UNIVERSIDAD DE CHILE
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS
DEPARTAMENTO DE INGENIERÍA QUÍMICA, BIOTECNOLOGÍA Y MATERIALES

DESIGN OF SUSTAINABLE AND RESILIENT ECO-INDUSTRIAL PARKS BY MEANS OF OPTIMIZATION TOOLS

TESIS PARA OPTAR AL GRADO DE DOCTOR EN CIENCIAS DE LA INGENIERÍA, MENCIÓN INGENIERÍA QUÍMICA Y BIOTECNOLOGÍA

GUILLERMO ANDRÉS VALENZUELA VENEGAS

PROFESOR GUÍA:
DR. FELIPE DÍAZ ALVARADO

PROFESORES CO-GUÍA:
DR. J. CRISTIAN SALGADO HERRERA
DR. JUAN A. ASENJO DE LEUZE

MIEMBROS DE LA COMISIÓN:
DRA. MARÍA ELENA LIENQUEO C.
DR. CARLOS A. MÉNDEZ
DR. ANDRÉS WEINTRAUB POHORILLE

Este trabajo ha sido financiado por CONICYT-PCHA/Doctorado Nacional/2014-21140400

SANTIAGO DE CHILE
ENERO 2019

RESUMEN DE LA TESIS PARA OPTAR AL GRADO DE:
Doctor en Ciencias de la Ingeniería
Mención Ingeniería Química y Biotecnología
POR: Guillermo Andrés Valenzuela Venegas
FECHA: Enero 2019
PROFESOR GUÍA: Felipe Díaz Alvarado

DISEÑO DE PARQUES ECO-INDUSTRIALES SUSTENTABLES Y RESILIENTES A TRAVÉS DE HERRAMIENTAS DE OPTIMIZACIÓN

Actualmente, el aumento en la producción industrial está ocasionando problemas ambientales ya que no posee una apropiada planificación y control. Una solución a este problema, son los Parques Eco-Industriales (PEIs), en donde las empresas cercanas se conectan entre sí para lograr ventajas sustentables tanto para éstas y como para el sector. Dado que estas ventajas dependen de la configuración del parque, su adecuada planificación y diseño son críticos. Además, la estabilidad de esta red industrial juega un papel fundamental cuando las empresas participantes sufren alguna detención en su producción.

Este trabajo busca proponer el diseño sistemático de un PEI para apoyar y fomentar la implementación de redes industriales con objetivos sustentables y de seguridad. Para lograr este objetivo, (i) se construye una base de datos de indicadores de sustentabilidad y se proponen cuatro criterios para su selección; (ii) se define un indicador de resiliencia para mejorar la seguridad en la operación de un PEI; y (iii) se formula un problema de optimización multi-objetivo para diseñar PEIs.

Se enumera un conjunto de indicadores de sustentabilidad y se clasifican de acuerdo con el número de dimensiones evaluadas: individual, si una dimensión de la sustentabilidad es evaluada, o integrado, si dos o más son evaluadas. Además. se proponen cuatro criterios para seleccionar subconjuntos pertinente de indicadores: *entendimiento*, *pragmatismo*, *relevancia*, y *representación parcial de la sustentabilidad*.

Se construye y propone un indicador para seguir la resiliencia de un PEI, con el objetivo de mejorar su seguridad, considerando la dinámica de los participantes para soportar eventos disruptivos. Este indicador se basa en dos características importantes de una red industrial: su topología y su operación; las que son evaluadas mediante la suma ponderada de dos sub-indicadores: Índice de Conectividad de la Red (NCI) e Índice de Adaptabilidad de Flujo (ϕ).

Se construye un modelo de optimización multi-objetivo basado en el complejo industrial de Ulsan, en Corea de Sur, con el objetivo de diseñar un PEI sustentable y resiliente. Se considera un subconjunto de indicadores de sustentabilidad, filtrados mediante los cuatro criterios, y el indicador de resiliencia propuesto.

Las configuraciones obtenidas logran mejorar simultáneamente los objetivos considerados, permitiendo el diseño de un PEI enfocado en la sustentabilidad y resiliencia. El uso del indicador de resiliencia como un objetivo adicional permite componer un PEI con una mejorada adaptación a la realidad, abordando la reticencia de las industrias a participar en redes industriales.

Finalmente, el modelo de optimización logra el diseño sistemático de nuevas configuraciones de PEIs, considerando los aspectos de sustentabilidad y resiliencia como objetivos en la optimización. Esta herramienta puede jugar un papel importante para apoyar a los responsables de diseñar redes industriales, generando nuevas alternativas más sustentables y más resilientes.

THESIS SUMMARY TO OBTAIN THE DEGREE:
PhD. in Engineering Sciences
mention Chemical Engineering and Biotechnology
BY: Guillermo Andrés Valenzuela Venegas
DATE: January 2019
ADVISOR: Felipe Díaz Alvarado

DESIGN OF SUSTAINABLE AND RESILIENT ECO-INDUSTRIAL PARKS BY MEANS OF OPTIMIZATION TOOLS

Nowadays, the increase in the industrial production is causing environmental problems when appropriate planning and control are absent. To overcome this situation, the Eco-Industrial Parks (EIPs) arise as a new way to plan and design industrial complexes, where the companies located together are connected with each other to achieve sustainability advantages for its participants and the sector. Since these advantages depend on its configuration, a proper planning and design is critical. Moreover, the stability of this network plays a significant part when a participant suffers a stop in production.

This work seeks to propose a mathematical-based design of an EIP to promote and support the implementation of industrial networks with sustainability and security objectives. To achieve this goal, (i) a database of sustainability indicators is built and four criteria for their selection are proposed; (ii) a resilience indicator for EIPs is defined to improve their operation security; and (iii) a multi-objective optimization problem is formulated to design EIPs.

A significant set of sustainability indicators are listed and classified regarding the number of assessed dimensions: *single*, if one sustainability dimensions is assessed, and *integrated*, if two or three are assessed. Moreover, to select a subset of proper indicators, four criteria are proposed: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*.

An indicator is constructed and proposed to follow the resilience of an EIP, improving the security of the whole system by considering the dynamic of the participants to endure a disruptive event. This indicator is based on two main characteristics of an industrial network: its topology and its operation; which are respectively assessed by the weighted sum of two sub-indicators: Network Connectivity Index (NCI) and Flow Adaptability Index (ϕ).

A multi-objective optimization model is constructed based on the industrial complex of Ulsan, in South Korea, in order to design a sustainable and resilient EIP. This model considers a subset of sustainability indicators and the proposed resilience indicator. The sustainability indicators are filtered with the four criteria for selection.

The resulting configurations improve all the considered aspects at the same time, allowing to design an EIP with focus on its sustainability and resilience. The use of the resilience indicator as an additional objective allows to compose an EIP with an improved adaptation to reality, addressing the reluctance of the industries to participate in this industrial network.

Finally, the optimization model achieves the systematic design of new EIPs, considering the sustainability and resilience aspects as objectives in the optimization. This tool could play an important role in supporting decision-makers to design industrial networks, generating new, more sustainable and more resilient alternatives.

- A mi familia, en especial, a mi abuelita,
que con sus enseñanzas y consejos de la vida
he aprendido a disfrutar todo.
- A los que transforman sus sueños en logros
y los comparten con los demás.

Agradecimientos

No sé por donde empezar ni a quien agradecer, pero trataré de mencionar a los grupos y a algunas personas en particular que fueron muy significativas para todo este proceso.

Quiero partir agradeciendo a Felipe, profesor guía y gran amigo, por haber confiado y creído en mí, ofreciéndome el tema de tesis cuando recién estaba comenzando, y además por apoyarme y ayudarme durante estos 4-5 años del doctorado (y más). Al profe Salgado, por sus consejos en cuanto al doctorado y a docencia con los que he podido entender lo difícil que es ser profe e investigador, pero que me sirvieron de motivación para seguir adelante. A los demás profesores de la comisión, que se dieron el tiempo de leer mi trabajo y darme comentarios de este.

A mi familia: papá, mamá, hermano, cuñada, sobrino y gatos; los que me apoyaron, acompañaron y me ayudaron cuando los necesitaba, incluso más allá del doctorado, cuando no sabía qué hacer en la vida. Ellos estuvieron siempre ahí para guiarme. Los quiero mucho. A la Maca, mi polola, que me sorprende y me asombra todos los días, cosa que es difícil... muy difícil. Gracias por todos esos momentos que hemos pasado, donde me has apoyado y hecho reír con tus tonteras y locuras, haciéndome disfrutar de la vida con cosas tan simples, pero que valen la pena.

A toda la gente que conocí por tenis de mesa, en especial a los de la rama, con los que compartí gran parte de mi tiempo (mucho tiempo) durante el doctorado, entrenando y conversando en las juntas que hemos hecho. En especial quiero agradecer a Seba GO, Leo, Víctor, Feña Jorquera, Feña Muñoz, Blanca, Linda, Seba Jaque, Seba Urbano, Dani, Peluka, Cata, Naty, Luciano; los que he podido conocer mucho más. ¿Cuándo el asado donde el Peluka?

A los integrantes de la oficina de ProSus y ex miembros de simbiosis. Muchas gracias por acogerme e incluirme en las múltiples cosas que hacían, lo pasé muy bien compartiendo con ustedes.

A la gente de afuera de la U (o que ya salieron). A mis más queridas amigas Sole y Elsa. Es bkn saber que continúas teniendo una gran amistad a pesar de no verse tanto. Las quiero! A Javi y Caro! Pucha que la paso bien con ustedes, conversando y comiendo. Somos tan pavos! jajaja. A Conejo, Mentor, Fernando, Alicia, Cami, Made, Clau, Juan Pablo, Seba, Caro, Bayron, Vale, Eduardo, Bastián, Julián, Juan, Mauricio; gracias por todas las juntas y conversaciones, se les extraña un poco (solo un poco).

A la Gabi, al Dani y al Panchi. Qué les puedo decir? Gracias por perder el tiempo conmigo, hacerme olvidar de las cosas que debía hacer y pasarme muchas horas "haciendo nada" jajaja Habría sido tan aburrido el doctorado si no los hubiera conocido. Creo que lo habría terminado ante. O no?

A Wax y Camilo. Gracias por todos esos momentos de procrastinación, de cafés, de sábados de trabajo, por las piscolas, micheladas, gim, viajes, etc... miles de cosas jajaja. Disfruté cada momento, olvidando el doctorado como también avanzando en él gracias a esto. Gracias!!

Como siempre, quiero agradecerme a mí por permitirme hacer lo que quiero y lograrlo, darme el apoyo y siempre enfrentar todo con la máxima energía y alegría. Gracias.

En fin, a todo el resto que conozco y no conozco, pero por espacio (¡maldito formato de tesis!) no puedo mencionar. Gracias por ayudarme a perder el tiempo haciendo otras cosas más que solo estudiar, sino que disfrutar de la vida. Creo que estos 4-5 años los he disfrutado mucho haciendo las cosas que quiero. ¡Aunque creo que de antes también lo hacia!

Contents

1 Introduction **1**
- 1.1 General background . . . 1
- 1.2 Objectives . . . 7
- 1.3 Thesis organization . . . 7

2 Defining a sustainability measure for EIPs **8**
- 2.1 Chapter summary . . . 8
- 2.2 Background: Assessing the sustainability of Eco-Industrial Parks . . . 9
- 2.3 Methods for Searching Indicators . . . 12
- 2.4 Results: indicators for Eco-industrial parks: selecting criteria, sustainability dimension, and classification . . . 13
  - 2.4.1 Criteria for selecting indicators on EIPs . . . 13
  - 2.4.2 Classification of EIP indicators . . . 16
- 2.5 Discussion . . . 18
  - 2.5.1 Applying the criteria for indicators choice over 249 indicators . . . 19
  - 2.5.2 Applying the criteria for indicators choice to an EIP in Kalundborg: hypothetical case . . . 21
  - 2.5.3 Sustainability dimensions . . . 23
  - 2.5.4 Final considerations . . . 25
- 2.6 Chapter conclusions . . . 26

3 Resilience in industrial networks: defining a resilience indicator **28**
- 3.1 Chapter summary . . . 28
- 3.2 Background: security issues in Eco-Industrial Parks . . . 29
- 3.3 Definition of the Resilience Indicator . . . 31
  - 3.3.1 Mathematical representation of an EIP . . . 33
  - 3.3.2 Network Connectivity Index . . . 35
  - 3.3.3 Flows Adaptability Index (ϕ) . . . 38
  - 3.3.4 Resilience Indicator . . . 44
- 3.4 Application of the Resilience Indicator over case studies . . . 44
  - 3.4.1 Small illustrative examples . . . 45
  - 3.4.2 A real example: Ulsan, South Korea . . . 47
- 3.5 Discussion . . . 51
- 3.6 Chapter conclusions . . . 54

4 Optimization model: designing a sustainable and resilient EIP **56**

4.1 Abstract . . . 56
4.2 Background: Optimizing Eco-Industrial Parks . . . 59
4.2.1 Multi-objective optimization . . . 63
4.3 Problem definition . . . 67
4.3.1 Ulsan EIP, South Korea . . . 67
4.3.2 General assumptions . . . 68
4.3.3 Superstructure formulation . . . 69
4.3.4 Selection of objective functions . . . 70
4.3.5 Modelling variables and equations . . . 72
4.3.6 General Model and data selection . . . 80
4.4 Results and discussion . . . 81
4.4.1 Comparison of the resulting configurations . . . 84
4.4.2 Selection of the optimal configuration . . . 91
4.4.3 Model considerations . . . 93
4.5 Chapter conclusions . . . 96

5 Concluding remarks **98**

Bibliography **111**

Appendices **112**

A Appendix **113**
A.1 Indicators . . . 113
A.2 Investment parameter calculation . . . 126
A.3 Pumping drop estimation . . . 128
A.4 Resulting publications of this work . . . 129

List of Tables

1.1 EIPs examples and applications of IS in the world. 4

2.1 Criteria for indicators choice and their description 16

3.1 Maximum (C_n^{max}) and minimum number of connections (C_n^{min}) among nodes in a park. 37
3.2 Illustrative cases and their values of NCI, ϕ, and resilience indicator. 45
3.3 Resilience Indicator applied over case studies. The values of NCI and ϕ are also shown. 48
3.4 Flows adaptability index for participants into each layer of Ulsan EIP. 50

4.1 Mathematics formulation for different industrial problems. Information obtained from Biegler (2010). 61
4.2 Supply and demand for each participant in the park. 80
4.3 Parameters for the present problem (DGFEZ, 2018; Green and Southard, 2018). The price of selling oil was considered as a negative cost. 81
4.4 Distances between participating firms. 81
4.5 Shared flows in Steam Layer for the sustainable configuration. All the flows in kg/s. 85
4.6 Summary of the results for each considered configurations respect to the assessed aspects. The relative gap is presented in parentheses in each column. 86
4.7 Specific gap for the assessed aspects respect to each layer in the resulting configurations. 86

A.1 Indicators obtained though the research, and their dimension and criteria classification. Ec: economic - En: environmental - Sc: social; U; understanding - P: pragmatism - R: relevance - S: partial representation of sustainability. . 113
A.2 Data for the installing and piping cost according to the pipe diameter (information taken from CYPE Ingenieros (2018)). The displayed information is assuming a stainless steel pipe. 127
A.3 Resulting parameters and coefficients of determination for each model. . . . 127

List of Figures

1.1 Eco-Industrial Park in Kalundborg. Continuous-blue lines indicate water exchanges, dotted-red lines heat exchanges, and dashed-green line residue exchanges. Figure obtained from Chertow (2008) 3

2.1 Conceptual model of the Industrial Ecology level. IS transforms the wastes or by-products from a firm into inputs of another by means of connections between them. Information taken and modified from Chertow (2000). 11
2.2 Histogram of indicators by criteria of selection and sustainability dimension. U: Understanding; P: Pragmatism; R: Relevance; S: Partial Representation of Sustainability; Ec: Economic; En: Environmental; Sc: Social. 17
2.3 Set of indicators proposed to assess the illustrative EIP in Kalundborg. . . . 24

3.1 Consequences over an eco-industrial park when one of their participants stops its activity. The dotted arrows show the affected connections; and the numbers in bold, the modified flows. 32
3.2 Main characteristics of the resilience applied in an EIP, and structure of the proposed resilience indicator to measured it. 33
3.3 Representation of an EIP through a multi-layer scheme and directed graphs. Each node represents a participating firm of the EIP, and the directed edges (arrows) represent the connections between participants (flows). 34
3.4 Defined linear function between minimum and maximum cases for NCI. . . . 37
3.5 Maximum and minimum cases for the Network Connectivity Index (NCI) considering five participants: 3.5a maximum case, and 3.5b minimum case. . 38
3.6 An Industrial network with their participants and connections. In the figure, it is highlighted the participants connected with a participant k: OUT_k, participants with outlet connections from k; and IN_k, participants with inlet connections to k. 40
3.7 Defined linear function between the worst and the best case for ϕ_k. 43
3.8 Network in Ulsan (information taken from Behera et al. (2012)). 48
3.9 Steam Network of Ulsan (obtained from Behera et al. (2012)). 49
3.10 Flows adaptability index of each participant in a layer of the illustrative case: Steam Network of Ulsan EIP. 50

4.1 Examples of a multi-objective optimization problem, where the opposed objective functions are: investment and untreated wastewater flow. In the figure, some important concepts of a multi-objective problem are highlighted: the Pareto front or *trade-off*, delimited by the curve; the Utopia point; the reference point, and the Optimal solution. Data in the graph correspond to an illustrative example. 65
4.2 EIP in Ulsan (information taken from Behera et al. (2012)). 68
4.3 Superstructure for the present problem in Ulsan, South Korea. 70
4.4 Current situation of Ulsan EIP. All flows are in kg/s. 82
4.5 Optimal configuration for Ulsan EIP considering economic objective. All flows are in kg/s. 83
4.6 Optimal configuration for Ulsan EIP considering environmental objective. All flows are in kg/s. 83
4.7 Optimal configuration for Ulsan EIP considering resilience objective. All flows are in kg/s. 84
4.8 Optimal configuration for Ulsan EIP considering economic and environmental objectives. All flows are in kg/s. 84
4.9 Optimal configuration for Ulsan EIP considering economic, environmental, and resilience aspects. All flows are in kg/s. Data for Steam layer are in Table 4.5 85

1. Introduction

1.1 General background

Nowadays, both the world population and the industrial production are increasing (Index mundi, 2014), causing environmental and resource usage problems when appropriate planning and control are absent (Naciones Unidas, 2005). In this context, the main impacts of the industry on the environment are the gas emissions, wastewater, solid waste and land pollution. All of them are consequences of the industrial plants operation, specifically from energy and material input and output flows, from leakage of some materials, human activity in the industry, and untreated discharges (Ministry of Environmental Protection, 2015; National Academy of Engineering and Richards, 1997).

All these problems largely affect some regions of the planet, producing variation of their temperature and climate conditions. This effect is known as climate change and is referred to any abrupt variation on the climate caused by direct and indirect human activity, modifying the natural condition of the environment (Intergovernmental Panel On Climate Change, 2007).

Some consequences of the climate change are the following (Pereira, 1999; UNESCO, 2015; Vicuña et al., 2011):

- Variation on the weather condition of a region, specially, changes in their extreme temperatures: maximum and minimum temperature.
- Melting of the ice caps due increasing of the general temperature, producing an increase in the water level of the oceans.
- Modification of the general hydrological cycle causing changes on precipitation and the magnitude of the natural water sources.

Specifically, one of the main sources of pollutant, and very largely responsible of the climate change, is the industrial growth. According to Intergovernmental Panel on Climate Change (IPCC), the emissions from industrial sector to the environment is about 30% of the total greenhouse gases, mainly from material processing and combustion of fossil fuels (Intergovernmental Panel On Climate Change, 2014).

In order to overcome this kind of problems, the United Nations (UN) has elaborated a report, *Our Common Future*, proposing the concept of sustainable development. In this document, they notice a growing concern on future generations and the coming scenarios of the planet (Brundtland, 1987; Klöpffer, 2003). Within the report, three fundamental dimensions are mentioned, which are related to economic, environmental and social aspects. To ensure the development of the future generations, these dimensions have to be satisfied in a timeframe (Azapagic and Perdan, 2000). As an alternative, the sustainability is the final state of the sustainable development where the existence of the humankind is preserved in the time, while the three dimensions are respected (Diesendorf, 2001).

In this sense, the concept of Industrial Ecology (IE), specifically, Industrial Symbiosis (IS) arises as an alternative to improve the sustainability in the industry. The IE studies production processes, emulating the description of natural systems developed by ecology: an industrial system is composed by conserving and reusing resources (Chertow, 2008). It studies the interaction of industrial development with environmental, social, and industrial system of different scales and aims at increasing business success, preserving environment and taking into account the life of local community (Chertow, 2007; Frosch and Gallopoulos, 1989). A specific area of this field is the Industrial Symbiosis, which *engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by- products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity* (Chertow, 2000). The main conception of the IS is to transform the wastes or by-products from the activity of a firm, into inputs of another by means of connections between them.

An industrial park can be classified as an Eco-Industrial Park (EIP) if the community of businesses cooperate with each other, sharing resources (PCSD, 1997). This type of industrial parks can receive their denomination of EIP because of different reasons, related with sharing materials, energy, or infrastructure. It's also possible to develop green infrastructure or foster scavenger companies in the park, so industrial symbiosis is one possible aspect of EIPs. The most accepted definition of an EIP (Lowe, 2001) proposes a community of businesses located together on a common property. These businesses seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues.

One of the best-known examples of this kind of park is Kalundborg, in Denmark (Knight, 1990). It presents a regional symbiosis where the participants exchange water, heat and by-products (Chertow, 2008). The participants are firms, local community, and a lake (see Fig. 1.1). Each of them is considered in the design. Among their benefits highlight the significant reduction in energy and water consumption, decrease in gases emissions, improvements in quality effluents, and reuse of waste from the production (Chertow, 2000; National Research Council, 1997).

One of the best reported examples of this kind of park is the EIP of Kalundbog, Denmark. This is the first place where the concept of IS was formally implemented according to the literature (Knight, 1990). Among their benefits highlight the significant reduction in energy and water consumption, decrease in gases emissions, improvements in quality effluents, and reuse of waste from the production (National Research Council, 1997).

In addition to Kalundborg, there are several examples where the IS has been implemented,

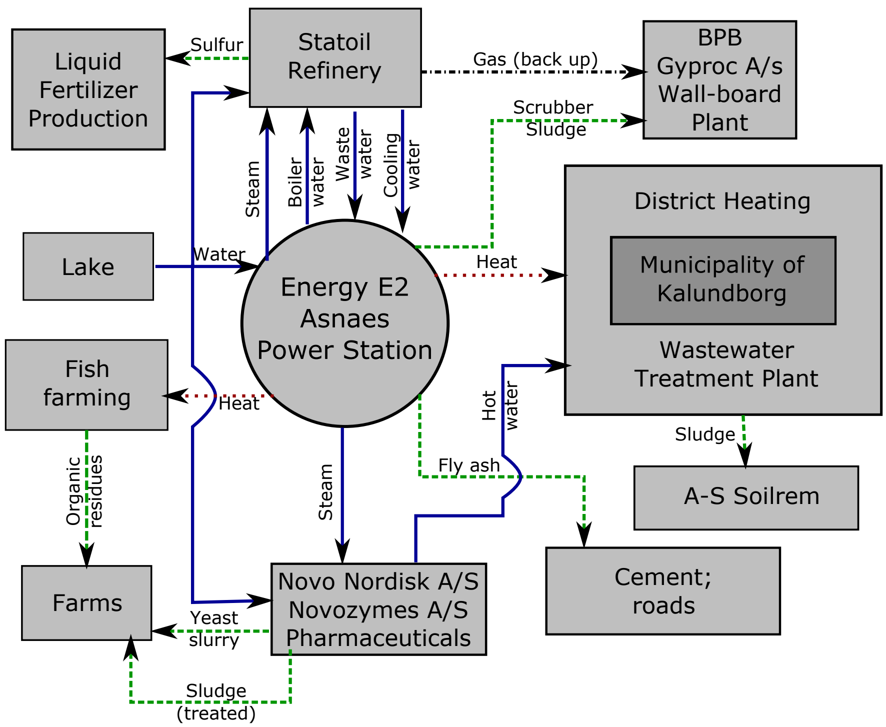


Figure 1.1: Eco-Industrial Park in Kalundborg. Continuous-blue lines indicate water exchanges, dotted-red lines heat exchanges, and dashed-green line residue exchanges. Figure obtained from Chertow (2008)

whether in an EIP or a supply chain of a firm (Chertow, 2007). For instance, in China, the concept of IS was applied on the supply chain of a sugarcane refining plant. It was motivated by the concern of the environmental impact generated by the process. In Australia, specifically Kwinana, the application of IS arise from the use of solid wastes from the metal, energy and mining processes. This IS implementation resulted in an integration where the residues are reused within the same processes. Another example is the IS network in Styria, Austria, where the participating firms form a complex network of industrial by-product exchanges. This recycling network serves as ecologically and economically benefits for the region. In addition to these examples, there are others identified in different countries. Some of them are mentioned in Table 1.1, where its place and a brief description are also included.

In general, the benefits of applying IS to an industrial park are significant, and related to firms profitability, environmental impact reduction, and concern for local communities, i.e., to the three dimensions of sustainability: economic, environmental and social (Azapagic and Perdan, 2000; Dunn and Steinemann, 1998; Gibbs, 2008; Brundtland, 1987). Its magnitude depends on the EIP configuration, specifically on the connections among participating firms, their location in the park, and on the presence or absence of certain firms. Therefore, the planning and the design of EIPs is critical to reduce the wastes generated by the participating firms, without negative impact on the economic benefits obtained, and concerning on the future of the local communities.

In this sense, to choose the best EIP configuration, a measurement of sustainability is required to compare different alternatives. An optimal EIP configuration minimizes the

Table 1.1: EIPs examples and applications of IS in the world.

Country/City	Description	Reference
EEUU	Park composed of 250 enterprises. I was founded in 1958, where 11 firms were organized around the IS.	Eckelman and Chertow (2013a)
Canada	EIP considering different chemical plants focused in gasification, carbon capture, energy, and ammonia production.	Kantor et al. (2012)
Brazil	Projects development to foster the design of EIPs in Rio de Janeiro.	Elabras Veiga and Magrini (2009)
Taiwan	Industrial park considering several high-tech industries related to semiconductors, computers, photoelectric, high-accuracy system, and biotechnology field.	Chen and Huang (2004)
New Haven	Industrial symbiosis that considers an industrial (with a energy plant) and residential sector, interacting each other to obtain advantages.	Baris et al. (2001)
Landskrona	Industrial symbiosis initiated in 2002, involving connections among 20 firms and 3 public organizations.	Mirata and Emtairah (2005)
Ulsan	Industrial park started as a traditional industrial network and evolved in a EIP due the strict environmental policies in South Korea. This is one of the most known IS examples.	Park et al. (2008); Behera et al. (2012)
Tianjin-Jiangsu-Shandong-Shanghai-Beijing-Guangdong	Some new eco-industrial parks developed in recent year in China. They have obtained significant results related to economic and environmental issues.	Tian et al. (2014); Yu et al. (2014)
Kawasaki	Eco-town in Japan, composed by 74 firms. The main members obtaining the greatest benefits are: an iron and steel company, a cement firm, a chemical plant, and a paper company.	Dong et al. (2014a)

negative impacts and maximizes the positives ones as a result of the activity of the park (Boix et al., 2015). However, how to measure the three sustainability dimensions in an EIP? How to integrate the three sustainability dimensions in a single measure?

To achieve a sustainable development, it is important to focus on the assessment and planning of industrial development of a firm or group of firms. In this sense, and considering the benefits obtained from different EIPs, it is necessary to replicate this effort to assist in the management of industrial sectors. However, is it possible to achieve the planning and design of these EIPs, e.g. Kalundborg or Ulsan, through a mathematically formulation? Moreover, is it possible to formalize the configuration of an EIP by means of Optimization and Process Engineering tools?

A formal way to reply the design and to decide the configuration of an EIP is by means of the formulation of an optimization problem. This is a mathematical tool to select the best alternative within possible options (Amaya A., 2003). This tool is widely used in engineering problems (Biegler and Grossmann, 2004; Boix et al., 2015), for example: to choose the operating condition of the reforming process (Díaz Alvarado and Gracia, 2012), to design and to plan a batch plant (Méndez et al., 2000, 2001; Sandoval et al., 2016), and to decide the allocation of certain equipment and routes of trucks in a process (Rey et al., 2009; Vera et al., 2003). Furthermore, the optimization has been also used in a bioprocess level in the synthesis and selection of polypeptides in the purification process (Lienqueo et al., 2009, 1999; Mahn et al., 2007).

In general, the engineering problems are classified in three groups (Biegler and Grossmann, 2004): Design and synthesis, Operation, and Control. Each of them, depending on their characteristics, can be modeled through different formulations: Linear Programming (LP) or Nonlinear Programming (NLP), if the equations representing the problem are linear or not; Mixed Integer Linear Programming (MIP) or Mixed Integer Nonlinear Programming (MINLP), if the variables used in the problems are continuous or integer (discrete variables). This classification will be broadly explained in Chapter 4.

Within the design and synthesis area, it is possible to find problems related to the design of industrial parks or eco-industrial parks. These problems have been formulated by means of NLP, MILP and MINLP models in order to solve the connections problems and the allocation problem among the participating firms (Biegler and Grossmann, 2004; Boix et al., 2015). For instance, in Karuppiah and Grossmann (2006), the authors propose a optimization model to design a water network in an industrial park by means of a NLP/MINLP formulation. Through case studies, they prove the effectiveness of the model in this kind of problems (Karuppiah and Grossmann, 2006). In Lovelady and El-Halwagi (2009), the authors optimize the use of fresh water of firms in an industrial park, using a source-interceptor-sink representation. They formulate a MINLP model, minimizing the cost of fresh water, and waste treatment. In this way, they solve the problem determining optimal design decisions for stream allocation for five plants in an EIP (Lovelady and El-Halwagi, 2009).

On the other hand, as mentioned above, the benefits of an EIP depends on its configuration, i.e., on their physical connections: material and energy flows among the participant forming an industrial network (PCSD, 1997). After reviewing the benefits of an EIP, an important point is whether these parks have issues to solve or prevent.

In this sense, while the design of an EIP is beneficial for the participant under the context of sustainability dimensions (Boix et al., 2015), the connections with other plants suffer the reluctance from companies. The connections among companies can also propagate failures within the network. Certainly, these operative aspects constitute a barrier for the industry, and for the implementation of new EIPs (Zeng et al., 2013). So, how to convince industries to be included in an EIP? Is it always safe to connect processes? What if a company undergoes a stop in production?

In computer science, a security or resilience factor is considered when defining a network so as to reduce its vulnerability. This measure takes into account the topology of the network, quantifying the potential damage to the whole network when the most critical element (e.g. the element with the maximum number of connections) is removed (Matta et al., 2014).

In the context of EIP design, the planning of an industrial network focusing on the stability of the whole activity within the park, when one of the participants is removed, it is fundamental for the industry to overcome this security barrier. In this sense, a pending issue in this field is to design the connections of a single plant considering the stability of the other participants and their flow requirements, specially during failures within the network (Xiao et al., 2016; Zeng et al., 2013). A new objective during the design phase could be added to improve the security of the network by increasing its resilience.

The aforementioned subjects motivate the present work, with a main focus on the mathematical-based design of EIP, in order to promote and support the implementation of Eco-industrial Parks with sustainability and security objectives. Accordingly, the contributions of this work are: (i) the proposal of a sustainability measurement to assess and compare EIPs; (ii) the definition of a resilience measure to be added in the design phase of an industrial network; and (iii) the design of an EIP considering sustainability and resilience aspects through an optimization problem.

1.2 Objectives

The main goal of this work is to formulate and solve a multi-objective optimization problem in order to design an eco-industrial park, considering the sustainability dimensions and a resilience factor in its configuration. To achieve this goal, the following specific aims are outlined:

- To develop criteria for selecting sustainable indicators, beside to build a database of single and integrated indicators that assesses social, environmental, and economic dimensions of EIPs.
- To define a resilience indicator for industrial networks.
- To design an EIP considering sustainability and resilience aspects by means of a multi-objective optimization problem.

1.3 Thesis organization

This work is composed by 5 chapters and an Appendix section. In chapter 1, a brief introduction of the work is presented in concert with its motivation and its contributions. In addition, the objectives are presented. In the chapters 2, 3 and 4, each specific aim is covered with its respective theoretical background and concluding remarks. Finally, Chapter 5 presents the concluding remarks, and future work.

2. Defining a sustainability measure for EIPs[1]

2.1 Chapter summary

A variety of indicators is available for assessing the economic, environmental, and social aspects of an Eco-industrial park (EIP). The managers of a sustainability assessment over these parks should overcome an important task at the beginning of the study: to select indicators.

To support this activity, the challenge is to list and classify a large set of sustainability indicators. Consequently, the main achievements of this chapter are a wide search and classification of sustainability indicators, and the development of four criteria to filter indicators when assessing an EIP. A literature search in ISI Web of Science's database is presented to explore feasible indicators. The definition of 249 indicators is provided in an annotated list.

An important difficulty to use these indicators is to select a proper subset. To deal with the aforementioned selection, this chapter proposes four criteria constructed to be functional, clear, and adaptable to the application context. The proposed criteria are: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*. The 249 indicators have been filtered using the four criteria, and have been classified according to three dimensions of sustainability (social, environmental, and economic dimensions). An indicator is denominated *single* when its value presents only one dimension of sustainability; and *integrated* if more than one dimension is represented.

The four criteria provide a formal way to filter a large set of possible indicators, improving the mechanism for their selection. In order to illustrate their application to select suitable indicators for the assessment of EIPs, a hypothetical case is constructed on the basis of an industrial park in Kalundborg. The selected indicators meet the four criteria and the evaluation goal.

Focusing on sustainability dimensions, many of the integrated indicators are related to

[1]The contents of this chapter have been published in Journal of Cleaner Production, DOI: 10.1016/j.jclepro.2016.05.113. See publication in Appendix A.4.

the economic and environmental dimensions. Nevertheless, few of them are related to social dimension. Therefore, to cover the main aspects of each dimension of sustainability, a combination of single and integrated indicators should be included in the assessment.

Finally, four recommendations are made to select proper indicators during the sustainability assessment of an EIP: start with a large set of possible indicators, as those presented herein, preselect those indicators linked to the objectives of the assessment, apply the four criteria for indicators choice, and prefer comparative indicators.

2.2 Background: Assessing the sustainability of Eco-Industrial Parks

As outlined in chapter 1, a precursor to EIPs is the regional industrial symbiosis at Kalundborg, Denmark, uncovered in 1990 and then described in the international press (Knight, 1990). The participants share water, waste-water facilities, steam, fuel, by-products and waste products, that become feedstock in other processes (Chertow, 2008). The benefits of the symbiosis for this industrial park and the surrounding community are (National Research Council, 1997):

- The significant reduction in energy consumption and coal, oil, and water use.
- The reduction in sulfur dioxide (SO_2) and carbon dioxide (CO_2) emissions and improved quality of effluent water.
- The transformation of traditional waste products such as fly ash, sulphur, and biological sludge, into raw materials for production.

On the other hand, many authors have measured the benefits of applying IS to different sustainability projects about enterprise management and city design, in order to reduce the carbon emissions. For example, in the work of Yu et al. (Yu et al., 2015), the authors make a quantitative evaluation of the effects of IS performance on carbon emission reduction in Xinfa Group, a comprehensive large enterprise group in China. They compare a scenario with IS and other without IS, and obtain that the first one exhibits a decrease of the carbon emission by 11% compared with the second one. Other example is the application of IS to cities presented in Dong et al. (Dong et al., 2014a). In this work, the authors study the CO_2 emissions reduction potential in IS projects in two cities of China, Jinan and Liuzhau. They design new scenarios to apply in the both real project, including energy network, waste plastics recycling, and others. They obtain a total reduction potential of 4,000 tCO_2/year and 2,300 tCO_2/year in Jinan and Liuzhau respectively. Based on the results, the authors propose several policies to promote IS model in China. Both examples show that IS is an important tool to reduce the environmental impact and to achieve the sustainability. This behavior may be extended to other aspects (as social), to promote the sustainability further than environmental or economic dimensions.

Benefits of applying IS to an industrial park are related to economic, environmental, and social aspects (Azapagic and Perdan, 2000; Brundtland, 1987), and they are focused on (i) to improve the profits and resilience of the companies, (ii) to reduce environmental impact, and (iii) to care about the life of people in local communities. Some of them are mentioned in the works of Dunn and Steinemann (1998) and Gibbs (2008). Economic benefits are reducing of waste disposal costs and decreasing of purchase of raw materials. The environmental achievements are a reduction of waste production and of exploitation rate of new resource inputs (Dunn and Steinemann, 1998). The social consequences of IS are not obvious, since increased company profitability will produce a trickle-down effect on local spending and on employability, improving both of them to the benefit of the wider local population (Gibbs, 2008). Other social effects are related to enhancement of life style and health in the surroundings of the EIP, due to the reduction of general emissions in the park. While the effects of economic and environmental benefits are easy to measure because they are often assessed in an industrial context, the social effects require a suitable evaluation because they are difficult to quantify and are usually not assessed. Therefore, all the sustainability dimensions must be properly assessed in order to quantify the total effect of applying IS to an industrial park.

To choose the best EIP configuration, a metric of sustainability is required to facilitate the comparison of different alternatives. An optimal EIP minimizes the negative impacts and maximizes the positives ones as a result of the activity of the park. However, how the social, environmental, and economic aspects of sustainability in an industrial park could be measured?

