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Knowledge management of eco-industrial park for efficient energy utilization through ontology-based approach

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HIGHLIGHTS

- An intelligent energy management system for Eco-Industrial Park (EIP) is proposed.
- An explicit domain ontology for EIP energy management is designed.
- Ontology-based approach can increase knowledge interoperability within EIP.
- Ontology-based approach can allow self-optimization without human intervention in EIP.
- The proposed system harbours huge potential in the future scenario of Internet of Things.

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ABSTRACT

An ontology-based approach for Eco-Industrial Park (EIP) knowledge management is proposed in this paper. The designed ontology in this study is formalized conceptualization of EIP. Based on such an ontological representation, a Knowledge-Based System (KBS) for EIP energy management named J-Park Simulator (JPS) is developed. By applying JPS to the solution of EIP waste heat utilization problem, the results of this study show that ontology is a powerful tool for knowledge management of complex systems such as EIP. The ontology-based approach can increase knowledge interoperability between different companies in EIP. The ontology-based approach can also allow intelligent decision making by using disparate data from remote databases, which implies the possibility of self-optimization without human intervention scenario of Internet of Things (IoT). It is shown through this study that KBS can bridge the communication gaps between different companies in EIP, sequentially more potential Industrial Symbiosis (IS) links can be established to improve the overall energy efficiency of the whole EIP.

1. Introduction

Based on synergy through cooperation between physically proximate businesses within a certain region, Eco-Industrial Park (EIP) is becoming a popular form of industry cluster. According to US Environmental Protection Agency (EPA), EIP is defined as "a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only" [1]. The key concept behind EIP is Industrial Symbiosis (IS), which requires an industrial system to be viewed not in isolation, but in concert with it surrounding systems [2]. In EIP, resources, including but not limited to materials, energy, water and information, can be reused at different levels through networks, both *intra-company* and *inter-company*, such that collective benefits can be achieved. These networks, and the processes through which they are generated, display a complexity and variety that is still poorly understood. Particularly for the energy networks in EIP, they are quite different from traditional urban or industrial energy systems [3]; because many companies in EIP produce and consume energy at the same

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time, this shift from consumer to prosumer blurs the distinction between supply side and demand side in energy systems, which brings additional complexity to the design and optimization of EIP energy systems [4,5]. The typical schematic of EIP energy system is shown in Fig. 1. As shown in Fig. 1, in EIP there are usually multiple companies serving as part of the energy network; sequentially, knowledge management becomes a main barrier for efficient energy utilization in EIP. Knowledge management refers to the process of creating, sharing and using knowledge; in the context of EIP, since there are various companies participating in the IS, thus there is possibility that one company is not aware that its waste energy can be utilized by other companies and viceversa. To overcome such heterogeneity, there must be a bridge linking all the companies together in terms of knowledge sharing; usually Knowledge-Based System (KBS) plays such a role.

A Knowledge-Based System (KBS) is defined as "a computer program that reasons and uses a knowledge base to solve complex problems" [6], the complex problem in this paper turns out to be energy utilization in EIP. In a broader sense, KBS belongs to the so-called Information and Communication Technologies (ICT). In fact, in 2008 the European Union (EU) pointed out that "addressing the challenge of energy efficiency through information and communication technologies" could significantly improve the energy efficiency across the whole society [7]. Unsurprisingly, application of KBS in energy sector has become an active area of research for the past two decades. James et al. [8] developed KBS for integrated modelling of urban energy system, the database of this tool contains models of different energy conversion and transportation technologies; the tool was applied to a case study of a UK ecotown and it showed its capability to screen the most proper energy conversion technologies and transport network for the town. Kontopoulos et al. [9] presented a KBS approach for optimizing domestic solar hot water system. The main function of the delivered approach is decision making support. In their research, the KBS was able to select the optimum system configuration according to different criteria through a user-friendly online interface. Ramakumar et al. [10] presented a KBS approach for the design of integrated renewable energy system. This approach can find the optimal combination of renewable energy sources and end-use technologies based on lowest capital cost criteria. The usefulness of the proposed approach is proved through an application case of renewable energy system design. Abbey et al. [11] proposed a KBS for control of two-level energy storage for wind energy system. The knowledge-based management algorithm can better schedule the power from two levels compared to an alternative scheduling approach. In such a context, the proposed study aims to demonstrate the possibility of using KBS to increase energy efficiency of EIP.

