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Quantitative tools for cultivating symbiosis in industrial parks; a literature review

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Abstract

The quantitative tools and methods that have been developed to identify and cultivate industrial symbiotic exchanges in existing industrial parks to minimize overall energy consumption and material wastes are reviewed. The issues relevant to adapting an existing park differs from those associated with constructing a new park using eco-industrial principles. Published literature was surveyed for methodologies which identify and establish viable inter-company exchanges for water, heat, power and materials. Studies which address issues associated with infrastructure alterations are specifically highlighted, as well as methods to quantify and manipulate any potential financial and/or ecological benefits gained by adopting proposed eco-industrial measures. Additional topics, such as network analysis, company motivation, confidentiality issues and introduction of new industries or facilities are included. This review surveys current quantitative methodologies that can be applied to the process of adapting established industrial park networks into eco-industrial park systems and case studies which are pertinent to this type of adaptation.

Contents

1 Introduction

Every industrial concern, regardless of time frame or size, is interested in understanding and improving its manufacturing processes. The specific aspects that are the focus of such attention can change over time or location, but the drive to get the most finished product in the best way, using the least amount of materials, cost and expenditure of effort, is universal.

The oil crisis in the 1970's greatly increased interest in energy conservation and efficiency in industrial processes. Later, rising awareness of ecological issues created a widespread drive to simultaneously decrease environmental impact. At present, one of the means developed to accomplish all such goals is by minimizing material and energy use through recycling and redirecting unavoidable by-products to other local industries. This is not a new idea, as published works on making practical use of materials regarded as waste predate the 1900's [160]. The modern day practice of creating clusters of factories located in industrial parks facilitates the growth of localized exchange networks and has given rise to the concept of 'eco-industrial parks' (EIPs). In an EIP the park occupants collaborate to minimize material and energy waste through reuse networks that reduce environmental impact while increasing or maintaining profitability.

While self-interest motivates studying and improving company owned plants and any constituent processes, the concept of an EIP raises questions regarding activities between individual companies. Inter-company integration forms a new area of inquiry with respect to describing the interaction between various separately owned component plants. From a park point of view, the points of interest centre around the use of shared or pooled resources, inter-plant recycling and collective benefits, as opposed to the traditional individual company profit viewpoint. For example, if the interest is water usage, one could measure the amount of water an individual unit operation requires and ascertain if it is possible to reduce that amount, perhaps by upgrading the equipment. Alternately, on a plant scale, one can discuss the amount of water used by all processes and if it is possible to reuse or recycle the water from processes to minimize total plant water intake. In either case, changes could be implemented to make the plant more profitable and/or lessen the environmental impact of operating the plant. From a park perspective, the same questions apply, but the potential solutions become more complicated, as inter-company interests for profitability may not align with optimal water conservation methods. If the waste water can be directly used between one company and an other, it seems clear that both could benefit by its reuse, but if the water requires some form of treatment prior to reuse, the issue becomes less clear.

The cyclic nature of a water network can be generalized to describe the inflow and outflow of all materials in a single plant, internal processes, or as a superstructure consisting of multiple plants each with individual component processes. The traditional arrangement, illustrated in **Figure 1**, can be viewed as a linear process where each plant operates independently. In this structure, the park authority supplies specific plant operating intake needs, *e. g.,* water and electricity, and provides waste treatment services for all plants. **Figure 2** shows a graphical illustration of a generalized cyclical network for an EIP network. This networked structure allows the by-products of any subsystem (plant, process or waste treatment) to be available for treatment and/or reuse by every other subsystem. Under this

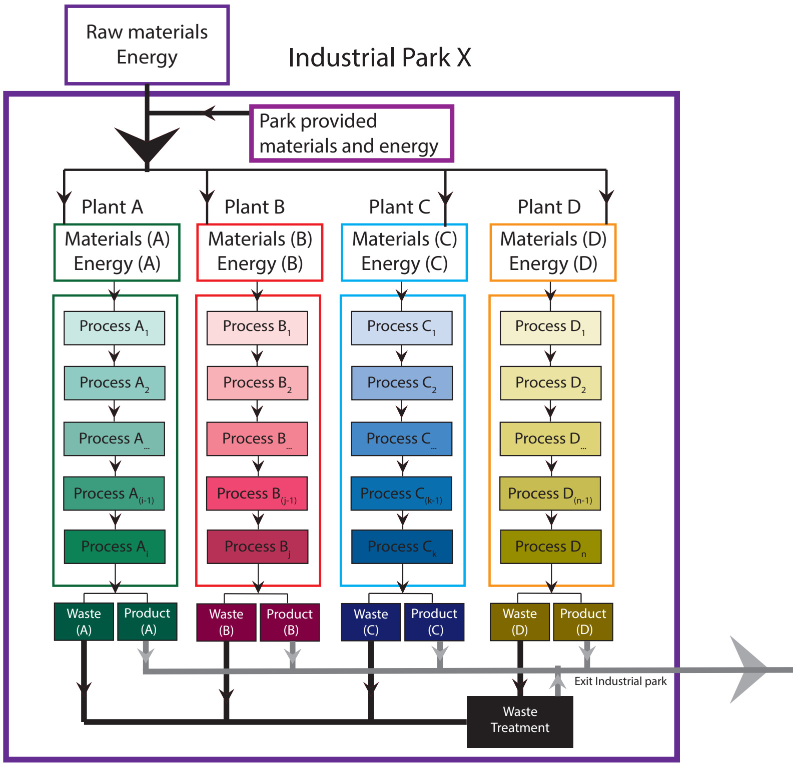

Figure 1: *Superstructure representation of an industrial park where the park provides some amount of utilities and waste treatment for discharge.*

idealized system, any input into the network can potentially be reused numerous times and only exits the network when it is unusable by any process in the park.

In an EIP framework, the features of interest become the connections and interactions between individual plants and how various occupants can benefit individually and collectively. In particular, the goal is to find ways to benefit multiple occupants, typically with respect to environmental impact, without jeopardizing individual profitability. Models of such systems tend to be centred on either specific goals, such as optimizing or system design, or areas of interest such as water use or greenhouse gases (GhGs) emitted.

The issues associated with cultivating EIPs have been studied from a wide range of perspectives, such as planning parks, behavioural types and developing metrics to assess the parks, among many other aspects [56, 85, 87, 91, 155, 174, 175, 178, 179, 185]. Chertow and Ehrenfeld [44] defined five types of existing eco-industrial park development models as:

- Build and Recruit; New construction where compatible industries are sought as occupants. Generally successful.
- Planned Eco-Industrial Park; Similar to Build and Recruit, but with a deliberate attempt to identify companies across different industries for inter-company exchanges, often with government support. Least successful type.