The answer comes from the quantitative sustainability indicators. Using these indicators it is possible to assess the effectiveness of an industrial park in terms of sustainable development. This quantitative sustainability assessment of an EIP is necessary to ease the comparison between different configurations and to support decisions on its design. Some examples of these indicators are *Value Added* (economic), *Ozone Depletion* (environmental), and *Income Distribution* (social) (Azapagic and Perdan, 2000). There are also integrated indicators grouping two or more of these single indicators. For instance, Eco-efficiency includes one economic indicator and three environmental indicators (raw material consumption, energy consumption, and CO_2 emissions) (Park and Behera, 2014).

Other tools used to analyze and to assess the sustainability level of industry are Life Cycle Analysis (LCA) and Material Flow Analysis (MFA). LCA is an analytical tool to systematically evaluate the environmental impact of a product (or service) through its complete life cycle (Chertow, 2008; Curran, 1996). It offers a quantitative comparison between different alternatives of product design in order to analyze each of them and to select the best one. MFA is similar to LCA, and it is based on the systematic accounting of physical units and the principle of mass conservation (Organisation for Economic Co-operation and Development, 2008; Sendra et al., 2007). The use of this tool can provide an integrated view of the economy and the environment; capture omited flows with relevant impact; and reveal how flows of material move among countries and within countries. An MFA can analyze several industry scale (as shown in Fig. 2.1) with different instruments depending on the concern and the goal of the assessment. Both LCA and MFA are widely used in the assessment of industrial parks and EIPs (Chen et al., 2013; Dong et al., 2013; Sendra et al., 2007; Wen and Meng, 2015; Yang et al., 2012; Zhang et al., 2016) and depends on indicators to measure the activity of the actors.

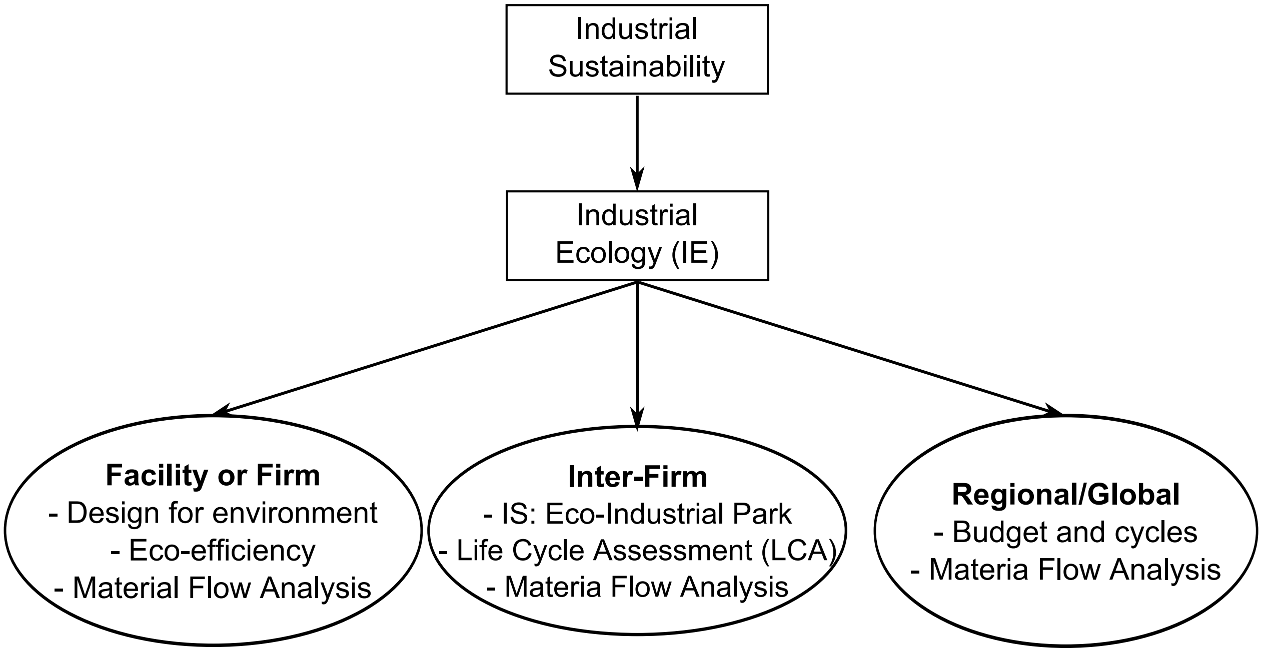


Figure 2.1: Conceptual model of the Industrial Ecology level. IS transforms the wastes or by-products from a firm into inputs of another by means of connections between them. Information taken and modified from Chertow (2000).

There are many articles about IS and the dynamic organization of an EIP (Boons et al., 2011; Chertow, 2000, 2007, 2008, 2012) where the authors explain the bases and propose models for IS. There are also many examples about EIP projects, which mimic the development of the regional industrial symbiosis in Kalundborg (Baas, 2011; Behera et al., 2012; Côté and Cohen-Rosenthal, 1998; Geng et al., 2010a; Sokka et al., 2011; van Beers et al., 2007; Zhang et al., 2010). There are works related to the design of EIPs where the authors optimize economic, environmental, and social aspects of each park (recently Boix et al. (2015) wrote a complete review on this topic). However, to our knowledge, there is no article focused on a wide repository of EIP indicators and their applicability to a quantitative assessment on the EIP sustainability. Besides other non-quantitative indicators could be useful to assess an EIP, this chapter covers quantitative indicators because of their wide application in sustainability assessment, and the suitability of this type of indicators to compare different EIP configurations or their progression in time (Azapagic and Perdan, 2000; Zhu et al., 2010).

An important difficulty to use indicators when assessing an EIP is to select a proper set among all possible indicators. To overcome this difficulty, the goals of this chapter are (i) to develop criteria in order to construct suitable indicators, (ii) to build a database of single and integrated indicators, and (iii) to classify them focusing on the assessment of EIPs. An important challenge is to cover a wide set of indicators. Accordingly, the keywords for this search have to be wide. After finding these indicators, a set of filters are presented herein for their classification aiming at sustainability. Therefore, a broad search and the respective classification of sustainability indicators are presented as results to readers.

The first effort is to present the indicators found in the literature and to propose suitable criteria to select indicators in order to assess an EIP. Two classifications of these indicators are reported: the compliance with the criteria proposed herein and the covering of the three dimensions of sustainability. For studying the applicability of the four criteria to select suitable indicators, an hypothetical case is presented. After a critical analysis, the last section summarizes the desirable features for an indicator to assess an EIP.

Instead of using this four criteria, the managers of an industrial park could select the indicators for the assessment of an EIP based on their own experience. Nevertheless, the four criteria presented herein provide a formal way to filter a large set of possible indicators, improving the mechanism to select proper indicators.

Naturally, there are other strategies to filter variables. It is possible to perform a multiple criteria data envelopment analysis (MCDEA) (Zhao et al., 2006), addressing qualitative and quantitative criteria. MCDEA is used to rank the alternatives through the consideration of the relative membership degree of qualitative factors in quantitative data. However, this type of analysis requires data. The criteria developed in the present chapter assume an scenario where the data is not yet provided.

2.3 Methods for Searching Indicators

Sustainable indicators are essential to assess the effectiveness of an EIP regarding the axes of sustainable development (economic, environmental, and social dimensions) (Azapagic and Perdan, 2000; Brundtland, 1987). These indicators have to capture the main characteristics of an EIP: to compare with other contexts and to support decisions concerning its configuration. The comparison of an EIP can be done with: (i) its historical performance, (ii) a new configuration of the same park, (iii) or other parks.

For a complete sustainability assessment, the indicators must quantify all impacts (internal, external, positives, and negatives) produced by the geographical location of firms and their connections through an industrial network.

This repository of indicators is based on publications registered in the ISI Web of Science (ISI-WoS). The keywords used in the search are subject to the following logic sentence: *(indicator OR quantitative assessment) AND ("industrial park" OR "industrial symbiosis")*. The search was performed over the abstract, title, and keywords of all publications in the database with the ISI-WoS searching engine. Through this search, 51 articles published between 2000 and 2014 were found.

The keywords used in the search are generic because a wide search is proposed considering all the indicators used in assessments. The resulting indicators could include indicators with no relation to sustainability. However, the resulting indicators also include those sustainability indicators not presented as sustainability indicators in bibliography. Therefore, after processing the results, the resulting indicators were classified in the respective dimension of sustainability and adjusted to the selection criteria.

In order to achieve the goals of this chapter, these publications were filtered by document type, publication year, and topic. The works passing this filter are related to industrial assessment and provide a set of indicators. Thus, publications about dynamic organization of EIP are excluded as well as studies of diseases caused by proximity to an EIP, and other specific evaluations.

Finally, 32 articles published between 2000 and 2014 in which industrial assessment is the main topic and which includes a set of indicators are considered.

To propose criteria for indicators choice, it is necessary to cover the context of the sustainability assessment. A review of criteria proposed in literature is performed in order to take into account previous efforts to guide the indicators selection. These criteria, proposed for a wide industrial context, will be adapted to the assessment of an EIP. This adaptation mainly consider the applicability of the criteria and their suitability to an industrial analysis of sustainability.

2.4 Results: indicators for Eco-industrial parks: selecting criteria, sustainability dimension, and classification

2.4.1 Criteria for selecting indicators on EIPs

Sustainability indicators allow to assess economic, environmental and social aspects of a process, a company, the development of a product, a city, an industrial park, and others. When applied to an industrial park, these indicators must capture the main characteristics of a process from a specific angle of the sustainability assessment. They must reflect the negative and positive impacts resulting from the activity of an EIP, focusing on a specific dimension of evaluation.

To reflect those characteristics of an EIP, indicators must achieve minimum requirements because they are often oversimplified, they include only some important characteristics, or some of them are difficult to quantify or understand (Azapagic and Perdan, 2000). As a general framework, other authors (Azapagic and Perdan, 2000) have presented a standardization of industrial indicators for their application to companies and included the following characteristics for them:

- Simple and informative.
- Relevant to the three dimensions of sustainability.
- Generic for all industry and sector.
- Normalized by a certain value depending on the goal of the assessment.

To achieve the goal of the evaluation and to assess different scales of companies, the authors Azapagic and Perdan (2000) define three types of analysis: product-, process-, and company-oriented analyses. These analyses normalize indicators by a certain value or functional unit. The first one is related to products sharing the same function but made by different competitors. The second one refers to the operation and production of a plant. The last one is focused on the performance of a company or of its parts. Each analysis informs the levels of sustainability (Azapagic and Perdan, 2000).

Other alternatives are the risk analysis (Tixier et al., 2002) and exergy analysis (Dewulf and Van Langenhove, 2002) among other types of analysis. As the classification based on scale is related with the sustainability assessment of an EIP, this type of analysis will be adopted. Specifically, the process-oriented analysis allows to identify aspects to overcome within a set of connected processes.

Even though it's possible to avoid the scale classification, this logic allows to properly separate these analyses developed for different types of assessment, most of them oriented to single entities: single companies, single processes, or single products. An alternative analysis could have a systemic view based on the integration of processes or companies. However, this type of analysis could also be classified in the former scale-based categories because an integrated process is still a process, and the integration of companies can be considered a new entity with the characteristics of a larger company. In general, the scale-based classification of analyses is well adapted to the sustainability assessment in an industrial context.

Most of the articles referenced in this chapter can be classified as process-oriented analyses. The goal in this classification is to separate the attention points of the variety of feasible analyses, looking at the outputs, operations, or corporations. Regarding an EIP, the most important factors are the chemical/physical operations and the energy and mass input/output flows. Therefore, a process-oriented analysis is considered, since the performance of an EIP is mainly related with their operations and connections.

Ten years later, Zhu et al. (2010) reported four characteristics of EIP indicators to evaluate the incorporation of candidate companies to an EIP. They adopted the following criteria for selecting indicators (Zhu et al., 2010):

- Comprehensive: In choosing scale indicators, the indicators must consider various factors including capacity of an EIP to incorporate a new enterprise and the characteristics of an enterprise, e.g., resource use and pollutant production.
- Available: Indicators must be measurable and based on existing (easy to obtain) information.
- Relevant: Indicators must be relevant to the EIP development goal and to the long term strategy of participating companies.
- Practical: The measurement and monitoring of the indicators are practical and reliable given the available resources in the park and in companies. The value of the indicators must also be easy to obtain.

Taking the aforementioned criteria presented by Zhu et al. (2010), the *Availability* criterion can be discussed. Since the creation of an inventory is a complex and expensive work, the indicators with less complexity and less cost have an advantage. Nonetheless, is it important to have existing information? Existing information tend to be inaccurate and questionable, so industries measure their behavior with a specific scope. To our understanding, the key point in this criterion is the advantage of *easy-to-obtain* information, not the availability of existing information. Using the *Availability* criterion proposed by Zhu et al. (2010) with focus on existing information could impose a bias when selecting sustainability indicators, preferring those based on existing information instead of other *easy-to-obtain* options adjusted to the purpose of the study.

Most of the criteria proposed by Zhu et al. (2010) for selecting indicators for an EIP assessment are similar to the characteristics for industrial indicators presented by Azapagic and Perdan (2000). The main difference is the evaluation goal because the first one is based on product-, process-, and company-oriented analyses (generic case for industry), while the second one is only based on a process-oriented analysis (specific case for an EIP). Another difference is the selected criteria for defining proper indicators.

Since the criteria presented by Azapagic cover the generic case of an industrial analysis (product-, process- and company-oriented analyses) and the criteria reported by Zhu are process-oriented, new criteria more similar to the last ones are defined . It is important to observe that the criteria by Zhu cannot be used directly in our scenario because they are only oriented towards the admissions of new members in an EIP.

The proposed new criteria are focused on selecting indicators to assess the EIP behavior. This new set is proposed combining the former criteria described by Azapagic and Zhu, and modifying some of them. This new reference to select indicators is constructed as follows.

Three modifications on this base are presented:

- The first one (i) is to join *available* and *practical* features together, because both address calculation. This criterion will be called *pragmatism* and will comprise all the features of the aforementioned criteria.
- Another modification (ii) concerns the feature *comprehensive*. A modification to reflect the simplicity of the indicators as exposed by (Azapagic and Perdan, 2000) is proposed. Accordingly, the meaning of the *understanding* criterion aims to simplicity instead of variety as the former *comprehensiveness* criterion by (Zhu et al., 2010). The new criterion does not aim to wideness. It aims to previous formation of the personnel and the tuning of the indicator with this training. The original idea proposed by Zhu can now be represented in the combination of the concept *relevant*. Therefore, EIP indicators must present the following criteria: *understanding*, *pragmatism*, and *relevance*. An EIP indicator exhibits the criterion *understanding* if it is easy to understand (simple). It shows *pragmatism* if the characteristics are measurable by input-output flow data or surveys, and if its value is easy to obtain. The availability of information before the assessment is helpful but not critical, so its existence is not included in this criterion. An indicator shows *relevance* if it is engaged with the goals of both the EIP and firms.

- The last modification to basic criteria (iii) is the addition of a new criterion, *partial representation of sustainability*, to state the proper representation of a dimension of sustainability by an indicator. All these definitions are shown in Table 2.1.

Table 2.1: Criteria for indicators choice and their description

Criterion	**Description**
Understanding	An indicator must be easy to understand.
Pragmatism	An indicator must be measurable, its value has to be easy to obtain.
Relevance	An indicator must be relevant to the goal of EIP development and to enterprises' future.
Partial Representation of Sustainability	An indicator must properly represent one or more sustainability dimensions, allowing to compare configurations or historical progression of an EIP.

Section 2.5 is focused on the discussion of the performance of the indicators showed in section 2.4.2 using the selected criteria as a filter.

2.4.2 Classification of EIP indicators

Classification by criteria for indicators choice

Several indicators have been used to evaluate the impact of an industrial park. For instance, in Lu et al. (2012), the authors assess the emissions of an EIP using a metabolic model and defining suitable indicators for this purpose. Other authors define considering energy performance (emergy and exergy) (Geng et al., 2010b; Jiang et al., 2010) or using Life Cycle Analysis (LCA) or hybrid-LCA strategies (Azapagic and Perdan, 2000; Chen et al., 2011).

At the beginning of a sustainability assessment, managers have to select indicators among all possible options. Different authors use a variety of indicators to evaluate the goals of EIPs or of companies. To ease the selection of indicators, a repository has been constructed through the search described in section 2.3. Table A.1 in Appendix A.1 presents all the indicators used in these articles, including their definitions. Table A.1 also presents an evaluation of the criteria defined in section 2.4.1 for each indicator. Fig. 2.2 shows a histogram for each selection criterion, as a synthesis of the classification in Table A.1. The green bars reflect the number of indicators meeting each criterion separately, and the red bars show the number of indicators classified according to each sustainability dimension. Additionally, single and integrated indicators are presented separately in order to analyze each category.

On the other hand, each indicator can also be classified according to its dimensions of sustainability (social, environmental or economic one). The following section is focused on this issue.

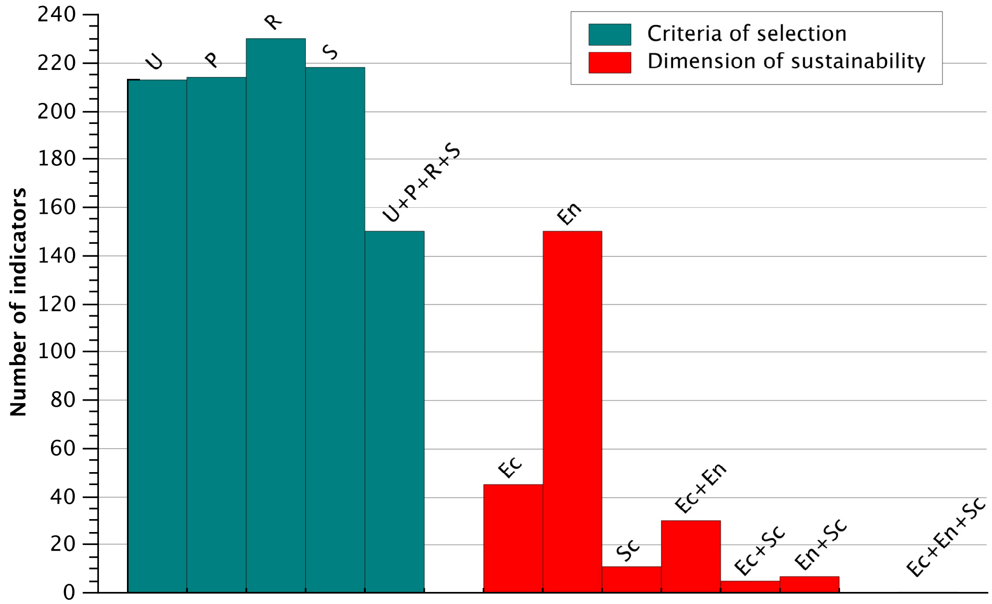


Figure 2.2: Histogram of indicators by criteria of selection and sustainability dimension. U: Understanding; P: Pragmatism; R: Relevance; S: Partial Representation of Sustainability; Ec: Economic; En: Environmental; Sc: Social.

Classification by dimensions of sustainability

Sustainability dimensions are economic, environmental, and social. Indicators in Table A.1 assess these dimensions and therefore they can be classified in these categories. Column *Dimen. of Sust.* in Table A.1 shows this classification.

For assigning a category to an indicator, its main objective is considered. Thus, if the main aspect assessed by the indicator is the use of resource, water, energy, by-product, and waste, it will be classified as environmental, even if this main aspect has also an economic or social impact. Recycling and reusing of material or energy will be also classified as environmental. An indicator will be considered as economic if it is related to the economic performance and capacities, or measures production efficiency. An indicator will be social if it is related to impacts on local community or workers of an EIP.

Some indicators, like ratios, assess more than one dimension. Examples of them are the *Chemical Oxygen Demand (COD) production per unit Industrial Value Added (IVA)* or the *ratio of industrial waste water utilization* (Bai et al., 2014; Zhu et al., 2010). In these cases, all the dimensions evaluated by the indicator are taken into account.

Accordingly, an indicator can evaluate one or more dimensions of sustainability. The classification of an indicator as *single* or *integrated* refers to this issue. In both cases, the sustainability dimensions addressed in the assessment are informed in Table A.1 including the number of dimensions in the corresponding column. In the case of integrated indicators, the dimensions included are separated by the character /. An indicator will be *single* if it evaluates only one dimension. Namely *acidification potential (AP)*, which measures the contribution of SO_2, nitrogen oxides (NOx), hydrogen chloride (HCl), ammonia (NH_3), and hydrogen fluoride (HF) to potential acid deposition (Azapagic and Perdan, 2000), in essence it is an environmental indicator. On the other hand, if the indicator assesses two or more dimensions, it will be considered as an *integrated* indicator. An example is *emergy-LCA index*, which is a ratio of economic to environmental aspects (Brown and Ulgiati, 1997; Song et al., 2013; Yang et al., 2003). Fig. 2.2 shows a histogram for each sustainability dimension and their combination in integrated indicators. It is important to remark the counting in this histogram, because single and integrated indicators assessing environmental aspects have been counted separately in their respective bars: *En*, for single indicators; and *Ec+En*, *En+Sc*, for integrated indicators. The same separation is valid for the other sustainability dimensions.

2.5 Discussion

The total number of indicators studied on this chapter is 249. They have been classified using the four criteria selected in section 2.4.1 and the dimensions of sustainability. The assessment managers should take into account the context of their application. This context could make a difference in the classification of indicators in our proposed categories. For instance, the availability of information or the formation of personnel could justify a change in *pragmatism* and *understanding* of an indicator, respectively.

As can be observed in Fig. 2.2, many indicators meet one of the four criteria, and only 150 meet all of them. Thus, some indicators are not suitable for assessing the activity of an EIP. Most of the rejected indicators need reserved information from companies, which is not easy to obtain. Other indicators were rejected because they were not directly understandable in an industrial context and demands a higher level of training for process managers than normal indicators.

Regarding the assessed dimension, the economic and environmental aspects have the largest number of single indicators (45 and 150 respectively), and only 11 are related to the social aspect. Integrated indicators have presented a similar distribution. There are many indicators evaluating the economic and environmental dimensions (30 indicators), and only a few of them are related to social aspects (5 economic-social and 7 environmental-social). On the other hand, there are no integrated economic-environmental-social indicators. The aforementioned distributions reflect the lack of indicators covering the social aspects and the need of constructing such indicators for the sustainability assessment of EIPs.

In the following sections the applicability of the four criteria over the indicators of Table A.1 are analyzed in order to understand what indicators are included or excluded under each of them. A hypothetical case related to an EIP in Kalundborg is also presented for selecting sustainability indicators using these four criteria. After that, the classification using the sustainability dimensions over the set of indicators is studied and discussed. Finally, a general discussion related to the main characteristics of suitable indicators for the EIP sustainability assessment is presented.

2.5.1 Applying the criteria for indicators choice over 249 indicators

The proposed criteria for classifying the performance of EIP indicators are: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*. Indicators in Table A.1 were filtered using these four criteria in order to simplify their further selection. The application of the four criteria is analyzed highlighting the attributes of the rejected indicators in each category. It is important to remark the flexibility of this filter. Each context of application could change the classification of indicators in three categories, because the *understanding*, *pragmatism*, and *relevance* depend on the context, because of the preparation of the personnel, availability of data, or measurement feasibility. These criteria also depend on the purpose, taking into account the goal of the assessment and the projected comparison after the analysis.

Understanding

In general terms, an indicator has been excluded from this category if its definition is hard to understand in an industrial context. Some indicators study the industrial interactions using a rationality based on metabolic pathways, as in biological networks. Thus, they were excluded according to the criterion of *understanding*. For instance, in Lu et al. (2012) (Lu et al., 2012), the authors define a *mutualism index* to reflect the ratio of positive to negative mutualism relationships between entities. These type of indicators were excluded from this category, because it is necessary to manage the concept of mutualism in an industrial context for their application. Emergy is referred to the energy required to provide a given product or flow (Odum, 1996). All emergy-based indicators were excluded from this category because the use of emergy concept is not easy to understand in an industrial environment. An example is *Absolute emergy saving* (Geng et al., 2014) that uses the emergy concept to measure savings concerning, for instance, nonrenewable resources and purchased resources, resulting from sharing by-products between companies.

It is important to highlight the hypothesis sustaining this filter: It has been supposed the use of these indicators by process managers. Naturally, if the assessment is executed by professionals with environmental, economic, and social formation, the *understanding* criterion impose a less restrictive filter. The knowledge about indicators can be modified at any context with information available in measurement manuals (Organisation for Economic Co-operation and Development, 2008).

Pragmatism

Some indicators are not easily measurable because they need a deep knowledge about the companies in the park. For instance *long term vision*, which needs information about projections and strategy of each company (Phillips et al., 2006). Since this information is not always available, all indicators exhibiting these characteristics were excluded under the criterion of *pragmatism*.

Among detailed analyses, LCA is probably the most important tool. It requires detailed data from companies participating in the production process, inside and outside the industrial park. The quality of information has to be guaranteed to support the analysis, so companies conduct audits. However, within a context, this information could be available or not. The necessary information to back up an LCA can already exist or its measurement can be possible. In both cases the related sustainability indicators are pragmatic. Nevertheless, the necessary information could be non-existent or impossible to be measured because of technical or economic reasons, turning the involved indicators in non-pragmatic. Consequently, the availability of information or its feasibility of measurement justify the classification of an indicator as pragmatic or not.

It was supposed that no detailed information is available when performing the assessment, so footprint-like indicators have been filtered because of the *pragmatism*. It is important to remark this classification is flexible and the *pragmatism* filter can change with the availability of information.

For instance, there are indicators using the carbon footprint to quantify the emissions. Although there are methodologies for measuring the carbon footprint, there is no warranty about the behavior of the companies in this area. Applying a carbon footprint with an LCA approach requires detailed information about companies and their providers from outside the park. This is a highly valuable approach. Nonetheless, its application is hard within the boundaries of an EIP. Since these indicators were proposed in a complete LCA approach, this class of indicators was excluded under the criterion of *pragmatism*. However, indicators applied under a Hybrid-LCA approach (Azapagic and Perdan, 2000) were accepted and, in this case, such indicators are considered pragmatic.

Other indicators reflect the presence or absence of specific institutions in the park. Even though this information is easy to obtain, it is not measurable using a continuous variable (continuous numerical space). Therefore, they were excluded under the criterion of *pragmatism* because they are only measurable with a binary variable (1 =presence; 0 =absence), and this class of variables was not fully integrable with other indicators during the sustainability assessment.

Relevance

The main units in the sustainability assessment of an EIP are firms and the EIP itself. A firm is the basic unit of an EIP and its activity causes economic, environmental, and social impacts on the whole park. Some indicators for sustainability work as black boxes instead of grey boxes over the EIP. A black box work as a simple input/output model of the whole park, while a grey box model includes information about partial steps (processes or firms). The representation of the complete activity of firms is impossible, and disregarding their existence is an oversimplification. As an example, the indicator *output rate of land* can be analized, which measures the value generated in the EIP per unit of used land (Su et al., 2013). This sustainability indicator only takes into account a sustainability assessment of the whole EIP without focus on each participating company.

Another group of indicators is focused on products, without paying attention to firms or EIP performance. As an example, the indicator *product durability* reflects the durability of a product and is oriented to consumers. All these indicators were excluded under the criterion of *relevance*, because they do not aim to assess an EIP as proposed in section 2.2. Relevant indicators allow to give feedback to companies in the EIP.

Partial Representation of Sustainability

Some of the indicators can be used to make a comparison between enterprises or products. However, some of them do not afford a comparison between the EIP and its history, or between different configurations of the park. Even though they make a suitable assessment for any sustainability dimension, these indicators do not achieve the second objective of the *partial representation of sustainability* criterion. For instance, the indicator *percent-added of park energy productivity*, can only be used to compare different firms incorporated in a park (Zhu et al., 2010).

Another set of indicators use characteristics of an industrial plant, when placed on different location. Therefore, this set of indicators was excluded from the *partial representation of sustainability* category because the comparison between firms in a park is not supported.

On the other hand, it is noteworthy that all indicators in Table A.1 assess some dimension of sustainability, and thus they meet the first part of the definition of *partial representation of sustainability*.

2.5.2 Applying the criteria for indicators choice to an EIP in Kalundborg: hypothetical case

The formation of the regional industrial symbiosis in Kalundborg, Denmark, is attributed to an evolutionary progress of exchanges between firms, into a complex network of symbiosis interactions (Jacobsen, 2006a). The main facilities in this regional integration are an oil refinery, a power station, a gypsum board facility, and a pharmaceutical company. Other firms have been located around these companies. The goal is to share ground water, surface water and wastewater, steam, fuel, and others by-products used as feedstock in other process (Chertow, 2000, 2008).

In order to evaluate the effectiveness of the criteria presented herein to select suitable indicators for the sustainability assessment of EIPs, it is proposed a set of indicators from Table A.1 to assess the example from a subset of companies in Kalundborg. A hypothetical example is constructed, assuming the availability of some data and the goal of the EIP composed by:

- Novo Nordisk.
- Novozymes.
- Novo Nordisk & Novozymes Land Owner's Association.
- Novozymes Wastewater & Biogas.

These entities share energy (steam, warm condensate, and district heating), water (surface water, cleaned surface water, and waste water), and materials (ethanol waste and biomass) (Kalundborg Symbiosis, 2015).

It should be clear the demonstrative purpose of this example. While the real case from Kalundborg is far more complex, the instance will be simplified to illustrate the applicability of the criteria presented in this chapter.

Defining the hypothetical case

Kalundborg is a regional industrial symbiosis where many companies share water, steam, by-products, or other resource, in order to increase the level of sustainability. Let's assume the following ideas to illustrate the application of the criteria for indicators choice, in the context of the aforementioned EIP composed by four participants:

- The main goals of this park are to reduce the main gases emissions (CO_2, NOx, and SO_2) and to increase the economic returns for each firms in the EIP.
- In this context, the achievement of the goals will be measured by a technical assistant from a Government department.
- This assistant has a basic academic training on process and environmental subjects.
- The available information to assess this EIP is a list of input/output flows of each industrial plant in the park.
- The goal of the assessment is to measure the main economic and environmental aspects of the park.

Now, based on the information and the four criteria previously identified, a set of indicators to be checked by the assistant is proposed.

Applying the criteria for indicators choice

- **Understanding:** This criterion depends on who is assessing the EIP. In the example, the applicant has a basic academic training on process and environmental subjects. As the supposed applicants in the definition of the *understanding* criterion are professionals with analogous formation as the hypothetical applicant in the example, all the indicators classified as *understanding* on Table A.1 may be used to assess this EIP in Kalundborg. For example, *CO_2 emission indicator*, *COD generation intensity*, *SO_2 emissions per added industrial value*, and *Net economic benefit*. In this case, the set of indicators has been reduced from 249 to 209.

- **Pragmatism:** This criterion depends on specific information, which reflects if the indicators are based on available or easy to obtain information. In the example, the available information is the input/output data of each firm in the park, therefore, only those indicators that measure characteristics using the input or output flow data are included. For instance, *Acidification*, *Air pollution*, *Direct Material Input*, and *Industrial value-added per capita*. The set of indicators has been reduced from 209 to 175.
- **Relevance:** This criterion considers the focus on the assessment and the goal of the evaluated park and firms. In the example, the goal of the EIP in Kalundborg considers the reduction of main emissions (CO_2, NOx, and SO_2) and the increase of economic return for all firms in the EIP. In this sense, the indicators as *Industrial value-added per capita*, *Increase company competitiveness*, *Park SO_2 emission change rate %*, *CO_2 emission indicator*, or *Eco-efficiency* may be used to assess these goals. The set of indicators has been reduced from 175 to 162.
- **Partial Representation of Sustainability:** This criterion considers the assessment of a sustainability dimension and the possibility of performing a comparison with the history of the EIP or with other feasible configurations. In the example, the indicators classified as environmental (En), economic (Ec), and those integrating both dimensions (En/Ec) are suitable for the assessment. The selected indicators have also allowed a comparison of the EIP performance with that of other feasible configurations or with its own performance in time. The set of indicators has been reduced from 162 to 131.

The application of the four criteria formalizes the indicators choice to assess the EIP. Despite the variety of economic and environmental indicators achieving the four criteria, they could be redundant. Thus, the most representatives of each class were selected in order to use them in the evaluation of the illustrative EIP in Kalundborg (see Fig. 2.3).

In Jacobsen (2006a), the author uses a similar set of indicators to study the progress of the IS in the regional integration in Kalundborg: saving cost by substitutions; reduction of carbon dioxide, sulfur dioxide, and nitrogen dioxide emissions; and , heat saving and water consumption. In this work, Jacobsen also selects heat saving and water consumption as indicator, because he has specific information about the power plant in Kalundborg, and the goal of the assessment is to evaluate the symbiotic exchange between companies. In the illustrative case, only input/output flow data and the goals are to measure the main economic and environmental aspects of the park are available.

2.5.3 Sustainability dimensions

If the purpose is to optimize an EIP, then the problem grows rapidly in size with the number of indicators or objectives (Copado-Méndez et al., 2014; Díaz-Alvarado, 2015). In this context is preferable to have more dimensions of sustainability integrated in less indicators. This

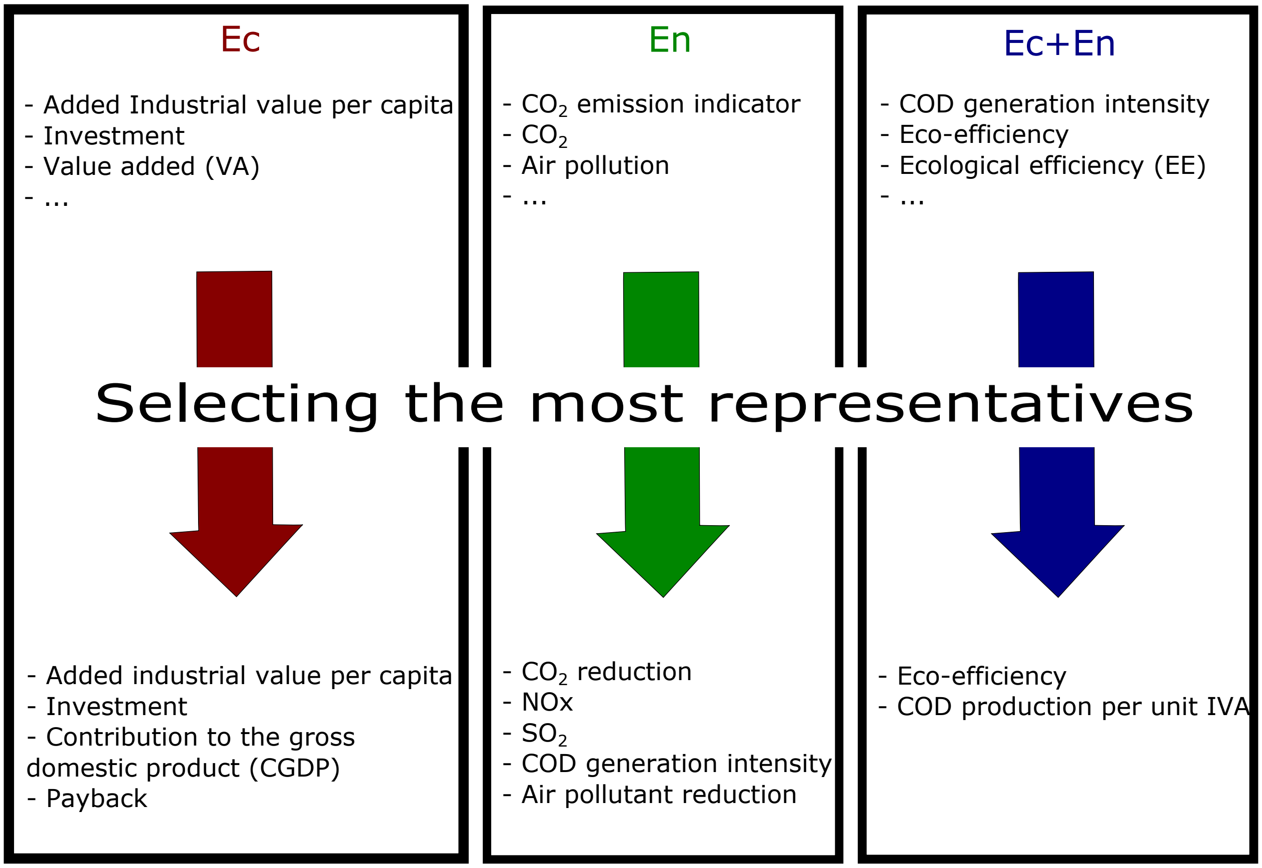


Figure 2.3: Set of indicators proposed to assess the illustrative EIP in Kalundborg.

approach involves an oversimplification risk. Since this issue depends on the objective of the sustainability assessment, it was not considered in the criteria detailed in section 2.4.1. The oversimplification risk has to be considered during the selection of indicators for the assessment.

The oversimplification risk comes from the selection of an integrated indicator instead of a set of single indicators. The integrated indicators could avoid details when compared with a set of single indicators. Other possible impact is the sensitivity difference between integrated or single indicators when describing real cases. For instance, For instance, assume the configuration of a park changes and a single indicator changes its value by 50%. Is this difference also represented by an integrated indicator? Is the reality well-captured by the single or the integrated indicator? Is important to remark the higher sensitivity of single indicators when compared to integrated indicators.

The desirable flexibility of single indicators to represent reality has a trade off with the increase of complexity. The level of detail is the cause of both. A proper set of indicators has to be pragmatic in the sense of an approachable complexity, not sacrificing its relevance in terms of the flexibility to represent the reality.

