42]. In addition, the ontology was applied to the Rotterdam-Rijnmond industrial cluster and an agent based model was developed to illustrate the design of a model of industry-infrastructure evolution [43]. Cecelja et al. [44, 45] developed an E-symbiosis ontology for promoting industrial symbiosis in EIP. [Through modeling resource and technology in EIP, it is claimed that their ontology is able to provide significant CO₂ emission and waste reduction effect in EIP.](#) Other ontology works were also reported for the sub-systems, such as electrical power system [46, 47] and transportation systems [48, 49]. [Moreover, ontologies have also been proved useful tools for solving the privacy-related issues during information fusion, which would be a great feature for enhancing usability in practice \[50\].](#)

Among the reported ontology works, a limited few are dedicated to the modeling and representation of industrial cluster systems. The existing ontology works dedicated to EIP systems normally deal with one or two facets of a complex system, for example supply chain or power system. In order to capture the system complexity, this work presents an ontology for EIP systems (OntoEIP) that is of higher dimension and resolution. The proposed ontology models and links the presented entities in a well-structured hierarchical network, by extending OntoCAPE. It strives to model industrial systems from the very bottom unit operations level, to the industrial processes level, to the manufacturing factories level, to industrial symbiosis level, and finally to the overall industrial park level. To achieve that goal, the system is viewed from different perspectives. The modeling process starts with the individual unit operations, which are considered as the basic element for chemical industry. At this level, the unit operations are described in detail, covering the geometry, construction material, functionality, design parameters, installation location, its connections to the environment, *etc.* Consequently, the chemical processes are modeled, followed by the represen-

tations at the plants. The description of a chemical process includes some basic information about its sub-constituents and the properties of the process as a whole, such as the required raw material, energy consumption, overall throughput, design capacity, *etc.*. The same applies for the modeling of a plant and any higher-level system (resource network, industrial park), detailed information about its element system is skipped while properties of the system as a whole are reflected. Additionally, the models from different modeling levels are well-bridged, such that the detailed model of a lower level can be smoothly plugged into that of a higher level. However, it is necessary to underline that ontology development is never a one-off job because human beings' cognition of the world keeps evolving and new application requirements always emerge; once new application cases appear, the ontology framework should be flexible enough to accommodate such modification and extension for the new application context. 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. [In this paper, we are mainly focusing on the information related to chemical engineering activity. The proposed ontology concerns with chemical engineering concepts, based on which relevant notions from other domains are defined, such as those conceptualized from electrical power system and transportation network.](#) The detailed structure of such ontology framework will be discussed in Section 3 and Section 4.

3. Hierarchical framework for information modeling of an 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 and its content, 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 [51, 52, 53].

Figure 3: A hierarchical framework for information modeling and management in EIPs. [52]

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, mathematical models that reflect system behavior. Potential applications of such information might be for the EIP governors to query the general operation state of the EIP. The detailed ontological modeling of the park layer is given in Section 4.1.

The second layer from the top 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, e.g. electrical power system and transportation system. The network participants and their roles in the network (whether it's a source, a sink or both) are specified. Such information is used as input for the corresponding optimization models for system designing and scheduling. 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 residing 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 emissions are specified. Such information might benefit the digitalization of chemical plants towards smart plant.

The fourth layer holds descriptions about the manufacturing processes, covering mathematical models that capture the parametric behavior of the process and 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. It is noted that though we did not specify mathematical models for each layer here, the other layers may also contain mathematical models, depending on the system evaluation needs.

Finally, it has to be underlined that there is no single correct manner for the ontological representation of a system. The described above systems could be approached from various perspectives at various levels of detail. In other words, which 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 parks – 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 [54]. 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. [14]

Table 1: The relevant eco-industrial park concepts.