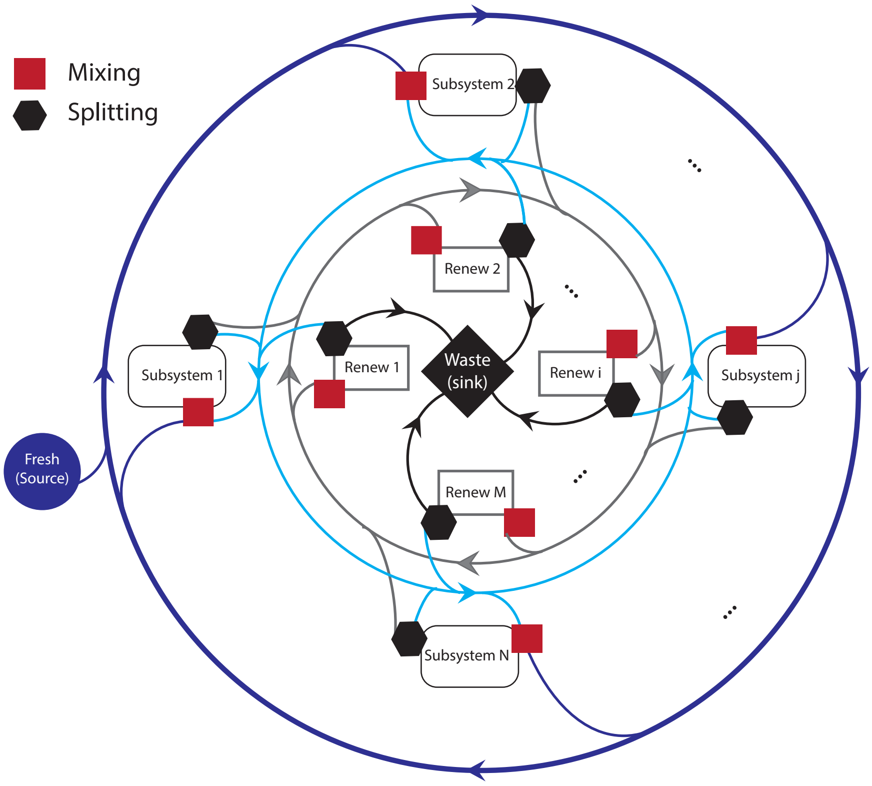

Figure 2: *Generalized network representation of a cyclical industrial network superstructure with N subsystems (or plants) and M regeneration (waste treatment) facilities.*

- Self-Organizing; Privately organized amongst occupants, generally exchanges develop from self-interest. Often unrecognized.
- Retrofit; Existing industrial parks are converted into EIPs. Success tends to be dependent on occupants' acceptance of ideas.
- Circular Economy; New form emerging in China intended to grow economy and reduce environmental impact simultaneously.

In this work, the interest is on the retrofitting scenario. Although there does not seem to be a definitive published figure, in 1998 it was reported that over 12,000 industrial parks existed worldwide [57], while another figure was given in 2011 as 12,000-20,000 [153]. The number of eco-industrial parks is equally vague, however figures given for 2001 range from at least 100–150 planned or operational [153]. The large number of existing parks, compared to existing or even planned EIPs, suggests that examining the quantitative methods and tools available to effectively retrofit an existing park is worthwhile. The prospect of retrofitting many of the existing parks seems desirable and, from a practical point of view, likely to be inevitable.

In the literature, there is rarely a clear distinction between quantitative methods which are directed towards designing an entire industrial park from the ground up and retrofitting an existing industrial park for more sustainable practices. Oftentimes the same methods can be used for both situations; however making alterations to existing structures has a different set of issues than new construction. The process of how to convert an industrial park into a more environmentally friendly eco-industrial park can be broken down into three elements. First, the park can be studied to identify potential connections between occupants. With a list of potential connections, various methods of constructing such connections can be explored. Lastly, new elements can be introduced into the park, such as carbon capture plants, additional wastewater treatment, renewable energy sources or new businesses which will create a reuse connection which did not previously exist.

The structure of this paper is as follows: Section 2 contains a list of quantitative case studies on existing parks and discusses models which have been developed to identify, describe or optimize network structures in an EIP. Section 3 reviews literature which has addressed construction aspects which arise with proposed alterations. In section 4, work which has included elements related to participant cooperation is described. The material presented in the previous sections is discussed in Section 5 to elucidate insights and review strategies which appear promising. In section 6 we make statements of general trends and make recommendations for future work.

2 Network modelling and optimization

The first consideration in creating inter-plant connections is to establish if any such potential connection does indeed exist. If a potential connection exists, then the second consideration is to establish if creating a connection would be economically or environmentally beneficial. For example, if waste heat from Plant A can be used in Plant B, a potential connection theoretically exists. However, if the distance between the plants is such that the heat will have dissipated before it arrives, such a connection is not viable. Further, as industrial concerns are first and foremost profit-making enterprises, any reuse/recycling scheme which will incur substantial additional costs is unlikely to be adopted unless there is a very favourable pay-back period.

The methods of modelling these quantities has typically been based on tools developed to optimize processes, such as pinch analysis or mixed integer linear programming (MILP) [64]. A review by Chen and Wang [41] provides a recent overview of methods developed for process system engineering over all the exchange and flow types. The process-level methods were adapted to deal with multiple processes, or an entire plant. Later, those same methods were again expanded to address inter-company exchanges. A single example of this progression is water cascade analysis. Initially developed for a single plant [119, 188], it was later adapted to inter-company networks [67]. Frequently in these studies, the line between plant-scale and inter-company scale becomes blurry. In this section we examine the modelling and optimization tools which have been developed to address the finding of potential, often optimal, connections to reduce resource usage by modelling and optimizing industrial park networks. A recent review by Boix et al. [30] provides a good overview of the current state of optimisation methods as relates to design issues for eco-industrial parks.