Even though it was found indicators meeting the four criteria, none of them considers the three dimensions of sustainability. However, some indicators were found convering two dimensions. For instance the ratio indicators measure the emission of certain pollutant divided by the added industrial value in products. In general, this type of integrated indicator takes into account an environmental characteristic of a system divided by an economic feature generated by the system. The most common environmental characteristics are resource consumption, generated emissions, reuse of by-product, water use or reuse, and amount of waste generated. The added industrial value is the most common economic characteristic. On the other hand, some indicators consider both economic and environmental characteristics as a measure of the energy required to provide a product or flow. An example is *emergy economic efficiency index*. It reflects the amount of local resource exploited compared to the amount of emergy investment (Brown and Ulgiati, 1997; Song et al., 2013; Yang et al., 2003). When used these indicators are not easy to classify into sustainability dimensions, because some of them commonly do not meet the criterion of *understanding*. The use of emergy concept is mainly associated with the energy. Then it should be considered as environmental, and its classification depends on the aim of the evaluation.

There are also integrated indicators known as Eco-efficiency indicators, which assess economic and environmental aspects as the ratio indicators. In general, they use the added industrial value divided by the sum of some characteristics measured by LCA.

The integrated indicators assess mainly economic and environmental aspects, and a few of them take into account the social dimension. There are two social integrated indicators applicable on EIPs: environmental-social and economic-social. The first one considers the specific emissions affecting the local community and the environment. For example, *health* indicator measures the air and water pollutant that could promote diseases as well as waste discharged by factories on the surrounding area (Chen et al., 2012a). The second one reflects an economic flow from companies to the local community or workers in the park. For instance, the indicator *expenditure on health and safety (EHS)* indicates the budget invested by an enterprise (an economic flow) in health and safety (social aspects) for its workers (Azapagic and Perdan, 2000).

Even though these integrated indicators meet the four criteria and assess two dimensions of sustainability, they do not cover all the factors related to a suitable social assessment. For instance, they do not evaluate the level of satisfaction of the surrounding population, the employment contribution of the enterprises, etc. In order to solve this lack of integrated indicators, single indicators may be considered. However, the use of these indicators must be aligned with the goal of the assessment and simplify the comparison between feasible configurations.

As integrated indicators do not cover the social dimension properly, single indicators included in Table A.1 should be used in order to couple this topic in the analysis.

2.5.4 Final considerations

Many indicators classified in this chapter assess the sustainability dimensions and meet the four criteria. Even though there are plenty of them, the assessment coordinator must wonder if all these indicators are necessary to assess a park. The use of the indicators will depend on the park under evaluation. Not all of these indicators show a significant change when comparing different feasible configurations of a park. Another possibility for potential reduction is revealed if the Pareto dominance structure of different parks is preserved when certain indicator is absent (Brockhoff and Zitzler, 2006; Díaz-Alvarado, 2015). Thus, the selected indicators must be significant for the assessed parks to represent the change in their characteristics. The selection of significant indicators can be addressed with the Pareto dominance analysis (Brockhoff and Zitzler, 2006; Díaz-Alvarado, 2015), artificial neural networks (ANN) or genetic programming (GP) (Muttil and Chau, 2007).

On the other hand, the four criteria allow to select suitable indicators to evaluate EIPs but these indicators do not necessary assess the three sustainability dimensions (economic, environmental, and social). In Jacobsen (2006a), the authors focused on a quantitative analysis of the economic and environmental performance of regional industrial symbiosis in Kalundborg. In order to measure these aspects, they used a set of economic and environmental indicators: saving cost by substitutions; reducing carbon dioxide, sulfur dioxide, and nitrogen dioxide emissions; and heat saving and water consumption. In this case, all these indicators pass the four criteria and therefore, they are suitable to evaluate the progress of the IS in the industrial park. Now, if the goal of the assessment is changed and a social analysis is added, the selected set of indicators would not be enough. In this case, this set will pass the four criteria. Nevertheless, they will not cover all the important aspects of social dimension, like investment of firms on near community and the job creations. Thus, to select a suitable set of indicators to assess EIPs, they should cover all the main aspects of the sustainability assessment and to achieve the four proposed criteria.

Finally, to select a suitable set of indicators during the sustainability assessment of an EIP, four recommendations are made: start with a large set of possible indicators, as those presented herein, preselect those indicators linked to the objectives of the assessment, apply the four criteria for indicators choice, and prefer comparative indicators.

2.6 Chapter conclusions

In this chapter, a significant set of sustainability indicators is listed in order to select a suitable subset to evaluate an EIP. Accordingly, four criteria were proposed to classify them all: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*. Under this classification, the excluded indicators use definitions difficult to understand in an industrial context, need a deep knowledge about companies in the park, only consider the EIP scale excluding the performance of the firms, or do not allow a comparison between feasible configurations of a park.

It is important to highlight the flexibility of the filter imposed by the criteria for indicators choice. Each context of application could change the classification of indicators in three of the four categories, because the *understanding*, *pragmatism*, and *relevance* depend on the context. From this point of view, the classification of indicators performed in this chapter can vary with the context. Future directions could report the most used indicators in the sustainability assessments of EIPs as an orientation to managers. This improvement should be translated to the *understanding* criterion, because the most applied indicators are also the most understood. Also, a pathway of the historical progression of an EIP following the change in the value of some indicators is suggested. This pathway could be a reference to new successful cases of Eco-industrial parks.

Under a hypothetical case, a set of suitable indicators were selected to assess an illustrative EIP in Kalundborg. These indicators were: *added industrial value per capita*, *investment*, *contribution to the gross domestic product*, *payback*, *CO_2 reduction*, *NOx*, *SO_2*, *COD generation intensity*, *air pollutant reduction*, *Eco-efficiency*, and *COD production per unit of IVA*. They were selected by using the four criteria and choosing the most representative ones from this resulting set of indicators. All of them achieved the four criteria and met the goal of the evaluation.

On the other hand, indicators were also classified under the assessed dimension of sustainability: *single* for one dimension, and *integrated* for two or more dimensions. This classification showed an abundance of integrated indicators assessing economic and environmental dimensions, and a few of them are related to the social dimension. To solve this problem, single indicators may be considered.

In order to optimize an EIP, the integrated indicators are useful to reduce the number of indicators during the assessment. Classified indicators assess two dimensions of sustainability: economic-environmental, environmental-social, or economic-social. Single indicators should also been included because the integrated indicators related to the social dimension do not cover all the main aspects.

Finally, to construct or select suitable indicators for the sustainability assessment of EIPs, they have to meet the four criteria presented herein, cover the main goal of the assessment, be significant in comparing historical or feasible configurations, and take the complexity vs sensitivity trade-off into account.

3. Resilience in industrial networks: defining a resilience indicator[1]

3.1 Chapter summary

An Eco-Industrial Park (EIP) is a community of businesses that seeks to reduce the global impact by sharing material. The connections among the industrial participants within this park improve the environmental performance of the industrial network. However, the connectivity also propagates failures. This risk is an important point of criticism and a barrier to industrial plants when evaluate their integration to an EIP.

This chapter proposes an indicator to follow the resilience of an EIP so as to improve the security of the whole system, considering the dynamic of the participants to endure a disruptive event. This metric could be used by decision-makers in order to include the resilience in the design phase of an EIP. Solving these security problems would expand the set of experiences of cleaner production, promoting the integration of industrial processes.

The proposed resilience indicator is based on two main characteristics of an industrial network: the number of connections among participants, and the capacity of each flow to change its magnitude when a participant suddenly stops sharing flows within the park. A network is separated in independent layers to quantify its flexibility when substituting flows. Each layer includes a single shared material. The resilience of a multi-layer park is then calculated as a weighted summation.

This indicator is applied first over five illustrative cases to analyze its applicability. Then, it is applied over one known EIPs: Ulsan, in South Korea. All these applications show consistent results, even when compared with reality, illustrating the performance of the proposed indicator. Although the proposed resilience indicator has been developed for material networks, it can be adapted to heat integration networks, considering each temperature as a kind of material in a multi-layer park. In this case, special attention should be payed to physical constraints as minimal temperature gradient.

[1]The contents of this chapter have been published in Journal of Cleaner Production, DOI: 10.1016/j.jclepro.2017.11.025; and Computer Aided Chemical Engineering, DOI: 10.1016/B978-0-444-63965-3.50328-7. See publications in Appendix A.4.

3.2 Background: security issues in Eco-Industrial Parks

In the previous chapter sustainable indicators for assessing EIPs has been reviewed, and four criteria for their selection has been defined. However, there is an aspect does not considered in the literature: the resilience. The goal of this chapter is to define a resilience indicator to assess EIPs. For this purpose, it will be first defined the necessity of this aspect in the planning of EIPs, and then a mathematical expression will be proposed, in addition with some examples to illustrate its use.

As mentioned in chapter 1, an eco-industrial park is a community of businesses located together in a common property, sharing materials, energy, or infrastructures (Lowe, 2001). It is motivated by economic, environmental, and social improvements achieved through the collaboration among the firms within the park. These relationships foster the implementation of industrial symbiosis, which seeks to transform wastes, by-products or products of a firm into inputs for another one taking advantage of their own connections (Chertow, 2000).

The benefits obtained by an EIP cover the three sustainability dimensions: economic, environmental, and social (Boix et al., 2015). The improvements are related to profitability, environmental impact reduction, and concern for local community next to the park (Valenzuela-Venegas et al., 2016). The magnitude of these benefits is associated to the configuration of an EIP, in other words, to connections among firms and their location. This configuration can be chosen by decision-makers at the design phase of EIPs.

In this sense, to design an EIP focusing on their benefits, an optimization problem can be formulated (Boix et al., 2015). Using the solution of a nonlinear or mixed-integer nonlinear programming problem (MINLP), it is possible to obtain an optimal network configuration (Biegler and Grossmann, 2004). This formulation can back up decisions during the design phase of an EIP, formalizing the industrial planning to make the industrial development more sustainable.

There are several works proposing a mathematical formulation to design an EIP. These efforts can be classified into three categories according to the type of exchanges among participants of the park (Tudor et al., 2007): water networks (e.g. Boix et al. (2011, 2012); Montastruc et al. (2013); Ramos et al. (2016); Rubio-Castro et al. (2011); Tiu and Cruz (2017)), energy networks (e.g. Chae et al. (2010); Kuznetsova et al. (2016); Liew et al. (2013)), and material networks (e.g. Haslenda and Jamaludin (2011); Tietze-Stöckinger et al. (2004); Zhang et al. (2017)). Each of these formulations optimizes the configuration of an EIP with focus on one or more sustainability dimensions.

For example, in the work of Lovelady and El-Halwagi (2009) the authors propose and solve a problem of water network design in order to minimize the total annualized cost using different strategies as recycling, reutilization, and separation. They compare this solution with the scenario of using only freshwater, and conclude that the recycling strategy is the most profitable. In Tiu and Cruz (2017), the authors propose a mathematical formulation to design a water network, simultaneously minimizing the economic and the environmental dimension through the reduction of piping, operating, freshwater, wastewater and treatment cost, and involving the volume and the quality of the water used in the EIP (Tiu and Cruz, 2017). They obtain a better result considering both sustainability dimension that just one of them. In Cimren et al. (2011), an optimization model over by-products in an industrial network is used to minimize economic and environmental indicators. This model is applied over an existing industrial network in USA and its solution is compared with a base case with no synergistic relationships among the companies. The resulting by-product network achieves the reduction on the costs and on the CO_2 emissions when is compared with the base case, illustrating the improvements offered by the design of an EIP using a mathematical formulation (Cimren et al., 2011).

In all these examples the main objectives of the EIP design problems are focused on sustainability dimensions (Boix et al., 2015). Even though EIPs are largely studied in the literature, they suffer of reluctance from industries. Indeed, the potential industrial participants are often hard to convince due to security issues when connecting processes, because failures are also propagated through a network (Zeng et al., 2013). In this sense, how to convince industries to be included in an EIP? Is it always safe to connect processes? What if a company undergoes a stop in production?

In computer networks, a security or resilience factor is considered when defining a configuration. This focus allows to reduce the vulnerability of the whole network (Goel et al., 2004). This measure takes into account the topology of the network, in other words, the way the elements are connected in it. In general, this factor quantifies the damage done to the whole network when the most critical element (e.g., the element with the maximum number of connections) is removed (Matta et al., 2014). The aforementioned damage is commonly quantified by the number of compromised nodes after the failure of a single node within the network.

Following the same idea, after obtaining an optimal configuration in the context of an EIP design, the question is what would happen if a participant is removed from the park. A pending issue in this field is to design the connections of a single plant considering the stability of the other participants and their flow requirements, specially during failures within the network (Xiao et al., 2016; Zeng et al., 2013). A new objective during the design phase could be added to improve the security of the network by increasing its resilience.

The point is how to measure the resilience of the park during the design phase. In this sense, some authors have defined metrics in order to measure this characteristic (Chopra and Khanna, 2014; Li and Xiao, 2017; Xiao et al., 2016; Zeng et al., 2013; Zhu and Ruth, 2013). In Chopra and Khanna (2012, 2014), the authors propose four metrics to measure the resilience of an EIP, focused in two aspects of an industrial network: its connectivity and its efficiency (Chopra and Khanna, 2012, 2014). The general goal of these metrics is to measure the impact of a partial and complete disruption over the park and their participants, focusing on the most affected nodes and on the loss of efficiency of the park. In Li and Xiao (2017), the authors propose a methodology to measure the resilience of a network, analyzing their topological aspects (Li and Xiao, 2017). They explore the resilience from a topological approach, determining the main characteristics of a network and quantifying the importance of each participant through these characteristics. Additionally, the authors note the necessity to use the flows of the participant firms to better represent the real relationships in the park.

Other works are focused on the cascading failure of the participants in a network, studying the responses of the firms after removing one of them. They base their analysis on the fact that if a critical component fails, it could lead to further participants decided to leave the network due to cascading failures (Zeng et al., 2013). In Xiao et al. (2016), the authors propose a model that can be used for more stable operation of an eco-industrial system (Xiao et al., 2016). With this purpose, they define two indicators respectively to assess two characteristics of an industrial network: its structural stability and its functional stability. The goal of the model is to measure the impact of the cascading failure, considering the decision of the firms to stay in or leave the park, i.e., the dynamic of the network after a disruptive event occurs.

All these measures and indicators about resilience of an eco-industrial system are focused on the efficiency of the network from a topological point of view, or on the cascading failures phenomenon, considering the decision of the participant to stay in or leave the park. However, there are no indicators focusing on the dynamic of the participant of an EIP when a disruptive event occurs, considering the decision of the firms to absorb the consequences of this failure.

Accordingly, the present chapter aims at creating a resilience measure for EIPs, considering the decision of the participant to absorb possible disruptive events on them. This indicator is constructed to support its future application in an optimization problem, so as to design EIPs with an additional resilience-oriented objective. The goal of this metric is to determine if the connections are enough to maintain the identity of the park and to quantify the performance of the participants when a firm stops sharing flows, after changes in their input and output flows. Beside the resilience measure, this indicator is applied first over five small examples to illustrate and analyze its use. Then, two application cases over a real EIP are introduced and assessed to compare the results with the reality. The objectives of this chapter are to define a resilience metric over EIPs and to apply this factor in existing EIPs.

After the present introduction, Section 3.3 explains the construction of the proposed indicator, and Section 3.4 illustrates its application by means of some examples. Section 3.5 presents the discussions about the application of the proposed indicator over the illustrative examples, and about some improvements in its construction. Finally, Section 3.6 presents the conclusions of this chapter.

3.3 Definition of the Resilience Indicator

This section explains some considerations about the representation of an EIP to back up the definition of the Resilience Indicator.

The starting point is the definition of resilience from Fiksel (2003), where the authors define this concept as *the capability of the system to absorb disruptions before it changes its properties that control its functionality. This property allows an IS network to endure the impact of unforeseen event.*

This definition takes into account the capability of a network to face a disruptive event.

In other words, resilience considers the adaptability of a network to withstand a disruptive event and to absorb their consequences. The present chapter considers a disruptive event when a firm interrupts its activity losing their inputs and outputs in the network.

Generally, from computer network studies, or other similar systems, the concept of resilience is focused on the number of connections. The most connected participant is identified as the critical node. When this node is removed from the network, the number of connections is detected (critical node), and the number of lost connections is quantified over the whole network comparing two scenarios: the base state, and the state where the critical element is not present (Matta et al., 2014).

In this sense, when a participant interrupts its activity, the network losses connections (edges) and modifies its flows: two effects are present in the network. After the disruption in the network, the remaining participants must compensate the flows they have lost. For instance, if a participant of a network interrupts its activity (see Fig. 3.1), its associated input and output flow would disappear (connections), changing the number of connections in the park. Since the network must continue working and producing, the remaining participants should modify the magnitude of their flows to compensate the losses without important changes in the network (entering of a new participant or creating new connections).

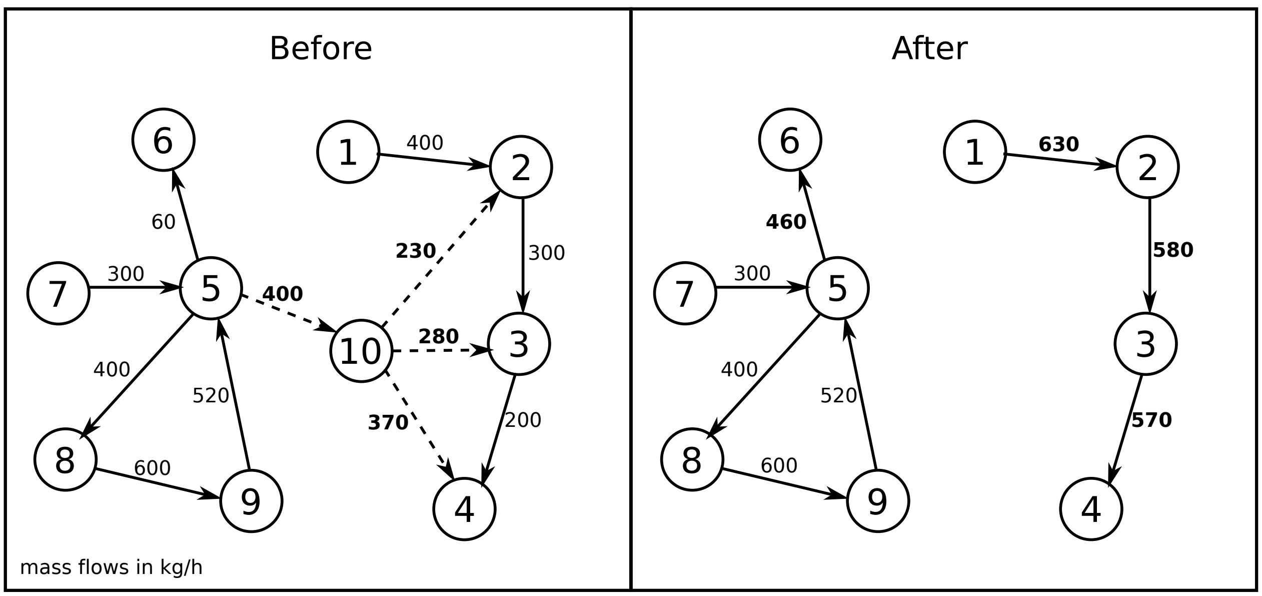


Figure 3.1: Consequences over an eco-industrial park when one of their participants stops its activity. The dotted arrows show the affected connections; and the numbers in bold, the modified flows.

In view of the foregoing, the resilience measure has to detect these consequences and assess if the park could maintain its operation. Accordingly, the indicator has to focus on two aspects: (i) if the connectivity of the industrial network is enough to withstand a disruptive event and (ii) if the other firms can compensate the lost flows when a firm interrupts its activity.

Therefore, the proposed resilience indicator measures two aspects of a network:

- The number of connections among participants, known as Network Connectivity Index (NCI).
- The capacity of the participants to compensate the flow demand when one participant interrupts its activity, or Flows adaptability index (ϕ).

The resilience indicator is defined as a combination of both metrics, the Network Connectivity Index and Flows Adaptability Index. Fig. 3.2 shows the structure of this indicator, remarking how it is constructed by two sub-indicators and what characteristics of the resilience, in the context of EIP, it measures.

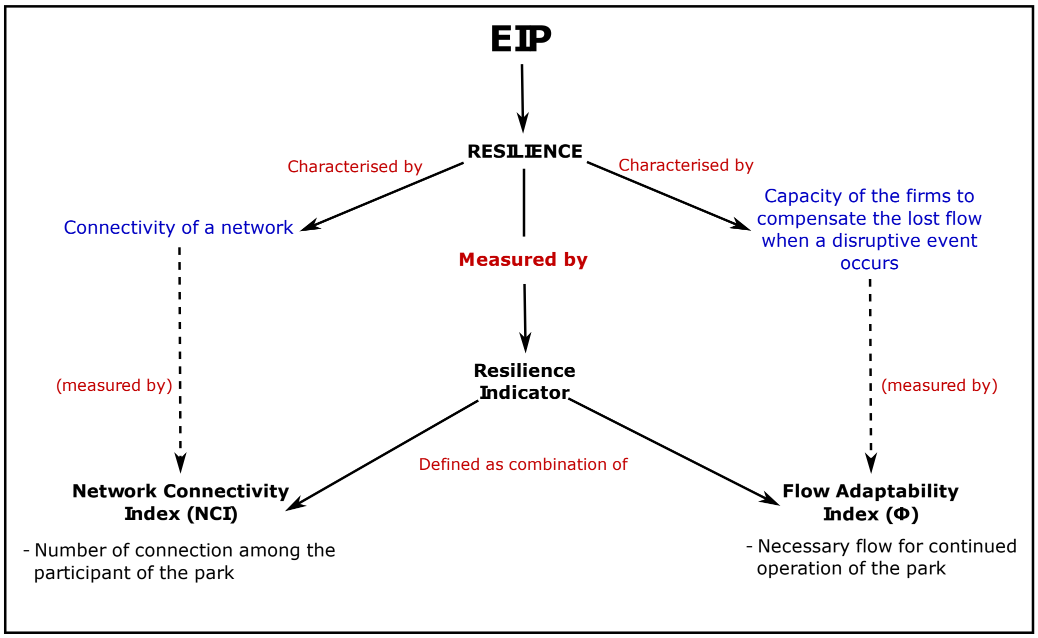


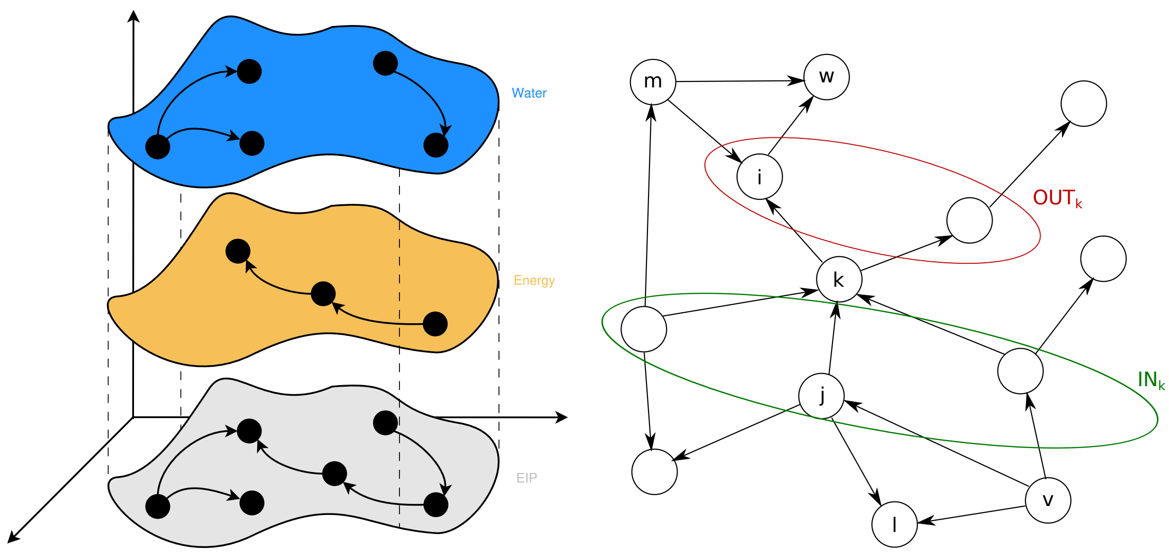
Figure 3.2: Main characteristics of the resilience applied in an EIP, and structure of the proposed resilience indicator to measured it.

The following subsection explains the mathematical representation used in the definition for both metrics.

3.3.1 Mathematical representation of an EIP

An EIP is a set of firms where the participants can share different elements such as material and energy. To facilitate the design and the analysis of these parks, the information about flows can be separated in order to compose a network for each shared component (see Fig. 3.3a). With this in view, the design of an EIP can be approached by a succession of sub-designs, each of them related to a single material or energy. In such sub-design, the exchange network is defined by the connections between the participants and their respective flows. During this work, an exchange network associated with a single component (e.g. water) is a *layer*.

Each exchange network can be designed through mathematical optimization tools,



(a) Mathematical representation of different layers in a park.

(b) Mathematical representation of a network in a single layer.

Figure 3.3: Representation of an EIP through a multi-layer scheme and directed graphs. Each node represents a participating firm of the EIP, and the directed edges (arrows) represent the connections between participants (flows).

deciding connections and allocations of each participant (Boix et al., 2011). These tools use a mathematical representation to formulate the optimization problem. These representations are graphs, where the participants of the park are represented by nodes, and the connections, by oriented edges (see Fig. 3.3b). This representation is adopted in order to define each metric and the resilience indicator of an EIP.

Due to the aforementioned points, the following terms and sets are defined:

- N: Set of park participants.
- C: Number of connections among park participants.
- n: Number of participants, $n = |N|$[2].
- L: Set of layers in the park.
- $|L|$: Number of layers in the park.
- IN_k: Set of participants that contribute an input into $k \in N$.
- OUT_k: Set of participants that have an output from $k \in N$.
- $Q_l^{max,in}$: Maximum input capacity of the participant $l \in N$.
- $Q_i^{min,in}$: Minimum input capacity needed for the participant $i \in N$ to operate.
- $Q_m^{max,out}$: Maximum output capacity of the participant $m \in N$.
- $F_{i,j}$: Magnitude of the flow between $i \in N$ and $j \in N$.
- ϕ_k: Flow sensitivity of the participant $k \in N$ in a network.
- $\phi_k^{layer_r}$: Flow sensitivity of the participant $k \in N$ in the layer $r \in L$ of the park.
- NCI: Network Connectivity Index of a park.

[2] $|\cdot|$:cardinality of a set.

- ϕ: Flow sensitivity of a park.

3.3.2 Network Connectivity Index

As in a computational network, in an EIP the connections among participant are important because they follow the existing exchanges within the network. In this sense, if one participant interrupts its activity, their surrounding connections are infeasible while the disruption persists. With a larger number of connections in the park, the network has greater possibilities to endure changes in its configuration because it will be able to keep its connectivity when a participant interrupts its activity. When a park has a lower number of connections, a disruptive event in a company can isolate others.

The Network Connectivity Index (NCI) aims at quantifying connections in a park and at measuring the endurance of the whole network against a possible disruption. Therefore, the main focus of NCI is the configuration of the park: its topology. In this sense, if the park is completely connected and a disruptive event occurs, other firms would not be isolated and would have other options to compensate their losses. In this situation, the park maintains its identity. Conversely, if the network has only one connection between each participant and one of them interrupts its activity, the park is divided and could present isolated participant. This metric defines the connectivity level as a reference to a maximum and minimum number of connections in the network.

It is important to remark the absence of orientation in this measure. The NCI takes into account the complexity of the network, but other aspects as orientation and flows will be considered in the other metric (flows adaptability index). Since an EIP can be configured as a multi-layer park, to count the number of connection, all the participants are considered in a unique layer, no matter what they are sharing. If between two nodes there are more than one connection, just one of them is considered. For example, if two participants (nodes) are connected in a direct or reverse direction (from A to B or from B to A), the NCI considers a unique connection (edge).

Minimum number of connections (C_n^{min})

The minimum number of connections of an EIP is defined as the minimum number of edges necessary to constitute a park. A basic assumption in this logic is that an EIP maintains its identity if each node (firm) has at least one connection, i.e., it is not isolated.

Accordingly, under this definition, the following scenarios are possible:

- If the park has three nodes, $n = 3$, the minimum number of connection to maintain the participants connected, without identity loss (node isolation), is $C_3^{min} = 2$.
- If a new node is added to the last configuration, $n = 4$, it is possible to create three new connections: one to each existing node. As the goal is to calculate the minimum

number of connections, it is possible to consider only one of them. In this case, the minimum number of connection for $n = 4$ would be 3. However, there is a possibility to reduce this value with no isolated nodes. In this case, it is possible to separate the network in two subsets. Therefore, the minimum number of connection for $n = 4$ is $C_4^{min} = 2$.

It is important to note that the case with two or less nodes is not considered because they do not constitute an EIP, where the collaboration among three firms is required (Chertow, 2008).

Table 3.1 shows a summary of the minimum number of connections C_n^{min} for different number of nodes n. From this table and the above progression, it is possible to infer the following for the minimum case: (i) if n is even, every node has a unique edge; and (ii) if n is odd, one node has two edges and the remaining nodes have a single edge.

Therefore, the equation for the minimum number of connection C_n^{min} for n nodes is expressed as follows:

$$C_n^{min} = n - \lfloor n/2 \rfloor \tag{3.1}$$

Where $\lfloor x \rfloor$ is the operation floor, which is the largest integer less than or equal x.

Maximum number of connections (C_n^{max})

The maximum number of connections (C_n^{max}) in a park of n participants is defined as the larger number of edges among participants. In this sense, the following procedure is necessary to define C_n^{max}:

- Considering a participant in a park composed by n members (p_1, where $p_1 \in N$), its maximum number of possible connections is $n - 1$.
- For another participant (p_2, where $p_2 \in N$), the maximum number of connections, without repeating the connections in the above scenario, is $n - 2$. This is because the connections have been considered unoriented.
- Following this logic, the maximum number of connection for the participant p_k, where $p_k \in N$ (without repeating considered connections), will be $n - k$.
- Thus, the maximum number of connections in a park with n participants is obtained by the following summation:

$$C_n^{max} = \sum_{k \in N} n - k \tag{3.2}$$

$$C_n^{max} = \frac{n(n-1)}{2} \tag{3.3}$$

For example, if the network is composed by 3 nodes, the maximum number of connections is 3; if the network is composed by 4 nodes, the maximum is 6. Table 3.1 shows a summary of C_n^{max} for different number of nodes in a network.

Table 3.1: Maximum (C_n^{max}) and minimum number of connections (C_n^{min}) among nodes in a park.

Number of nodes (n)	Minimum number of connections (C_n^{min})	Maximum number of connections (C_n^{max})
3	2	3
4	2	6
5	3	10
6	3	15
7	4	21
8	4	28
9	5	36
10	5	45

Definition of Network Connectivity Index (NCI)

Establishing the maximum and minimum number of connections in a park, it is possible to define the Network Connectivity Index (NCI) associated with each of them. If the network has the maximum number of connections, C_m^{max}, then, $NCI(C_n^{max}) = 1$. If the network has the minimum number of connections, C_m^{min}, then the $NCI(C_n^{min}) = 0$. With these values, a linear function between both cases (see Fig. 3.4) allows to interpolate other cases. It is worth to remark the use of a linear function in order to simplify the definition of NCI. In future works, it could be changed according to properly represent the behavior of this characteristic between these two points.

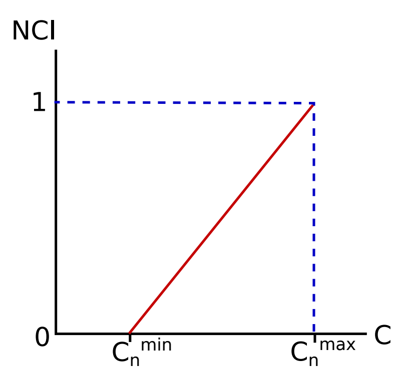


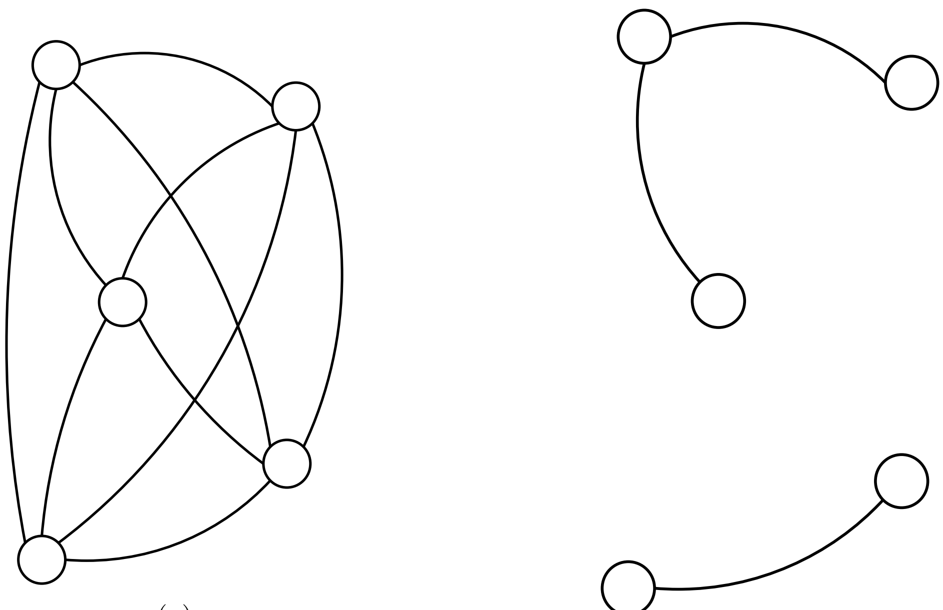
Figure 3.4: Defined linear function between minimum and maximum cases for NCI.

Finally, the NCI is defined as follow:

$$NCI(n, C) = \frac{2(C - n + \lfloor \frac{n}{2} \rfloor)}{n^2 - 3n + 2\lfloor \frac{n}{2} \rfloor} \tag{3.4}$$

Where C is the number of connections of the network (edges) and n is the number of participants of the network (nodes). It is worth noting that NCI is an adimensional index and indicates the connection level of a configuration network with n participants according to its maximum and its minimum number of connections.

This section has presented the construction of the Network Connectivity Index, which seeks to quantify the connection level of a park through the number of its connections. This index sets the maximum and the minimum number of possible connections, and establishes the level of connections of the park configuration. So, if $NCI = 1$, it means that the park is completely connected and can endure a firm activity interruption (see Fig. 3.5a). Conversely, if $NCI = 0$, it means that some participants are isolated when a disruptive event occurs (see Fig. 3.5b).



(a) (b)

Figure 3.5: Maximum and minimum cases for the Network Connectivity Index (NCI) considering five participants: 3.5a maximum case, and 3.5b minimum case.

3.3.3 Flows Adaptability Index (ϕ)

After constructing the NCI in the above section, it remains to present the quantification of the Flows Adaptability Index (ϕ) in order to compose a resilience metric, which represents the necessary flow magnitude for the continued operation of a park if a disruptive event occurs.

The goal of this metric is to quantify if the flows and the participant capacities of the park are enough to compensate a disruptive event. This metric must quantify the necessary flow to sustain the operation of the park and the flexibility of the network to modify the remaining flows consequently.

Unlike the previous index, oriented connections were considered to quantify ϕ because the flows under study imply mass or energy transfer from one participant to another. The measure is based on demands from the nodes and their provisions before and after the disruptive event.

In this sense, when a participant of a park interrupts its activity, its inputs and outputs disappear. These flows are also inputs for and outputs from other participants which need them to maintain their operations. Accordingly, the magnitude of other inlets and outlets in the surrounding nodes must change to compensate this loss during this event. With this purpose, a security range has been considered for every plant: a minimum and a maximum flow to operate. These values are defined for the inlets and outlets of every node. The inlet and outlet capacities for each participant k were defined as $Q_k^{max,in}$ and $Q_k^{max,out}$ respectively, with $k \in N$. It is also necessary to define the sets IN_k and OUT_k to include the nodes connected with $k \in N$ through an input or output of k, respectively (see Fig. 3.6).

Since the flows of the participants of a network have different magnitude and quality, they are not easily replaceable. To substitute these flows, the new ones have to comply the same characteristics of the original. To simplify this behavior, it is possible to assume that all the flows can be substituted by any inlets or outlets in a layer of the network, i.e., all the flows comply the requirements about quality if they belong to the same layer.

It should be noted that the terms defined in the following sections refer to a unique layer. Since an EIP can be configured by different layers, an extended definition will be provided in the section 3.3.3 for a park with multiple layers.

Defining changes over the elements in the set IN_k after a disruptive event in node k

When a participant $k \in N$ interrupts its activity, all its input flows $F_{j,k} \forall j \in IN_k$ are lost (see Fig. 3.6). To ensure the continuous operation of the park, each of these flows has to be redistributed in the remaining outputs of the affected firms $j \in IN_k$, i.e. in $l \in OUT_j \setminus \{k\}$. The feasibility of this change depends on the capacity of each firm receiving the additional flow and its committed capacity. This value is defined as *the inlet available capacity for the participant l*, denoted as:

$$Q_l^{in} = \left(Q_l^{max,in} - \sum_{v \in IN_l; v \neq k} F_{v,l} \right) \qquad \text{with } l \in OUT_j \setminus \{k\} \tag{3.5}$$

It is worth to note that Q_l^{in} is minimum when l is working at maximum capacity ($\sum_{k \in IN; v \neq k} F_{v,l} = Q_l^{max,in}$). Conversely, Q_l^{in} is maximum when $F_{j,l}$ is the unique inlet of node l ($\sum_{k \in IN; v \neq k} F_{v,l} = F_{j,l}$).

