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Design technologies for eco-industrial parks: From unit operations to processes, plants and industrial networks

Ming Pan [a], Janusz Sikorski [a], Jethro Akroyd [a], Sebastian Mosbach [a], Raymond Lau [b], Markus Kraft [a,b,*]

[a] Department of Chemical Engineering and Biotechnology, University of Cambridge, New Museums Site, Pembroke Street, Cambridge CB2 3RA, UK
[b] School of Chemical and Biomedical Engineering, Nanyang Technological University, 62 Nanyang Drive, 637459, Singapore

HIGHLIGHTS

- A four-level modelling framework is built for the EIP research.
- Advanced mathematical modelling approaches are proposed for each level of problem.
- Efficient optimisation methodologies are developed for solving EIP problems.
- Industrial symbiosis is addressed combining material, water and energy networks.

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ABSTRACT

The concept of eco-industrial park (EIP) has recently become the subject of a great deal of attention from industry and academic research groups. This paper proposes a series of systematic approaches for multi-level modelling and optimisation in EIPs. The novelties of this work include, (1) building a four-level modelling framework (from unit level to process level, plant level and industrial network level) for EIP research, (2) applying advanced mathematical modelling methods to describe each level operation, (3) developing efficient methodologies for solving optimisation problems at different EIP levels, (4) considering symbiotic relations amongst the three networks (material, water and energy networks) at the top EIP level with the boundary conditions of economic, social and legal requirements. For methodology demonstration, two cases at process level and industrial network level respectively are tested and solved with the developed modelling and optimisation strategies. Finally, the challenges and applications in future EIP research are also discussed, including data collection, the extension of the current networks to EIPs, and the feasibility of the proposed methodologies for complex EIP problems. The extended EIPs include the combination of material exchanges, energy systems and waste-water treatment networks. The aspects considered for future industrial ecology are carbon emission, by-product reuse, water consumption, and energy consumption. The main object of this paper is to explain the detailed model construction process and the development of optimisation approaches for a complex EIP system. In future work, this system is expected to share services, utility, and product resources amongst industrial plants to add value, reduce costs, improve environment, and consequently achieve sustainable development in a symbiosis community.

1. Introduction

Numerous aspects of eco-industrial parks (EIPs) have been widely studied over the past decades. According to Chertow [1], in an EIP system, businesses cooperate with each other and the local community to reduce waste and pollution, efficiently share resources (such as information, materials, water, energy, infrastructure, and natural resources), and minimise environmental impact to increase business success. Several definitions for the concept of EIP have been reported in the literature. However, a basic principle for EIP is that the total benefit (improvements to social, economic and environmental impacts) achieved by working cooperatively is higher than working as a standing alone facility [2]. Kastner et al. [3] reviewed the recent developed quantitative tools and methods identifying and cultivating industrial symbiotic exchanges in existing industrial parks to minimise overall energy

* Corresponding author at: Department of Chemical Engineering and Biotechnology, University of Cambridge, New Museums Site, Pembroke Street, Cambridge CB2 3RA, UK.

E-mail address: mk306@cam.ac.uk (M. Kraft).

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Nomenclature

Indices

- d — demand that can receive materials with land transportation
- ds — demand that must receive materials with sea transportation
- i — input parameters of an HDMR surrogate model (Eqs. (1) and (2))
- j — input parameters of an HDMR surrogate model (Eqs. (1) and (2))
- r — source that can transport their materials with land transportation
- rs — source that need to transport their materials with sea transportation

Sets

- D — set of all demands that can receive materials with land transportation
- D_s — set of all demands that must receive materials with sea transportation
- R — set of all sources that can transport their materials with land transportation
- R_s — set of all sources that need to transport their materials with sea transportation