Classes	Definition
<i>IndustrialSymbiosis</i>	Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products [55].
<i>Eco-industrialPark</i>	An <i>Eco-industrialPark</i> is a concrete realization of the industrial symbiosis concept. It is composed of several subsystems, where the park occupants collaborate to minimize material and energy waste through reuse networks that reduce environmental impact while increasing or maintaining profitability. [2, 55]
<i>WaterNetwork</i>	A <i>WaterNetwork</i> is also known as water distribution system. It represents a type of industrial symbiosis realization where industry entities collaborate with each other via the exchange of water streams. [3, 1]
<i>EnergyNetwork</i>	An <i>EnergyNetwork</i> is an industrial symbiosis realization via the exchange of energy streams. [1]
<i>MaterialNetwork</i>	A <i>MaterialNetwork</i> refers to any type of material exchange among the possible entities (can be operation units, chemical producing processes, and manufactory plants that are of the same or different types) represented in an EIP. [1]
<i>ElectricPowerSystem</i>	An <i>ElectricPowerSystem</i> is a network of electrical components, including power generation, power transmission, transforming and power consumption, deployed to supply, transfer, and utilise electric power.
<i>TransportationNetwork</i>	A <i>TransportationNetwork</i> is a realization of a spatial network, describing a structure which permits either vehicular movement or flow of some commodity.
<i>ChemicalPlant</i>	A <i>ChemicalPlant</i> 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 give a 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 from 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. The project intends to develop an expert system called J-Park Simulator (JPS), which is a quantitative simulation environment built upon a virtual, hierarchical representation of an EIP. The representation involves not only data, but importantly also physical or surrogate models, which encode knowledge about the behavioural characteristics of the represented entities to be used in simulations, optimisations, inference and reasoning. It is noted that the notion *MathematicalModel* is defined for the description of the behavioural aspect of a *System*, which implies that a system of any level that is modelled in the current work may have its mathematical model representation. We would like to stress out that, at the current stage, the mathematical models are first encoded into an executable format, i.e. MATLAB files, MoDS projects and GAMS codes. While building the ontological knowledge bases (OKBs), information about the executable files/projects, such as the location of the executable and other required auxiliary documents, is then included in the OKBs, so that it can be readily solved by the corresponding commercial software package. However, this is not the only and final solution for the mathematical model description. We also represent the mathematical models in GAMS syntax, which is then included in the OKBs and can later on be utilized to formulate GAMS project and solved. For the future development of the project, it is very likely that detailed information about the mathematical models, such as its parameters, variables, boundaries *etc.*, will be further reflected in the ontology, thus to facilitate more flexible and efficient ways of problem solving as well as application requirement. 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
<i>Organization</i>	An <i>Organization</i> is a group of people, companies, or countries, which is set up for a particular purpose [56].
<i>DesignCapacity</i>	<i>Capacity</i> denotes the maximum amount of product that a factory, company, machine etc. is designed to produce or deal with. [57]
<i>AddressArea</i>	An <i>AddressArea</i> represents the geographic location on the Earth's surface where a system resides, it provides the connection to the road network. [58]

<i>GeographicCoordinateSystem</i>	A <i>GeographicCoordinateSystem</i> 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. [59]
<i>ProjectedCoordinateSystem</i>	A <i>ProjectedCoordinateSystem</i> is defined on a flat, two-dimensional surface. It has constant lengths, angles, and areas across the two dimensions. [60]
<i>Cost</i>	<i>Cost</i> describes all kinds of costs that may arise with respect to producing a product.
<i>CapitalCost</i>	<i>CapitalCost</i> 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. [61]
<i>OperatingCost</i>	<i>OperatingCost</i> 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. [62]
<i>LaborCost</i>	<i>LaborCost</i> denotes the expenses which are related to manpower for the operation of a business or a system.
<i>Earnings</i>	<i>Earnings</i> denotes the net benefits of a corporation's operation. [63]
<i>Price</i>	<i>Price</i> denotes the currency per unit weight of a product. [64]
<i>PollutantEmission</i>	<i>PollutantEmission</i> represents the pollutant (liquid or gaseous) discharged from a possible entity (can be an operation unit, a chemical plant, a building or an industrial park) to the environment.
<i>Resource</i>	<i>Resource</i> denotes natural, or commercial resources that could be used to produce certain type of products.

<i>Product</i>	<i>Product</i> denotes for an economic goods or service.
<i>SurrogateModel</i>	A <i>SurrogateModel</i> , also known as metamodel, reduced order model or response surface model, is an approximation model that mimic the behavior of the simulation process as closely as possible while being computationally cheaper to evaluate [65, 66].

4.2. Ontological representation of chemical industry

Process and unit level ontologies are already well established in OntoCAPE, thus this study mainly focuses on ontologies at resource network level, plant level and industrial park level. The term industrial symbiosis defined by Chertow [55] 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 [1]. Other important concepts are the the electric power system and the 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 [5]. Through the network, the waste and 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 a description of a 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 [5]. 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 material sources. It should be noted that the widely studied water network, as one type of industrial symbiosis system, is

regarded as one type of material network in this work. 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, the physical location (noted as *AddressArea*) is 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-referencing 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 material sources.

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

(a) Representing a chemical plant.

(b) Representing the physical address of an entity.

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

Table 3: Relevant terminology for resource network representation.