The *total output available capacity for the participant $j \in IN_k$ when k interrupts its*

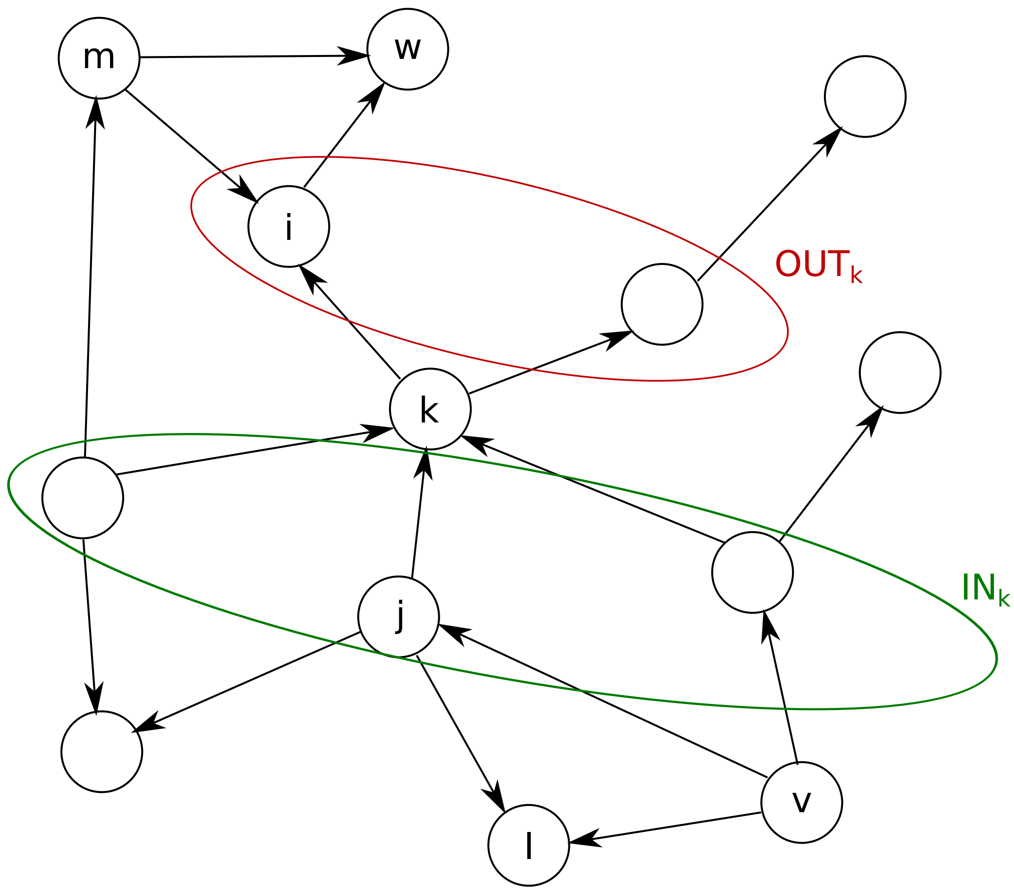


Figure 3.6: An Industrial network with their participants and connections. In the figure, it is highlighted the participants connected with a participant k: OUT_k, participants with outlet connections from k; and IN_k, participants with inlet connections to k.

activity is:

$$Q^{out}_{j-k} = \sum_{l \in OUT_j; l \neq k} Q^{in}_l \qquad \text{with } j \in IN_k \tag{3.6}$$

Calculating this term, the feasible increase, in the outputs of $j \in IN_k$, is inferred to compensate the lost flow $F_{j,k}$. To compare both values and to determine if this capacity is greater or equal to the lost flow, the definition of *the lack of flow for the participant j when k interrupts its activity* is provided as:

$$\mathcal{L}^{in}_{j-k} = \max\{0, F_{j,k} - Q^{out}_{j-k}\} \qquad \text{with } j \in IN_k \text{ and } k \in N \tag{3.7}$$

This term is 0 if the park can compensate the lost flow of the participant j when k interrupts its activity; or it takes the magnitude of the flow to compensate the loss.

Defining changes over the elements in the set OUT_k after a disruptive event occurs in node k

As in the previous case, when a participant $k \in N$ interrupts its activity, all their outputs $F_{k,i} \forall I \in OUT_k$ are lost (see Fig. 3.6). To ensure the continued and normal operation of the park, each of these flows has to be compensated increasing the remaining inputs of the affected firms $i \in OUT_k$, i.e. $m \in IN_k \setminus \{k\}$. The feasibility of this substitution of flows depends on the capacity of each firm receiving the increased flow and its committed capacity. With this focus, *the outlet available capacity for the participant m* is defined as:

$$Q_m^{out} = \left(Q_m^{max,out} - \sum_{w \in OUT_m; w \neq k} F_{m,w} \right) \qquad \text{with } m \in IN_i \setminus \{k\} \tag{3.8}$$

It is important to note that Q_m^{out} is minimum when m is working at its maximum capacity ($\sum_{w \in OUT_m; w \neq k} F_{m,w} = Q_m^{max,out}$). The available capacity of m is maximum when $F_{m,i}$ is the unique outlet of node m ($\sum_{w \in OUT_m; w \neq k} F_{m,w} = F_{m,i}$).

Then, the *total input available capacity for the participant $i \in OUT_k$ when k interrupts its activity* is:

$$Q_{i-k}^{in} = \sum_{m \in IN_i; m \neq k} Q_m^{out} \tag{3.9}$$

Calculating this term, the feasible increase. in the inputs of $i \in OUT_k$, is inferred to compensate the lost flow $F_{k,i}$.

In the situation after disruption, it is not necessary to share the same flow than before to maintain the participant i in operation. Plant i can operate at its minimum capacity. It is necessary to define *the minimum capacity of i to continue its operation*, $Q_i^{min,in}$. This value depends on the security factor of each participant and complies with $Q_i^{min,in} \leq \sum_{m \in IN_i} F_{m,i}$. Since after the disruption the participant i is working at its minimum capacity and has lost one input, the minimum flow necessary to feed is $Q_i^{min,in} - \sum_{m \in IN_i; m \neq k} F_{m,i}$. It is important to highlight that if this value is negative or zero, the minimum capacity is already satisfied by the remaining inlets and it is not necessary to increase other flows.

In view of the above, it is deemed necessary to compare $Q_i^{min,in} - \sum_{m \in IN_i; m \neq k} F_{m,i}$ and Q_{i-k}^{in} so as to determine if this capacity is equal or greater than the minimum required flow. For this purpose, *the lack of flow for the participant i when k interrupts its activity* is denoted as:

$$\mathcal{L}_{i-k}^{out} = \max\{0, Q_i^{min,in} - \sum_{m \in IN_i; m \neq k} F_{m,i} - Q_{i-k}^{in}\} \qquad \text{with } i \in OUT_k \text{ and } k \in N \tag{3.10}$$

This term is 0, if the park can compensate the lost flow of the participant i when k interrupts its activity; or it will take the magnitude of the minimum flow to compensate the loss.

Defining the flows adaptability index

Using the aforementioned values, the required flow to compensate the absence of one participant in the park is calculated. It is worth noting that both metrics, $\mathcal{L}^{in}_{j-k}$ and $\mathcal{L}^{out}_{i-k}$, identify the participant that interrupts its activity and just one of their inputs and outputs respectively. To calculate the total required flow associated with the activity interruption of a participant, consider the summation of $\mathcal{L}^{in}_{j-k}$ over all the inputs ($j \in IN_k$) and also consider the summation of $\mathcal{L}^{out}_{i-k}$ over all the outputs ($i \in OUT_k$). The combination of both summations takes account of the necessary flow to compensate the disruption over k.

The *total lack of flows related to a disruption in* k is defined as:

$$\mathcal{L}_k = \sum_{j \in IN_k} \mathcal{L}^{in}_{j-k} + \sum_{i \in OUT_k} \mathcal{L}^{out}_{i-k} \qquad \forall k \in N \tag{3.11}$$

Using this term, the total required flow to compensate the activity interruption of a network is obtained. In the same way as the NCI, the worst and the best scenarios were taken to establish a linear function between them in order to simplify the calculation.

The worst scenario for the park is when the network and their participants are working at their full capacity, i.e. when $\mathcal{L}_k$ is maximum: $Q^{out}_{j-k} = Q^{in}_{i-k} = 0$. $\mathcal{L}_k$ would be:

$$\mathcal{L}^{max}_k = \sum_{j \in IN_k} F_{j,k} + \sum_{i \in OUT_k} Q^{min,in}_i \tag{3.12}$$

The best scenario for the park is when the network can totally compensate the activity interruption of one of its participants. In this scenario, $\mathcal{L}_k$ is minimum: $Q^{out}_{j-k} \geq F_{j,k} \wedge Q^{in}_{i-k} \geq Q^{min,in}_i \implies \mathcal{L}^{in}_{j-k} = \mathcal{L}^{out}_{i-k} = 0$. Then, $\mathcal{L}_k$ would be:

$$\mathcal{L}^{min}_k = 0 \tag{3.13}$$

Establishing these worst and best scenarios for the park, the flows adaptability index ϕ_k is defined for the network affected by the interruption in the activity of the participant k. If the park is working at the worst scenario, $\phi_k(\mathcal{L}^{max}_k) = 0$; if the park is working at its best scenario, $\phi_k(\mathcal{L}^{min}_k) = 1$. With these values, the following linear function is created to quantify intermediate cases (see Fig. 3.7):

$$\phi_k(\mathcal{L}_k) = \phi_k(\mathcal{L}_k^{max}) - \left(\phi_k(\mathcal{L}_k^{min}) - \phi_k(\mathcal{L}_k^{max})\right)\left(\frac{\mathcal{L}_k - \mathcal{L}_k^{max}}{\mathcal{L}_k^{min} - \mathcal{L}_k^{max}}\right) \tag{3.14}$$

$$\phi_k(\mathcal{L}_k) = 1 - \frac{\mathcal{L}_k}{\sum_{j\in IN_k} F_{j,k} + \sum_{i\in OUT_k} Q_i^{min,in}} \qquad k \in N \tag{3.15}$$

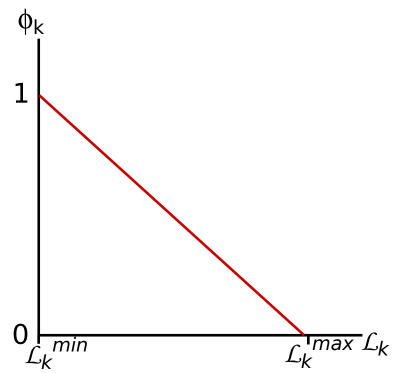


Figure 3.7: Defined linear function between the worst and the best case for ϕ_k.

This equation can apply over each participant k of the park. In order to obtain a measure over the whole park, the average of this metric is calculated over all the participants under analysis:

$$\phi = \frac{1}{n}\sum_{k\in N}\phi_k \tag{3.16}$$

It is important to remark that the value of ϕ belongs to the interval $[0, 1]$. This is useful for a further combination with NCI. Since the average complies with this requirement, this function is applied to calculate the flows adaptability index of the whole park.

Final considerations about flows adaptability index

As mentioned before, an eco-industrial park is characterized by a complex network where different materials or energy are shared, composing different exchange networks. These different networks can be separated into layers. Since the flows adaptability index measures the required flow to compensate the loss of a participant in a specific exchange network, ϕ has to consider this fact.

In this sense, ϕ can be calculated for each layer. Onwards, a superscript in ϕ will indicate the considered layer. Then, the flows adaptability index for the specific layer r is calculated as:

$$\phi^{layer_r} = \frac{1}{n}\sum_{k\in N}\phi_k^{layer_r} \tag{3.17}$$

Therefore, the flows adaptability index for the whole park is constructed covering all the layers in the set L:

$$\phi(park) = f(\phi^{layer_1}, \phi^{layer_2}, \ldots, \phi^{layer_r}) \qquad \text{with } r \in L \tag{3.18}$$

To simplify the notation, a linear combination of layers is considered. It is important to note that the weights in the summation are all identical. Thus, the index is defined as:

$$\phi(park) = \frac{1}{|L|} \sum_{r \in L} \phi^{layer_r} \tag{3.19}$$

3.3.4 Resilience Indicator

NCI and ϕ have been conceived to measure, respectively, the connectivity of a park and its capacity to endure a disruptive event by replacing flows. Both characteristics are important to assess the resilience of a park. Accordingly, the following equation is proposed so as to define a resilience indicator:

$$RI_{EIP} = a \cdot NCI + (1 - a) \cdot \phi \tag{3.20}$$

Where a and $1 - a$ indicate the importance of each characteristic: the connectivity of a park, measured by NCI, and the capacity of the park to endure a disruptive event by replacing flows, measured by ϕ. The same importance is proposed for both aspects, that is: $a = 0.5$. This decision should be taken by the stakeholders of the park. Further developments in this line could be done so as to adapt this combination to reality. A feasible route to address this issue is to apply a multi-criteria decision-making tool. Finally, the resilience indicator is defined as:

$$RI_{EIP} = 0.5 \cdot NCI + 0.5 \cdot \phi \tag{3.21}$$

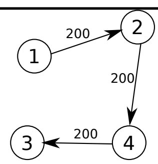
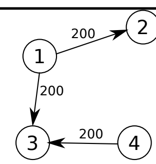
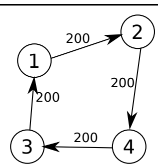
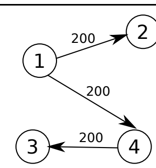
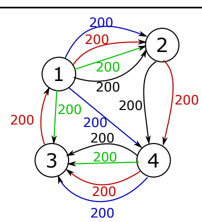
3.4 Application of the Resilience Indicator over case studies

The following sections present different illustrative cases in order to analyze the applicability of the proposed resilience indicator. In section 3.4.1, some small examples are composed and discussed. In section 3.4.2, two cases close to reality are presented and analyzed. While first cases (small examples) are constructed to better understand how the indicator works, the last ones are presented to study its applicability over a real EIP. Beside presenting the illustrative cases, a brief discussion about the use of NCI and ϕ over each of them is developed. It is worth to note that the specific discussion about the application over the illustrative examples close to reality is shown in section 3.5.

3.4.1 Small illustrative examples

To analyze the applicability and the inner working of the proposed indicator, four illustrative cases are created, where the connections among the participants are different in each of them (Table 3.2). Moreover, to demonstrate the applicability of the indicator to an scenario with a higher complexity, a new case is composed considering all the previous examples.

Table 3.2: Illustrative cases and their values of NCI, ϕ, and resilience indicator.

Example	Configuration	Results	Example	Configuration	Results
1		$\phi_1 = 0$ $\phi_2 = 0$ $\phi_3 = 0$ $\phi_4 = 0$ $\phi_{config.} = 0$ $NCI = 0.25$ $RI_{EIP} = 0.125$	3		$\phi_1 = 0.667$ $\phi_2 = 0.5$ $\phi_3 = 0.125$ $\phi_4 = 1$ $\phi_{config.} = 0.573$ $NCI = 0.25$ $RI_{EIP} = 0.441$
2		$\phi_1 = 0$ $\phi_2 = 0$ $\phi_3 = 0$ $\phi_4 = 0$ $\phi_{config.} = 0$ $NCI = 0.5$ $RI_{EIP} = 0.25$	4		$\phi_1 = 0$ $\phi_2 = 0.25$ $\phi_3 = 0$ $\phi_4 = 0.2$ $\phi_{config.} = 0.112$ $NCI = 0.25$ $RI_{EIP} = 0.181$
5		$\phi^{layer_1} = 0$ $\phi^{layer_2} = 0$ $\phi^{layer_3} = 0.573$ $\phi^{layer_4} = 0.112$ $\phi_{park} = 0.171$ $NCI = 0.75$ $RI_{EIP} = 0.461$			

The first sub-indicator, Network Connectivity Index (NCI), considers the topology of a network, measuring the existence of connections in the park using the number of connections among the firms. Accordingly, if a network obtains a high NCI value, there are a lot of connections in the park, and therefore, the network does not loose connectivity when a disruptive event occurs. In contrast, if a network obtains a low NCI value, the park is weakly connected, and thus, the network has isolated participant during disruptions. This behavior can be seen on examples 1 and 2 (Table 3.2), where as the number of connection grows, the NCI increases its value. In the first example, if one participant interrupts its activity, it is highly probable that the network has isolated nodes. For instance, if the participant 2 interrupts its activity, participant 1 will loose connectivity. Conversely, in the example 2, since all participant have two connections, forming a closed loop, they will be always connected if any of them suffers a disruptive event. For example, if participant 2 interrupts its activity, the network maintains its connectivity. For this reason, the last configuration has the highest NCI value.

On the other hand, the second sub-indicator, Flow Adaptability Index (ϕ), considers the performance of an industrial network, measuring the magnitude of the sharing flows and the feasibility of their substitution during disruptions. Therefore, if a network obtains a high ϕ value, the participants can endure the activity interruption of any of them, and therefore, the network can continue working.

The performance of this sub-indicator can be observed on example 1, 3, and 4 (Table 3.2), where the number of connections is kept constant ($NCI = 0.25$ for both of them), but the connected participant are changed. In the example 1, since all the participants obtain $\phi_k = 0$, they cannot be replaced, and therefore, the network cannot endure any disruptive event. In the example 4, the connection between participant 2 and 4 is changed for the connection between 1 and 4. This change makes modify the ϕ value of the network, suffering a little increase compared to the previous example. In this new configuration, participant 2 and 4 can be partially replaced for the other members when they suffer a disruptive event. In the example 3, the connection between participant 1 and 4 of the example 4 is changed for the connection between 1 and 3. In this new configuration, all the participant can be partially replaced by the other members, then ϕ of the network grows. This is because as some participants have more than one inputs or outputs, they do not depend just on one of them.

According to the resilience indicator, the example 3 has the most resilient configuration. This result is consistent by comparing with the other examples because this configuration has a reasonable number of connection to maintain connected the park and the participants can be replaced when a disruptive event occurs. It is important to note that even though the example 2 has the highest NCI value, the orientation of the connections does not allow to compensate any disruptive event over the participants of the network, and then ϕ is null.

On the other hand, as mentioned above, an eco-industrial park is composed by a set of firms sharing different type of materials (e.g. water, biomass, oil, etc.). Each of these exchanges can be analyzed through different sharing layers belonging to the same park, or by unconnected subsets within the park. In this context, two examples in the literature of these kind of parks are Kalundborg (Knight, 1990) and Ulsan (Behera et al., 2012). In the first case, the industrial network is composed by different sharing layers, where the same set of firms share water, sludge, steam, among others; in the latter, there are different unconnected subsets of firms sharing different type of materials, as steam, waste oil, and zinc powder, among others. An illustrative example (example 5) is provided with this logic, considering a park composed by all the previous examples, sharing different type of material at once (Table 3.2).

In this example, the number of connections among the participant is 5 since this sub-indicator consider all the firms in a unique layer, no matter what they are sharing. Therefore, the NCI is 0.75 because this configuration presents almost all the possible connections among the participant, except from 2 to 3.

On the other hand, since the flow adaptability index consider every layer of the park, it can be calculated using the Eq. 3.19, obtaining a value of 0.171. This result is low in comparison with the example 3, because there are several layers with a low or zero flow adaptability index.

Finally, the resilience indicator of this multi-layer park can be calculated, and its value is 0.461. It is worth to note that this park presents a best resilience value than example 3 (best configuration among the first examples) despite it have a low ϕ value. This is due to its NCI value is higher by consider all the participant in a unique layer, and because the resilience indicator is calculated as an average between NCI and ϕ.

3.4.2 A real example: Ulsan, South Korea

In order to analyze the applicability of the resilience indicator in a example close to reality, an illustrative case based on one particular EIP is considered: Ulsan, in South Korea (see Fig. 3.8). First, the application of the indicator is addressed in just one single layer of this EIP; and finally, the study of multiple layers is covered considering the entire park. A brief explanation about Ulsan is presented below, as an introduction to the illustrative cases.

Ulsan EIP, South Korea

Ulsan is located in the southeast of South Korea. This city has many important industrial complexes at a national and regional level. Among these complexes, two of them are analyzed: Ulsan-Mipo and Onsan. These Complexes employ $100,000$ workers and cover $63,256\ km^2$ of the territory (Behera et al., 2012).

In 2005 started the implementation of a government initiative in the Mipo/Onsan complex, focused on the development of an EIP in the region. This program established the *Ulsan EIP center* in 2007, aiming at sharing materials and energy within the network. There are 13 exchanging flows among the firms operating in this EIP, which includes 41 companies. The main benefits obtained by this exchanges are related to reduce the CO_2 emissions and other gaseous pollutants, and to increase the economic utilities of the companies (Behera et al., 2012).

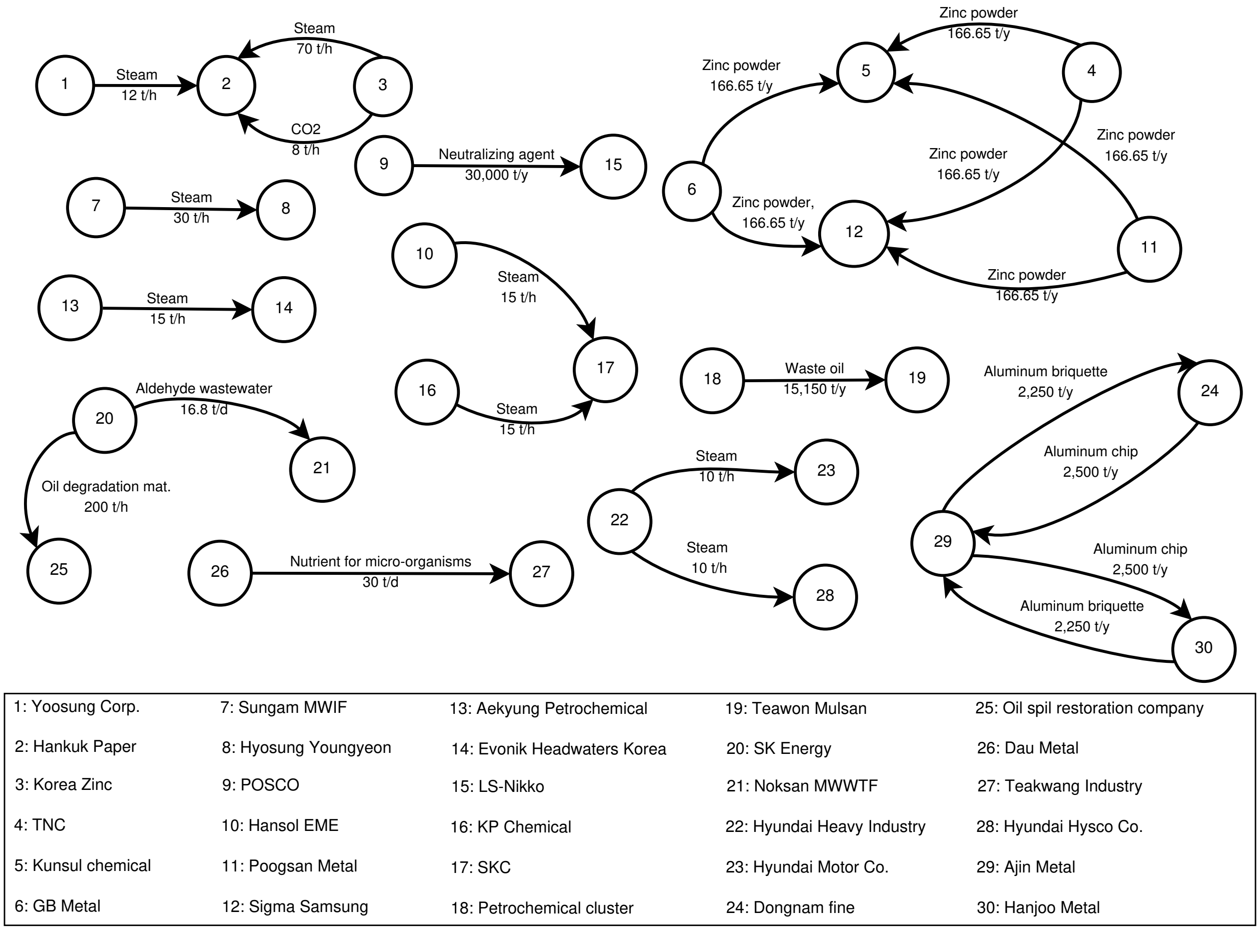


Figure 3.8: Network in Ulsan (information taken from Behera et al. (2012)).

Case 1: Application of the Resilience Indicator on networks with a unique layer

To study the applicability of the resilience indicator on networks with a unique layer, consider the steam network of Ulsan as subject of analysis (see Fig. 3.9). In this case, the steam network was considered as a conventional material network, with no constraints on the temperature requirements of the participants. It is worth remarking the base to calculate: the data used to describe the connections and flows depend on the available information. The first row of Table 3.3 show a summary about the values obtained for the resilience indicator, NCI, and ϕ in steam network. The plot in Fig. 3.10 shows a comparison among the participants of the the network with focus on ϕ.

Table 3.3: Resilience Indicator applied over case studies. The values of NCI and ϕ are also shown.

Case study	NCI (%)	ϕ (%)	RI_{EIP} (%)
Ulsan steam network	0.01	0.170	0.100
Ulsan EIP (multilayer)	0.01	0.180	0.100

The main goal of this case study is to illustrate the application of the resilience indicator

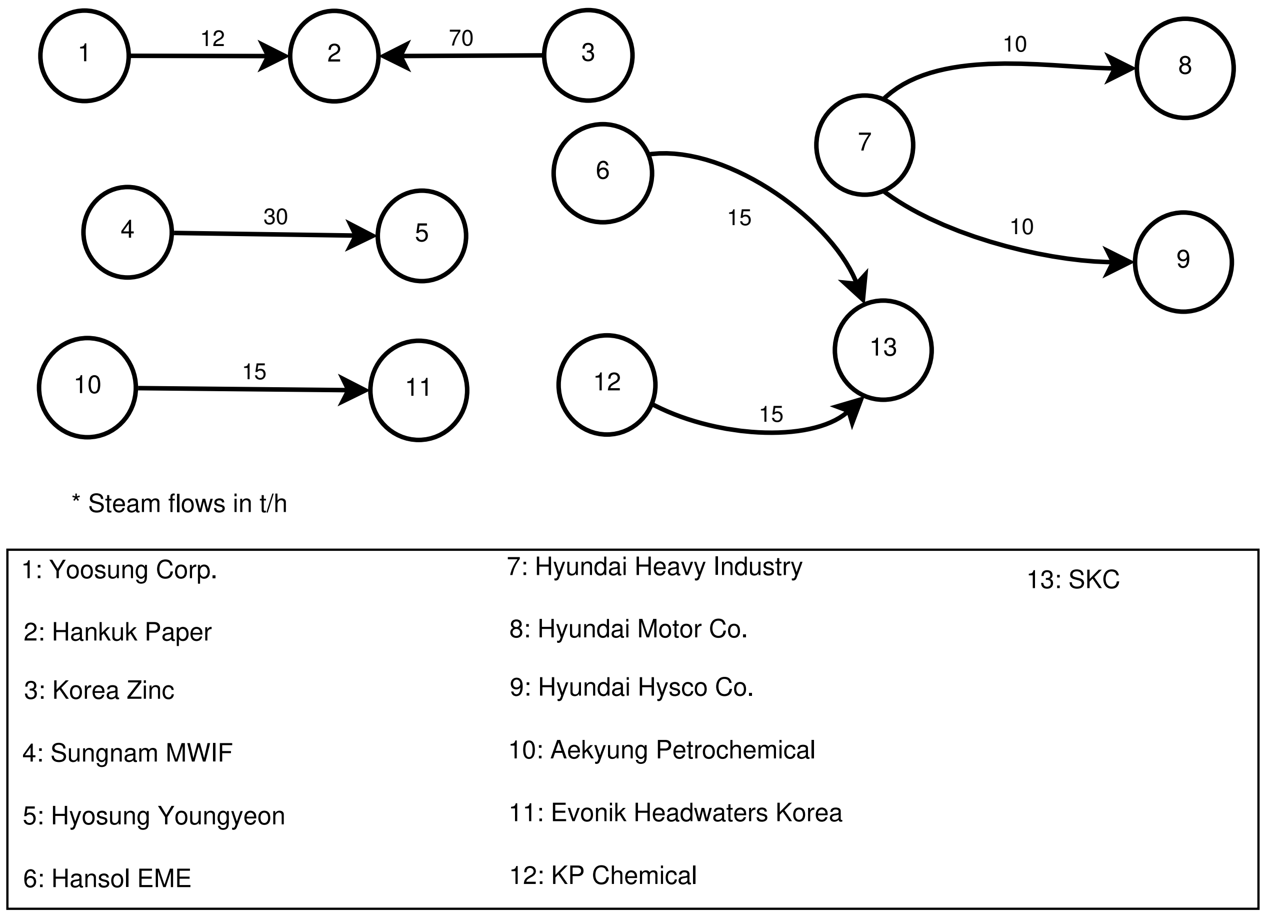


Figure 3.9: Steam Network of Ulsan (obtained from Behera et al. (2012)).

over a unique layer of a real EIP. In this sense, the value of the resilience indicator is low due mainly to the network structure, i.e., to NCI. As can be seen from Fig.3.9, the level of connectivity among the participants is low since almost all of them have just one connection, except participants 2, 13 and 7 that have two connections. So, the NCI value is almost the minimum (near to zero). Additionally, this structural characteristic of the configuration has a negative impact on the capacity of the participant to endure a disruptive event since they do not have another alternative to share material if one of them interrupts its activity. Therefore, following this logic, the point is how this network would be configured if the resilience indicator were applied at the design phase. To their understanding, the Ulsan's steam network can improve its resilience taking into account this consideration.

Case 2: Application of the Resilience Indicator over an EIP with multiple layers

The variety of material exchanges in Ulsan EIP (see Fig. 3.8) were considered to study the application of the resilience indicator over an EIP with multiple layers, closing its applicability to reality. Regarding the information available on the literature, the analysis take into account 8 material exchanges among the firms in the park: steam, zinc powder, oil, neutralizing agents, aldehyde, nutrients for microorganism, aluminum, and carbon dioxide. Each of them forms a layer in the EIP. The second row of Table 3.3 shows the results obtained for the

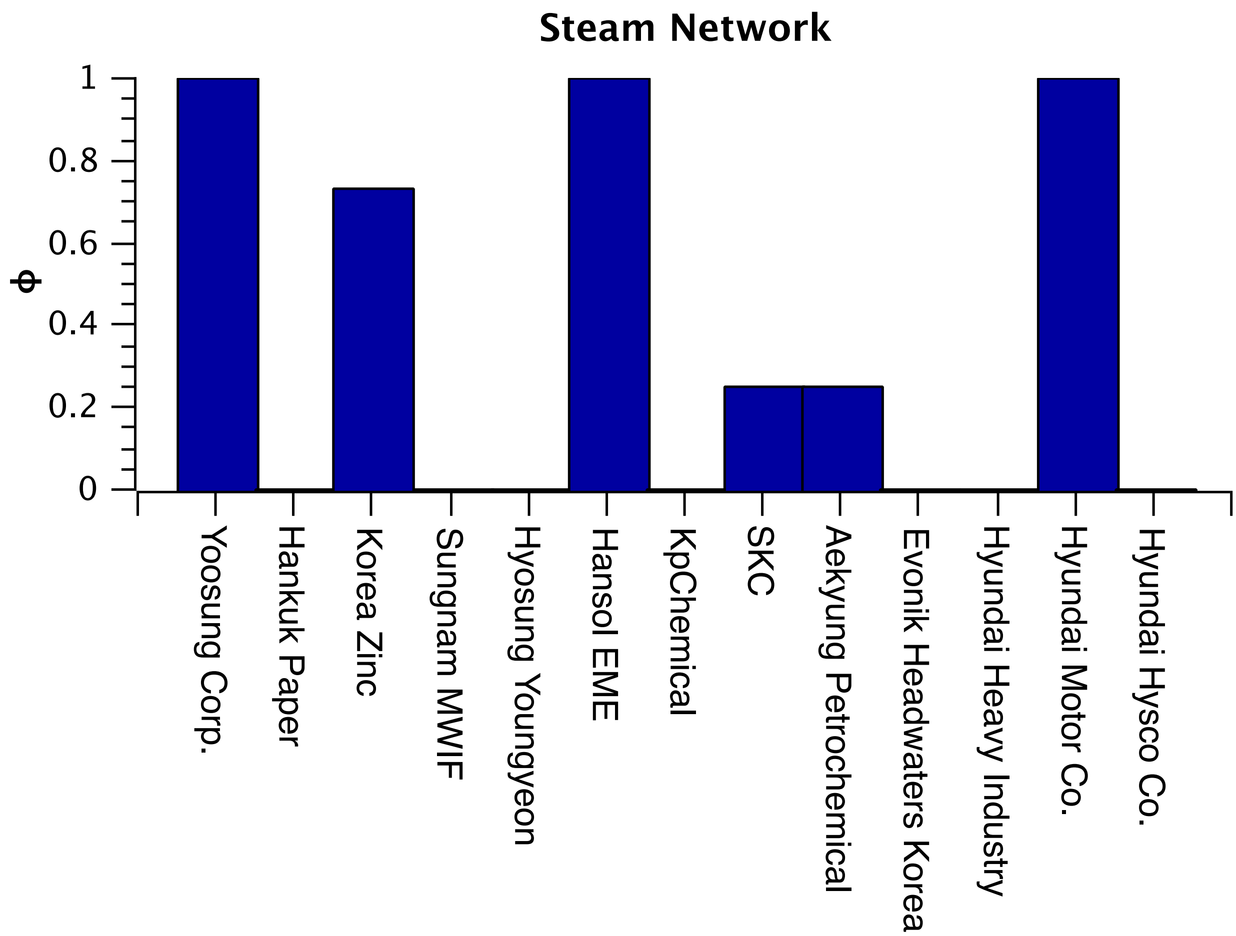


Figure 3.10: Flows adaptability index of each participant in a layer of the illustrative case: Steam Network of Ulsan EIP.

resilience indicator, and the respective values for NCI and ϕ. Table 3.4 shows a comparison among the participants of each layer, with focus on their Flows Adaptability Index.

Table 3.4: Flows adaptability index for participants into each layer of Ulsan EIP.

Steam Network	**Zinc Powder Network**	**Oil Network**	**Neutralizing Agents Network**	**Aldehyde Wastewater Network**	**Nutrient for Micro-organism Network**	**Aluminum Network**	**Carbon Dioxide Network**
$\phi_1 = 1.00$ $\phi_2 = 0.00$ $\phi_3 = 0.73$ $\phi_7 = 0.00$ $\phi_8 = 0.00$ $\phi_{10} = 0.00$ $\phi_{13} = 0.00$ $\phi_{14} = 0.00$ $\phi_{16} = 0.00$ $\phi_{17} = 0.00$ $\phi_{22} = 0.00$ $\phi_{23} = 0.25$ $\phi_{28} = 0.25$	$\phi_4 = 1.00$ $\phi_5 = 0.75$ $\phi_6 = 1.00$ $\phi_{11} = 1.00$ $\phi_{12} = 0.75$	$\phi_{18} = 0.00$ $\phi_{19} = 0.00$ $\phi_{20} = 0.00$ $\phi_{25} = 0.00$	$\phi_9 = 0.00$ $\phi_{15} = 0.00$	$\phi_{20} = 0.00$ $\phi_{21} = 0.00$	$\phi_{26} = 0.00$ $\phi_{27} = 0.00$	$\phi_{24} = 0.52$ $\phi_{29} = 0.00$ $\phi_{30} = 0.52$	$\phi_2 = 0.00$ $\phi_3 = 0.00$

Extending the analysis of the Ulsan steam network in the previous section to the whole Ulsan EIP, the resilience is low mainly because of the value of NCI. The structure of the Ulsan

EIP has many subsystems: non-connected sub-parks. Although this structure is functional to share materials and energy among neighbors, the concept of EIP is not fully developed in the sense of connectivity, and the structure of the park is not as safer as highly connected parks (e.g. example 5 from previously section). In this sense, an early application of the Resilience Indicator at the design phase can improve the capacity of the whole park to overcome disruptions, and allow decision-makers to measure and compare different alternatives in this field.

3.5 Discussion

This chapter presents an indicator to measure the resilience of an eco-industrial park. This index considers the connectivity of a network and the capacity of the participants to endure a disruptive event. These aspects have been quantified with two sub-indicators: the Network Connectivity Index (NCI) and the Flows Adaptability Index (ϕ), respectively. The resilience indicator has been applied to illustrative cases and a real case, and after this exercise is possible to analyze the performance of the metric.

As defined before, the resilience indicator depends on two indexes: the Network Connectivity Index (NCI) and the Flows Adaptability Index (ϕ). The first one is a topologic measure of a network, measuring the number of connections among EIP participants. This characteristic is not exclusive to an industrial context since it is present in every network. The NCI reports the existence of a connection between two members of a network.

If a network obtains a high NCI value (near to 1) there are many connections among the network participants. In this case, if a participant interrupts its activity, other participants in the network will remain connected. It is possible to appreciate this behavior in the example 5 of the first cases presented (see Table 3.2). This network obtained a NCI value of 0.75, which is high compared with the other cases. In this example, by removing one participant, either of them, the remaining participants will be still connected through the remaining lines.

In contrast, if NCI has a near-zero value the network is weakly connected. In this case, if a participant disappears from the network there will be isolated members. In the Ulsan steam network (see Fig. 3.9), a NCI value of 0.01% is obtained. This value means that if a participant disappears (e.g. participant 2), some members of the network will be unconnected and part of the network is lost.