The necessity and benefits of applying KBS in EIP energy management are also closely related to the emerging trend of Industry 4.0 and Internet of Things (IoT). Industry 4.0 is a newly emerging conception of industrialization, it creates what has been called a "smart factory" [12]. Within the modular structured smart factories, cyber-physical systems monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. In the future scenario of Industry 4.0, networking and integration of different companies through consistent integration of information and communication technology is allowed. IoT is a key enabler for Industry 4.0. IoT allows to collect and exchange data through network. However it is expected that during the data fusion process, great difficulties will emerge: for instance, two databases from different sources may use different identifiers for the same concept; or the statistics from one agent can serve as feed stream for another software agent while the format heterogeneity between them will hinder the possibility of autonomous communication. In all these cases, an ontology intermediary to enhance the performance of linked data which means that the capability of KBS to deal with complex and unstructured data, makes it indispensable in knowledge management of complex systems such as EIP.

In the future scenario of Industry 4.0 and IoT, knowledge management in EIP could be totally different from what it is now. The current design and optimization approaches that need large-scale human intervention will not be suitable in such application contexts. Considering the complexity and heterogeneity of processes and operations occurring in EIP, traditional human-based approaches may need to deal with large amount of information every day, which would result in huge human resources to be consumed. Hence developing KBS that can properly handle the complex and unstructured big data from EIP seems to be a promising trend in the future scenario of Industry 4.0. At least two requisites must be fulfilled in order to develop such a KBS: firstly, an explicit knowledge base that contains core concepts as well as the relationships between the concepts within the domain of discourse should be designed; secondly, the syntax and semantics of knowledge representation must be both human-readable and machine-interpretable to enable effective communication not only between people, but also between machines. In this context, ontology-based approach becomes a perfect candidate due to its abilities in tackling these problems.

Based on these background introductions, an ontology-based approach for knowledge management of EIP is proposed in this paper. Specifically, firstly a systematic ontology data framework that can serve as an overall knowledge repository for EIP energy system is established; secondly, a KBS based on such an ontology, namely J-Park Simulator (JPS), is described in the paper; finally, the advantages of KBS based EIP energy management are demonstrated through a case study. Under such an arrangement, the reminder of this paper is structured as follows: Section 2 gives a brief introduction about the fundamentals of ontology, the development of EIP energy system domain ontology is also described in this section; Section 3 describes the ontology-based KBS named JPS; Section 4 presents the results and discussion of a case study which demonstrates the system capabilities in reconciling semantic heterogeneity and intelligent decision making; Section 5 summarizes the accomplishments and indicates the roadmap for future work.

2. State of the art: why ontology?

A key concept in the proposed KBS is ontology. Ontology, philosophically representing "theory of existence", is defined as explicit description of domain conceptions and their relationships in engineering science. While ontology has been an active tool in the community of artificial intelligence for several years, only recently is gaining popularity in many other disciplines, such as gene informatics, medicine and energy [13–15]. Three basic components of ontology are: *classes* which correspond to concepts in natural language, *slots* which correspond to attributes of concepts, *instances* which correspond to examples of certain concepts. More complex ontology may also have object properties which describe the relationship between different classes as well as rules and axioms [16]. Since ontology is formalized conceptualization, it needs to be populated with instances. A simple example of ontology is given here to facilitate the understanding of it. In this example, the knowledge "water has boiling point of 100 °C" is meant to be shared. So, firstly *classes* (i.e. material, property and value) need to be defined; for then *slots* (i.e. magnitude and unit) are defined; also, the relationship between *slots* and *classes* needs to be defined (i.e. "material has property, property has value"); and finally, "water", "boiling point" and "100 °C" are assigned as *instances* of material, property