One often used abstract representation of an industrial process, or network, is as a collection of sinks and sources, as shown in **Figure 3**. Under this terminology, a sink is any process or plant which takes in, or consumes, a resource, and a source makes a resource available to the general system. External resources brought into the system are a source (entrance), while waste and finished products go an exit sink. Any single plant, process or treatment facility can be both a sink and a source simultaneously. Many studies have used a sink and source representation to describe a plant, particularly with respect to water networks however, this structure can easily be adapted to an entire industrial park (IP). If in **Figure 2**, a subsystem is defined as an individual plant which has an entire process network inside of it, the sink and source superstructure can be used to discuss exchanges between distinct companies on the top level, between plants, or between the components of each subsystem.

Industrial park networks have traditionally been broken into categories of water, power (including heat) and materials, to which we will adhere in this section. One of the more ubiquitous features of papers on eco-industrial parks is the inclusion of a case study of a real or hypothetical park which examines one or more of these flow types. **Table 1** is a complied list of papers which have examined specific industrial parks and presented case studies within these categories. The list contains only case studies based on existing parks; all 'hypothetical' case studies have been excluded.

In this section, we have attempted to minimize, insofar as possible, the inclusion of studies which deal with specific processes or individual plants. In addition, almost all studies of this nature are focused on reducing the quantities used, be it power, water or materials, which can be converted into financial saving, but may not address costs associated with building the needed infrastructure.

Location	Exchange types studied	References
Europe		
Kalundborg Industrial Park (Denmark)	P/W/M	[55, 59, 61, 89]
Forest Industry (Finland)	P/M	[93, 102–104, 126, 139, 161]
Le Havre (France)	P/W/M	[72]
Supply Chain (Portugal)	P/M	[141]
Händelö (Sweden)	P/M	[121]
Stenungsund Industrial Park (Sweden)	P/W/M	[10, 73–77]
Asia		
Kola Peninsula (Russian Federation)	M	[154]
Yeosu Industrial Complex (South Korea)	P/W/M	[154]
Guangdong (China)	P	[165]
Changchun (China)	P/W/M	[198]
Nanning Sugar Co. Ltd (China)	M	[187]
Sichuan Province (China)	M	[35]
Africa		
North America		
Brownville, Texas (USA)	P/W/M	[123]
Central and South America		
Guyayama (Puerto Rico)	P/W/M	[46, 47]
Multiple parks (Puerto Rico)	P/W/M	[47]
Oceania		
Kwinana (Australia)	P/W/M	[106, 107]
Dairy Farm (New Zealand)	P/W/M	[180–183]
Multi-national		
International ports (analysis of case studies)		[36]

Table 1: *Industrial parks - published case studies.*

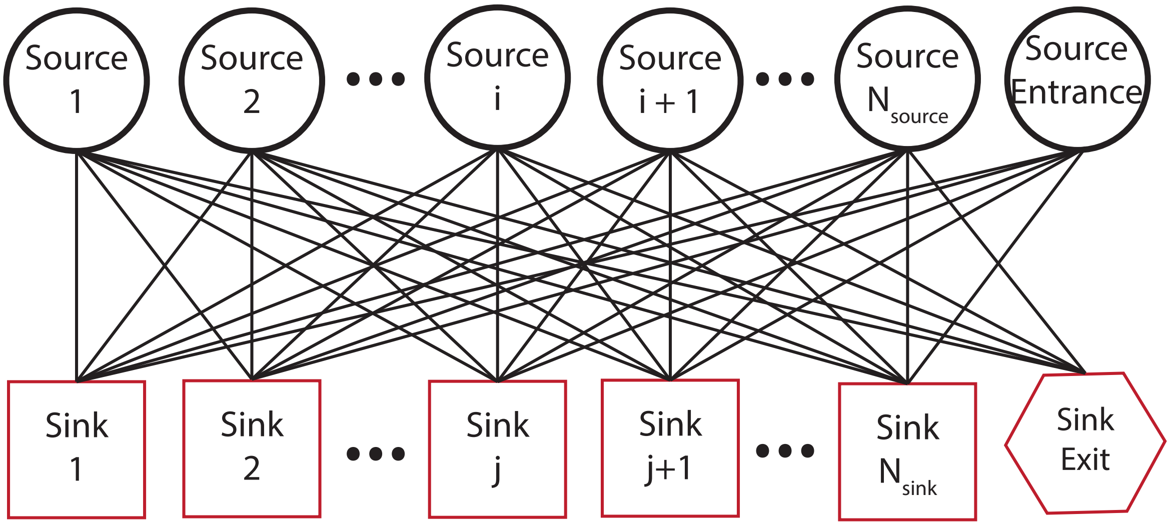

Figure 3: *Sink and source representation of an industrial network with N_{source} + 1 sources, N_{sink} + 1 sinks where the additional source/sink represents fresh intake and waste outflow.*

2.1 Energy and heat systems

At a process level, heat exchange networks (HENs) could be viewed as the starting point for process optimization. One of the fundamental methods of process systems optimisation is pinch analysis, originally developed by Flower and Linnhoff [66], which has become a mainstay of process design. The basic notion of pinch analysis is that ideal targets for a set of process streams can be established using a graphical representation and then a network design can be chosen or developed which approaches or meets that target [95]. Dhole and Linnhoff [58] adapted pinch analysis into Total Site Analysis (TSA) for application to an entire plant. In the first instance, a single plant linked by a central utility system was analysed for purposes of initial design and retrofitting an existing plant acquiring additional processes [58]. Maréchal and Kalitventze [120] combined TSA with MILP methods to develop tools designed to address site scale applications for heat and steam systems. More recently, Becker and Maréchal [26] proposed a method to use Pareto fronts to optimise HENs with restrictions such that central units are able to perform exchanges with all subsystems and independent subsystems have a limited ability to exchange heat with each other.

The study of HENs on an IP level could be said to begin with the work of Ahmad and Hui [1], where logical localized clusters within a process plant were classed as ‘areas of integrity’ and heat transfers across such areas, directly between processes and indirectly via a central utility systems were examined. Amidpour and Polley [9] applied a zoning methodology to find the cost savings which could be obtained with simpler HEN designs using defined zones compared to overall targets. In Bagajewicz and Rodera [24], Rodera and Bagajewicz [143], the concept of assisted and unassisted heat transfers was introduced and applied to targeting a system consisting of two plants and later extended to

n plants [22, 24]. Unassisted heat transfer was defined as when the optimal target can be met by direct transfers from one plant to another [22, 24]. Assisted is defined as the situation when additional transfers, in either direction, need to occur to reach the target [24, 143]. Direct and indirect heat integration, *i. e.* connections directly between process streams as opposed to using an intermediate fluid such as steam, across plants has also been investigated [144].