One goal of a resilient network is to maintain the connectivity in the remaining network when a member interrupts its activity. In this sense, the NCI takes into account this property. The values obtained in all the illustrative cases are consistent with the described reality.

The second index used to construct the resilience indicator, ϕ, is a measure of the network performance. This index focuses on the magnitude of the sharing flows and the feasibility of their substitution during disruptions. This characteristic is fundamental in an industrial context and constitutes a difference with other kind of networks. If a network obtains a high value of ϕ the participants can endure the absence of any member suffering a disruptive event. For example, a $\phi = 0.573$ is obtained in the example 3 of the first set of illustrative examples. This value means that if a network participant interrupts its activity (e.g. participant 2) (see Table 3.2), other members can take over the lost inputs and outputs. This attribute allows the other members to maintain their operations.

If the network obtains a low ϕ the members within the network will not be able to supply the lost flows. The park could not continue its operation. For example, a $\phi = 0.17\%$ is obtained in the Ulsan steam network. In this case, if the network loses a participant, for instance Korea Zinc (see Fig. 3.10), a participant as Yoosung Corp. cannot change the magnitude of its flows because the defined capacity is not enough to completely endure this event.

Another goal of a resilient network is to endure any disruptive event by modifying the magnitude of its flows. The values obtained for ϕ are fair with the described cases.

An assumption considered over this sub-indicator is regard to the quality (composition) of the substituted flows. To simplify the calculation, consider that all the flows can be substituted by others in a layer of a network no matter the different compositions of them. Since in the reality the quality of the flows is important in order to comply with the requirements of the participants, this aspect can be considered in ϕ through the use of different layers. If a set of firms need to comply with certain requirements about flow composition, they can be separated in a different layer and to obtain an additional ϕ^{layer_r}. In this way, the quality of the flows is considered in the flow adaptability index.

It is worth noting that the value of ϕ will depend on the capacity of each firm to change the magnitude of its inputs and outputs. ϕ also depends on the connectivity. For instance, in the last example, if Hankuk Plant interrupts its activity the remaining participants will not be able to endure this event, because the affected members do not have more connections than the lost ones (see Fig. 3.9).

In this context, the question is whether both factors are independent. As noticed before, ϕ depends on the connections. ϕ depends on NCI. This dependence is sustained on a physical fact: every flow of a certain material requires an existing connection in the network. The aforementioned idea is not reversible, and the existence of a connection does not imply a specific material sharing. The existence of a connection allows the sharing of one material or more. Nevertheless, it is possible to have a physical connection with no sharing flow. NCI does not depend on ϕ.

The proposed resilience indicator is a weighted sum of both indexes: NCI and ϕ. If one of them has a higher influence over the reality it should have more importance in the equation. The same weights were assumed as a first approximation. NCI includes topological characteristics of a network, while ϕ is related to operative aspects which is supported by its topology. A pending issue is to define specific weights to represent the global resilience in an industrial network. This definition could be constructed on the basis of a comparative analysis of many application cases. An idea to guide this definition is to state what is more important to the resilience of an industrial network: topology or operation.

The resilience indicator was created to be applied over EIPs sharing different materials, i.e. parks with multiple layers. This characteristic is captured by ϕ through the weighted sum of single layers (ϕ^{layer_r}). To simplify the notation, it was assumed that each layer had the same specific weight (see Eq. 3.19). In other words, all these layers have the same importance for the EIP. As can be seen in the illustrative case of Ulsan EIP, there is a subset of layers with ϕ^{layer_r} equal to 0 (see Table 3.4). This situation results in a low value of ϕ for the whole park (0.18). Even though this assumption could be correct, it is a pending issue to properly describe the importance of each layer. To cover this point, the number of participants in a single layer or the criticality of a shared material could indicate the relative importance of a layer. As illustrated in Fig. 3.8, there are many layers with different number of participants.

Regarding the resilience indicator, even though it was created with the goal to measure resilience over eco-industrial parks, it can be applied over any system where the participants share materials, e.g. industrial parks, regional integrations, and eco-cities.

The adopted definition of resilience considers the withstanding capacity to undergo a disruptive event. During this chapter, a disruptive event was assumed as a complete interruption in the activity of a network participant. However, when an industrial plant suffers a disruptive event, it is not always complete. Sometimes this event is partial. Even though the proposed indicator does not consider this aspect, it could be modified so as to consider the partial activity interruption of a participant. Since this characteristic is related with the operation of a participant, the flows adaptability index has to be modified. In Eqs. 3.7 and 3.10 it is possible to add a term representing this partial activity interruption as follows:

$$\mathcal{L}^{in}_{j-k} = \max\{0, F_{j,k} - p^{in}_k Q^{out}_{j-k}\} \qquad \text{where } j \in IN_k \text{ and } k \in N \tag{3.22}$$

$$\mathcal{L}^{out}_{i-k} = \max\{0, Q^{min,in}_i - p^{out}_k Q^{in}_{i-k}\} \qquad \text{where } i \in OUT_k \text{ and } k \in N \tag{3.23}$$

In this equation, p^{in}_k and $p^{out}_k \in [0,1]$ are the factors representing the partial stop of a firm for its input and output flows, respectively. These factors are defined as 1 when a firm completely stops its operation.

Another aspect to discuss is the probability of disruptions. The definition of resilience considers that every participant has the same risk to suffer a disruptive event. However, the reality is different: there are firms with highly effective prevention programs to avoid stops in production while other ones are unstable. This fact can be translate into a probability of suffering a disruptive event. This value could be estimated taking into account the history of each participant. To consider this probability in the resilience indicator, the flows adaptability index should be modified since the disruption probability is an operative characteristic of each firm. As shown in Eq. 3.17, this index is applied over each firm and averaged to calculate ϕ^{layer_r}. This average can be replaced by a weighted sum, where the weights are calculated over respective disruption probabilities.

The configuration of an EIP can be based on sharing material or energy in a network. For example, in the steam network of Ulsan (see Fig. 3.9), even though the main focus is material sharing, it is also important the temperature or pressure since the participants could need to comply with certain operational requirements to work. In this sense, the resilience indicator should also consider the case of energy networks. In this chapter the resilience indicator is conceived for material networks, based on its connections and sharing flows. Beside analogous characteristics from energy networks, it is deemed necessary to include the temperature of each flow as a constraint to sharing and substitution of flows during disruptions. These constraints come from heat transfer gradients. Since the indicator herein proposed has considered the connections and the flows of a network, it is adapted to measure the resilience of material networks. The extension of this indicator to consider temperatures, or the development of a new resilience indicator for heat transfer networks, can be addressed in further work.

3.6 Chapter conclusions

This chapter has proposed a resilience indicator to assess EIPs. This indicator is based on two important aspects of an industrial network: its topology and its operation. These main ideas sustain the creation of two sub-indicators oriented to measure the connectivity and flexibility of flows, respectively.

The novelty of the proposed indicator lies into consider the dynamic of the assessed eco-industrial park after one of their participants suffers a disruptive event, taking into account the decision of the remaining firms to modify their input and output flows to absorb this perturbation and to prevent the fault propagation on the park. The resilience indicator is constructed to support the evaluation of multi-layer park, where more than one material is shared.

The resilience indicator has been created for both assessing and designing eco-industrial parks. The design phase can be addressed with optimization tools. In this context, the resilience indicator can be included in a multi-objective formulation. The objectives of this formulation can also cover environmental, social, and economic dimensions of the sustainability, so as to improve the performance of the whole park by design.

The proposed indicator has been applied over five small examples, where the number of connections and the orientation of them are modified; and one illustrative case based on a well-known EIP: Ulsan, in South Korea. In this sense, consistent results are obtained regarding both sub-indicators and the resilience indicator. On the other hand, the application over Ulsan EIP shows a significant potential to improve its resilience, which is conditioned by the structure of the park.

There is a possible improvement in this development: the defined sub-indicators are not independent. This dependence is sustained on physics, because the existence of a flow requires a connection. This idea backs up the dependence of ϕ on NCI. This limitation can be overcome in the future by calculating the resilience indicator through a weighted sum of NCI and ϕ. The specific weighs must be properly defined taking into account the aforementioned dependence, since one of them may be overestimated. Industrial stakeholders should define which aspect is more important in the network: topology or operation.

In the future, the resilience indicator can be modified in order to capture a more realistic behavior of an EIP, where some firms are most likely to suffer a disruptive event or they have contingency plans in this situations. For example, the indicator can consider partial disruptive events over the participants of the park. It is also possible to include the probability of each firm to suffer a disruptive event. Since both of them are related to operative aspects, these changes could be addressed by modifying ϕ.

Finally, the proposed indicator measures the resilience of material network, taking into account connections and flows among the participants. Since an EIP can be configured to share material or/and energy, the extension of this indicator to heat transfer networks is proposed for further work.

4. Optimization model: designing a sustainable and resilient EIP

4.1 Abstract

An Eco-Industrial Parks is a community of business located together, exchanging material and energy with each other, to achieve sustainability advantages for its participants and the sector. The main benefits of this kind of parks are related to the three dimensions of sustainability: economic, environmental, and social. Since the magnitude of these benefits depends on the configuration of the EIP, its planning and design is critical to reduce the wastes generated by the participating firms, without negative impacts on the economic benefits, and concerning on the future of the local communities. In this context, the connectivity of this network plays a significant role, because of the material and energy sharing, and the new dependence: the failures are also propagated within the network.

In this sense, the goal of this chapter is to formulate and solve an optimization problem to design an EIP, considering sustainability and resilience aspects in this effort. Specifically, this problem is constructed based on a well-known EIP: Ulsan, in South Korea. The novelty of the present model is to simultaneously consider both aspects, configuring an EIP, which not only optimize its usual economic benefits but also enhances its topology to improve the resilience. Therefore, the resulting configuration would achieve economic and environmental benefits, ensuring the operation of the park if any participant suffers a disruptive event.

In order to analyze and to compare the use of this optimization model when designing EIPs, five configurations are obtained: three single-objective solutions, optimizing the economic, environmental, and resilience aspects, separately; and two multi-objective solutions, considering the economic and environmental aspects, and the economic, environmental and resilience aspects, simultaneously.

The resulting individual configurations present the best value for each assessed characteristic among all the considered cases, even when comparing with the current situation of the park, which was been constructed with an environmental focus. However, these configurations do not present simultaneously enhancement in all the assessed characteristics.

On the other hand, the multi-objective configurations simultaneously present more than

one of these characteristics. In particular, the economic-environmental-resilient configuration of the EIP presents the optimal configuration from a sustainability and resilience point of view since it simultaneously shows general improvements in all the assessed aspects.

Finally, even though the proposed model presents several simplifications, it allows to design more resilient and more sustainable EIPs. In this sense, this model could support decision-makers in the industrial design, generating new optimal alternatives.

Nomenclature

Sets

i and j — Participants in the sets I^{layer_r} and J^{layer_r}, respectively.

L — Set of layers or exchanged material considered in the problem.

$$L = \{\text{Steam}, \text{CO}_2, \text{Oil}\}$$

J^{layer_r} — Set of participants in layer r, demanding input material.

$$\begin{aligned} J^{Steam} &= \{2, 8, 14, 17, 23, 28\} \\ J^{\text{CO}_2} &= \{2\} \\ J^{Oil} &= \{19, 25\} \end{aligned}$$

I^{layer_r} — Set of participants in layer r, supplying output material.

$$\begin{aligned} I^{Steam} &= \{1, 3, 7, 10, 13, 16, 22\} \\ I^{\text{CO}_2} &= \{3\} \\ I^{Oil} &= \{18, 20\} \end{aligned}$$

Parameters

$Q_i^{out,layer_r}$ — Supply of material by participant $i \in I^{layer_r}$ in layer $r \in L$.

$Q_j^{in,layer_r}$ — Demand of material by participant $j \in J^{layer_r}$ in layer $r \in L$.

$Q_i^{max,out,layer_r}$ — Maximum output capacity of participant $i \in I^{layer_r}$ in layer $r \in L$.

$$Q_i^{max,out,layer_r} = 1.25 Q_i^{out,layer_r}$$

$Q_i^{min,out,layer_r}$ — Minimum output capacity of participant $i \in I^{layer_r}$ in layer $r \in L$.

$$Q_i^{min,out,layer_r} = 0.25 Q_i^{out,layer_r}$$

$Q_j^{max,in,layer_r}$	Maximum input capacity of participant $j \in J^{layer_r}$ in layer $r \in L$. $$Q_j^{max,in,layer_r} = 1.25 Q_j^{in,layer_r}$$
$Q_j^{min,in,layer_r}$	Minimum input capacity of participant $j \in J^{layer_r}$ in layer $r \in L$. $$Q_j^{min,in,layer_r} = 0.25 Q_j^{in,layer_r}$$
ε	relative effective roughness height of the pipe.
ρ^{layer_r}	Density of the fluid for layer r.
μ^{layer_r}	Dynamic viscosity of the fluid for layer r.
m^{layer_r}	Smallest flow accepted as distinct to 0 for each shared material in layer r.
v^{layer_r}	Velocity of the fluid for layer r.
η	Efficiency of a pump.
g	Gravitational acceleration.
Re	Reynolds number.
$L_{i,j}$	Length of the pipe between participant i and j.
$a1$ and $a2$	Construction and installing cost coefficients per unit of pipe length. $a1$ in USD/m^2 and $a2$ in USD/m.
b	Pressure rating and material of construction coefficient per unit of pipe length (USD/m).
c	A dependent factor of the pipe diameter.
E_{cost}	Price of the electricity in Ulsan (USD/kwh).
$Price_{Oil}$	Selling price of an oil flow outside the park, estimated by the exports price of Ulsan (USD/t).
$Source_{Cost}^{layer_r}$	Cost of obtaining raw material from outside the park (USD/t).
$Sink_{Cost}^{layer_r}$	Cost of treating the gases outside the park.

Variables

$F_{i,j}^{layer_r}$	Shared flow between participant $i \in I^{layer_r}$ and participant $j \in J^{layer_r}$.
$Source_j^{layer_r}$	Flow from a source to participant $j \in J^{layer_r}$ in layer $r \in L$.
$Sink_i^{layer_r}$	Flow to a sink from participant $i \in I^{layer_r}$ in layer $r \in L$.
RI_{EIP}	Resilience indicator composed by two sub-indicators: Network Connectivity Index and Flow Adaptability Index.
NCI	Network Connectivity Index. Sub-indicator measuring the topological characteristic of a network.

ϕ	Flow Adaptability Index. Sub-indicator measuring the operational characteristic of a network.
$\phi_k^{layer_r}$	Flow sensitivity of the participant k in a laer r.
$\mathcal{L}_k^{layer_r}$	Total lack of flows related to a disruption in k in a laer r.
P_{pump}^{real}	Real pressure drop for a pump (kwh).
P_{pump}	Pressure drop (kwh).
FO_{Ec}	Economic objective function.
FO_{En}	Environmental objective function.
FO_{Re}	Resilience objective function.
FO_i	Objective function for aspect i.
$FO_i^{WorstCase}$	Worst expected value for the aspect i.
$FO_i^{BestCase}$	Expected value for the aspect i.
γ	Deviation of each objective function in the goal programming method.
gap	Relative changes for each assessed aspect regard to its optimal and worst obtained value.
$D_{i,j}^{layer_r}$	Diameter of the connection (pipe) between participant i and j.

4.2 Background: Optimizing Eco-Industrial Parks

Chapter 2 has defined selection criteria for sustainability indicators, in addition to a large list of these kind of indicators. In chapter 3, a resilience indicator has been defined to assess and design eco-industrial parks. The present chapter addresses the simultaneous use of both indexes: sustainability and resilience; in order to design an eco-industrial park, considering both aspects in its configuration.

In the previous chapters, an Eco-Industrial Park (EIP) has been defined as a set of companies located together in a common property with the goal of sharing resources efficiently, and to improve the sustainability of the sector (Boix et al., 2015; PCSD, 1997).

In this sense, its main benefits are related to firm profitability, environmental impact reduction of the sector, and concern for local community next to the park, i.e., improvements on the sustainability dimensions (Azapagic and Perdan, 2000; Gibbs, 2008; Valenzuela-Venegas et al., 2016). Since the magnitude of these benefits depends on the EIP configuration, i.e. connections among its participants, and their location in the park (PCSD, 1997), it is important to make a proper planning and design to obtain the maximum possible benefits.

In particular, to establish a possible connection between two firms, and to define an EIP configuration, the main barriers are to comply with the operation requirements of each of them (e.g., flow magnitude, composition, temperature, etc.), and to establish a feasible and suitable location. Moreover, if these elements are defined for a set of firms, its configuration should improve the economic, environmental, and social aspects for each participant and the whole park.

All these considerations make an EIP a more complex system than the stand-alone operation of a firm, where it works with no other external interaction. Due to the aforementioned, a system integration approach has become necessary to facilitate the configuration of an EIP, and to help the decision-makers to plan and design complex systems (Lovelady and El-Halwagi, 2009). Some approaches have been historically defined with this purpose. Some of them are *brainstorming and solution though scenarios*, *adopting/evolving earlier designs*, and *heuristics* (El-Halwagi, 2012a). The first strategy consists in generating different scenarios, comparing their feasibility and performance in order to select the best one. This task can be carried out with a group of engineers and scientist for whom the process is well-known. The second approach consist in selecting a solution identifying a related problem that has been solved earlier. In this way, the previous solution is copied, adapted or evolved to fit the problem that is being resolved and to aid in the generation of similar solutions. The last approach is based on the fact that the design problems may be categorized into groups, each of them having a recommended way of solution. Through this approach, a problem is solved using experience-derived knowledge and rules of thumb to a certain group.

Even though these approaches are widely used and give a solution to industrial problems, they have limitations. For example, not all the possible solutions can be obtained, because the number of scenarios resulting from the brainstorming is limited, or the experience-derived knowledge is not enough to find a similar solution. Moreover, since the number of solutions is limited, there is no guaranty of finding the best one (optimal solution) (Sikdar, 2001).

Another way to systematically design complex industrial systems without the aforementioned limitations is through the formulation and solution of an optimization problem (El-Halwagi, 2012b; Biegler and Grossmann, 2004; Stephanopoulos, 1981). In this approach, the goal is to find the best solution for a set of equations by means of variation on a set of variables (Amaya A., 2003).

The structure of this kind of problem consists in three main elements (see Eq. 4.1): objective function ($F(x, y) \in \mathbb{R}$), which is improved through the solution of the problem; decision variables ($x \in \Omega$), which are determined by the solution of the problem, and can be continuous ($x \in \mathbb{R}^N$) or integer ($y \in \mathbb{Z}^M$); and constraints ($g(x, y) \leq 0$ and $h(x, y) = 0$), which are the equations to model the problem.

$$
\begin{aligned}
\min \quad & F(x,y) \\
\text{s.t.} \quad & \\
& g(x,y) \leq 0 \\
& h(x,y) = 0 \\
& x \in \mathbb{R}^N \\
& y \in \mathbb{Z}^M
\end{aligned}
\tag{4.1}
$$

This approach is widely used in the industry to solve several kind of problems, such as *process design and synthesis*, *process operation*, and *process control* (Biegler, 2010). Since these problems present different characteristics, they may be solved through different type of formulations depending on their decision variables and the nature of their equations: Linear Programming (LP), Mixed Integer Linear Programming (MILP), Nonlinear Programming (NLP), and Mixed Integer Nonlinear Programming (MINLP). Table 4.1 contains a summary about the main industrial problems in each of these categories, and the general formulation used to solve them.

Table 4.1: Mathematics formulation for different industrial problems. Information obtained from Biegler (2010).

	LP	**MILP**	**NLP**	**MINLP**
Process Design and Synthesis				
Heat Exchangers	✓	✗	✓	✓
Mass Exchangers	✓	✓	✓	✓
Separations		✓	✓	✓
Reactors	✓		✓	✓
Flowsheeting			✓	✓
Process Operation				
Scheduling	✓	✓		✓
Supply Chain	✓	✓		✓
Real-Time Optimization	✓		✓	
Process Control				
Model Predictive Control (MPC)	✓			
Nonlinear MPC			✓	
Hybrid MPC		✓		

In particular, the design of EIPs falls within the *Process Design and Synthesis*, since different firms or process are connected to configure an industrial network sharing resources.

In general, the EIP design aims at improving the sustainability dimensions (objective function), deciding over the location of the participants in the park, their connections, and concentration of a contaminant (decision variables). All this decisions are subject to operation requirements, process limitations and context of the park (constraints) (Grossmann, 1985).

As mentioned in the previous chapters, there are several works where the authors formulate an optimization problem to design an EIP (e.g. Ahmetović and Grossmann (2011); Aviso et al. (2010); Chae et al. (2010); Haslenda and Jamaludin (2011); Hirata et al. (2004); Karlsson and Wolf (2008); Liew et al. (2013); Lovelady and El-Halwagi (2009); Rubio-Castro et al. (2011); Tietze-Stöckinger et al. (2004). All these works are classified in water, material and energy network design according to the type of exchanges among participants of the park (Tudor et al., 2007). In the Introduction and chapter 3 some of these examples are explained in greater depth.

In these examples, the authors configure different EIPs through an optimization problem, only considering one sustainability dimension in its formulation. Since an EIP improves on the three dimensions, this mathematical formulation and its solution should also capture this behavior.

Accordingly, to simultaneously consider more than one objective, a multi-objective formulation approach should be considered. In a single-objective optimization, the objective function corresponds to an scalar value, $F(x) \in \mathbb{R}$, while in a multi-objective optimization, it is a vector of objective functions, i.e., $F(x) \in \mathbb{R}^M$, with $F(x) = [F_1(x), ..., F_M(x)]^T$[1]. In section 4.2.1, a brief background about multi-objective optimization is presented.

In the literature, there are several works about the design of an EIP considering more than one objective function. In chapter 3 several works are presented and explained. In all of them, the authors configure EIPs considering mainly economic and environmental dimensions, integrating the social dimension in other dimension, typically economic. This behavior is mainly due to the lack of social indicators, and because these indicators require complex information about each participant (firms, process, etc.) (Valenzuela-Venegas et al., 2016).

On the other hand, as mentioned in chapter 3, it is also important to take into account other aspects related to security issues when processes are connected in an EIP, especially when its proper operation depends on these connections. Since some of its participants could suffer disruptive events during its normal operation, the optimal EIP configuration should also ensure the continuous operation of each participant and the whole park (Valenzuela-Venegas et al., 2018).

In this sense, in the previous chapter a resilience indicator has been proposed to determine if the connections of the EIP can maintain the identity of the park when a disruptive event affects a participant, and to quantify the performance of the operative participants when a firm stop sharing flows. Accordingly, this indicator should be considered at the design phase of an EIP, in other words, added as an objective function in the optimization problem.

To our knowledge, there is no previous work focused on the design of an EIP considering its sustainability and its resilience at the same time. Therefore, the main goal of this chapter is to systematically design an EIP by means of a mathematical formulation of a multi-objective optimization problem, considering the sustainability dimensions and the resilience of the park

[1] v^T is the transposed vector of v.

as objective functions.

The well-known EIP in Ulsan, South Korea (Behera et al., 2012) is used as a case study to illustrate the use of this formulation. A mono-objective formulation is defined first to configure a park considering economic, environmental, and resilience aspects separately. Then, two multi-objective problems are formulated: to address an economic-environmental configuration and to address an economic-environmental-resilient configuration.

The present chapter is organized as follows: section 4.2.1 presents a brief introduction to multi-objective optimization; in section 4.3, the optimization problem and case study are defined; in section 4.4, the results and °discussions are presented and explained; and, finally, in section 4.5, the main conclusions are presented.

4.2.1 Multi-objective optimization

A multi-objective optimization problem is a kind of problem with more than one objective function. Usually, these objectives are opposed. In other words, to improve one of them, other objective functions should become worse (Coello et al., 2002).

For example, to design a treatment plant with the aim of decreasing the process wastewater, it might be desirable to minimize: (i) the cost associated to its construction, i.e. investment, and (ii) the untreated wastewater flow. In this case, both objectives are opposed because to decrease the flow of untreated wastewater, it is necessary to invest in a larger (and more expensive) treatment plant. In contrast, to decrease the construction investment, the treatment plant should be smaller and to treat less wastewater.

In a single-objective formulation, the solution would be a lager plant if the objective function were to reduce the flow of untreated wastewater, or the solution would be a smaller plant if the objective were only the investment. In contrast, if a multi-objective formulation is applied, the size of the plant will be intermediate between the previous solutions, depending on the relative importance of each objective.

In mathematical terms, a multi-objective optimization problem is defined as follows (Coello et al., 2002; Marler and Arora, 2004; Ngatchou et al., 2005):

$$
\begin{aligned}
\min \quad & F(x) = [F_1(x), ..., F_M(x)]^T \\
\text{s.t.} \quad & \\
& g(x) \leq 0 \\
& x \in \mathbb{R}^N
\end{aligned}
\tag{4.2}
$$

In this general formulation, $F(x)$ is a vector of objective functions (also called cost functions), M is the number of objective functions, $g(x)$ are the problem constraints, and

$x \in \mathbb{R}^N$ is a vector of decision variables with dimension N. The space spanned by the objective vector is known as *objective space*, while its subspace that satisfies all the constraints is called *feasible space* ($\Omega = \{x \in \mathbb{R}^N | g(x) \leq 0\}$).

On the basis of the foregoing, some concepts are necessary to define the optimal solutions in a multi-objective problem. Some of them are *Pareto Dominance*, *Pareto Optimally* and *Utopia Point* (Coello et al., 2002; Marler and Arora, 2004; Ngatchou et al., 2005), which are defined in the following paragraphs.

In a minimization problem, a decision vector $u \in \mathbb{R}^N$ is *Pareto-dominant* over another vector $v \in \mathbb{R}^N$, if and only if $\forall i \in \{1, ..., M\}, F_i(u) \leq F_i(v)$ and $\exists k \in \{1, ..., M\} : F_k(u) < F_k(v)$. This concept is used to compare and to rank different decision vectors of a multi-objective problem, and it is denoted as $u \preceq v$ (u dominates v).

On the other hand, a solution vector, $u \in \mathbb{R}^N$, is *Pareto optimal* if and only if there is no other solution with dominance over u, i.e. if there is no other better solution without affecting the performance of any objective function. The set of all Pareto optimal solutions is known as *Pareto optimal set*, and is defined as $\mathcal{P} := \{x \in \Omega | \nexists x' \in \Omega F(x') \preceq F(x)\}$. In addition, the evaluation of the objective functions ($F(x)$) in any $x \in \mathcal{P}$ is called *Pareto dominant vector*, while the set of set of Pareto dominant vector is known as *Pareto Front* and is defined as $\mathcal{PF} := \{f = F(x) | x \in \mathcal{P}\}$.

Finally, a point $F^0 \in \mathbb{R}^M$ is a *Utopia point* if and only if $\forall i \in \{1, 2, ..., M\}, F_i^0 = \min_x \{F_i(x) | x \in \Omega\}$. In general, this point is unattainable through the solution of an optimization problem and does not correspond to a point of the Pareto front. In order to obtain the optimal solution of the problem, a trade-off between the problem and the context should be established: the optimal solution would be as close as possible to the Utopia point but on the Pareto front.

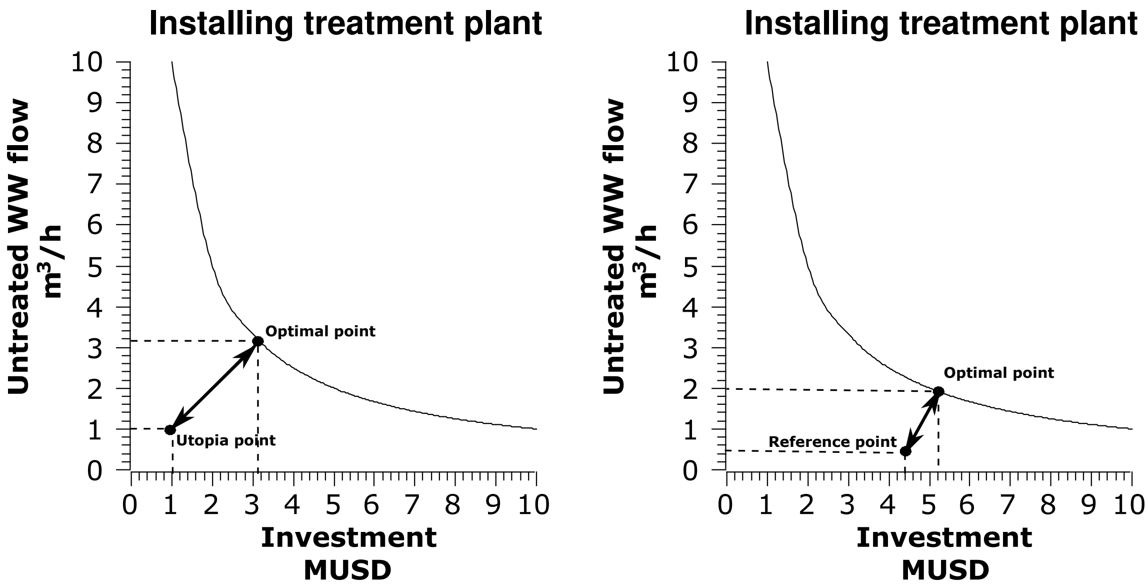
Following the aforementioned example about the design of a wastewater plant, the objective functions are the investment associated with its construction and the untreated wastewater flow. In this case, both objectives are opposed, forming a Pareto front (see Fig. 4.1a). This curve represents a trade-off to choose different possible solutions for the problem. If a function is improved, the other is worsened.

To define the Utopia point, each objective function is individually optimized in a single-objective problem, obtaining its optimal value. Each of them represents a coordinate of the Utopia point. Once the Utopia point is defined, the optimal solution can be selected, corresponding to the shortest distance between the Utopia point and the Pareto front (see Fig. 4.1a).

In the present example, if the untreated wastewater flow is minimized as a single objective, the optimal value is 1 m^3/h. On the other hand, if the investment is minimized, its optimal value is 1 $MUSD$[2]. Then, the Utopia point is defined at (1; 1), and the optimal solution is determined at (3.16; 3.16): this point defines the shortest distance between the Utopia point

[2] $MUSD = 10^6 USD$.

and the Pareto front (see Fig. 4.1a).



(a) Case where the Utopia point is used to select the optimal solution.

(b) Case where the a reference point is used to select the optimal solution.

Figure 4.1: Examples of a multi-objective optimization problem, where the opposed objective functions are: investment and untreated wastewater flow. In the figure, some important concepts of a multi-objective problem are highlighted: the Pareto front or *trade-off*, delimited by the curve; the Utopia point; the reference point, and the Optimal solution. Data in the graph correspond to an illustrative example.

It is worth to note that depending on the context of the problem and the decision-maker, one objective function may be more important than the other ones. In this case, the Utopia point is displaced to another reference point (see Fig. 4.1b), defining a new optimal point on the Pareto front. In the example of Fig. 4.1b, it is assumed that in accordance with the context, it is preferable to ensure the treatment of the wastewater over the investment incurred in its construction. In this case, the reference point (*new* Utopia point) is selected in $(4.4; 0.5)$, where the treated wastewater is benefited, and the optimal point is $(5.2; 2.0)$.

On the other hand, since a multi-objective problem simultaneously presents more than one objective in its formulation, a different approach is necessary to systematically obtain its optimal solutions. In this sense, different authors have defined specific methodologies. Some of them are listed below (Coello et al., 2002; Marler and Arora, 2004; Ngatchou et al., 2005):

- **Weighted sum method**: this method converts a multi-objective problem into a mono-objective problem (problem with only one objective function) through a linear combination of the objective functions (see Eq. 4.3).

$$
\begin{aligned}
\min \quad & \textstyle\sum_{i=1}^{M} w_i F_i(x) \quad \text{with } w_i \geq 0 \text{ and } \displaystyle\sum_{i=1}^{M} w_i = 1 \\
\text{s.t.} \quad & \\
& g(x) \leq 0 \\
& x \in \mathbb{R}^N
\end{aligned} \tag{4.3}
$$

In Eq. 4.3, the weights, w_i, indicate the relative importance of each objective. It is worth to note that the choice of each w_i is essential to configure the solution and requires a wide knowledge of the problem.

- **ε-constraint method**: this method looks for the solution of the problem through the optimization of only one objective function, converting the others into constraints. Each extra constraint is bounded by some feasible range $\varepsilon_i \in \mathbb{R}$.

$$
\begin{aligned}
\min \quad & F_k(x) \quad \text{with } k \in \{1, 2, ..., M\} \\
\text{s.t.} \quad & \\
& F_i(x) \leq \varepsilon_i \quad \forall i \in \{1, ..., M\}, i \neq k \\
& g(x) \leq 0 \\
& x \in \mathbb{R}^N
\end{aligned} \tag{4.4}
$$

- **Goal programming method**: this approach minimize the deviation of each objective function from pre-specified goals, F_i^*. As ε-constraint method, each objective is converted into a constraint, adding a new variable, γ, to represent its deviation, and parameters, w_i, to indicate the importance of each objective in the solution. Finally, the variable γ is minimized.

$$
\begin{aligned}
\min \quad & \gamma \\
\text{s.t.} \quad & \\
& F_i(x) - w_i \gamma \leq F_i^* \quad \forall i \in \{1, ..., M\} \\
& g(x) \leq 0 \\
& x \in \mathbb{R}^N
\end{aligned} \tag{4.5}
$$

In Eq. 4.5, F_i^* represents the goal of each objective function F_i, and w_i indicates the relative importance of each objective. The choice of each goal and weights is essential for the solution of the problem and needs a wide knowledge of the context.

In addition to the aforementioned methods, there are others that modify their structure: for example, alternative ways to define the weight of each objective function, or application of additional methods such as genetic algorithm among the solutions to score each one of them.

The main disadvantages of all these approaches are: (i) the need of specific knowledge to establish the weights or the boundary range according to each case; (ii) the potential problems when converting a multi-objective problem into a mono-objective problem oriented to address the trade-off among the objective functions; and (iii) the high computational cost and difficulties about the use of each method when the number of objective functions is high (Marler and Arora, 2004; Ngatchou et al., 2005).

4.3 Problem definition

To formulate an optimization problem, some important elements, such as superstructure, objective function, and constraints must be defined, in addition with the context of the problem. In the following sections, each of these elements are introduced and explained.

With this purpose, the section 4.3.1 explains the context of a case study, highlighting its main participants and the current situation of the Ulsan park. Sections 4.3.2 mentions the general assumptions for the problems, and section 4.3.3 defines its superstructure. The selection of objective functions and its considerations are mentioned in section 4.3.4, while all the modelling equations (constraints, mathematical formulation of objective functions, and multi-objective formulation) are defined in section 4.3.5. Finally, in section 4.3.6, the proposed multi-objective optimization model is presented.

All the parameters and terms introduced through this chapter are defined in the Nomenclature, at the beginning of this chapter.

4.3.1 Ulsan EIP, South Korea

South Korea is one of the leading countries in adopting the industrial ecology. This country developed an ambitious project to change the traditional way to design industrial complexes, to one based on the efficient use of residues and sub-products.

Specifically, this project has been divided in 3 main phases. The first one, consisted in converting traditional industrial complexes into EIPs, understanding the material and energy flows shared among the participating firms, as well as collecting data of each operation. The second one, related to spread the knowledge and experience in designing EIPs. And the third one, which is currently in development, consists in detecting and evaluating the successes and failures of the previous phases (Behera et al., 2012; Park and Won, 2007).

Within these industrial complexes, the most important is Mipo-Onsan, located in Ulsan, in the southeast of South Korea. This EIP project played a fundamental role to implement future industrial symbiosis in other industrial complexes in South Korea when the *Ulsan EIP Center* was established in 2007.

This EIP exchanges 13 different kind of materials among the operating firms, including 41 companies. These exchanges are related to steam, organic waste, ammonia in wastewater, neutralizing agent, waste aluminum, waste oil, zinc and sludge. The main benefits obtained in this EIP are related to reduce the CO_2 emissions and other gaseous pollutants, and to increase the economic utilities of the companies (Behera et al., 2012). Fig 4.2 shows the industrial network and the participating firms of Ulsan EIP.

