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Applying Industry 4.0 to the Jurong Island Eco-industrial Park

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Abstract

This paper presents new insights into the implementation of Industry 4.0 technologies (novel mathematical and computer-based methods) for designing and optimising the eco-industrial park (EIP) of Jurong Island in Singapore. The concept of Industry 4.0 translation to an EIP is introduced, which delivers an expert system allowing users to monitor, control, and optimise the social, economic and environmental repercussions of the industrial activities on Jurong Island. This expert system is a cyber-infrastructure making use of the latest advances in high performance computing (HPC), advanced mathematical modelling, and semantic web technologies. The proposed work addresses end-user driven demands by harnessing HPC resources and advanced data analytics to enable intelligent design, operation, and management of all entities on Jurong Island. The outcome of the work can serve stakeholders from both the private and public sectors.

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Keywords: Eco-industrial park; cyber-infrastructure; high performance computing (HPC); mathematical modelling; semantic web

1. Introduction

The concept of eco-industrial parks (EIPs) has recently become the subject of a great deal of attention from industry and academic research groups. The interest stems from the structural ability of an EIP to create more sustainable industrial activities through the use of localised symbiotic relationships [1]. An EIP is an industrial park where businesses cooperate with each other and, at times, with the local

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community to reduce waste and pollution, efficiently share resources (such as information, materials, water, energy, infrastructure, and natural resources), and minimize environmental impact while simultaneously increasing business success.

Numerous aspects of EIPs have been widely studied in the expert literature over the past decade. Currently, the primary existing way to design an optimal EIP is to create the exchanges of materials, water and energy through a network between tenants of the EIP, where the benefits are evaluated based on improvements to social, economical and environmental impacts. Mathematical programming optimisation is the main approach for solving EIP problems. Keckler and Allen [2] used linear and other mathematical programming approaches to evaluate water reuse opportunities for retrofitting industrial water networks, and stated that the linear programming method may be a useful tool for approaching a wide variety of material flow analyses in their work. Liao et al. [3] developed a two-stage method to consider multiple plant water networks, where the connections between plants and the target of fresh water usage were determined with solving a mixed integer nonlinear programming (MINLP) formulation in the first stage, and a mixed integer linear programming (MILP) problem is formulated to achieve a flexible water network to meet the freshwater target in all periods in the second stage. The MIND method (Method for analysis of INDustrial energy systems) based on MILP was developed by Karlsson [4] to optimise industrial energy systems from the food industry to the pulp and paper industry, where the main issues stated by the European Commission were considered, such as reduction of greenhouse gas emissions, improvements regarding security of supply and increased use of renewable energy. Kantor et al. [5] introduced life cycle concepts into the optimisation of hydrogen production in an EIP, and applied LCA metrics and methods to optimise a system of production processes with the optimisation of materials and energy usage. More recently, Cimren et al. [6] incorporated mathematical programming techniques into a graphical software package called Eco-Flow™, which was applied to model and analyze available synergies in an existing by-product synergy (BPS) network centered in Kansas City, Missouri. They also stated that their modelling approach was being extended to better represent the dynamics of industrial and ecological processes.

There are various strategies have been reported to achieve optimisation in an EIP. However, as discussed by Boix et al. [1], the optimisation of EIP lies on the decoupling of networks at the present state, and the existing research is based on either the water network, or the energy links or waste disposal facilities, typically focusing on a single aspect of the three. The optimal symbiotic relations among industries in an EIP require considering all resources simultaneously within the whole network. More importantly, variability of resource supplies should be addressed in more realistic model due to inherent uncertainties. Complete understanding of the complexity of these issues requires a substantial amount of supporting data relative to each potential member of the EIP. Thus, this paper presents a new insight on implementing Industry 4.0 technologies to overcome the aforementioned barriers, where a cloud-based cyber-infrastructure of a virtual EIP is developed with the use of high performance computing (HPC), advanced mathematical modelling and semantic web technologies. Several aspects of the technical problems that arise in terms of model building, data representation and uncertainty are addressed in Kraft and Mosbach [7] and will form the important elements of the virtual EIP. The paper is structured as follows. First of all, Jurong Island is introduced, and the issues that exist for the stake holders are identified, followed by the discussion of Industry 4.0 translation to Jurong Island. Finally, the modelling methodologies used for the EIP cyber-infrastructure of Jurong Island are presented.

2. Jurong Island in Singapore

Jurong Island is an artificial island created by land reclamation based around seven offshore islands. The land space is occupied by a large industrial park spread over an area of approximately 32 square kilometers which forms an important part of Singapore's economy. More than 100 companies are resident on Jurong Island, the most prominent being ExxonMobil, Shell, BP, Singapore Petroleum Company, LANXESS, BASF, Celanese, Evonik, DuPont, Mitsui Chemicals, Chevron Oronite, and Sumitomo Chemical all of which produce a wide range of products including petroleum products, fine chemicals and pharmaceuticals, as shown in Fig. 1.