Classes	Description
<i>Source</i>	A <i>Source</i> represents a place, organization, or process from which a particular resource can be obtained.
<i>Sink</i>	A <i>Sink</i> denotes a place, organization, or process that consumes a certain type of resource.
<i>UtilityHub</i>	A <i>UtilityHub</i> is a centralized infrastructure that serves as storage tank to help the management of utility distribution.
<i>NetworkInfrastructure</i>	A <i>NetworkInfrastructure</i> 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 systems are 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 [67]. 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 [68]. 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 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 transferred to the distribution system via transmission lines. High voltage (HV) transmission lines are used for long distance electric power transmissions (from the 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 [67]. Utilization subsystems (loads) are categorized into industrial, commercial, and residential. Industrial loads refer

to manufacturing 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 and 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 domains of expertise, which is illustrated in Fig. 10.

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

Figure 10: Representing a pump, both as a plant item of a chemical plant and as a power load in the corresponding power grid.

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 separate from the original model developer and maintainer [69]. 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 outsiders.

Fig. 11 is a schematic representation of the proposed decentralized information management system. It shows how the proposed ontological framework can be utilized to facilitate the establishment of a hierarchical information representation and sharing system for the participants in EIP. By ap-

plying 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 11: A schematic representation of the decentralized knowledge management system.

The proposed method is applied to Jurong Island, a 32 km² 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. 12 shows a snapshot of the ontological representation of Jurong Island. As is shown, Jurong Island is an 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. 13 gives the ontological representation for a bio-fuel plant. It takes methanol and tripalmitin as raw materials, producing biodiesel as the main product and glycerol as by-product. It discharges waste steam and CO₂ 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. 14, 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 groups of people with authorizations. Fig. 15 illustrates a 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. 16. The yellow node sitting in the middle represents Jurong Island, while the pink nodes connected to it represent the subsystems (chemical plants, electrical power system, transportation system, etc.).

Figure 12: Ontological representation of Jurong Island, showing the subsystem, including chemical plants, electrical power system, transportation system, water network system and so on.

Figure 13: Ontological representation of the Ibris Bio-fuel Plant, showing its physical address, raw material, product, and pollutant emission.

Figure 14: Ontological representation of a biodiesel producing process, showing the technical components (machines and equipments) that compose the process system.

Figure 15: 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.

Given the OKB shown in Fig.16, the utility of ontology could be realized through various applications and facilitating industrial symbiosis could be a good demonstration. Intra-plant waste heat utilization is given as an example in the paper - there are five different chemical plants on Jurong Island EIP and each plant has its own utility supplier. A plant may waste some hot streams which it may not need but could be useful for other plants as shown in Fig.17. One main obstacle to establish such IS connections comes from the information interoperability, this is where our OKB could help to enhance information integration. In the given case, different chemical plants use different terminologies to describe the waste heat conception: plant A uses *waste* whereas plan B uses *by-product*. In such context, the reasoner of

our ontology, together with the object properties (e.g. axiomatic constructs), is smart enough to figure out that *waste* and *by-product* are equivalent as shown in Fig.17. Based on such inference functionality of ontology, intra-plant waste heat utilization opportunities could be better found. This is a small case study to demonstrate how our OKB could be used.

Figure 16: 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.

Figure 17: OKB enabled Industrial Symbiosis (IS) and intra-plant waste heat utilization on Jurong Island through reasoning functionality.

6. Conclusion and future work

This paper presents a skeletal ontology for the information modeling and management of eco-industrial parks (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 a general description of the EIP as a whole. Industrial networks describes at the resource network (water network, energy network and material network) in EIP and their supporting engineering systems, namely the electrical power system and transportation network. Groups of manufacturing processes are represented at the plant level. *The process level holds a description of individual manufacturing processes, while the unit level reflects knowledge of the unit operations.*

Based on such conceptualization framework, detailed serialization of ontological modeling of EIP is achieved in the paper. The ontology consists of several parts including eco-industrial park, resource network, chemical plant, transportation network, and electrical power system as well as several other modules adapted from OntoCAPEs modules (chemical process system and 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 elabo-

rated on 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 interoperability of information could be improved to facilitate industrial symbiosis. The proposed methodology is applied to Jurong Island in Singapore. [A set of ontological knowledge bases is developed for the represented entities and intra-plant waste heat utilization is used to show the advantages of the proposed ontology for information sharing.](#)

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, it is already clear that the ontology needs to be improved, with moderate efforts, for other applications. On top of the Ontological Knowledge Base (OKB), agents with different capabilities are going to be developed to carry out desired activities, such as system self-diagnosis, 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. The capabilities that ontology has to reconcile data heterogeneity and promote knowledge sharing make it an indispensable ingredient on the road map towards future smart eco-industrial park. We believe much more potential for the EIP's optimal operation could be unleashed given the growing data availability and machine computational power. We hope this work would appeal to more collaborative efforts towards the future smart EIP.

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Supporting Materials

Supporting online materials are available for this paper at <https://github.com/chuanzhang1990/OntoEIP>.

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