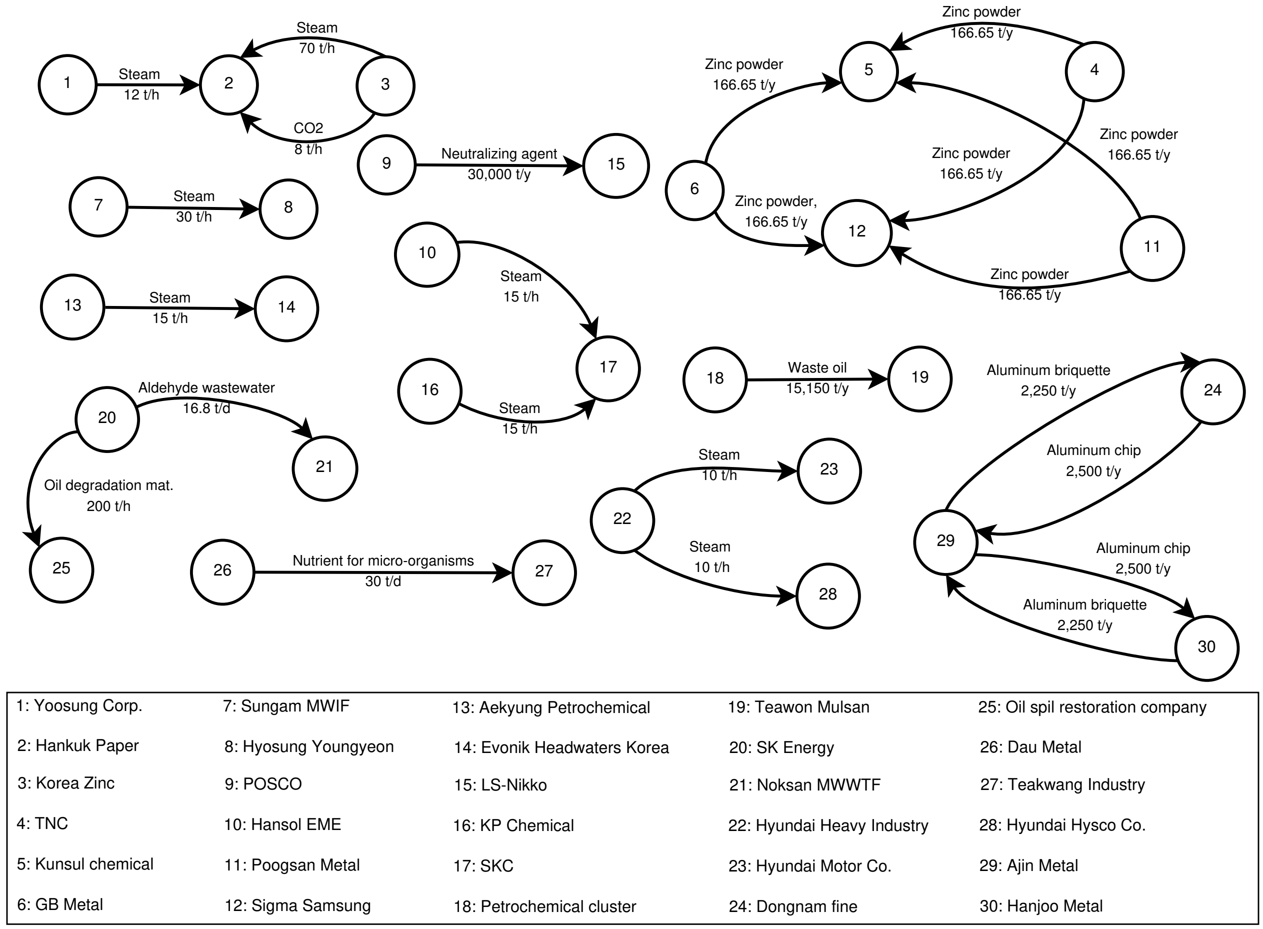


Figure 4.2: EIP in Ulsan (information taken from Behera et al. (2012)).

4.3.2 General assumptions

As mentioned before, the goal of the present chapter is to design an EIP using a multi-objective optimization approach, considering sustainability and resilience aspects in its configuration. To formulate this problem, the Ulsan industrial complex is considered as case study.

In particular, different materials are shared among the participants of this EIP (see Fig. 4.2). In order to define a suitable mathematical formulation, the following assumptions and simplifications about the context and limits of the problem are considered.

- Due to the difficulty in obtaining information about each participant and its shared flows, only three exchanged materials are selected: Steam, CO_2, and Oil (*Oil* *degradation material* and *Waste oil* networks from Fig. 4.2). These exchanges define the L set utilized to formulate the present problem.

$$L = \{\text{Steam}, \text{CO}_2, \text{Oil}\}$$

- In the present formulation, shared materials are separately followed in different layers and only participants in the same layer could share material in the respective network.
- From Fig. 4.2, two set of participants are identified in each layer: those who supply a certain flow of material (denoted as I^{layer_r}), and those who demand a certain flow of material (denoted as J^{layer_r}).
- Since there is no reported information in the literature about the industrial processes in each participating firm, this study only considers their respective supply ($Q_i^{out,layer_r}$) and demand of material ($Q_j^{in,layer_r}$) (see Table 4.2). This information is obtained from Behera et al. (2012).
- The maximum and minimum capacities for each participant in the park is considered as a fraction of its supplied and demanded flows. This assumption is necessary to overcome the lack of information in the problem, and it is only used in the resilience indicator. In this sense, the maximum and minimum capacity of a participant is defined as 1.25 and 0.25 times the required material flow, respectively (both for input and output flows).
- In addition to the original participants of the park, external sources and sinks are considered. They are located outside the park, and provide all the necessary material and services for the operation of the park. These elements are not considered as a part of the park.

4.3.3 Superstructure formulation

A superstructure is a graphical representation of the optimization problem, where all its feasible solutions are represented. It helps in the mathematical formulation of variables, equations and constraints to compose an optimization problem.

In the EIP design, the superstructure must represent all the participants, and the possible connections among them.

In this sense, the following assumptions have been considered to construct the superstructure associated with the present problem:

- The participating firms are represented by a node, and numerated following the notation of Fig. 4.2.
- The possible connections among the participants are considered as material flows between two participants and are represented by oriented edges, connecting the respective participants ($F_{i,j}^{layer_r}$ with $i \in I^{layer_r}$, $j \in J^{layer_r}$ and $r \in L$).
- As aforementioned, only 3 exchanged materials are taken into account, each of them represented as an independent layer ($r \in L$).

- Since two sets of participants are identified (see the last section), two types of nodes are defined: those who only present output edges, $i \in I^{layer_r}$ (supplying a certain flow of material); and those who only present input edges, $j \in J^{layer_r}$ (demanding a certain flow of material).
- To represent the external sources and sinks, two extra nodes for each layer are considered. Each connection between them and a participant of a layer ($i \in I^{layer_r}$ or $j \in J^{layer_r}$) is denoted as $Source_j^{layer_r}$ and $Sink_i^{layer_r}$.

With these considerations, the superstructure shown in Fig. 4.3 is proposed.

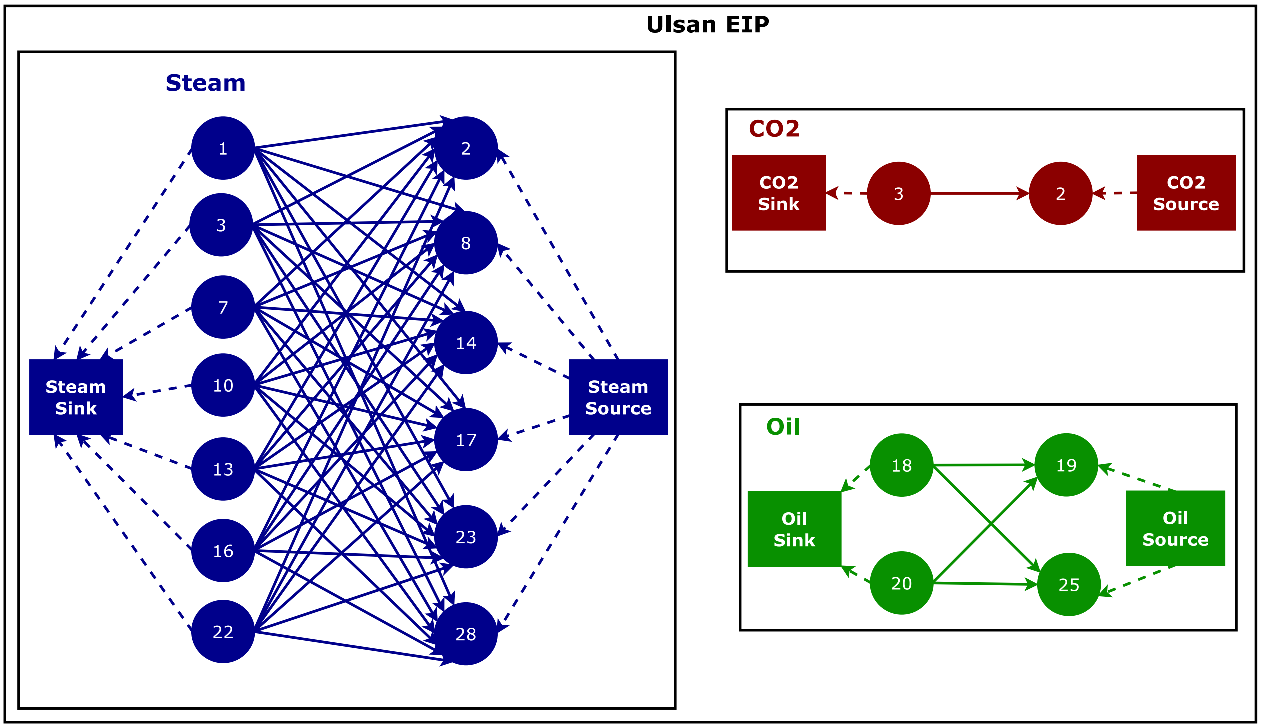


Figure 4.3: Superstructure for the present problem in Ulsan, South Korea.

It is worth to note that in spite of firm 2 (Hankuk Paper) and firm 3 (Korea Zinc) share two types of material: Steam and CO_2; they are considered simultaneously in different layers to facilitate the modelling of the problem.

4.3.4 Selection of objective functions

The main goal of the section 4.3 is to formulate an optimization problem to design an eco-industrial park in Ulsan, optimizing sustainability and resilience aspects and deciding a new configuration.

In chapter 2, four criteria has been defined to select suitable indicators to assess the sustainability of an EIP. These criteria are: Understanding, Pragmatism, Relevance, and Partial Representation of Sustainability (see their definition on Table 2.1); which should be achieved to capture the main characteristics of an EIP.

Under the context of Ulsan, the indicators obtained from the literature review in chapter 2 have been filtered according to these criteria. Accordingly, all the indicators classified as Understanding, Pragmatism, and Representation of Sustainability criteria are considered, i.e indicators easy to understand, measurable with the available information from literature, and assessing some sustainable dimension.

It is worth to note that since the relevance criterion depends on the goals of the EIP development and its participants' future, and there is not enough available information to properly define them, this criterion is more complicated to apply in this case. Therefore, it has been relaxed and only considered the aims of the EIP, assuming as goals the reduction of residues and cost of the park.

In consequence, the sustainability indicators filtered from Table A.1 in Appendix A.1 are *Direct Material Input (DMI), Direct Material Output (DMO) and Investment*. Additionally, some extra economic indicators are also considered: *raw material cost*, *pumping cost*, *gas treatment cost*, and *economic benefit* obtained through the sell of products. All of them also comply with the four criteria for selection.

It is important to highlight that no social indicator has been selected because they require inaccessible information under the present context.

In order to mathematically formulate these indicators, the following considerations are taken into account:

- The investment indicator only considers the construction cost related to pipes and installation.
- The raw material cost considers any external input to the participants in the park.
- The pumping cost considers the pressure drop in the pipe lines and the power required to move a fluid through the network.
- The price of the electricity is established for the context of the problem, i.e., Ulsan.
- The gas treatment cost considers a service from an external process or plant.
- The selling price associated to any oil product is fixed by the import and export price in Ulsan.
- Since there are some indicators, such as DMI, DMO, and cost of raw material, among others, which depend on time; a period of 5 years will be considered to normalize their units and to compare all the indicators.

With these assumptions, the environmental and economic indicators are determined. In section 4.3.5, all of them are explained and mathematically defined according to the present problem.

On the other hand, to measure the resilience of the EIP configuration, the resilience indicator (RI_{EIP}) defined in Chapter 3 is adapted and used for the present problem. Specifically, this indicator measures topographical and operational characteristics of a network through the weighted sum of two sub-indicators: Network Connectivity Index (NCI), and Flow Adaptability Index (ϕ).

Since the present problem considers more than one objective function to be simultaneously solved, a multi-objective approach needs to be used. In this sense, the goal programming method is considered (see Section 4.2.1) with some modifications in its formulation, specifically, in the normalization of the objective function. In section 4.3.5, all these considerations are detailed.

4.3.5 Modelling variables and equations

In the previous sections, general assumptions for the present problem are provided along with its superstructure and the objective functions. In the following sub-sections, the decision variables and equations of the mathematical model (constraints and objective functions) are declared in order to formulate the optimization problem.

Decision variables

In an EIP design problem, the main decision variables are related to its configuration, i.e. connections among the participants, and their location. In the present problem, only the first variables are considered, keeping the location of the participant fixed to the present layout of the park.

It is worth to note that this decision is considered since the optimization problem is based on an existing EIP. In the design of a new park, both the connections and the location would be considered as a variables since they are not predefined.

Therefore, two kind of variables are defined to represent the connections of the problem: the first one, related to the shared flow and considered as a continuous variable; and the second one, related to the existence of connections and considered as a binary variable. In particular, the first kind is used to decide the magnitude of the flows among firms, sources, and sinks; while the second one, to establish the existence of a connection. This last variable is specifically relevant in the resilience index and some other constraints.

It is worth to note that both variables are linked, since if there is a flow between two participants, this connection should exist. This behavior is captured through a proper constraint formulated in the following sub-section.

Therefore, the following decision variables are formulated for the present problem. All the sets and parameters are defined in the Nomenclature, at the beginning of this chapter.

- **Flow magnitude between participants:** continuous variable to measures the shared flow between participant i and j in layer r.

$$F_{i,j}^{layer_r} \in \mathbb{R}^+ \tag{4.6}$$

with $i \in I^{layer_r}$, $j \in J^{layer_r}$, and $r \in L$.

- **Flow magnitude between sources and firms:** continuous variable to measure the shared flow between the source and participant j in layer r.

$$Source_j^{layer_r} \in \mathbb{R}^+ \tag{4.7}$$

with $j \in J^{layer_r}$, and $r \in L$.

- **Flow magnitude between firms and sinks:** continuous variable to measure the shared flow between participant i and the sink in layer r.

$$Sink_i^{layer_r} \in \mathbb{R}^+ \tag{4.8}$$

with $i \in I^{layer_r}$, and $r \in L$.

- **Existence of a connection:** binary variable to represent the existence of a connection between participants i and j in layer r.

$$x_{i,j}^{layer_r} = \begin{cases} 1, & \text{if there is a flow between firm } i \text{ and } j \text{ in layer } r \\ 0, & \text{otherwise} \end{cases} \tag{4.9}$$

with $i \in I^{layer_r}$, $j \in J^{layer_r}$, and $r \in L$.

It is important to note that the binary variables are only defined to facilitate the implementation of the resilience indicator in the problem. Accordingly, they are only used when the resilience indicator is considered.

On the other hand, to mathematically formulate the objective functions, some auxiliar variables are necessary. In consequence, the following expressions are defined:

- **Pipe diameter:** this variable is assumed constant along a connection (pipe) but changes with its respective flow. Assuming that the volumetric flow is defined by the cross section velocity (v) and area (A), i.e. $F_{vol} = vA$, and the geometry of the pipe is cylindrical ($A = \pi D^2/4$), the diameter variable is expressed as follows:

$$D_{i,j}^{layer_r} = 2\sqrt{\frac{F_{i,j}^{layer_r}}{\pi v^{layer_r} \rho^{layer_r}}} \tag{4.10}$$

where v^{layer_r} is the velocity of the fluids within the pipe in layer r, and ρ^{layer_r} is the density of the fluid.

For this case, v^{layer_r} is considered constant for each layer, and depend on the type of shared material (see Table 4.3).

- **Number of connections:** this auxiliar variable measures the number of total connections in the park, considering all the participants in a unique layer, no matter what they share.

In order to capture this behavior through the decision variables, the following expression is determined:

$$C = \sum_{r \in L} \left(\sum_{i \in I^{layer_r}} \left(\sum_{j \in J^{layer_r}} x_{i,j}^{layer_r} \right) \right) - x_{3,2}^{Steam} x_{3,2}^{CO2} \tag{4.11}$$

Since participants 2 and 3 are in two layers: Steam and CO_2 (see Fig. 4.2), they are considered only once in the calculation of the auxiliar variable C.

In the following section, the constraints and objective functions are mathematically formulated using the decision variables and auxiliar variables defined above.

Constraints and mathematical formulation of objective functions

The constraints in an EIP design problem are often related to mass and energy balance, requirements of the participants, and physical constraints in their connections. Since there is a lack of information about the processes of the participating firms, only their inputs and outputs are taken into account in the problem.

Therefore, the following equations (see Eqs. from 4.12 to 4.15) define the constraints of the present problem.

- **Compliance of flow requirements for participants in the park:** each participant complies with its demand and supply of material ($Q_j^{in,layer_r}$ and $Q_i^{out,layer_r}$) by means of exchanges with other participants, sourcess and sinks.

$$Sink_i^{layer_r} + \sum_{j \in J^{layer_r}} F_{i,j}^{layer_r} = Q_i^{out,layer_r} \quad \forall i \in I^{layer_r} \text{ and } \forall r \in L \tag{4.12}$$

$$Source_j^{layer_r} + \sum_{i \in I^{layer_r}} F_{i,j}^{layer_r} = Q_j^{in,layer_r} \quad \forall j \in J^{layer_r} \text{ and } \forall r \in L \tag{4.13}$$

- **Consistency between decision variables:** as mentioned in the previous section, there is a relationship between flow variables ($F_{i,j}^{layer_r}$) and existence variables ($x_{i,j}^{layer_r}$). In this sense, if there is a flow between two firms, there is also a connection between them, and vice versa.

$$F_{i,j}^{layer_r}(1 - x_{i,j}^{layer_r}) = 0 \quad \forall i \in I^{layer_r}, \forall j \in J^{layer_r} \text{ and } r \in L \tag{4.14}$$

$$m^{layer_r}(2x_{i,j}^{layer_r} - 1) \leq F_{i,j}^{layer_r} \quad \forall i \in I^{layer_r}, \forall j \in J^{layer_r} \text{ and } r \in L \tag{4.15}$$

with m^{layer_r} the smallest accepted flow as distinct to 0 for each shared material (see Table 4.3). This parameter has been defined to avoid the smallest flows that do not make a significant contribution to the solution. In this sense, it has been defined considering one order of magnitude lower than the the flows of each layer.

On the other hand, the mathematical formulation of each objective function is expressed as follows:

- **DMI:** it measures all the input flows from outside the park, used by the firms, i.e., the flows from the source nodes.

$$DMI = \sum_{r \in L} \sum_{j \in J^{layer_r}} Source_j^{layer_r} \tag{4.16}$$

- **DMO:** it measures all the output flows from the park, treated or sold, i.e., the flows to the sink nodes.

$$DMO = \sum_{r \in L} \sum_{i \in I^{layer_r}} Sink_i^{layer_r} \tag{4.17}$$

- **Investment:** it measures the piping and installing costs as two fixed costs, as a function of the length and diameter of the pipes in each layer.

  This equation is obtained and adapted from Akbarnia et al. (2009), where the investment is expressed as follows:

$$\text{Investment} = (a1D + a2) + be^{cD} \tag{4.18}$$

  with $a1$ and $a2$, the construction and installing cost coefficient per unit of pipe length; b, the pressure rating and material of construction coefficient per unit of pipe length; c, a dependent factor of the pipe diameter; and D, the pipe diameter.

  It is worth to note that the installing cost is estimated with a linear model, while the material cost, by means of an exponential model, both depending on the diameter of the pipe.

  For the present problem, these coefficients (see Table 4.3) were estimated through a parameter fitting over installing and material cost data. More details are available in Appendix A.2.

  Finally, the investment indicator is defined as follows:

$$\text{Investment} = \sum_{r \in L} \left(\sum_{i \in I^{layer_r}} \left(\sum_{j \in J^{layer_r}} \left(\left(a1D_{i,j}^{layer_r} + a2 + be^{cD_{i,j}^{layer_r}} \right) L_{i,j} \right) \right) \right) \tag{4.19}$$

  where $L_{i,j}$ is the length of the pipe between participant i and j[3] (see Table 4.4).

- **Raw material cost:** it measures the cost associated with the purchase of raw materials from outside the park, i.e., the cost related to the flow from source nodes.

$$\text{Raw Material Cost} = \sum_{r \in L} \left(Source_{Cost}^{layer_r} \sum_{j \in J^{layer_r}} Source_j^{layer_r} \right) \tag{4.20}$$

  where $Source_{Cost}^{layer_r}$ is the cost of obtaining raw material from outside the park in USD/t (see Table 4.3).

[3]The length of the pipes are calculated by the distance among the involved participants.

- **Pumping cost:** it measures the energy cost to pump the shared material through the network.

  Since this information depends on the pump and the pressure drop within each pipe, the following expression is calculated from the well-known Darcy-Weisbach and Bernoulli equations, and from an approximation of Colebrook equation (Genić et al., 2011) (more details about this calculation in Appendix A.3).

$$P_{pump} = 0.0055 \left[1 + \left(20000\frac{\varepsilon}{D} + \frac{10^6\mu}{\rho v D}\right)^{1/3}\right] \frac{Lv^2}{2D} F \tag{4.21}$$

  where P_{pump} is the theoretical power of the pump, L is the length of the pipe, D is the diameter of the pipe, v is the cross section velocity of the fluid, g is the gravitational acceleration, ρ is the density of the fluid, μ is the dynamic viscosity of the fluid, ε is the relative pipe roughness, and F is the mass flow of the fluid.

  On the other hand, the real power imparted on the fluid by the pump depends on its efficiency, η, and the power needed by the fluid, P_{pump}. Accordingly, the efficiency of the pump is defined as follows:

$$\eta = \frac{P_{pump}}{P^{real}_{pump}} \tag{4.22}$$

  Therefore, the real power pumping for the present problem is expressed as follows (all the parameters are reported in Table 4.3 and Table 4.4):

$$P^{real}_{pump} = \sum_{r\in L}\left(\sum_{i\in I^{layer_r}}\left(\sum_{j\in J^{layer_r}}\left(0.0055\left(1 + \left(20000\frac{\varepsilon}{D^{layer_r}_{i,j}} + \frac{10^6\mu^{layer_r}}{\rho^{layer_r}v^{layer_r}D^{layer_r}_{i,j}}\right)^{1/3}\right) \frac{L_{i,j}(v^{layer_r})^2}{2D^{layer_r}_{i,j}} F^{layer_r}_{i,j}\eta^{-1}\right)\right)\right) \tag{4.23}$$

  with $D^{layer_r}_{i,j}$, the diameter of the connection (pipe) between participant $i \in I^{layer_r}$ and $j \in J^{layer_r}$, calculated using Eq. 4.10.

  Finally, the pumping cost is calculated as below:

$$\text{Pumping Cost} = P^{real}_{pump}E_{Cost} \tag{4.24}$$

  where E_{Cost} is the price of the electricity in Ulsan (see Table 4.3).

- **Gas treatment cost:** it measures the cost associated with treating the gases outside the park, i.e., the cost related with the flow to sink nodes.

$$\text{Gas treatment cost} = \sum_{r\in L}\left(Sink^{layer_r}_{Cost} \sum_{i\in I^{layer_r}} Sink^{layer_r}_{i}\right) \tag{4.25}$$

  where $Sink^{layer_r}_{Cost}$ is the cost of treating the gases outside the park (see Table 4.3).

- **Benefits:** it measures the benefits of selling certain product outside the park, specifically, the product derived from oil.

$$\text{Benefits} = Price_{Oil} \sum_{i \in I^{layer_r}} Sink_i^{Oil} \tag{4.26}$$

where $Price_{Oil}$ is the selling price of an oil flow outside the park, estimated by the exports price (see Table 4.3).

- **Resilience:** it measures topological and operation characteristics of an EIP by means of two sub-indicators: NCI and ϕ.

$$RI_{EIP} = a \cdot NCI + (1-a) \cdot \phi \tag{4.27}$$

where a is a scalar indicating the importance of each sub-indicator ($0 \leq a \leq 1$), NCI is the Network Connectivity Index, and ϕ is the Flow Adaptability Index as defined in the section 3.3. For the present case, both sub-indicators are considered with the same importance. Accordingly, a is equal to 0.5.

In order to implement and add this indicator in the formulation, some considerations are taken into account:

(i) From the previously section, there are 13 participants for the Steam network, 2 for CO_2 network, and 4 for Oil network. (ii) Since the participants of CO_2 network are also in the Steam network, the total number of participants in the EIP is 17. Therefore, the NCI sub-indicator (see Eq. 3.4) is expressed as below (with $N = 17$):

$$NCI = \frac{(C-9)}{127} \tag{4.28}$$

where C is the number of connections in the park configuration.

(iii) On the other hand, to apply the Flow Adaptability Index, the equations to define this measurement are modified and adapted. In this sense, since ϕ measures whether the firms of a park can adapt its flows to withstand disruptive events over them, it considers only participants within the park, and none external.

As mentioned before (see Section 4.3.2), both sources and sinks are not considered as part of the park. Accordingly, their flows must not be considered in the sub-indicator ϕ.

Therefore, ϕ is expressed as follows for the present problem[4]:

$$\phi = \frac{1}{|L|} \sum_{r \in L} \left(\frac{1}{|I^{layer_r}| + |J^{layer_r}|} \left(\sum_{k \in I^{layer_r}} \phi_k^{layer_r} + \sum_{k \in J^{layer_r}} \phi_k^{layer_r} \right) \right) \tag{4.29}$$

$$\phi_k^{layer_r} = 1 - \frac{\mathcal{L}_k^{layer_r}}{\sum_{i \in I} F_{i,k}^{layer_r} + \sum_{j \in J} Q_j^{min,in,layer_r}} \tag{4.30}$$

And the equation for $\mathcal{L}_k^{layer_r}$ is modified as below:

[4] $|\cdot|$:cardinality of a set.

$$\mathcal{L}_k^{layer_r} = \sum_{i \in I^{layer_r}} \max\Bigg\{0, F_{i,k}^{layer_r} - \sum_{l \in J^{layer_r}, l \neq k} \Bigg(\Big(Q_l^{max,in,layer_r} - Source_l^{layer_r}\Big) - \sum_{v \in I^{layer_r}, v \neq k} F_{v,l}^{layer_r}\Bigg)\Bigg\} x_{i,l}^{layer_r}$$
$$+ \sum_{j \in J^{layer_r}} \max\Bigg\{0, \Bigg[\Big(Q_j^{min,in,layer_r} - Source_j^{layer_r}\Big) - \sum_{m \in I^{layer_r}, m \neq k} F_{m,j}^{layer_r} x_{m,j}^{layer_r}\Bigg]$$
$$- \sum_{m \in I^{layer_r}, m \neq k} \Bigg[\big(Q_m^{max,out,layer_r} - Sink_m^{layer_r}\big) - \sum_{w \in J^{layer_r}, w \neq k} F_{m,w}^{layer_r}\Bigg] x_{m,j}^{layer_r}\Bigg\} x_{k,j}^{layer_r} \quad (4.31)$$

Finally, considering all the aforementioned indicators, and a period of 5 years, the three main objective functions for Ulsan EIP are defined as follows:

- **economic objective**

$$FO_{Ec} = (\text{Raw material cost} + \text{Pumping cost} + \text{Gas treatment cost} + \text{Benefits}) 365 \cdot 24 \cdot 5 + \text{Investment} \ \ (USD) \quad (4.32)$$

- **Environmental objective**

$$FO_{En} = (\text{DMI} + \text{DMO}) 365 \cdot 24 \cdot 5 \ \ (\text{tons of material}) \quad (4.33)$$

- **Resilience objective**

$$FO_{Re} = RI_{EIP} \quad (4.34)$$

In this section, all the objective functions are expressed as a mathematical formulation for the optimization problem. Since they need to be simultaneously solved to obtain the optimal solution, the goal programming method is adapted and used. In the following section, all these considerations are explained and, finally, the mathematical formulation for the optimization problem is defined.

Multi-objective modelling

The current problem is a multi-objective optimization problem, where economic, environmental, and resilience aspects are considered together to design an EIP in Ulsan.

In this case, the goal programming method is used to find the optimal solution (see section 4.2.1), where its general expression is the following:

$$
\begin{aligned}
\min \quad & \gamma \\
\text{s.t.} \quad & \\
& FO_i(x) - w_i\gamma \leq FO_i^* \quad \forall i \in \{1, ..., M\} \\
& g(x) \leq 0 \\
& x \in \mathbb{R}^N
\end{aligned} \tag{4.35}
$$

In the last expression, $\{1, 2, ..., M\}$ is the set of functions considered in the multi-objective optimization problem; $FO_i(x)$, the objective function for the aspect i; w_i, the relative weight for the aspect i; FO_i^*, the expected value for the objective function i; and γ, the deviation of each objective function.

In particular, since the value of each objective function ($FO_i(x)$) is non-normalized when compared to its expected value (FO_i^*), the deviation (γ) may be affected in different scale. For example, if the difference between the magnitude order of two objective functions is significant (for instance, $\sim 10^2$), when γ is numerically minimized, most of the optimization algorithm will prefer to reduce the greatest objective function since it will produce greatest reduction in γ. To avoid this issue, the objective functions need a proper normalization, where the reduction of each of them should be significant.

To normalize in the present case, the proposed normalization value is the difference between the worst and best case for each aspect ($FO_i^{\text{Wort Case}}$ and $FO_i^{\text{Best Case}}$, respectively), where their values represent the maximum and the minimum value obtained in a single-objective optimization problem for the aspect i.

$$
\begin{aligned}
FO_i^{\text{Worst Case}} = \max \quad & FO_i(x) \\
\text{s.t.} \quad & \\
& g(x) \leq 0 \\
& x \in \mathbb{R}^N
\end{aligned}
\qquad\qquad
\begin{aligned}
FO_i^{\text{Best Case}} = \min \quad & FO_i(x) \\
\text{s.t.} \quad & \\
& g(x) \leq 0 \\
& x \in \mathbb{R}^N
\end{aligned}
$$

with $FO_i^{\text{Best Case}}$, the expected value for the aspect i, i.e., $FO_i^{\text{Best Case}} = FO_i^*$, and $FO_i^{\text{Worst Case}}$ is the worst expected value for aspect i.

It is important to note that for both economic and environmental aspects, the worst and best cases are obtained by maximizing and minimizing their respective objective function (Eqs. 4.32 and 4.33, respectively). Conversely, for the resilience aspect, its worst and best cases are obtained by minimizing and maximizing the resilience objective function (Eq. 4.34).

Finally, the goal programming equations are expressed as follows:

$$\begin{array}{lcr}
\min & \gamma & \\
\text{s.t.} & & \\
& \frac{FO_i(x)}{FO_i^{\text{Worst Case}} - FO_i^{\text{Best Case}}} - w_i\gamma \leq \frac{FO_i^{\text{Best Case}}}{FO_i^{\text{Worst Case}} - FO_i^{\text{Best Case}}} & (4.36) \\
& g(x) \leq 0 & \\
& x \in \mathbb{R}^N & \\
\text{with} & i \in \{1, 2, ..., M\} &
\end{array}$$

4.3.6 General Model and data selection

In the previous sections, superstructure, decision variables, objective functions and constraints are defined for the present problem. Therefore, the mathematical model for the design of an EIP in Ulsan, considering economic, environmental, and resilience is formulated (see Eq. 4.37).

$$\begin{array}{llll}
\min & \gamma & & \\
\text{s.t.} & & & \\
& \frac{FO_k(F,x)}{FO_k^{\text{Worst Case}} - FO_k^{\text{Best Case}}} - w_k\gamma \leq \frac{FO_k^{\text{Best Case}}}{FO_k^{\text{Worst Case}} - FO_k^{\text{Best Case}}} & \forall k \in \{Ec, En, Re\} & (4.37) \\
& Sink_i^{layer_r} + \sum_{j \in J^{layer_r}} F_{i,j}^{layer_r} - Q_i^{out,layer_r} = 0 & \forall i \in I^{layer_r}, \forall r \in L & \\
& Source_j^{layer_r} + \sum_{i \in I^{layer_r}} F_{i,j}^{layer_r} - Q_j^{in,layer_r} = 0 & \forall j \in J^{layer_r}, \forall r \in L & \\
& F_{i,j}^{layer_r}(1 - x_{i,j}^{layer_r}) = 0 & \forall i \in I^{layer_r}, \forall j \in J^{layer_r}, \forall r \in L & \\
& m^{layer_r}(2x_{i,j}^{layer_r} - 1) - F_{i,j}^{layer_r} \leq 0 & \forall i \in I^{layer_r}, \forall j \in J^{layer_r}, \forall r \in L & \\
& F_{i,j}^{layer_r} \in \mathbb{R}^+, x_{i,j}^{layer_r} \in \{0, 1\} & &
\end{array}$$

where the objective functions, FO_k, are defined by Eqs. 4.32 to 4.34 and their relative importance is considered to be the same, i.e., $w_k = 1$, $\forall k \in \{Ec, En, Re\}$.

Table 4.2: Supply and demand for each participant in the park.

I^{Steam}	$Q_i^{out,Steam}$ (kg/s)	J^{Steam}	$Q_j^{in,Steam}$ (kg/s)	I^{CO_2}	Q_i^{out,CO_2} (kg/s)	J^{CO_2}	Q_j^{in,CO_2} (kg/s)	I^{Oil}	$Q_i^{out,Oil}$ (kg/s)	J^{Oil}	$Q_j^{in,Oil}$ (kg/s)
1	3.333	2	5.556	3	19.444	2	19.444	18	0.48040	19	0.48040
3	2.222	8	8.333					20	0.00634	25	0.00634
7	8.333	14	4.167								
10	4.167	17	8.333								
13	4.167	23	2.778								
16	4.167	28	2.778								
22	5.556										

Table 4.3: Parameters for the present problem (DGFEZ, 2018; Green and Southard, 2018). The price of selling oil was considered as a negative cost.

General parameters		Parameter for each layer	Steam	CO_2	Oil
ε (m)	0.0000015	v (m/s)	50	30	1
η_{pump} $(-)$	0.8	ρ (kg/m^3)	22.183	1.4	963.7
Evaluation period $(year)$	5	μ (kg/ms)	0.000018	0.000018	0.08985539
Electricity cost (USD/kwh)	0.07076	$Sink_{Cost}^{layer_r}$ (USD/t)	0	18.14	$-1,308.8$
a1 (USD/m^2)	17.095	$Source_{Cost}^{layer_r}$ (USD/t)	81.86	$5,593.7$	$1,363.3$
a2 (USD/m)	6.824	m^{layer_r} (kg/s)	0.001	0.001	0.00001
b (USD/m)	4.1288				
c $(-)$	22.856				

Table 4.4: Distances between participating firms.

Steam (m)	2	8	14	17	23	28
1	$30,070$	$22,330$	$18,940$	$20,990$	$16,430$	$17,130$
3	$7,540$	860.74	$5,340$	$1,650$	$6,710$	$6,410$
7	$7,620$	835.63	$4,190$	$2,100$	$7,150$	$7,050$
10	$7,310$	901.18	$5,450$	$1,850$	$6,940$	$6,640$
13	$18,830$	$4,130$	651.97	$3,980$	$6,460$	$6,850$
16	$7,520$	528.07	$5,090$	$1,650$	$6,810$	$6,550$
22	$13,020$	$7,890$	$10,410$	$6,860$	$6,050$	$5,110$

CO_2 (m)	2
3	$7,540$

Oil (m)	19	25
18	$7,800$	$13,250$
20	$1,910$	$9,360$

4.4 Results and discussion

The main goal of this chapter is to configure an EIP, improving its sustainability and resilience by means of an optimization problem. To achieve this goal, a multi-objective optimization model is formulated for the industrial complex in Ulsan. Since this model corresponds to an MINLP problem, its solution is obtained with a global solver as *BARON* (Sahinidis, 1996) included in GAMS software (General Algebraic Modeling System) (Bussieck and Meeraus, 2004). All the parameters used in this problem are defined in Tables 4.2 to 4.4, in addition with extra information of the case study.

On the basis of the foregoing, five EIP configurations are composed, optimizing different aspects in each of them:

- Economic effects (economic configuration).
- Environmental effects (environmental configuration).
- Resilience (resilient configuration).
- Economic and environmental effects simultaneously (economic-environmental configuration).
- Economic effects, environmental effects, and resilience simultaneously (economic-

environmental-resilient configuration).

Table 4.6 shows a summary of the results obtained for each configuration, highlighting the value of each assessed aspect. While in each individual configuration the respective optimized aspects obtain the best result, in the multi-objective configurations the aspects are improved but they do not reach the same optimal values. On the other hand, the current configuration of the industrial complex is assessed considering each aspect in order to compare the present configuration with the five optimized configurations.

Table 4.7 shows the relative changes (gap) for each assessed aspect regard to its optimal and worst obtained value. This comparison has been made using the following equation:

$$gap = \frac{X^{opt.} - X}{X^{opt.} - X^{worst}} \times 100\%$$

where $X^{opt.}$ and X^{worst} are the optimal and worst value for aspect X (economic, environmental, resilience) among the obtained configurations.

In the following sections (sections 4.4.1) each configuration is discussed in detail, comparing their results and with the current situation of the park. Additionally, the best configuration among the five assessed cases is selected in section 4.4.2, highlighting its characteristics and enhancements. Finally, the scopes of the model are discussed in section 4.4.3, underscoring constraints, objective functions and the multi-objective approach utilized in the problem.