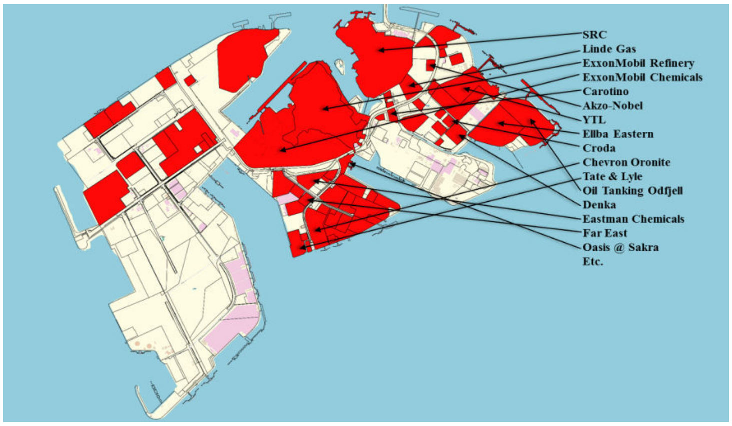

Fig. 1. Map of Jurong Island in Singapore.

The overall investment in Jurong Island is in the order of S$50 billion. In addition to the various manufacturing plants, a considerable infrastructure has been created to serve both industries and employees. The density of industrial activities in the area leads to a substantial release of greenhouse gases, amounting to up to 30% of the total greenhouse gas emissions in Singapore. Such a concentration of industrial installations raises concerns which have to be carefully taken into account to ensure the safety of the employees and the environment. A further important feature of Jurong Island is its continual growth, which creates a very dynamic environment with respect to all of the aspects described above. The growth and development of Jurong Island currently does and will continue to play a very important role to the overall economic growth of Singapore. Thus, the successful operation and development of the infrastructure and industries on Jurong Island is a challenging task.

3. Industry 4.0 concept for EIP modelling

Industry 4.0 is a term that originated in the area of manufacturing engineering and represents the fourth industrial revolution: the ability of industrial components to communicate with each other. This communication may be within intranet facilities or external internet and will lead to datasets which are too big to be stored in a conventional database structure. Hence, technologies for the analysis of "Big Data" will have to be employed to adequately control and manipulate these datasets.

In order to achieve this, it is proposed to associate each technical component in a plant with its own semantic representation which will also include executable mathematical models. These models are fed data from sensors in each device using techniques developed from machine learning and statistics. A plant forms a network of such models which can, in turn, be represented by a surrogate model after employing model reduction techniques. The process by which these semi-empirical models are formed requires analysis of the vast amounts of data that are constantly being produced by the plant. Fig. 2 describes the framework of EIP modeling based on Industry 4.0.

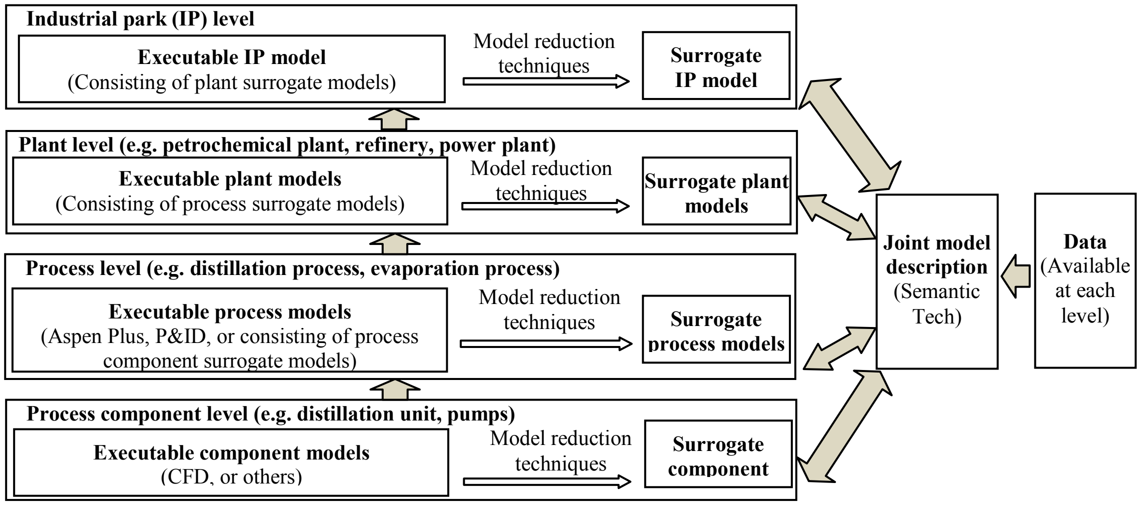

Fig. 2. Framework of EIP modelling based on Industry 4.0.

It is also envisaged that this system will make it possible to facilitate the automation of process planning, commissioning, and controlling a safely operating chemical plant. As a consequence, economic, social, and legal requirements will form the boundary conditions for an industrial plant's structure and operation without additional human intervention. For example, an order for a certain reactant will be automatically placed when the filling level of a vessel is below a predefined threshold or stirrer intensity will be increased as newly available physical data leads to a different optimal operating point.