Another method founded on TSA for heat and power networks is R-curves, originally proposed by Kenney [96], which is based on cogeneration efficiency concepts. R-curves were developed for grassroots or retrofit situations by including constraints for the existing system by Kimura and Zhu [98]. R-curve methodology has been applied to an industrial region in Japan to identify potential energy savings [124]. Karimkashi and Amidpour [92] later adapted R-curves to include emission and economic factors with respect to utility network retrofitting or initial design scenarios.

MILP models without targeting or building targeting into the process have also been developed to acertain ways to capture heat from steam and waste water for economic and environmental optimization [37]. Shenoy [159] combined targeting and network design, specifically a 'nearest neighbour algorithm,' to create multiple network designs for an energy network optimised on carbon emissions for general regions and regions sub-divided into sectors.

Hackl et al. [76] performed a TSA study on a chemical cluster in Sweden where the suggested alterations were broken into three categories; possible with moderate changes (*i. e.* only additional heat exchangers), technically feasible (*i. e.* additional heat exchangers and reconfiguring in-place equipment), and infeasible. They found that some heat savings could be accomplished with moderate changes and additional savings could be obtained with more drastic, but possible, changes [76]. This work was later extended into a systematic framework using a holistic approach for reducing energy consumption in the chemical cluster by introducing inter-plant heat exchanges [73].

2.2 Water

The study of water networks has progressed along similar lines where the IP studies are founded in the process level models and optimization methods, including the application of water pinch analysis. The superstructure model constructed by Takama et al. [169] could be considered to be the starting point of contemporary water network analysis. El-Halwagi and Manousiouthakis [62] stated the problem in more general terms by applying pinch analysis to mass exchange networks. Wang and Smith [184] adapted the mass exchange pinch methodology to specifically address water networks. The details about the various process or single plant water network analysis methods can be found in the reviews of graphical [22], algebraic [60] and mathematical programming [68] methods.

While methods similar to those applied to HENs can be used, water networks have a number of features specific to water usage. Water in its purest form can be used in any process or plant, and waste water may be reused within the same plant or another, depending on the contamination level of the water and the requirements of the processes. Wastewater treatment plants also have the ability to regenerate water by removing contaminants, which allows further reuse. Thus, water has complications related to contamination levels which are specific to this type of network exchanges.

The beginning point of analysis of park level water network optimization is typically given as the study performed by Olesen and Polley [137] where, in a fashion similar to [1], a single plant of 15 processes was divided into three geographic zones and then optimized using load tables and pinch analysis. Each zone was individually optimized and then inter-zone transfers were considered [137]. Later, waster cascade analysis was applied to the same single plant multi-zone system [68]. The issue of periodicity, wherein the amount of water available for reuse from suppliers may be variable over time, was addressed in Liao et al. [109] using targeting to obtain a water network diagram that can be operated over different periods. An optimization model was developed by Geng et al. [70] which included potential direct water reuse, freshwater blending and water treatment plants to calculate water savings. Superstructures were used to study pulp and paper plants with internal reuse, external reuse and water treatment [118] which was later expanded to be applied to any EIP [117]. The superstructure model was also adapted to a property-based approach, which tracked water paths based on the impurity concentrations with treatment facilities available in the paths [116]. Chew et al. [50] applied an automated targeting methodology which found global optimal values for an inter-company water network by optimizing over both individual networks and the entire network. Multiobjective optimization has been applied by Boix et al. [29] where fresh water intake, wastewater treatment and the number of connections are minimized using Pareto fronts. While most models treat the systems as consisting solely of continuous processes, Chen et al. [40] proposed a two-phase approach where the network was first synthesized by treating batch units as continuous to determine the storage configuration, which is minimized in the second phase. Lee et al. [108] used a similar method in a system where there were fewer batch processes than continuous.

Aside from water use minimization, the collateral environmental impact of water usage has been discussed. Lim and Park [110] constructed a model which minimized the associated carbon footprint in an industrial water network by introducing inter-company exchanges. Aviso et al. [17] developed a fuzzy input-output model to study the water footprints in eco-industrial supply chains.

2.3 Materials

Establishing material exchanges is a different prospect and is more of an identification problem, than an optimisation or allocation one. While most, if not all, industrial concerns make use of heat and water in some fashion, material needs are specific to a given plant. However, once the identification of a potential exchange has occurred, the establishing of such an exchange can be a much simpler matter and largely breaks down into economic factors, *e. g.,* if transportation costs and material quality and quantities make the exchange feasible. The task of identifying exchanges and examining the viability of such exchanges has been approached from a variety of distance frameworks, within the park, city and further to regional exchanges. One interesting aspect of these exchange systems is that the focus is on unwanted by-products, not the primary product created by the plants.

Kincaid and Overcash [100] presented a methodology along with the results of a U.S. Environmental Protection Agency project which identified potential by-product exchanges in a six-county metropolitan area in North Carolina, USA. Information about by-products and inputs were acquired by a voluntary survey of the industrial concerns in the region and then mapped using Geographical Information Systems (GIS) software to identify potential exchanges [99]. Sendra et al. [157] performed a study adapting material flow accounting (MFA) [65] and its associated indicators from a regional context to an industrial park framework.

In an interesting counterexample to the overwhelmingly positive finding of creating exchanges, Salmi [154] presented an eco-efficiency study of material exchanges in a Russian mining community. The actual development, which used end-of-pipe solutions, was compared to a hypothetical development, based on original discarded plans to construct the area as an exchange network. Mixed results were produced insofar that the end of pipe emission reduction was similar to those of the EIP theoretical reductions [154], suggesting that traditional methods of pollutant reduction may be preferable to developing EIP networks in some situations.

2.4 Multiple type exchanges

While the majority of the published work has focused on a single exchange element, *i. e.* water, heat or materials, in reality an industrial park has all of these elements. In this category, the growing area of studies which have presented models or studies which can be applied across these divisions are discussed.

Chew et al. [51] presented a flowrate targeting algorithm which addressed unassisted [51] and assisted cases [48], *i. e.* as defined earlier in reference to [143], with hydrogen and water networks as worked examples. A mathematically rigorous treatment of the algebraic and graphical methods of targeting was developed by Sahu and Bandyopadhyay [152] that dealt with two plants for a generalized resource allocation network.