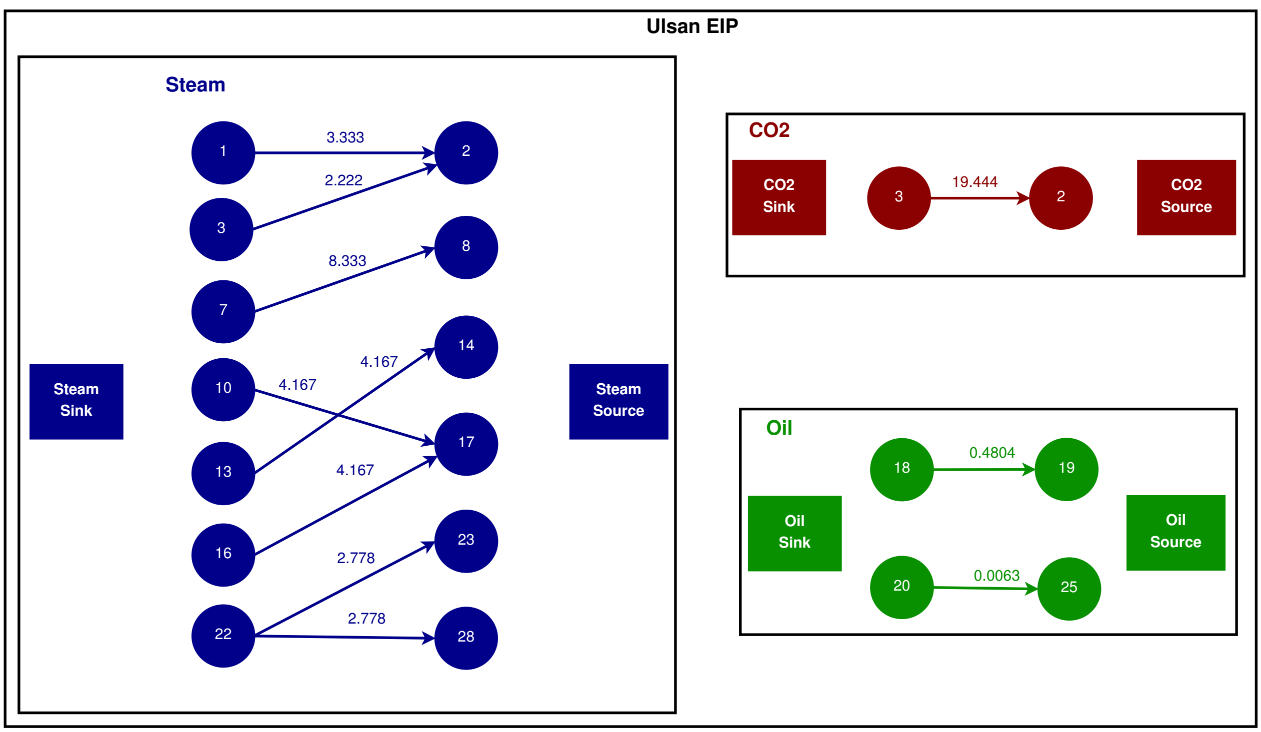


Figure 4.4: Current situation of Ulsan EIP. All flows are in kg/s.

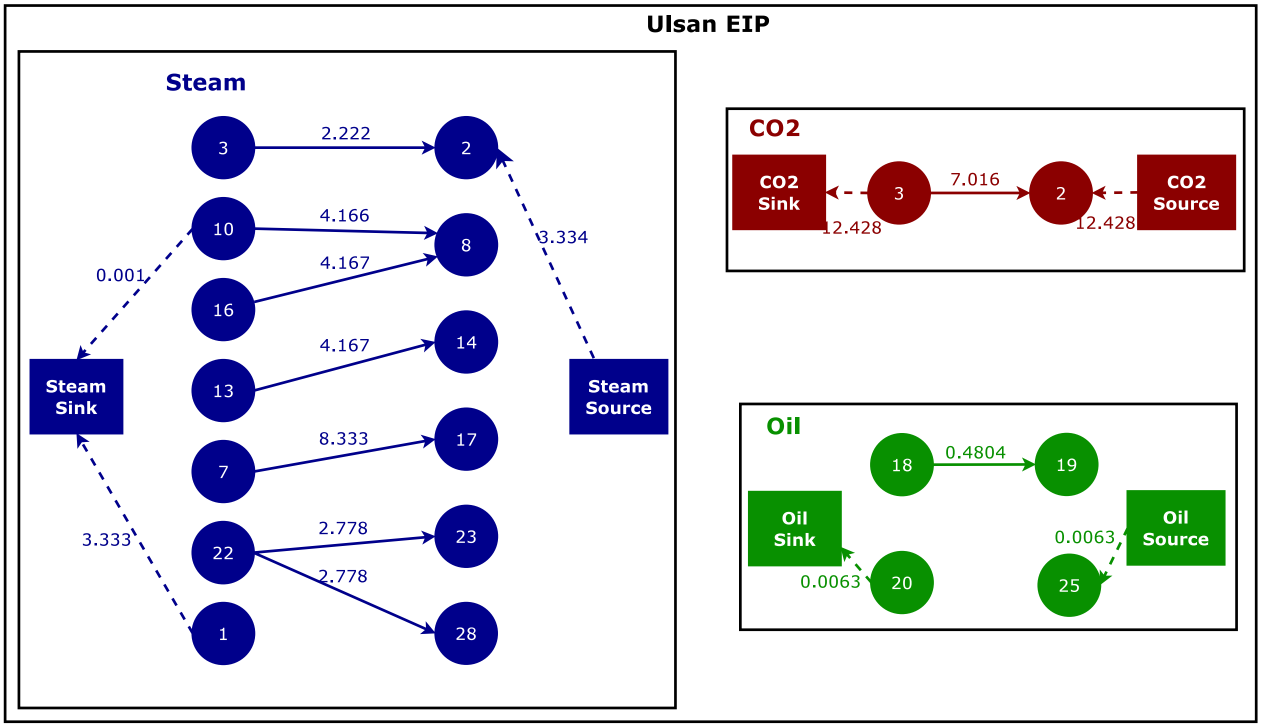


Figure 4.5: Optimal configuration for Ulsan EIP considering economic objective. All flows are in kg/s.

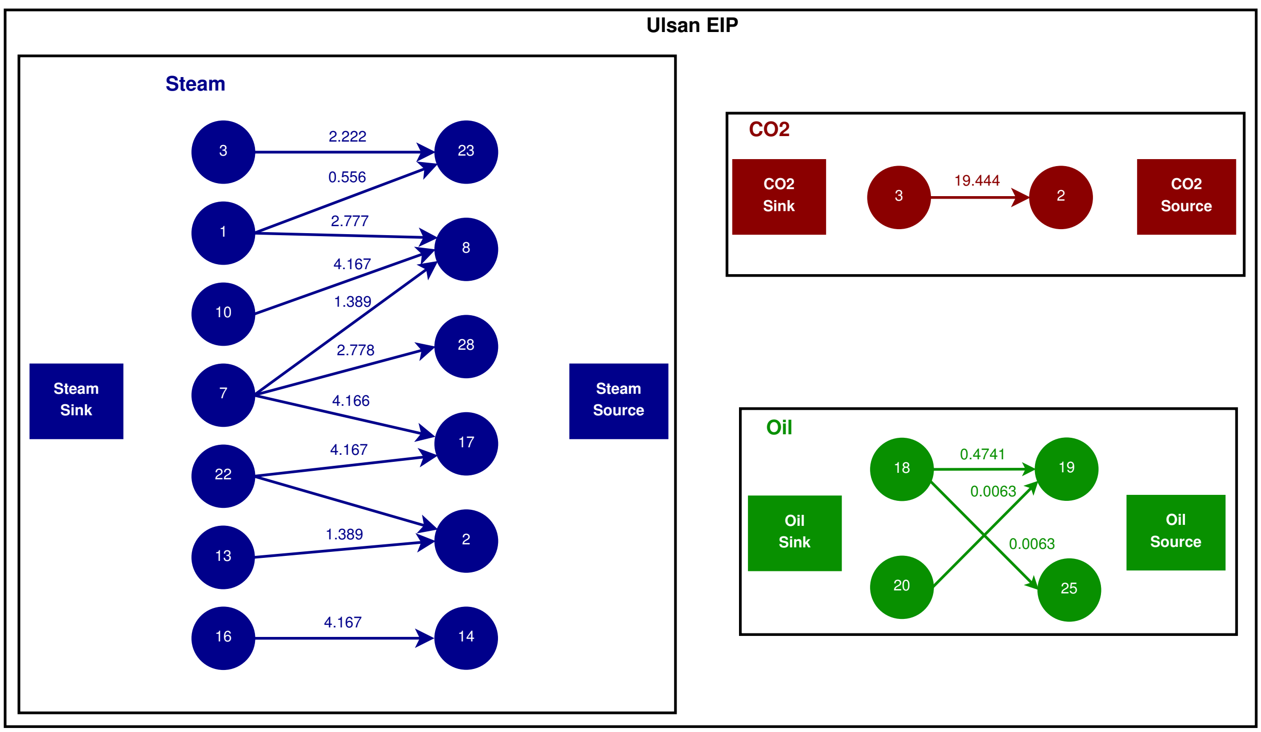


Figure 4.6: Optimal configuration for Ulsan EIP considering environmental objective. All flows are in kg/s.

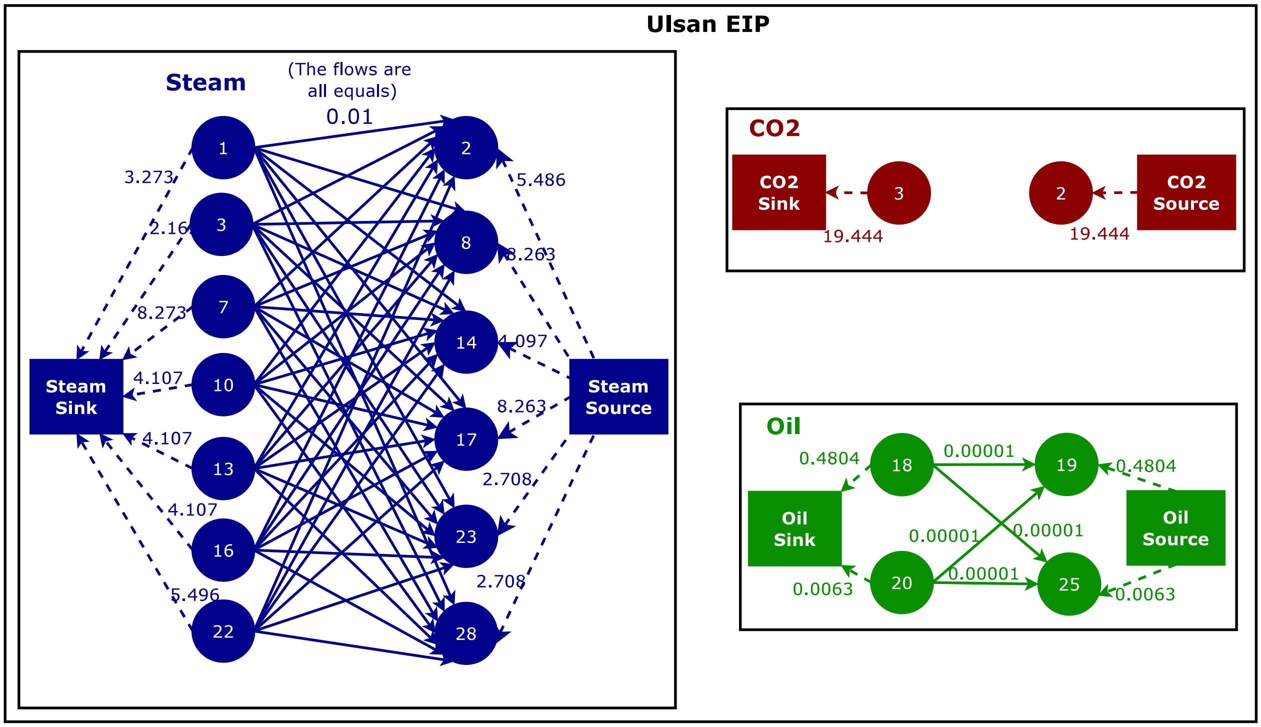


Figure 4.7: Optimal configuration for Ulsan EIP considering resilience objective. All flows are in kg/s.

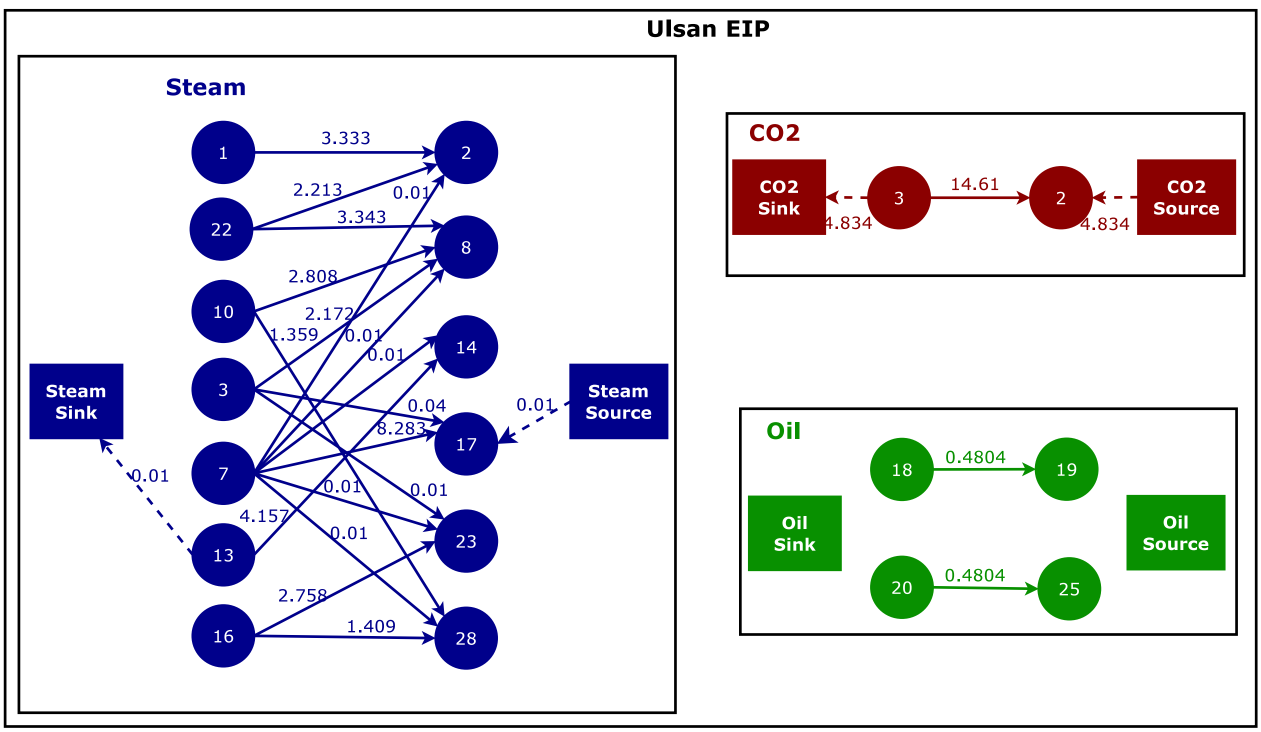


Figure 4.8: Optimal configuration for Ulsan EIP considering economic and environmental objectives. All flows are in kg/s.

4.4.1 Comparison of the resulting configurations

As aforementioned, Table 4.6 shows that the best result for each assessed aspect is obtained in its respective individual configuration.

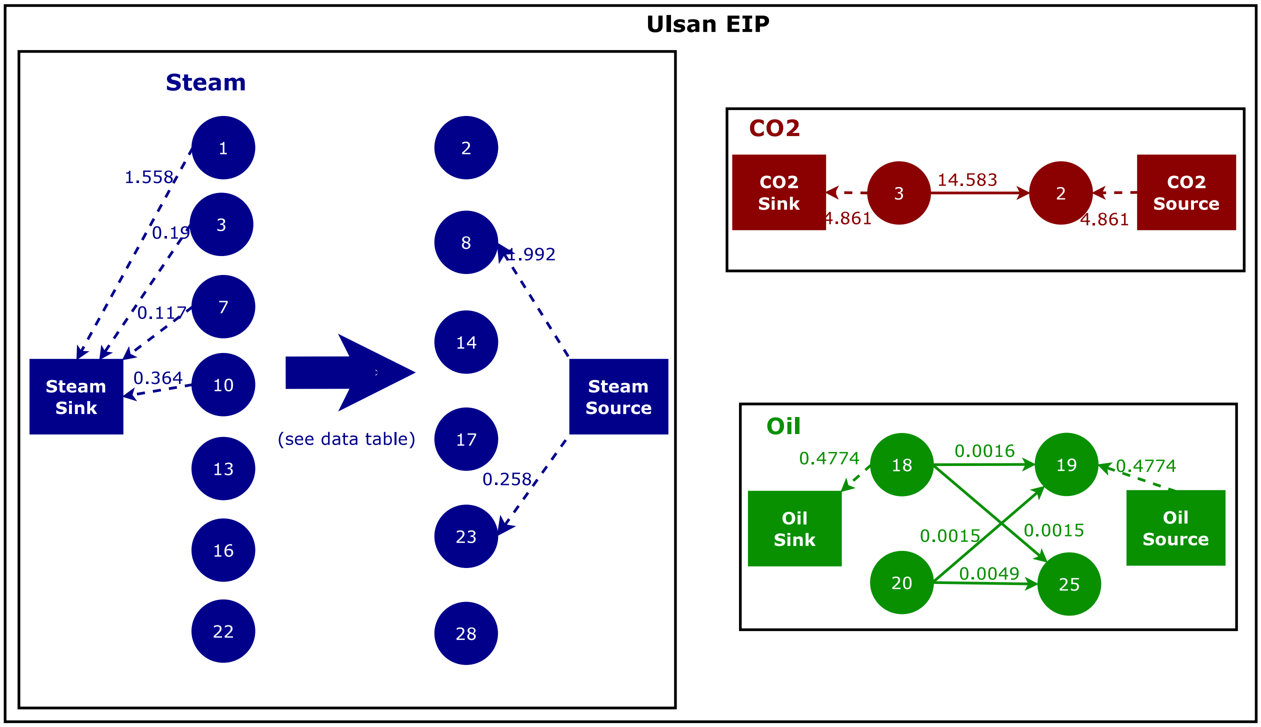


Figure 4.9: Optimal configuration for Ulsan EIP considering economic, environmental, and resilience aspects. All flows are in kg/s. Data for Steam layer are in Table 4.5

Table 4.5: Shared flows in Steam Layer for the sustainable configuration. All the flows in kg/s.

Participants	2	8	14	17	23	28
1	1.571	0.018	0.018	0.113	0.018	0.018
3	0	0.02	0.001	0.022	0.017	1.971
7	2.383	1.693	0.888	1.194	1.663	0.394
10	0.001	0.284	0.941	2.289	0.001	0.323
13	0.001	1.116	0.001	2.349	0.698	0.001
16	1.599	0.179	2.317	0.001	0.001	0.07
22	0.001	3.066	0.001	2.366	0.121	0.001

Regarding the economic aspect, the best value of this objective function is shown by the economic configuration, reaching a value of 12.28 $GUSD$. This park configuration presents the lowest number of connections among its participants in comparison with the other assessed cases (see Fig. 4.5). Moreover, each of these connections obtains significant magnitude, higher than the smallest accepted flow. Specifically, the three layers of the economic configuration present connections with sources and sinks. While the CO_2 and Oil layers present two significant external connections, the Steam layer presents three external connections. However, one connection of the Steam layer is not significant and could be removed since reaches the smallest accepted flow ($m^{Steam} = 0.001$).

This resulting configuration is due to the economic indicators considered in the objective

Table 4.6: Summary of the results for each considered configurations respect to the assessed aspects. The relative gap is presented in parentheses in each column.

Configurations	Assessed aspects (objective functions)		
	Economic ($GUSD^a$)	***Environmental (Mt^b)***	***Resilience (−)***
Current situation	1,300.7 (99.99%)	0 (0%)	0.062 (100%)
Economic	12.28 (0%)	4.973 (30.65%)	0.220 (72.95%)
Environmental	1,300.8 (100%)	0 (0%)	0.210 (74.66%)
Resilient	17.71 (0.42%)	16.227 (100%)	0.646 (0%)
Economic-environmental	130.1 (9.14%)	1.528 (9.42%)	0.242 (69.18%)
Economic-environmental-resilient	128.6 (9.03%)	2.390 (14.73%)	0.552 (16.10%)

[a] GUSD: 10^9 USD.
[b] Mt: 10^6 tons.

Table 4.7: Specific gap for the assessed aspects respect to each layer in the resulting configurations.

Configurations	Economic			Environmental			Resilience				
							ϕ^{layer_r}			ϕ	NCI
	Steam	***CO_2***	***Oil***	**Steam**	**CO_2**	***Oil***	***Steam***	***CO_2***	***Oil***		
Current situation	10.4	100	1.4	0.00	0.00	0.00	100	100	100	100	94.6
economic	0.00	0.00	0.00	10.6	63.9	1.3	100	50.0	50.0	62.3	100
Environmental	34.8	100	3.0	0.00	0.00	0.00	60.4	100	48.6	70.8	81.6
Resilient	100	0.39	97.9	100	100	100	0.00	0.00	0.00	0.00	0.00
economic-environmental	25.0	9.1	1.4	0.03	24.9	0.00	48.3	50.0	98.6	68.0	68.2
economic-environmental-resilient	57.7	9.0	100	7.1	25.0	98.2	0.00	50.0	5.9	21.0	0.00

function. While the gas treatment cost and raw material cost favour the existence of connections among participants, the investment reduces the number these connections. For this part, since the pumping cost considers the magnitude of the flows and the distances between participants, it favours the connections between near participants and flows with small magnitude. However, as the number of connections among participants is reduced by other indicators, the magnitude of these connections should be relevant to achieve the material requirements of the participants. In consequence, the economic configuration presents a small number of significant connections among participants, and with external sources and sinks.

It is worth to note that even though this configuration obtains an optimal value in its economic aspect, it presents detriment in the other assessed characteristics. For example, the environmental aspect of this configuration obtains a gap of 30% respect to its optimal case, while the resilience aspect obtains a gap of 72%.

Comparing the economic configuration with the current situation in Ulsan (see Fig. 4.4), both of them present different gaps in their assessed characteristics (see Table 4.6). For example, for their economic aspect, while the economic configuration obtains a gap of 0%, the current configuration obtains a gap of 100%. This issue is also observed in the environmental and resilience aspects, where both of them reach different gaps. This behavior is due to their physical configurations. While the current situation does not consider the use of external sources and sinks, the economic configuration use significant external connections. This difference makes both cases present different values in their assessed aspects.

A configuration with similar value in its economic aspect is the resilient case, obtaining a gap of 0.42% (see Table 4.6). This configuration presents almost all the connections among participants, and with external sources and sinks (see Fig. 4.7). However, only the external connections are significant since the others obtain magnitudes near to the smallest accepted flow. Comparing this case with the economic configuration, both of them are physically different, only coinciding on their CO_2 layer. This behavior is verified in Table 4.7, where the specific gap for the Steam and Oil layers is almost 100% but for the CO_2 layer, the gap is just 0.39%.

This great difference between both configurations but similar value in their economic assessment is due to the magnitude of the cost parameters in the CO_2 layer (see Table 4.3). Since it presents the highest values, the economic assessment is mainly focused on this layer, presenting a high importance compared with the other layers. Therefore, if the CO_2 network does not present great changes in its configuration, the economic aspect will not obtain significant changes, despite the other layers present changes in their configurations.

A similar behavior is observed in the economic-environmental and economic-environmental-resilient configurations. In both cases their configurations are different to the economic case (see Fig. 4.8 and Fig. 4.9). Indeed, they present a high gap in the Steam and Oil layers (see Table 4.7), except the Oil layer in the economic-environmental configuration, which obtains a gap of 1.4%. However, the gaps of the whole configurations are approximately 9% in both cases (see Table 4.6). This issue is due to the CO_2 layer, where for both configurations, the economic specific gap is just 9%. Since the economic evaluation is focused on this layer, the gap of the whole park will be similar to its specific gap.

The worst case of the economic aspect is the environmental configuration, obtaining a value of $1,300.8\ GUSD$ in its assessment (see Table 4.6). In this configuration, the participants only share material among them to achieve their material requirement, without use of external sources and sinks (see Fig. 4.6). As in the previous cases, both the Steam and the Oil layers of this configuration do not present the worst economic evaluation (see Table 4.7). However, the CO_2 layer obtains a highest specific gap, leading the environmental configuration to be considered as the worst economic configuration.

On the other hand, respect to the environmental aspect, the best case is the environmental configuration (without considers the current situation of the park), reaching a value of 0 tonnes of external material (see Table 4.6). In this case, the participants of each layer only share material among them, not using external sources and sinks.

This behavior is due to the indicators considered in the environmental assessment, measuring the use of external sources and sinks. When they are improved, the external flows are reduced, leading the participant to comply their material necessities only sharing material among them.

As in the previous case, although the environmental configuration obtains the best results for the environmental aspect, the economic and resilience characteristics present worsening in its assessment. For example, for the economic aspect the gap reaches a value of 100% since its CO_2 layer presents great differences respect to the optimal economic configuration. For its part, for the resilient aspect the gap reaches a value of 74% respect to its optimal case. This value is mainly due to the number of connections among participants and the absence of external connections. Since the environmental configuration does not present a high number of connections, its resilient assessment obtains a low value. Moreover, this configuration does not present connections with external sources and sinks. Therefore, if any participating firm suffers a disruptive event, the operation of the whole park could be affected, resulting in a deteriorating of the resilience indicator.

Comparing this configuration with the current situation of the park, it can be observed that both of them present similar gap in their economic and environmental aspects: 100% and 0%, respectively; but different value in their resilience characteristic: 74.7% for the environmental configuration, and 100% for the current situation of the park (see Table 4.6).

Specifically, the similar gap obtained in their economic and environmental characteristic is mainly due to the absence of external connections. On one hand, since the economic aspect is focused in the CO_2 layer and in both cases the two participants share material between them, they obtain the same gap. On the other hand, since the environmental indicators is focused in the external connections, and both of them do not present these connections, they obtain the same evaluation in this characteristic. For its part, the gap difference for the resilience aspect is due to the different number of connections among the participants in each layer. From Table 4.7 it can be seen that only the CO_2 layer presents the same specific gap, while the other networks present different values. Specifically, since both of them present the same number of connections between the participants in the CO_2 layer, their specific gaps are the same and equals to 100%. In contrast, since the Steam and Oil networks in the environmental configuration present a higher number of connections than the current situation, it presents a best specific gap in these layers (60.4% and 48.6% for the environmental configuration, respectively, vs 100% in both layers for the current situation of the park). Consequently, the environmental configuration presents a better gap than the current situation of the park.

A configuration with similar value in its environmental aspect is the economic-environmental configuration, presenting a gap of 9.4% (see Table 4.6). Since this configuration is focused on both economic and environmental aspects, it obtains a small gap. From Fig. 4.8 it can be seen that few participants use external sources and sinks to comply their material necessities. Therefore, its environmental assessment is similar to the environmental configuration, where no participants use external elements.

Another configuration with small gap in its environmental assessment is the economic-environmental-resilient configuration, reaching a value of 14.7%. Like the previous case, since it is configured improving the three assessed aspects, it obtains a small gap in its environmental characteristic. From Fig. 4.9 it can be seen that it presents few external connections in each layer. Specifically, for the Steam layer, only six participants use external sources and sinks; for the CO_2 layer, two participants use these elements; and for the Oil layer, two participants.

Even though the total number of external connections is higher than environmental configuration (11 external connections), and even than the economic-environmental configuration, this number is far from the resilient configuration. Moreover, almost all these connections obtain lower magnitudes than in the resilient configuration. Therefore, the environmental assessment of this configuration is low, reaching a small gap. This behavior can be ratified from Table 4.7, which shows that each layer obtains a small gap, except for the Oil layer, where the external connections are relevant to comply with the material necessities of the participants.

On the other hand, the worst case of the environmental aspect is the resilient configurations, obtaining a value of 16.227 Mt in its assessment. In this case, all the external connections play an important role to achieve the material requirements of the participants (see Fig. 4.7). Since the environmental indicator measures the material exchange with external sources and sinks, it obtains a high value.

Comparing this configuration with the environmental configuration, they present different gaps in all the assessed aspects (see Table 4.7). This issue is due to the focus of both configurations. While the environmental configurations is focused on share material among participants, the resilient configurations is focused on ensure the operation of the park through the use of external sources and sinks. Consequently, both configurations could be considered opposed since they favour different goals.

It is worth to note that for the environmental aspect, there are two optimal configuration among the obtained cases: the current situation of the park and the environmental configuration. While the fist one was constructed by the decision-makers in order to reduce environmental impact, reutilizing the residues generated by the participants of the park; the second one is obtained as a solution of the optimization problem, following a similar goal: to reduce the external connections. As a consequence, both configurations obtain a gap of 0% in the environmental characteristic, and are considered as an optimal configuration under the environmental aspect.

Regard to the resilience aspect, the best case is the resilient configuration, obtaining a value of 0.646 in its assessment (see Table 4.6). As mentioned previously, this configuration presents almost all the connections among the participants, and with external sources and sinks (see Fig. 4.7). Since the magnitude of the connections among participants reaches a low value, the external connections play an important role to achieve the material requirements of the participants in each layer.

This resulting configuration is due to the characteristics assessed by the resilience indicator. This indicator measures the topological and operational characteristics of a network by means of two sub-indicators: Network Connectivity Index (NCI) and Flow Adaptability Index (ϕ). While the NCI is focused on the connectivity of the participants through the number of connections among them, the ϕ is focused on to maintain the operation of the participating firms and the whole park when one participant suffer a disruptive event. In this sense, when the first one is improved, the number of connections is increased to maintain the connectivity of the park if one participant stops working. On the other hand, when the second sub-indicator is improved, if there are no external sources and sinks in the park, the existing connections would become significant to comply with the necessities of the participants and to maintain their operating if one of them stop working. However, since external sources and sinks are considered in the design of this park, it is more favourable to achieve the material requirements using these external elements because the indicator does not consider disruptive events on them. Therefore, the resulting configuration presents a higher number of connections, and significant material exchanges with external sources and sinks.

It is worth to note that unlike previous cases, where a single sustainable characteristic is improved, this configuration optimize aspects related to the topology and operation of an industrial network. In this sense, the configuration could not be strictly considered as an EIP since its design goal is not to improve the sustainability of the sector (see definition of EIP in Introduction). However, to analyze the addition of the proposed resilience indicator in the design of industrial networks and to compare with the other EIP configurations, this park is considered as an EIP.

Comparing the resilient configuration with the current situation of the park, it can be seen that the second one obtains the worst value in its resilience aspect (see Table 4.6). This issue is due to the absence of external connections and the reduced number of connections among participants in this configuration, like the environmental configuration.

Considering the economic and environmental characteristics of both configurations it can be seen that they present different specific gaps in each layer (see Table 4.7). On one hand, since the CO_2 layer of the resilient configuration does not present connections between the participants, and the current situation only present this connections, they obtain different values in its economic assessment. On the other hand, the current situation does not present external connections with sources and sinks, and the resilient configuration presents all of them. Therefore, both configurations obtain different values in its environmental assessment.

A configuration with small gap in its resilience aspect is the economic-environmental-resilient configuration, obtaining a value of 16.1% (see Table 4.6). This configuration present all the connections among participants but only some connections with external sources and sinks. For example, in the Steam layer, only six participants are connected with external sources and sinks, unlike in the resilient configuration, where all the participants present external connections. Additionally, this configuration reaches the lowest specific gap in each layer for the resilience aspect, only presenting a high value in the CO_2 layer ($gap = 50\%$) (see Table 4.7). This behavior is mainly due to the significant connection between the participants 2 and 3. Since the resilient configuration does not present this connections, they present different gaps.

The worst case for the resilience aspect is the environmental configuration (omitting the current situation of the park). As mentioned before, this configuration presents only connections among participants to comply the requirements of material. Since the resilience aspect favour the connections with external sources and sinks to comply this goal, beside the connections among participants, this configuration reaches the worst value in each sub-indicator of the resilience indicator (see Table 4.7).

Despite the resilient configuration ensure the operation and connectivity of the park, it presents deteriorating in other characteristics. For example, in the environmental aspect, this configuration reaches a gap of 100%, presenting an important breach of the goals of an EIP. Therefore, even though the design of an EIP can be configured following its resilience characteristic, it should be added along with other sustainability indicator.

In this sense, in the following section, the configuration of an EIP considering the sustainability and resilience aspects is analyzed and discussed.

4.4.2 Selection of the optimal configuration

In the previous sub-section, each assessed aspect and its optimal configurations have been discussed and compared, highlighting the desirable characteristics for each one of them.

In this sense, when the economic aspect is improved, the resulting configuration will favour the existence of a reduced number of connections among participants, as well as the formation of significant flows. This behavior was observed for each layer, except for the CO_2, where it is preferable to use external source and sink over exchanged material among participants. However, since the value of its parameters are higher than those for other layers, the economic assessment is mainly focused on the CO_2 network. Therefore, the desirable characteristic is focused on this layer, despite the behavior of the others.

On the other hand, when the environmental aspect is improved, only connections among participants are favoured. No external connections are used to comply the necessities of the participants.

Regarding the resilience aspect, when it is improved the resulting configuration prefers to create almost all the connections among participants, and with external sources and sinks. Moreover, only the external connections reach significant flows, while the connections among participants reach almost the smallest flow accepted (m^{layer_k}).

All these characteristics describe the optimal configuration from an economic, environmental, and resilience point of view. As mentioned before, even though each optimal configuration is obtained with each aspect (economic, environmental, and resilient configurations, respectively), they do not present simultaneous enhancements on all of them. In this sense, if one individual configuration obtains optimal value in some assessed aspect, it presents detriment in other.

For example, in the economic configuration, the economic aspect is improved. However, the resilience aspect presents worsening in its assessment, obtaining a gap of 72%. In the environmental configuration, while it obtains the optimal case for the environmental aspect, its economic and resilience characteristics obtains a gap of 100% and 74%, respectively. On the other hand, in the resilient configuration, the gap of the resilience aspect is 0%. Nevertheless, even though for the economic characteristic the gap is near to 0%, its environmental aspect is 100%.

Consequently, an important issue is to determine if a configuration can simultaneously present all these desirable characteristics. To achieve this goal, two multi-objective case were configured, considering the economic and environmental aspects, and the economic, environmental, and resilience aspects.

For the economic-environmental configuration the gap of the economic and environmental characteristics are approximately 9% for both of them. As in the economic and environmental configuration, this case favours the connections among participants over the use of external sources and sinks. Particularly, only for the CO_2 layer the use of external sources and sinks is significant, while in the Steam and Oil layers is very small or zero.

This resulting configuration achieves the main goal of an EIP: to simultaneously improve the sustainability dimensions. Comparing this configuration with the current situation of the park, it presents a small deteriorating in the environmental aspect but a considerable improvement in the economic aspect. Moreover, through this modification in the configuration, the resilience characteristic is also enhanced, despite it is not optimized, reaching a gap of 70% compared with 100% of the current situation.

In this sense, the systematical configuration of an EIP considering the sustainability dimensions shows considerable improvements in comparison with the current situation of the park and the other individual configurations. However, it could not ensure the continue operation and connectivity of the participants if one of them suffers a disruptive event. For example, if the participant 7 stops its operation, several firms would be affected since it presents many connections of the park. Likewise, if the participant 18 stops working, the participants 19 will be affected, losing connectivity and the possibility to continue working.

Consequently, this configuration is considered as a sustainable case but not secure from a topological and operational point of view. To ensure these characteristics, the resilience aspect should be also included in the optimization problem as a goal.

This configuration can be considered as a sustainable case but not secure from a topological and operational point of view. To ensure these characteristics of the whole network, the resilience aspect should be also improved.

In this sense, the economic-environmental-resilient configuration achieves these goals. In other words, its economic, environmental and resilience characteristics are enhanced by means of an optimization problem, reaching small gaps: 9.0%, 14.7% and 16.1%, respectively. This configuration presents all the connections among participants, reaching most of them significant value. Moreover, some participants use external connections, playing a relevant role for the CO_2 and Oil layers.

Particularly, the CO_2 layer presents exchanges among participants, and with external sources and sinks, causing a small gap in the economic assessment. All the connections obtaining relevant flows as in the economic and economic-environmental configurations.

On the other hand, although external connections are used to comply the material requirements of the participants, its environmental assessment does not present a great gap. It is due to the total magnitude of these connections are although greater than the environmental and economic-environmental cases, they are far from the resilient and economic configuration. Indeed, the resulting configuration is more similar to the economic-environmental case, where some external flows are significant.

Respect to the resilience aspect, this configuration presents a small gap because the number of connections among participants is increased as in the resilient configuration. Moreover, since some participants use external sources and sinks, the resulting configuration is more secure if a disruptive event occurs in the park.

As a consequence of the aforementioned, the economic-environmental-resilient configuration can be considered as the best case since it simultaneously improve the three assessed aspects. While the individual and the economic-environmental configurations obtains worsening in one or more than one characteristic, this case reaches improvements in all of them (small gaps).

It is worth to note that even though the resulting configuration is considered as the best case, it only presents improvements in its economic and resilience aspect respect to the current situation of the park. While the multi-objective configuration obtains a gap of 14.7% in the environmental assessment, the current situation obtains a gap of 0%. This issue is due to the current situation does not consider external sources and sinks in its design, configuring an insecure EIP (low resilience). However, since the economic-environmental-resilient configuration presents external connections to improve the other aspects, specifically, the resilience aspect, it obtains worsening in its environmental assessment.

Moreover, the current situation presents almost the worst case for the economic and resilience characteristics ($gap \sim 100\%$). However, this multi-objective configuration obtains small gaps due to the external connections. In this sense, even though this configuration presents deteriorating in the environmental aspect respect to the current situation of the park, it presents a general enhancement on the assessed characteristics.

Therefore, the multi-objective configuration considering the economic, environmental, and resilience aspects meets the best characteristics of each individual cases, improving the current situation of the park. In this sense, the proposed optimization model properly achieves to configure an EIP, considering economic, environmental and resilience aspects in its design.

4.4.3 Model considerations

In the present chapter, an optimization model (see section 4.3.6) is proposed in order to configure a sustainable and resilient EIP in the industrial complex of Ulsan. This model takes into account in a simple manner the material requirements of 17 firms by means of sharing material among them, and using external sources and sinks. Additionally, three objectives are considered for the park: an economic function, an environmental function, and a resilience function; which are simultaneously added in the model through the goal programming method.