4. Methodologies of modelling Jurong Island EIP

The idea of an EIP is to harness the synergy of having many industrial plants in close proximity. For example, the water and steam distribution networks can be optimised over a whole ensemble of chemical plants. However, the mathematical optimisation is normally performed using simplified models of specific aspects of the eco-park which can lead to substantial discrepancies. The development of a virtual Jurong Island which would allow for dynamic changes that also takes constant data flow into account would enable many such issues to be studied and resolved. In this virtual Jurong Island, each physical entity will have an avatar in the cyber-infrastructure. The proposed EIP expert system's aim is to answer important questions from stakeholders regarding social, economic, and environmental aspects.

In this work, the methodologies of modelling an internal combustion (IC) engine as proposed by Smallbone et al. [8] and Brownbridge et al. [9] is adapted to address EIP modelling, which can be separated into three sub-components, data extraction and conversion, data storage and representation, and model validation, optimisation and visualisation.

4.1. Data extraction and conversion

The physical entities of Jurong Island are represented by chemical plants, refineries, power stations *etc*. In order to successfully model Jurong Island, useful data must be obtained for use in analysis or modelling, sometimes taking the form of physical observations. Observations are usually carried out using electronic devices which are used to produce plant operating data such as pressure, temperature and flow-rate measurements, resource consumption, and CO_2 emission. Collected data must then be converted to a usable format, which can be accomplished by storing the data and converting it to something useful via an instrumental model. The conversion incurs additional uncertainty, as it is often based on a set of parameters determined from correlations, hence the associated error must also be stored and its influence considered whenever adopted.

4.2. Data storage and representation

In this work, eXtensible Markup Language (XML) is used as the fundamental code of EIP data storage and representation. It is important that any EIP database structure should be built for the long term, hence XML is considered the most favourable because it has a tree-like structure, and is both human and machine readable with many programming languages carrying the I/O libraries. Its structure is fully extensible allowing for the easy addition of future model developments. It also has an open standard and is platform independent and thus is ideal for Process Informatics approaches. In addition, an XML schema can be adopted to ensure consistency between files created from multiple users and multiple programs, which is important in large collaborative research activities such as model development. XML has been successfully used for the IC engine data model reported by Smallbone et al. [8] and Brownbridge et al. [9], who also transformed XML data in such a way that the semantic relationship of the data resource is defined using a proper statement of RDF (Resource Description Framework) firstly, and URI (Uniform Resource Identification) is utilized to uniquely identify each resource whilst containing the full information about its higher level resources. These proposed semantic web technologies can be adopted to create a shared data model resource for the EIP development community.

4.3. Model validation, optimisation, and visualisation

An advanced software tool, MoDS (Model Development Suite) [10], is utilised for model validation, optimisation and visualisation. Fig. 3 presents the model development process based on the methodologies. The procedure of using MoDS for modelling has been simplified through an intuitive user interface which supports the design process and guides the users through the following work-flow: (a) Start from an initial raw data exploration, MoDS supports querying and filtering of large data sets in multiple formats. (b) Help data selection through flexible plotting of the raw data and key subsets. (c) Configure and set-up model or user defined mathematical expressions with intelligent error checks. (d) Execute and batch processing of the model according to the selected chain of algorithms. (e) Flexible data collation: post-processing, querying and plotting of model and algorithm outputs.

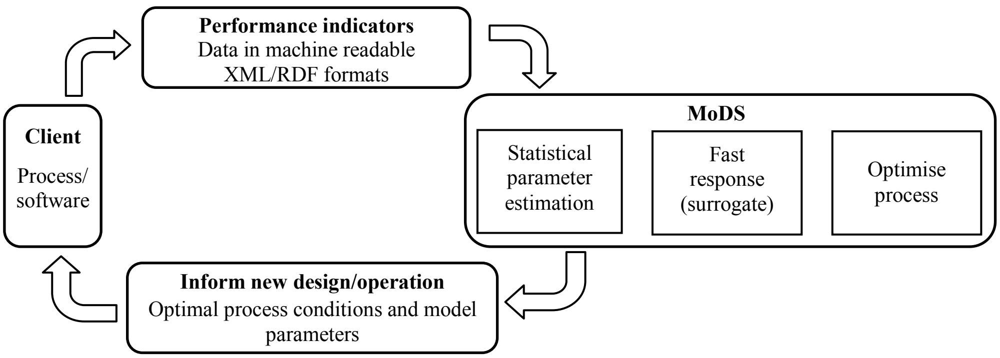

Fig. 3. The proposed model development process.

5. Conclusions

To achieve the reality of Jurong Island EIP, a set of specific tasks has been considered, including semantic representation of data, models, and algorithms, detailed process models on different scales, parameterisation of high-dimensional models, numerics of networks of parameterised models, geographic representation of industrial park for virtual reality, and evaluation of models with global sensitivity and uncertainty analysis. The aim of the work is to enable stakeholders to make informed decisions on how to reach their strategic targets in the optimal way whilst minimising their environmental impact.

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Biography

Dr. Markus Kraft is a Professor in the Department of Chemical Engineering and Biotechnology, University of Cambridge and the director of the Singapore-Cambridge CREATE Research Centre. He has a strong interest in the area of computational modelling and optimisation targeted towards developing carbon abatement and emissions reduction technologies.