Power and water networks, sometimes referred to as ‘interplant water-allocation and heat exchange networks’ (IWAHENs), which are inherently intertwined in manufacturing, have recently been the subject of some tandem studies. Boix et al. [28] used a sequential method where the heat and water systems were separately optimized in a single plant. Then the energy consumption was minimized subject to the bounds defined by the first step by parameterizing the number of heat exchangers and the number of connections. Zhou et al. [199] constructed a multiscale state-space superstructure model for fixed flow rate processes in IWAHEN networks. The model was later expanded to address fixed flow rate and fixed contaminant systems [200].

Materials and energy combinations have also been studied. Karlsson and Wolf [93] demonstrated a ‘Method for analysis of INDustrial energy systems’ (MIND) method on energy and materials to evaluate system costs and other heat and power metrics with a standalone situation and different forms of inter-company exchanges in an industrial/forestry setting. The same system was used to evaluate CO_2 emissions [186]. Gu et al. [72] presented a generalized model for an eco-industrial park which mathematically represented feasible exchanges in a tensor matrix and incorporated production and delivery costs to optimize total economic benefits.

Utility networks, typically comprised of steam, water and electric, have also been studied and optimised. Kim et al. [97] presented a model along with a case study which produced environmental and economic optimised results with seasonal fluctuations. A petrochemical and refinery system was modelled by Zhang et al. [196] to couple process plants with utility systems allowing for three increasing levels of integration between the processes and the steam network.

Another widely used approach which crosses exchange type boundaries is Life Cycle Analysis (LCA). LCA is a holistic approach used in describing industrial processes and is typically performed with respect to environmental considerations. A product is selected (which generally may be goods or services) and the entire 'life' from cradle to grave of the object is systematically quantified in terms of energy and materials which contribute to its creation and eventual disposal [32]. A subsidiary type of study is Life Cycle Inventory Analysis (LCI), which consists all of the phases of a full LCA study, excepting the impact phase. The use of LCA has become widespread enough that the International Organization for Standardization has published a set of guidelines and definitions as described in [32, 33]. LCA methods can be used to study the impact of all exchange types and have been applied to EIP's to assess the benefits obtained through various exchange forms, although there has been discussion regarding how to appropriately handle industrial symbiosis elements with LCA [122, 125, 126]. Examples of such studies that have been published include a Finnish forest industry complex industrial symbiosis assessment by Sokka et al. [161]. Sokka et al. [162] performed a LCI study of the same system for impact of industrial symbiosis on GhG and fuel consumption. Oliveira and Antunes [138] employed economic input-output LCA (EIO-LCA) to construct a model based on inter-industry links.

There are some other areas of study which address related concepts from a different perspective, if not specifically eco-industrial parks directly. Supply chain management uses many of the same modelling tools and often addresses the same set of issues, under the auspices of 'collaborative supply chain management.' Supply chain management studies which are closely connected to eco-industrial concepts include such topics as energy systems [163], environmental and economic considerations [141, 177], and trust between collaborators [3]. Facilities management has also been applied to enable industrial symbiosis [128].

There has also been interest from a social sciences perspective, particularly with respect to the networking aspect of EIPs. Schiller et al. [156] recently published a review of such social-material network studies. Of particular interest to a retrofitting framework is vulnerability issues which may result from developing interdependent networks, similar to the disaster related domino effect [197] physical proximately already entails [11]. Vulnerability and resilience has been studied in IS networks using network analysis and cascading failure models to understand inter-company impact [54, 191–193].

3 Infrastructure

Reusing by-products, either within ones own network or provided by another network, will inherently involve transportation, oftentimes by building a piping network for steam, heat or water. One of the earliest feasibility studies of this type of external connection was by Stovall [168], where the costs of constructing a steam pipe from a nuclear power plant to a nearby industrial park were assessed. The piping and installation costs, piping length and diameter with respect to pressure loss were studied. In this section we focus on work which has addressed feasibility and other practicle issues associated with creating connections, such as distance factors and capital investment costs.

3.1 Heat and power

Implementation of interplant heat and power transfers can involve a wide array of issues. Even from the early stages of total site integration, the viability of direct heat transfer between processes due to start-up, shutdown, plant layout and capital costs has been questioned [86]. Akbarnia et al. [2] adapted pinch analysis methods for HENs to include piping costs in the targeting methodology. Chew et al. [53] assembled a list of key issues which need to be considered when performing total site heat integration, which address design, operation and reliability issues. Moreover, these issues can become more complicated and of increasing difficulty to resolve when considering inter-plant transfers. With studies related to inter-company issues, the economic factors, in the form of increasing or decreasing capital and operating costs, are the central issues.

One specific industrial sector where there has been a number of related studies is in the area of refinery and petrochemical complexes. Although such studies may not meet a strict definition of an EIP, they typically involve building connections between multiple plants with a single owner. One approach, presented by Feng et al. [63] was applied to different plants in a petrochemicals complex and allowed for different boundaries encompassing the entire plant or individual processes within a given plant to generate potential retrofitting schemes. Al-Qahtani and Elkamel [4] presented a methodology for designing and analyzing process integration networks and production capacity expansions in a multiple refinery complex by using different feedstock. In a merger and acquisition context Yoon et al. [189] presented a model and study for vertical mergers within petrochemical concerns which took merging process and material streams into consideration.

Bagajewicz and Rodera [23] addressed the drawbacks involved in heat transfers between plants by suggesting the use of a single circuit ‘heat belt’ of intermediate fluids which could reduce transport costs and improve flexibility. A related modification is the use of different intermediate fluids to accomplish heat transfer. Changes in the fluids can reduce the effective heat transfer interval, however fewer pumps and compressors may need to be used, which could be offset by the increase in the number of heat exchangers. Use of a fluid with a higher heat capacity will result in lower pumping costs, possibly decreased safety concerns due to spillage and simplification of control [143]. Use of heat exchange mediums other than steam, such as thermal oil to minimize the flow rate for indirect interplant integration, was investigated by Bade and Bandyopadhyay [20]. The use of heat recovery loops (HRLs) with thermal storage have been proposed for indirect heat transfer between individual plants with low pinch temperatures [12]. HRLs have been found to be useful where the waste heat temperature is such that it would be uneconomical to raise steam, instead water may be heated and transported via the HRL [13, 180]. Additional work has been focused on the storage temperature and optimising the area distribution of a HRL using MILP methods [181]. Reclamation of low temperature waste heat for use between plants has also been proposed by using an organic Rankin cycle to produce electrical power [84].