Parameters

- acf — annual cost factor
- $A_{i,k}$ — the first order coefficients in a reformatted surrogate model (Eq. (3))
- $B_{i,j,k,n}$ — the second order coefficients in a reformatted surrogate model (Eq. (3))
- C — constant term of a reformatted surrogate model (Eq. (3))
- $celp$ — CO_2 emission per material amount and distance for land pipelines
- cet — truck CO_2 emission for transporting per material amount per distance
- $cewp$ — CO_2 emission per material amount and distance for short-sea pipelines
- $clpt$ — transportation cost per material amount and distance for land pipelines
- $cset$ — short-sea shipping CO_2 emission for transporting per material amount per distance
- $csst$ — short-sea shipping transportation cost per material amount and distance
- ct — truck transportation cost per material amount and distance
- $ctax$ — carbon tax
- $cwpt$ — transportation cost per material amount and distance for short-sea pipelines
- dj_d — total amount of material transported to demand d
- djs_{ds} — total amount of material transported to demand ds
- $drt_{r,d}$ — distance between source r and demand d
- $dwt_{rs,ds}$ — sea distance between source rs and demand ds
- f_0 — mean value of $f(x)$ in an HDMR surrogate model (Eqs. (1) and (2))
- $iclpt$ — installation cost per distance for installing land pipelines
- $icwpt$ — installation cost per distance for installing short-sea pipelines
- ify — interest factor of the project lifetime
- ip_r — prices of source r sold in the local market
- ips_{rs} — prices of source rs sold in the local market
- k — exponent of x_i in a reformatted surrogate model (Eq. (3))
- K — maximum exponent of input parameters in a reformatted surrogate model (Eq. (3))
- M — a sufficiently large positive number
- N — number of input parameters of an HDMR surrogate model (Eqs. (1) and (2))
- n — exponent of x_j in a reformatted surrogate model (Eq. (3))
- pri_r — production of source r
- $pris_{rs}$ — production of source rs
- x_i — input parameters of a reformatted surrogate model (Eq. (3))
- x_j — input parameters of a reformatted surrogate model (Eq. (3))
- y — function value of a reformatted surrogate model (Eq. (3))

Variables – Continuous

- $clpt_{r,d}$ — transportation CO_2 emission for transporting source r to demand d with land pipelines
- $crt_{r,d}$ — transportation CO_2 emission for transporting source r to demand d with trucks
- $cwpt_{rs,ds}$ — transportation CO_2 emission for transporting source rs to demand ds with short-sea pipelines
- $cwt_{rs,ds}$ — transportation CO_2 emission for transporting source r to demand d with short-sea ships
- $ilptc_{r,d}$ — installation cost of land pipelines for transporting source r to demand d
- $iwptc_{rs,ds}$ — installation cost of short-sea pipelines for transporting source rs to demand ds
- $lptc_{r,d}$ — transportation cost for transporting source r to demand d with land pipelines
- $mit_{r,d}$ — amount of transporting source r to demand d with international shipping
- $mlpt_{r,d}$ — amount of transporting source r to demand d with land pipelines
- $mrt_{r,d}$ — amount of transporting source r to demand d with trucks
- $mwit_{rs,ds}$ — amount of transporting source rs to demand ds with international shipping
- $mwpt_{rs,ds}$ — amount of transporting source rs to demand ds with short-sea pipelines
- $mwt_{rs,ds}$ — amount of transporting source rs to demand ds with short-sea ships
- obj — total cost of the material network in a certain project lifetime
- ri_r — total amount of material transported from source r
- ris_{rs} — total amount of material transported from source rs
- $rtc_{r,d}$ — transportation cost for transporting source r to demand d with trucks
- tce — total material transportation CO_2 emission in a material network
- tpc — total material purchasing cost in a material network
- $wptc_{rs,ds}$ — transportation cost for transporting source rs to demand ds with short-sea pipelines
- $wtc_{rs,ds}$ — transportation cost for transporting source rs to demand ds with short-sea ships

Variables – Binary

- $it_{r,d}$ — 1 if source r is transported to demand d with international shipping; otherwise, it is 0
- $lpt_{r,d}$ — 1 if source r is transported to demand d with land pipelines; otherwise, it is 0
- $rt_{r,d}$ — 1 if source r is transported to demand d with trucks; otherwise, it is 0
- $wit_{rs,ds}$ — 1 if source rs is transported to demand ds with international shipping; otherwise, it is 0
- $wpt_{rs,ds}$ — 1 if source rs is transported to demand ds with short-sea pipelines; otherwise, it is 0
- $wt_{rs,ds}$ — 1 if source rs is transported to demand ds with short-sea ships; otherwise, it is 0