A MILP and a two-stage stochastic approach that targeted capital and operating costs was used to address the question of planning total site implementation of energy savings over the long term [21]. Installation and operating costs for additional heat exchangers needed to support a cross-plant optimisation were included in Rodera and Bagajewicz [144]. A methodology was presented by Hackl and Harvey [75] which calculated investment costs, payback time and the reduction in CO_2 emissions for alterations to the HEN in a chemical cluster with little existing common utility infrastructure. That methodology grew out of a series of detailed studies of a Swedish chemical cluster. Hackl et al. [77] performed a TSA study of the cluster which resulted in a collection of proposed measures to increase energy efficiency through collaboration, classified by degrees of feasibility. Andersson et al. [10] took a group of the most feasible to implement measures and presented potential designs with respect to steam network, hot water, cooling and fuel usage, as well as a preliminary cost-analysis. Hackl and Harvey [74] took promising options for the cluster and performed a detailed economic study which allowed for staged implementation of the adopted measures.

Stijepovic and Linke [166] proposed a model specific to identifying potential inter-plant waste heat reuse connections which maintained current plant configurations by only allowing additional heat exchangers. The feasibility of creating exchanges was assessed and levels were constructed of capital costs which directly affect the amount of heat recovery, as higher quality equipment will entail a higher capital cost. This methodology was later expanded to include the possibility of cogeneration (heat and power) potential [167]. Chen and Lin [38] performed a study of retrofitting steam power plants based on creation of additional exchanges.

Integration of existing utility systems has also been investigated in a variety of contexts. Hipólito-Valencia et al. [83] constructed a model for inter-plant trigeneration systems consisting of a steam Rankine cycle, an organic Rankine cycle and an adsorption refrigeration cycle. Adding a heat transfer to a material exchange, by transferring materials while still hot, has been studied with a MILP model to improve HENs [194] and in conjunction with utility systems to increase steam production [195].

3.2 Water networks

As with heat and steam, the delivery and reuse of water can incur piping/connection building costs. However, water networks can also contain the additional features of wastewater treatment plants, with associated construction and operating costs that are dependent on the type of contamination and processes required to treat the water for reuse. Keckler and Allen [94] published a model of an IP which constructed feasible flows and analysed the various pathways of water reuse based on water prices and wastewater treatment prices, including the possibility of blending water sources. Using the same method of constructing feasible water exchanges, Nobel and Allen [135] used GIS software to calculate pumping costs over distance and elevation. However, neither of these models addressed the capital costs involved in building the infrastructure to support the connections. Zbontar and Glavic [190] performed a case study of a petrochemicals plant using some pinch analysis ideas which included water treatment costs and capital costs. Process and environmental regulations were used as constraints in a global optimization model proposed by Rubio-Castro et al. [148, 149] with annual costs, including water treatment and piping costs, where the problem of finding a global minimum was investigated further in [151]. Another model in which environmental and economic relationship were expanded, used LCA and Life Cycle Costing (LCC) to find designs which reduced both emissions and costs in remodelling an industrial park [111]. Possibly the most direct study of retrofitting an IP is the work of Rubio-Castro et al. [150] where a MILP model was proposed to optimize retrofitting an IP, including additional piping and waste treatment facilities, optimized to minimize annual costs, which incorporated capital and operating costs. Montastruc et al. [131] followed up the study by [29] by examining the degree of flexibility in pollutant levels that was allowable by the park occupants and how increasing the number of connections could improve that with respect to the cost of creating new connections. A multi-period study was presented by Bishnu et al. [27] which optimized the water network over different time periods, including short term and the planning horizon for future expansion.

Types of delivery and storage systems have also been examined. Chew et al. [49] performed a study using a mathematical model comparing the use of a direct (plant to plant) and indirect (plant to central hub) connections between water networks, with a third case that included water treatment in the hub. Chen et al. [39] studied the effect of using centralized and decentralized water mains in inter-company connections. Liu et al. [113] investigated optimal placement of waste water treatment facilities in a scarcity context. An extensive study of inter-plant piping systems was presented by Alnouri et al. [7] that considered merging existing piping systems with forward and backward branching scenarios. Another model which included spatial constraints with direct recycling was proposed by Alnouri et al. [8] which considered optimal configurations based on detailed piping information as well as existing service corridors and access ports to determine shortest paths and most efficient designs. This deterministic model [8] was compared to a stochastic optimization approach to examine possible trade-offs in capital investment and water usage targets [6].

3.3 New elements

The introduction of new industries or power generation systems has also been a topic of discussion. With material exchanges, a new industry can move into the industrial park to take advantage of previously discarded waste material. In effect, the perspective changes from the retrofit classification given by Chertow and Ehrenfeld [44] to ‘build and recruit’ actions.

Energy systems may currently be the most visible networks for retrenching. The introduction of renewable energy sources is a widely discussed topic with far-reaching applications and associated issues. As addressing this topic far exceeds an IP framework and is beyond the scope of this work, we refer interested readers to review papers on biofuels [19, 34, 173], solar energy [127], wind energy [81], energy storage [25], energy efficiency optimisation [176], smart grids [142] and distributed power generation [114, 147]. In an IP park specific context, Starfelt and Yan [165] presented a simulation based feasibility study of retrofitting the cogeneration system by incorporating gas turbine technology with a heat recovery steam generator (HRSG) to replace the current diesel engine with HRSG and absorption chillers. A study of using solar heating with HRLs was presented by Walmsley et al. [182] with constant and variable storages temperatures. This work was extended by Walmsley et al. [183] where solar and industrial waste heat were considered as potential heat sources. Hashim et al. [78] presented an optimisation model for a power grid which has a wide variety of traditional and alternative energy generation sources which was designed to be optimised for economic considerations, environmental considerations or both. Martin and Eklund [121] presented a study incorporating biofuels into an industrial symbiosis context using by-product synergies. Christensen and Kjaer [55] presented a study of methods and issues associated with integrating biofuels into existing heat and power systems. The implementation of co-production of heat and power (CHP) systems was investigated by Korhonen [103] by considering the establishment of a power plant being placed as an anchor tenant in the industrial park.

The recent emphasis on carbon emissions has also been examined. Nørstebø et al. [136] presented a model of carbon capture in an industrial park with a variety of taxation and user scenarios. This was followed up with a park integration study, which considered expansion by including six different types of industries, including a carbon capture plant, from an investment point of view, that included various taxation scenarios [130] .

3.4 Beyond park boundaries

While the defined idea of an eco-industrial park is to have exchanges and sharing within the defined boundaries of the industrial park, it is not too far-fetched an idea to route residual heat, power or other materials to areas outside the formal boundaries, such as to neighbouring residential areas or within a larger region.

The idea of exporting excess heat and power from an industrial park to local residential areas has been addressed and implemented in some cases [89]. Morandin et al. [132] performed a study on the economic feasibility of using excess heat in a residential area with CO_2 emissions taken into consideration. Perry et al. [140] discussed use of locally distributed renewable energy sources along with TSA in an industrial context which could be extended to include local offices and other non-industrial concerns. Korhonen [102] also considered involving district heating systems into EIP formulations.

4 Independent actors issues

One element which cannot be removed from any action of converting an IP into an EIP is the actions and opinions of the participants [107]. Not only is passive cooperation needed, but active participation is required on the part of the existing occupants in order for any retrofitting scheme to be enacted. In this section we review publications which have addressed issues relating to cooperation or non-cooperation of the IP residents.

4.1 Motivational models

One obstacle to introducing changes in an already existing system is that costs will be incurred and the question of how costs will be distributed is fundamental to establishing if the alterations will occur. As the exchanges which are built as way of reducing resource use effect more than one party, this becomes more complicated because if the potential future savings and the capital costs are not deemed acceptable by all parties concerned, the scheme may not be adopted. The benefits of EIPs typically are discussed in terms of economic, environmental or social benefits, often referred to as a 'Triple bottom line' [106]. In the industrial parks that have been developed, economics and profits are often ascribed to be the primary motivation for the building of exchange networks [80, 139, 158] and are assuredly factors driving any changes in existing systems [88].

Game theory has been applied to IP studies on multiple fronts. Lou et al. [115] constructed an emergy based model which used game theory to determine optimal operating conditions for integrated plants. With respect to heat and power, Hiete et al. [82] performed an energy integration study where cooperative and coalitional game theory concepts were used to explore acceptable network structures with respect to the economics of the participating companies. Cheng and Chang [42] used a sequential method and Nash equilibrium constraints to optimize an interplant heat exchange network. Further, with an optimized design obtained, Cheng et al. [43] distributed the costs over all participants using cooperative game theory. Tan and Aviso [170] presented an inverse optimization approach with game theory to produce incentives or penalties to induce park tenants to more environmentally sound practices.

Water network designs have also been subjected to game theory methods. Chew et al. [50] used a system where direct connections were constructed between independent plants and constructed models for profitability and sustainability (reduction of water and waste production). Cooperative and non-cooperative game theory cases were examined to select designs which would be beneficial to all effected plants. This work was later extended to include indirect connections via the inclusion of a central utility hub [52].

Fuzzy logic methods have been applied to EIP settings, wherein fuzzy 'goals' are defined as a range of values which a given participant would deem satisfactory. Aviso et al. [15] used fuzzy optimization to simultaneously optimize goals of multiple individual plants with respect to the water network. Bi-level fuzzy optimization was then developed [16] to take into account the conflicts between motivations, such as the park organizers or another external upper level agent being concerned with environmental aspects while the park occupants (lower-level) want to minimize costs. This model was later extended to include a centralized hub for water regeneration and reuse [171]. Fuzzy logic models have also been adapted to use emergy, *i. e.* where all contributing factors are expressed as an equivalent solar energy unit, analysis in conjunction with water reuse in EIPs [172]. The changes that take place with multiple owner involvement was examined in a study of integrating a palm oil processing complex with respect to energy and materials. Initially, by treating the complex as being under the control of a single owner [133] and then with a companion study where the complex had multiple owners[134] and owner satisfaction was taken into account using fuzzy optimisation.

Agent based modelling (ABM) has also been proposed as a means to study and predict viable ways of evolving EIPs [18, 105]. One of the more attractive features of ABM is the ability to propose 'what-if' situations by defining a variety of agents or agent-types which have different goals and responses, and running those types through varied scenarios. The appropriateness of using ABM lies in the fact that EIPs can be considered to be self-decision making, interactive, symbiotic systems which are based on large number of factors [201]. Albino et al. [5] presented an agent-based model to study the effect on innovation in an inter-organized industrial district with a homogeneous range of products. A four agent system, of types business, technical, community and labour, for an EIP was constructed by Jian and Zengqiang [90] to identify key elements in an EIP's development. Cao et al. [35] used an agent based modelling system based on emergy, where the entities in a park are classed into factory, consumer and environment agents and ran simulations based on a constructed pricing system, where the environmental agents could impose penalties if their capacity was exceeded. An agent based model proposed by Romero and Ruiz [146], based on a modelling framework previously developed in [145], evaluates potential cooperative relationships and incorporates game theory concepts. Repercussions of mutualism and competitive systems with respect to firm survival were investigated using ABM by Knight et al. [101] on Marshallian and hub-and-spoke type districts. One of the few found developments with respect to the electrical grid in eco-industrial parks has been an application of ABM. Mert et al. [129] presented an ABM study to address the fragility caused by centralization in the EIP grid by using microgrids and possible integration of renewable energy sources. System dynamics, although not as frequently utilized, has been proposed as an alternative to ABM [146, 198].

4.2 Actor secrecy

The vast majority of studies which deal with IP's assume that detailed information about process streams, contaminant levels and any other feature of interest or key quantities will be made readily available by the companies involved. For many existing parks, this assumption may be wildly optimistic, particularly when competing industries are resident in the same park. This leads to issues related to the usefulness and applicability of many of the previous methods, for example any form of pinch analysis to a heat network will need extensive and detailed information about the processes and heat requirements of a given plant. If that information is not forthcoming, there is a problem in creating any exchanges, much less optimal exchanges.

Although a difficult aspect, some researchers have attempted to address this issue. Aviso [14] presented a robust water network model which identified near optimal solutions which are resilient to system changes by including weights in the objective function based on the probability of the occurrence of that particular scenario. With this model, all water sink and source matches are meant to be functional in all the considered scenarios, so future information or other alterations can be adjusted for. Zhao et al. [198] made use of grey clusters, a mathematical method for handling incomplete information [112], with a systems dynamics approach into a series of redesign simulation scenarios of material, water and energy exchanges for an existing IP. Hackl et al. [76] defined three different information types:

- Black box – process represented by utility demand;
- Grey box – process to utility heat exchange information;
- White box – detailed process information available, including between process heat exchangers.

and used black and grey box situations in an EIP study.

5 Discussion

There are many issues associated with the adaption of an industrial park into an EIP. In one of the earliest works addressing development of eco-industrial parks, Spriggs et al. [164] described the challenges involved in terms of two classes; technical/economic (TE) and organizational/commercial/political (OCP). Using these two categories as a basis for reflection upon the work discussed in the previous sections, the vast majority of the advances have been based in the TE category, while progress with respect to OCP aspects has only recently been addressed. However, even these efforts have largely been grounded in the TE framework, by adding game theory, fuzzy logic and other methods to the analysis.

Looking strictly at the TE developments, the methodologies have become rather mature and have been proven with respect to multiple aspects of EIPs. One observation that can be made is that the methods that have been applied generally are adaptations or expansions of process systems optimisation. Targeting was combined with or replaced with MILP for processes, then adapted to plants and interplants. While these methods may be appropriate, one cannot help but wonder if alternate methods, which are not founded in process systems may be applicable and could lend additional insights. Another drawback to the optimisation methodologies is that the optimal values are defined by an objective function and they are fixed values which rarely take future alterations into consideration. The assumption to these methods is that the existing occupants of the park will be willing to adopt the proposed changes, when that may not be the case.

The OCP aspects on the other hand are equally important and could be considered to be fundamental to actually realizing an EIP from a retrofitting point of view. Adopting EIP principles requires the introduction of interdependencies within the members of the park, an attitude which may not be embraced by the concerned parties. This concern can be alleviated, to a certain extent, by using centralized utilities rather than attempting to create direct plant to plant connections; however that solution may not be practical in all contexts, may not be agreeable to all occupants and does not apply to material exchanges. Further, as pointed out by Boons and Baas [31] "coordination does not automatically mean cooperation." As the underlying assumption to a successful EIP relies on cooperation, it could be suggested that if a spirit of cooperation is cultivated, the evolution into an eco-industrial park can follow. However, attempting to coerce unwilling occupants into adopting eco-industrial practices may lead to undesired consequences, such as cursory adherence or loss of tenants, for example. An eco-park from design may employ such infrastructure from the initial stages, however an existing and operating park will need to tread more carefully, lest rather than improving ongoing operations they become endangered or limited. The idea should be to find ways to cause less ecological impact, not to cause the same ecological impact to occur elsewhere.

The economic benefits may act as an inducement; however they are not the only consideration. Gibbs [71] draws attention to the pragmatic issues involved in such a venture, specifically with respect to the level of trust involved in creating interdependencies. The creation of exchanges may also create vulnerabilities. While utility sharing may be a tempting starting point to foster industrial symbiosis, the evidence given by the case studies suggests that material by-product exchanges may be a better starting point for existing parks. Material exchanges have less potential to adversely effect the receiving company and frequently evolve spontaneously Chertow [45], Frosch and Gallopoulos [69].

Certain characteristics can be observed in the case studies. The EIPs which have been reported have material exchanges with a single exception, while shared utilities have a bit less of a presence. The introduction of material exchanges may have had less of an infrastructure impact. From the point of view of the participating companies, the creation of a material exchange can have a financial benefit for both parties with a minimum of alteration in existing structures. In a way, a material exchange can be viewed as the creation of an additional supplier or customer, which entails little to no risk to current operations. Heat and water however, may require substantial capital investment and can entail risk with respect to supply variability which may impact operations.

Another element which warrants mention is the degree of complexity which can be incurred when implementing an 'ideal' solution with respect to thermodynamics or water networks. While the successful EIPs may have a large number of exchanges and complicated networks, the social networking analysis can lend insights regarding the structures and connectivity patterns which are found to be successful. In the case of Kalundborg, most of the exchanges are provided by the 'core' industries with no interaction between the peripheral companies [59]. This would suggest that in a retrofitting situation, identifying potential core industries and building a network outward may be more viable then initially attempting to create a complicated structure involving all entities. It is likely that a simpler network structure will incur a lower cost in infrastructure changes incurred, and may meet with less resistance in adoption. Further, the accurate development of complicated optimal systems often requires detailed knowledge of the internal workings of the plant, which the owners may be reluctant to make available.

The addition of new industries to create exchanges should not be underestimated and should be taken into consideration with respect to any plan for retrofitting. Introducing a new firm into the park may be more advantageous than attempting to make connections within the pre-existing network. One example, as reported by Haskins [79], in Kalundborg, the gypsum plant relocated to the park specifically to take advantage of the exchange opportunities with the existing entities.

A further insight from that instance which has not been often addressed is that of having backup systems for the exchanges. Haskins [79] reported that 90% of the gas for the gypsum plant was supplied through the exchange from flare gas. The other 10% was supplied by purchased butane, which was used during the gas suppliers maintenance period and the gypsum plant could operate without the exchange indefinitely. With any proposed exchange system, the prospect of supplier breakdown should be provided for, a point which has not been substantially studied in the literature [54]. One of the key issues appears to be that an EIP is a network, rather than a collection of stand-alone entities and insights from disciplines which operate within a network framework, power systems for example, may offer additional tools which can address these issues.

Overall, given an existing industrial park and a desire to convert it into an eco-industrial park, the literature supplies a substantial tool kit in order to analyse and propose alterations from a technical and economic point of view. Possible fruitful directions of future work would include methods to cultivate willingness to participate in exchanges within the existing tenants and ways to minimize any perceived vulnerabilities and potential limitations for future growth.

6 Conclusions

The existing literature on eco-industrial parks was reviewed with a view towards retrofitting an existing industrial park to improve environmental and economic performance. The technical and financial aspects of optimising and redesigning the parks is found to be sophisticated and largely based on adaption of process systems techniques. Once identified, material exchanges appear to be the least complicated form of exchanges to implement, which could form a basis for future, more elaborate networks. The aspect of cultivating willingness to adopt EIP methods was found to be newly investigated with interesting developments using game theory and fuzzy logic methods. The application of social network theory may produce significant insights, particularly if combined with more technical elements. Suggestions for future work should attempt to combine these two perspectives and to improve the understanding of the vulnerabilities and other risk related elements which the creation of interdependencies incurs.

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Nomenclature

Abbreviations

ABM	Agent based modelling
CHP	Co-production of heat and power
EIO-LCA	Economic input-output life cycle analysis
EIP	Eco-Industrial Park
GhG	Greenhouse gas
HEN	Heat exchange network
IWAHEN	Interplant water allocation and heat exchange network
IP	Industrial park
LCA	Life cycle analysis
LCI	Life cycle inventory
MILP	Mixed interger linear programming
OCP	Organizational/commercial/political
TE	Technical/economic
TSA	Total Site Analysis

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