The present optimization problem is classified as a MINLP problem containing non-lineal expressions and binary variables in its constraints and objective functions. These elements make the problem difficult to solve, specifically, to find the global solution, even when an specific solver is used. This issue could become critical when large-scale problems are solved since they present many more non-linearities, making the feasible region non-convex. In future works, it should be considered the use of different algorithms and the comparison of their performance in solving the problem, before to select one of them, to avoid issues related to find the global optimum and to the time consuming of each solution.

The present problem does not consider all the original participants of the industrial complex (see Fig. 4.2) since there are not enough information to properly formulate the whole problem. However, the model can be extended to take into account all of them with their respective constraints. Moreover, also other constraints related to mass and energy balance, temperature requirements, feasibility of some connections, or some extra information about the processes in the firms, could be added.

In this sense, if all these additional constraints and information are included in the model, it becomes more complex but capturing a more realistic behavior of the park.

According to the selected sustainable indicators (objective functions), even though they are relevant for the assessment of an EIP, measuring its economic and environmental aspects, they present limitations. For example, one of the main characteristics of the sustainability is to maintain the life condition. However, this aspect is not measured by the selected indicators, only considering the impact of the park on the sustainable dimensions.

On the other hand, the social aspect is not considered in the model since the required information is hard to obtain. This problem could affect the proper assessment of the EIP and its impact on the nearby communities, considering an economically and environmentally suitable configuration but socially detrimental.

Both limitations on the indicators should be considered in future works in order to capture in a proper manner the sustainability of the park.

According to the modified goal programming method, it is worth to note that is fundamental the choice of the normalization values (worst and best values for each objective), as well as its weight (w_i). These values are not easy to define since they depend on the context of the problem and on the decision-makers. For the present problem, the worst and best cases are considered as the minimization and maximization of each objective, respectively, while the importance is considered the same for each optimized characteristic.

On the other hand, it should be recalled that the multi-objective problems are based on the opposition of each objective function. This characteristic is fundamental for the selected indicators since they are assumed opposed in the model. Even though there are some sustainability indicators complying with this characteristic, there are some other favouring the same characteristic in the configuration of the EIP. For example, the raw material cost and the gas treatment cost favour the connections among participants, while the DMI and DMO also favour this behavior. Both indicators cause the same effect: to increase the connections among participants; and therefore they are not opposed. This behavior should be considered in future works, taking into account opposed indicators.

As mentioned before, an issue in the present model is the magnitude of the flows in each considered layer, affecting the comparison of each of them and the assessment of the whole park. For example, the CO_2 network presents greater value in its cost parameters by comparing with the other ones since it is the only material considered as emission affecting the environment and needs to be treated (the steam does not to be treated: 0 cost; and the oil is sold outside of the park: negative cost). Moreover, this raw material presents the highest cost due to its obtainment process, in contrast to the steam and oil, which are obtained heating water or its cost is treated as a commodity, respectively. This behavior affects to the assessment of the whole park since only the evaluation of the CO_2 network will be considered, despising the other networks. In order to properly capture each behavior in the evaluation of the park, they should be normalized.

The main limitation for the model is the lack of information, significantly affecting its accuracy and complexity. The present problem is modeled with constraints only related with the available information. In this case, this information is associated with inputs and outputs. Any other constraint related to mass and energy balances, pressure and temperature requirements, composition of a contaminant, etc., could not be taken into account since there is no information about them.

Since no specific information about the processes and firms is reported, each participant loses their identity in the model. They are treated as black boxes. Therefore, the present formulation is not capturing the correct operation of the participants of the park when they are sharing material. In this sense, a proper representation of each participant should be considered to illustrate its real operation in the park.

On the other hand, the utilized information or some assumptions could not be suitable for the problem, presenting some numerical error. For example, the distances between firms are assumed in a straight line, no matter if there are some impediment in the connection between them. Another point is the flows magnitude which are assumed constant in the considered period of time (5 years). This behavior is not completely correct since the firms or plants do not always produce the same, presenting flow variations in time.

Taking these points into account, is there a systematically way to deal with this problem?

To cover this question, an uncertainty model or a time-dependent model (dynamic model) should be considered. In the first one, all the parameters or variables that present variation on their value could be established as a stochastic variable. For example, the possibility of each participant to suffer a disruptive event. In the present case, all the participants are considered with the same probability but it could be modeled by a stochastic variable, depending on historical information of each firm. On the second kind of model, all the variables and parameters have a dependence on a certain period. For example, there are data about supply and demand, which depends on the previous period or on internal conditions of each company. This behavior can be modeled by means of a dynamic model, considering the supply and demand condition of the previous period or the decisions of storage of each firm. In future works, these kind of models could be considered, generating a model closer to reality.

4.5 Chapter conclusions

In the previous sections, an optimization model has been proposed to design an eco-industrial park considering the sustainability and resilience aspects in its design. Specifically, this model is applied in the industrial complex of Ulsan, where different configurations have been composed through a multi-objective approach: the goal programming method.

The novelty of the present model is to simultaneously consider both aspects, composing a multi-layer EIP (sharing different kind of materials). This model not only optimizes the usual economic benefits but also enhances the topology and operation of the park. Therefore, the resulting configuration would achieve economic and environmental benefits, ensuring the operation and connectivity of the park if any participant suffers a disruptive event.

In order to analyze the use of this optimization model, five configurations have been composed based on Ulsan EIP: three of them considering the individual optimization of an objective (economic, environmental, and resilience); one of them, the simultaneous optimization of economic and environmental objectives; and the last one, the sustainability and resilience optimization (all the previous aspects simultaneously).

From the single-objective optimization, it has been observed that by improving each aspect separately, the resulting configurations present the best value for each assessed characteristic even compared with the current situation of the park. However, they do not simultaneously present enhancement in all of them, obtaining a detriment in one or more than one aspect. Furthermore, it has been observed that the current situation of Ulsan EIP presents similar configuration to one of these individual exercises, specifically, to the environmental optimization.

Even though the single objective optimization does not obtain a sustainable and resilient configuration at the same time, this exercise defines the desirable characteristics for each improved aspect:

- When the economic aspect is improved, the resulting configuration favours the existence of a small number of connections among participants, and with external sources and sinks, as well as the creation of significant flows.
- When the environmental aspect is improved, the resulting configuration prioritizes the exchange of materials among participants, with no external connection.
- When the resilience aspect is optimized, the resulting configuration presents almost all the possible connections among participants, and with external sources and sinks. However, only the external connections reach significant flows, while the exchanges among participants reach almost the smallest accepted flow.

Based on the the multi-objective optimization, it has been observed that the resulting configurations present more than one of these desirable characteristics. Even though the objective values do not reach the same optimal value as in the single-objective configurations, the multi-objective optimized solutions include the sustainability and resilience aspects in a unique EIP configuration. In this sense, the resulting configuration produces small impacts in the economic and environmental dimensions, and maintains the stability of the park, ensuring its operation and connectivity.

The proposed optimization model achieves the goal of designing an EIP, improving the sustainability and resilience aspects at the same time. However, it could be improved. For example, the lack of information can be an important issue. In future works, the present model could be extended in a simple manner, if specific data about the park and its participants are available.

Another possible improvement is related to the selected sustainable indicators. One of the main characteristics of the sustainability is to preserve the current condition of the planet in time. However, the selected indicators only measure the impact of an EIP in the sustainability dimensions, not ensuring the sustainability in a timeframe. Moreover, these indicators only consider the economic and environmental dimensions: they do not measure the social dimension since the supporting information is not available. In future works, the selection of indicators measuring the preservation of the current condition in the time and the social dimension should be addressed in order to properly configure an EIP.

An important point in the formulation of an optimization model to design EIPs is the certainty and time dependency of its parameters and variables. In general, they are assumed constant. However, this assumption could differ from reality since some variables or parameters depend on external conditions and previous periods, such as company goals, disruptive events, weather conditions, supply and demand of material, etc. In this sense, an uncertainty model or a dynamic model should be considered. In the first one, all the elements depending on external factors are formulated as stochastic variables; and in the second one, all the dynamic elements are modeled with time-dependent variables.

Finally, it is worth to note that even though the present model has several simplifications and some limitations in its construction, it achieves the configuration of an optimal EIP, considering the sustainability and resilience aspects in its design. In consequence, this model can support decision-makers in the industrial design, generating optimal alternatives, which are not easy to obtain by other heuristic methods or adapting known solutions. Moreover, the addition of the resilience indicator in the design of an EIP support a better adaptation of the configured part to reality, because this indicator addresses an important issue for companies to participate in EIPs.

5. Concluding remarks

The climate change is affecting some regions of the planet, producing an accelerated variation on their temperature and climate conditions. One of its causes is the industrial production through the gas emissions, wastewater, solid waste and land pollution of the industrial plants operation. To overcome this kind of problems, the design of eco-industrial parks (EIPs) have been raised as a solution, connecting companies located together to improve the sustainability of each participants and the whole park.

The general benefits of this kind of parks are related to firm profitability, environmental impact reduction, and concern for local communities, in other words, the three dimensions of the sustainability: economic, environmental, and social. Since the magnitude of these benefits depends on the configuration of the network, the planification and the design of EIPs are critical in order to reduce the waste generated by the participating firms, without negative impacts on the economic benefits, and concerning on the future of the local communities. Moreover, an important issue is to ensure the stability of the whole network when participants suffer disruptive events, because the failure may be propagated within the network due to the connectivity, affecting the reluctance from industries to participate in EIPs.

In this context, the main focus of the present work is on the mathematical-based design of an EIP in order to promote and support the implementation of industrial networks with sustainability and security objectives. This goal has been accomplished with the following partial results:

A significant set of sustainability indicators has been listed, each of them assessing the impact of an EIP on the sustainability dimensions. To classify and select a subset of proper indicators, four criteria have been proposed: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*. It is worth to note that these criteria impose some filters in selecting sustainability indicators, varying with their application context. In this sense, it is important to properly define the context of the assessment and who is performing the classification in order to select a representative subset of the indicators.

All the listed indicators have been also classified under the number of assessed dimensions: single, if only one dimension is assessed, and integrated, if two or three of them are assessed. Under this classification, a lack of single and integrated indicators assessing the social dimension is observed. On the other hand, this classification allows to select integrated indicators in order to reduce the number of objective functions during the formulation of an optimization model to design an EIP.

In future works, some proposed criteria can be modified in order to report the most used indicator in the sustainability assessment of an EIP. Furthermore, a pathway of the historical progression of an EIP following the change in the value of some indicators is suggested. This pathway could be a reference to new successful cases of EIPs.

A resilience indicator has been constructed and proposed in order to assess security issues on an EIP, addressing the reluctance problems of companies when they evaluate the participation in an EIP. This indicator has been constructed on the basis of two main characteristics of an industrial network: its topology and its operation. Each of them measured by a sub-indicator: Network Connectivity Index (NCI), and Flow Adaptability Index (ϕ), respectively.

The novelty of this indicator is to take into account the dynamic of the assessed EIP after one participant suffers a disruptive event, considering the decision of the remaining companies to modify their input and output flows to absorb this perturbation and to prevent the fault propagation. Additionally, this indicator is constructed to analyze multi-layer parks, where more than one kind of material is shared.

The proposed indicator has been applied over five small illustrative examples and over a well-known EIP: Ulsan, in South Korea. The obtained value for the resilience indicator in each example shows consistency with its configuration, properly capturing the resilience of an industrial network. Moreover, the application over the Ulsan EIP shows significant potential to improve its resilience, demonstrating the utility of this indicator to be included in the design of an EIP.

The proposed indicator can present improvements, considering the existing dependence between the sub-indicators or the capturing of a more realistic behavior of an EIP when a participant suffers a disruptive event. The first one can be addressed by the definition of the weights of each sub-indicator in the resilience indicator, while the second one can be addressed by the inclusion of failure probabilities for the participating firms.

A multi-objective optimization model has been proposed in order to design an EIP, considering its sustainability and resilience aspects at once. Specifically, this model has been applied over the industrial complex of Ulsan, in South Korea, taking into account the economic, environmental, and resilience aspects.

Five configurations has been constructed based on Ulsan in order to analyze the use of the proposed optimization model: three of them, considering the individual objectives (economic, environmental, and resilience); and two of them, considering more than one objective (economic and environmental, and economic, environmental and resilience).

By means of the individual optimization, the three resulting EIPs obtain improvements in their respective optimized aspects. These configurations present significant differences with the current situation of the park, with the exception of the environmental configuration, which obtains different physical configuration but the same value on its environmental assessment.

The concluded configurations vary with the respective objective function when a single-objective model is adopted: for the economic objective, the resulting configuration presents a small number of connections among all the considered participants, as well as the creation of large flows; for the environmental objective, the resulting configuration avoids external connections, only supplying flows within the park; and for the resilience objective, the resulting configuration presents all the possible connections among participants and external element

Based on the multi-objective optimization, the obtained configurations present more than one of these desirable characteristics, improving all the assessed aspects at the same time but not reaching the same optimal value as in the individual optimization. In this way, these resulting EIP configurations incorporate the sustainability and resilience aspects in their design, producing small impacts in the economic and environmental dimensions, and ensuring the the stability of the network when its participants suffer a disruptive event. It is important to remark the relative importance of these objectives. The stake holders of a park should define this importance through multi-criteria decision-making tools.

The proposed optimization model achieves the goal of designing an EIP, improving the sustainability and resilience aspects at the same time. In particular, the addition of the resilience indicator as an objective in the optimization back up a better adaptation of the park to reality, covering the reluctance of the companies to participate in EIPs.

In the future, this model could be modified in order to consider improvements in its formulation: for example, to consider the timeframe of the sustainability in the sustainability indicators, to include the social dimension as an objective function, or to consider an uncertainty or a time-dependent model in order to capture a more realistic behavior of the park.

Finally, through the optimization of the present model, new EIP configurations can be obtained, supporting decision-makers in designing and promoting the implementation of new industrial networks with focus on its sustainability and security. This tool could play an important role in the EIP design, simultaneously considering more than one sustainability dimension, incorporating security issues, and generating optimal alternatives, which are not easily obtained by other methods.

Bibliography

Ahmetović, E. and Grossmann, I. E. (2011). Global superstructure optimization for the design of integrated process water networks. *AIChE Journal*, 57(2):434–457.

Akbarnia, M., Amidpour, M., and Shadaram, A. (2009). A new approach in pinch technology considering piping costs in total cost targeting for heat exchanger network. *Chemical Engineering Research and Design*, 87(3):357–365.

Amaya A., J. (2003). Introducción. In Universidad de Chile, editor, *Optimizacion para estudiantes de ingenieria*, pages 2–3. Departamento de Ingeniería Matemática y Centro de Modelamiento Matemático, Santiago.

Aviso, K., Tan, R., and Culaba, A. (2010). Designing eco-industrial water exchange networks using fuzzy mathematical programming. *Clean Technologies and Environmental Policy*, 12(4):353–363.

Azapagic, A. and Perdan, S. (2000). Indicators of Sustainable Development for Industry. *Process Safety and Environmental Protection*, 78:243–261.

Baas, L. (2011). Planning and Uncovering Industrial Symbiosis: Comparing the Rotterdam and Östergötland regions. *Business Strategy and the Environment*, 20(7):428–440.

Bai, L., Qiao, Q., Yao, Y., Guo, J., and Xie, M. (2014). Insights on the development progress of National Demonstration eco-industrial parks in China. *Journal of Cleaner Production*, 70:4–14.

Baris, M., Dion, K., Nelson, C., and Zhang, Y. (2001). Industrial Symbiosis in New Haven Harbor: English Station West.

Behera, S. K., Kim, J.-H., Lee, S.-Y., Suh, S., and Park, H.-S. (2012). Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. *Journal of Cleaner Production*, 29-30:103–112.

Biegler, L. (2010). *Nonlinear Programming*. Society for Industrial and Applied Mathematics.

Biegler, L. T. and Grossmann, I. E. (2004). Retrospective on optimization. *Computers & Chemical Engineering*, 28:1169–1192.

Boix, M., Montastruc, L., Azzaro-Pantel, C., and Domenech, S. (2015). Optimization methods applied to the design of eco-industrial parks: a literature review. *Journal of Cleaner Production*, 87:303–317.

Boix, M., Montastruc, L., Pibouleau, L., Azzaro-Pantel, C., and Domenech, S. (2011). A multiobjective optimization framework for multicontaminant industrial water network design. *Journal of environmental management*, 92(7):1802–8.

Boix, M., Montastruc, L., Pibouleau, L., Azzaro-Pantel, C., and Domenech, S. (2012). Industrial water management by multiobjective optimization: from individual to collective solution through eco-industrial parks. *Journal of Cleaner Production*, 22(1):85–97.

Boons, F., Spekkink, W., and Mouzakitis, Y. (2011). The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. *Journal of Cleaner Production*, 19(9-10):905–911.

Brockhoff, D. and Zitzler, E. (2006). Are All Objectives Necessary? On Dimensionality Reduction in Evolutionary Multiobjective Optimization. In Runarsson, T., Beyer, H.-G., Burke, E., Merelo-Guervós, J., Whitley, L., and Yao, X., editors, *Parallel Problem Solving from Nature - PPSN IX SE - 54*, volume 4193 of *Lecture Notes in Computer Science*, pages 533–542. Springer Berlin Heidelberg.

Brown, M. and Ulgiati, S. (1997). Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. *Ecological Engineering*, 9(1-2):51–69.

Brundtland, G. H. (1987). Our common future. *United Nations World Commission on Environment and Development (WCED), Rio de Janeiro.*

Bussieck, M. R. and Meeraus, A. (2004). General Algebraic Modeling System (GAMS). In Kallrath, J., editor, *Modeling Languages in Mathematical Optimization SE - 8*, volume 88 of *Applied Optimization*, pages 137–157. Springer US.

Chae, S. H., Kim, S. H., Yoon, S.-G., and Park, S. (2010). Optimization of a waste heat utilization network in an eco-industrial park. *Applied Energy*, 87(6):1978–1988.

Chen, B., He, G., Qi, J., Su, M., Zhou, S., and Jiang, M. (2013). Greenhouse Gas Inventory of a Typical High-End Industrial Park in China. *Scientific World Journal*, 2013:7.

Chen, C.-H., Liu, W.-L., Chiou, I.-J., and Liaw, S.-L. (2012a). Methodology and System of Total Quantity and Sustainability Management for Industrial Parks. *Environmental Engineering Science*, 29(10):934–945.

Chen, C.-J. and Huang, C.-C. (2004). A multiple criteria evaluation of high-tech industries for the science-based industrial park in Taiwan. *Information & Management*, 41(7):839–851.

Chen, X., Fujita, T., Ohnishi, S., Fujii, M., and Geng, Y. (2012b). The Impact of Scale, Recycling Boundary, and Type of Waste on Symbiosis and Recycling. *Journal of Industrial Ecology*, 16(1):129–141.

Chen, X., Xi, F., Geng, Y., and Fujita, T. (2011). The potential environmental gains from recycling waste plastics: simulation of transferring recycling and recovery technologies to Shenyang, China. *Waste management (New York, N.Y.)*, 31(1):168–79.

Chertow, M. (2008). Industrial Ecology in a Developing Context. In Clini, C., Musu, I., and Gullino, M., editors, *Sustainable Development and Environmental Management SE - 24*, pages 335–349. Springer Netherlands.

Chertow, M. (2012). Industrial symbiosis.

Chertow, M. R. (2000). INDUSTRIAL SYMBIOSIS: Literature and Taxonomy. *Annual Review of Energy and the Environment*, 25:313–337.

Chertow, M. R. (2007). "Uncovering" Industrial Symbiosis. *Journal of Industrial Ecology*, 11(1):11–30.

Chopra, S. S. and Khanna, V. (2012). Toward a network perspective for understanding resilience and sustainability in industrial symbiotic networks. In *IEEE International Symposium on Sustainable Systems and Technology*.

Chopra, S. S. and Khanna, V. (2014). Understanding resilience in industrial symbiosis networks: Insights from network analysis. *Journal of Environmental Management*, 141:86–94.

Cimren, E., Fiksel, J., Posner, M. E., and Sikdar, K. (2011). Material Flow Optimization in By-product Synergy Networks. *Journal of Industrial Ecology*, 15(2):315–332.

Coello, C. A. C., Van Veldhuizen, D. A., and Lamont, G. B. (2002). Basic Concepts. In Goldberg, D. E. and Koza, J. R., editors, *Evolutionary algorithms for solving multi-objective problems*, pages 1–55. Springer, 2nd editio edition.

Copado-Méndez, P. J., Guillén-Gosálbez, G., and Jiménez, L. (2014). MILP-based decomposition algorithm for dimensionality reduction in multi-objective optimization: Application to environmental and systems biology problems. *Computers & Chemical Engineering*, 67:137–147.

Côté, R. P. and Cohen-Rosenthal, E. (1998). Designing eco-industrial parks: a synthesis of some experiences. *Journal of Cleaner Production*, 6(3-4):181–188.

Curran, M. (1996). Environmental life-cycle assessment. *The International Journal of Life Cycle Assessment*, 1(3):179.

CYPE Ingenieros (2018). Gas. Instalaciones. Chile. `http://www.chile.generadordeprecios.info/obra_nueva/Instalaciones/Gas.html`. Accessed: 2018-11-14.

Dewulf, J. P. and Van Langenhove, H. R. (2002). Quantitative Assessment of Solid Waste Treatment Systems in the Industrial Ecology Perspective by Exergy Analysis. *Environ. Sci. Technol.*, 36(5):1130–1135.

DGFEZ (2018). Electricity Rates in Korea. `http://www.dgfez.net/eng/page.php?mnu_uid=489`. Accessed: 2018-11-14.

Díaz Alvarado, F. and Gracia, F. (2012). Oxidative steam reforming of glycerol for hydrogen production: Thermodynamic analysis including different carbon deposits representation and CO2 adsorption. *International Journal of Hydrogen Energy*, 37:14820–14830.

Díaz-Alvarado, F. A. (2015). An example of Pareto dominance for dimensionality reduction in multi-objective optimization. *Computers & Chemical Engineering*, 79:135–136.

Diesendorf, M. (2001). Models of sustainability and sustainable development. *International Journal of Agricultural Resources, Governance and Ecology*, 1(2):109–123.

Dong, H., Geng, Y., Xi, F., and Fujita, T. (2013). Carbon footprint evaluation at industrial park level: A hybrid life cycle assessment approach. *Energy Policy*, 57:298–307.

Dong, H., Ohnishi, S., Fujita, T., Geng, Y., Fujii, M., and Dong, L. (2014a). Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki. *Energy*, 64:277–286.

Dong, L., Gu, F., Fujita, T., Hayashi, Y., and Gao, J. (2014b). Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China. *Energy Policy*, 65:388–397.

Dunn, B. C. and Steinemann, A. (1998). Industrial Ecology for Sustainable Communities. *Journal of Environmental Planning and Management*, 41:661–672.

Eckelman, M. and Chertow, M. (2013a). Life cycle energy and environmental benefits of a US industrial symbiosis. *The International Journal of Life Cycle Assessment*, 18(8):1524–1532.

Eckelman, M. J. and Chertow, M. R. (2013b). Life cycle energy and environmental benefits of a US industrial symbiosis. *International Journal of Life Cycle Assessment*, 18(8):1524–1532.

El-Halwagi, M. M. (2012a). Introduction to Sustainability, Sustainable Design, and Process Integration. In *Sustainable Design Through Process Integration*, pages 1–14. Elsevier.

El-Halwagi, M. M. (2012b). Overview of Optimization. In *Sustainable Design Through Process Integration*, pages 255–286. Elsevier.

Elabras Veiga, L. B. and Magrini, A. (2009). Eco-industrial park development in Rio de Janeiro, Brazil: a tool for sustainable development. *Journal of Cleaner Production*, 17(7):653–661.

Eurostat (2001). *Economy-wide material flow accounts and derived indicators: a methodological guide*. Office for Official Publ. of the Europ. Comm., Luxembourg.

Fiksel, J. (2003). Designing Resilient, Sustainable Systems. *Environmental Science & Technology*, 37(23):5330–5339.

Frosch, R. A. and Gallopoulos, N. E. (1989). Strategies for Manufacturing. *Scientific American*, 261:144–152.

Geng, Y., Fu, J., Sarkis, J., and Xue, B. (2012). Towards a national circular economy indicator system in China: an evaluation and critical analysis. *Journal of Cleaner Production*, 23(1):216–224.

Geng, Y., Liu, Z., Xue, B., Dong, H., Fujita, T., and Chiu, A. (2014). Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone. *Environmental Science and Pollution Research*, 21(23):13572–13587.

Geng, Y., Tsuyoshi, F., and Chen, X. (2010a). Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. *Journal of Cleaner Production*, 18(10-11):993–1000.

Geng, Y., Zhang, P., Côté, R. P., Fujita, T., and Cote, R. P. (2009a). Assessment of the National Eco-Industrial Park Standard for Promoting Industrial Symbiosis in China. *Journal of Industrial Ecology*, 13(1):15–26.

Geng, Y., Zhang, P., Côté, R. P., and Qi, Y. (2008). Evaluating the applicability of the Chinese eco-industrial park standard in two industrial zones. *International Journal of Sustainable Development & World Ecology*, 15(6):543–552.

Geng, Y., Zhang, P., Ulgiati, S., and Sarkis, J. (2010b). Emergy analysis of an industrial park: the case of Dalian, China. *Science of the total environment*, 408(22):5273–5283.

Geng, Y., Zhu, Q., Doberstein, B., and Fujita, T. (2009b). Implementing China's circular economy concept at the regional level: a review of progress in Dalian, China. *Waste management (New York, N.Y.)*, 29(2):996–1002.

Genić, S., Aranđelović, I., Kolendić, P., Jarić, M., Budimir, N., and Genić, V. (2011). A review of explicit approximations of Colebrook's equation. *FME transactions*, 39(2):67–71.

Gibbs, D. (2008). Industrial Symbiosis and Eco-Industrial Development: An Introduction. *Geography Compass*, 2:1138–1154.

Goel, S., Belardo, S., and Iwan, L. (2004). A resilient network that can operate under duress: to support communication between government agencies during crisis situations.

Green, D. W. and Southard, M. Z. (2018). *Perry's chemical engineers' handbook*. McGraw Hill Professional.

Grossmann, I. E. (1985). Mixed-integer programming approach for the synthesis of integrated process flowsheets. *Computers & Chemical Engineering*, 9(5):463–482.

Haslenda, H. and Jamaludin, M. (2011). Industry to Industry By-products Exchange Network towards zero waste in palm oil refining processes. *Resources, Conservation and Recycling*, 55(7):713–718.

Hirata, K., Sakamoto, H., O'Young, L., Cheung, K.-Y., and Hui, C.-W. (2004). Multi-site utility integration—an industrial case study. *Computers & Chemical Engineering*, 28(1-2):139–148.

Index mundi (2014). Tasa de Crecimiento. http://www.indexmundi.com/g/g.aspx?v=24&c=xx&l=es. Accessed: 2018-11-14.

Intergovernmental Panel On Climate Change (2007). Climate change 2007: The physical science basis. Technical Report 07, Intergovernmental Panel On Climate Change, Switzerland.

Intergovernmental Panel On Climate Change (2014). Fifth Assessment Report - Mitigation of Climate Change.

Jacobsen, N. B. (2006a). Industrial symbiosis in Kalundborg, Denmark - A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology*, 10(1-2):239–255.

Jacobsen, N. B. (2006b). Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. *Journal of Industrial Ecology*, 10(1-2):239–255.

Jiang, M., Zhou, J., and Chen, G. (2010). Unified process assessment for resources use and waste emissions by coal-fired power generation. *Communications in Nonlinear Science and Numerical Simulation*, 15(9):2723–2733.

Kalundborg Symbiosis (2015). Kalundborg Symbiosis is the world's first working industrial symbiosis.

Kantor, I., Fowler, M., and Elkamel, A. (2012). Optimized production of hydrogen in an eco-park network accounting for life-cycle emissions and profit. *International Journal of Hydrogen Energy*, 37(6):5347–5359.

Karlsson, M. and Wolf, A. (2008). Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry. *Journal of Cleaner Production*, 16(14):1536–1544.

Karuppiah, R. and Grossmann, I. E. (2006). Global optimization for the synthesis of integrated water systems in chemical processes. *Computers & Chemical Engineering*, 30:650–673.

Klöpffer, W. (2003). Life-Cycle based methods for sustainable product development. *The International Journal of Life Cycle Assessment*, 8:157–159.

Knight, P. (1990). A rebirth of the pioneering spirit. *Financial Times*, 14:15.

Kuznetsova, E., Zio, E., and Farel, R. (2016). A methodological framework for Eco-Industrial Park design and optimization. *Journal of Cleaner Production*, 126:308–324.

Li, X. and Xiao, R. (2017). Analyzing network topological characteristics of eco-industrial parks from the perspective of resilience: A case study. *Ecological Indicators*, 74:403–413.

Lienqueo, M., Salgado, J., Giaverini, O., and Asenjo, J. (2009). Computer-aided design to select optimal polypeptide tags to assist the purification of recombinant proteins. *Separation and Purification Technology*, 65(1):86–94.

Lienqueo, M. E., Salgado, J. C., and Asenjo, J. A. (1999). An expert system for selection of protein purification processes: experimental validation. *Journal of Chemical Technology & Biotechnology*, 74:293–299.

Liew, P. Y., Wan Alwi, S. R., Varbanov, P. S., Manan, Z. A., and Klemeš, J. J. (2013). Centralised utility system planning for a Total Site Heat Integration network. *Computers & Chemical Engineering*, 57:104–111.

Lovelady, E. M. and El-Halwagi, M. M. (2009). Design and integration of eco-industrial parks for managing water resources. *Environmental Progress and Sustainable Energy*.

Lowe, E. A. (2001). Eco-industrial park handbook for Asian developing countries. *Report to Asian Development Bank*.

Lu, Y., Su, M., Liu, G., Chen, B., Zhou, S., and Jiang, M. (2012). Ecological network analysis for a low-carbon and high-tech industrial park. *The Scientific World Journal*, 2012.

Mahn, A., Lienqueo, M. E., and Asenjo, J. A. (2007). Optimal operation conditions for protein separation in hydrophobic interaction chromatography. *Journal of chromatography. B, Analytical technologies in the biomedical and life sciences*, 849:236–42.

Marler, R. T. and Arora, J. S. (2004). Survey of multi-objective optimization methods for engineering. *Structural and Multidisciplinary Optimization*, 26(6):369–395.

Matta, J., Borwey, J., and Ercal, G. (2014). Comparative Resilience Notions and Vertex Attack Tolerance of Scale-Free Networks. *arXiv preprint arXiv:1404.0103*, pages 1–9.

Méndez, C., Henning, G., and Cerdá, J. (2000). Optimal scheduling of batch plants satisfying multiple product orders with different due-dates. *Computers & Chemical Engineering*, 24:2223–2245.

Méndez, C., Henning, G., and Cerdá, J. (2001). An MILP continuous-time approach to short-term scheduling of resource-constrained multistage flowshop batch facilities. *Computers & Chemical Engineering*, 25:701–711.

Ministry of Environmental Protection (2015). Israel Ministry of Environmental.

Mirata, M. and Emtairah, T. (2005). Industrial symbiosis networks and the contribution to environmental innovation. *Journal of Cleaner Production*, 13(10-11):993–1002.

Montastruc, L., Boix, M., Pibouleau, L., Azzaro-Pantel, C., and Domenech, S. (2013). On the flexibility of an eco-industrial park (EIP) for managing industrial water. *Journal of*

Cleaner Production, 43:1–11.

Muttil, N. and Chau, K.-W. (2007). Machine-learning paradigms for selecting ecologically significant input variables. *Engineering Applications of Artificial Intelligence*, 20(6):735–744.

Naciones Unidas (2005). Agua e industria en la economía verde. Technical report, ONU.

National Academy of Engineering and Richards, D. J. (1997). The Industrial Green Game: Overview and Perspectives. In Richards, D. J., editor, *The Industrial Green Game: Implications for Environmental Design and Management*, pages 1–34. The National Academies Press, Washington, DC.

National Research Council (1997). Examples of Environmental Design and Management. In *The Industrial Green Game: Implications for Environmental Design and Management*, pages 117 – 123. The National Academies Press, Washington, DC.

Ngatchou, P., Zarei, A., and El-Sharkawi, M. A. (2005). Pareto Multi Objective Optimization.

Odum, H. T. (1996). *Environmental accounting*. Wiley.

Ohnishi, S., Fujita, T., Chen, X., and Fujii, M. (2012). Econometric analysis of the performance of recycling projects in Japanese Eco-Towns. *Journal of Cleaner Production*, 33:217–225.

Organisation for Economic Co-operation and Development (2008). *Measuring Material Flows and Resource Productivty*, volume I. OECD.

Pakarinen, S., Mattila, T., Melanen, M., Nissinen, A., and Sokka, L. (2010). Sustainability and industrial symbiosis—The evolution of a Finnish forest industry complex. *Resources, Conservation and Recycling*, 54(12):1393–1404.

Park, H. and Won, J. (2007). Ulsan Eco-industrial Park: Challenges and Opportunities. *Journal of Industrial Ecology*, 11(3):11–13.

Park, H.-S. and Behera, S. K. (2014). Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks. *Journal of Cleaner Production*, 64:478–485.

Park, H.-S., Rene, E. R., Choi, S.-M., and Chiu, A. S. (2008). Strategies for sustainable development of industrial park in Ulsan, South Korea—From spontaneous evolution to systematic expansion of industrial symbiosis. *Journal of Environmental Management*, 87(1):1–13.

PCSD (1997). President's Council on Sustainable Development, Eco-Industrial Park workshop. In *Eco-Industrial Park Workshop*, pages October 17–18, 1996, Cape Charles, Virginia.

Pereira, C. J. (1999). Environmentally friendly processes. *Chemical Engineering Science*, 54:1959–1973.

Phillips, P. S., Barnes, R., Bates, M. P., and Coskeran, T. (2006). A critical appraisal of an UK county waste minimisation programme: The requirement for regional facilitated development of industrial symbiosis/ecology. *Resources, Conservation and Recycling*, 46(3):242–264.

Ramos, M. A., Boix, M., Aussel, D., Montastruc, L., and Domenech, S. (2016). Water integration in eco-industrial parks using a multi-leader-follower approach. *Computers & Chemical Engineering*, 87:190–207.

Rey, P. A., Muñoz, J. A., and Weintraub, A. (2009). A Column Generation Model for Truck Routing in the Chilean Forest Industry. *INFOR: Information Systems and Operational Research*, 47:215–221.

Rubio-Castro, E., Ponce-Ortega, J. M., Serna-González, M., Jiménez-Gutiérrez, A., and El-Halwagi, M. M. (2011). A global optimal formulation for the water integration in eco-industrial parks considering multiple pollutants. *Computers & Chemical Engineering*, 35(8):1558–1574.

Sahinidis, N. V. (1996). BARON: A general purpose global optimization software package. *Journal of Global Optimization*, 8(2):201–205.

Sandoval, G., Espinoza, D., Figueroa, N., and Asenjo, J. (2016). MILP reformulations for the design of biotechnological multi-product batch plants using continuous equipment sizes and discrete host selection. *Computers & Chemical Engineering*, 84:1–11.

Sendra, C., Gabarrell, X., and Vicent, T. (2007). Material flow analysis adapted to an industrial area. *Journal of Cleaner Production*, 15(17):1706–1715.

Sikdar, S. (2001). *Process design tools for the environment*. CRC Press.

Sokka, L., Pakarinen, S., and Melanen, M. (2011). Industrial symbiosis contributing to more sustainable energy use - an example from the forest industry in Kymenlaakso, Finland. *JOURNAL OF CLEANER PRODUCTION*, 19(4):285–293.

Song, Q., Wang, Z., and Li, J. (2013). Sustainability evaluation of e-waste treatment based on emergy analysis and the LCA method: A case study of a trial project in Macau. *Ecological Indicators*, 30:138–147.

Stephanopoulos, G. (1981). Synthesis of process flowsheets: an adventure in heuristic design or a utopia of mathematical programming? In *Foundations of Computer-Aided Chemical Process Design*, volume 2, page 439. Engineering Foundation New York.

Su, B., Heshmati, A., Geng, Y., and Yu, X. (2013). A review of the circular economy in China: moving from rhetoric to implementation. *Journal of Cleaner Production*, 42:215–227.

Tian, J., Liu, W., Lai, B., Li, X., and Chen, L. (2014). Study of the performance of eco-industrial park development in China. *Journal of Cleaner Production*, 64:486–494.

Tietze-Stöckinger, I., Fichtner, W., and Rentz, O. (2004). A model to minimize joint total costs for industrial waste producers and waste management companies. *Waste Management & Research*, 22(6):466–476.

Tiu, B. T. C. and Cruz, D. E. (2017). An MILP model for optimizing water exchanges in eco-industrial parks considering water quality. *Resources, Conservation and Recycling*, 119:89–96.

Tixier, J., Dusserre, G., Salvi, O., and Gaston, D. (2002). Review of 62 risk analysis methodologies of industrial plants. *Journal of Loss Prevention in the Process Industries*, 15(4):291–303.

Tolmasquim, M. T., Cohen, C., and Szklo, A. S. (2001). CO2 emissions in the Brazilian industrial sector according to the integrated energy planning model (IEPM). *Energy Policy*, 29(8):641–651.

Tudor, T., Adam, E., and Bates, M. (2007). Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): A literature review. *Ecological Economics*, 61(2-3):199–207.

UNESCO (2015). Climate Change Assessment and Adaptation. `http://www.unesco.org/new/en/natural-sciences/priority-areas/links/climate-change/`. Accessed: 2017-12-01.

Valenzuela-Venegas, G., Henríquez-Henríquez, F., Boix, M., Montastruc, L., Arenas-Araya, F., Miranda-Pérez, J., and Díaz-Alvarado, F. A. (2018). A resilience indicator for Eco-Industrial Parks. *Journal of Cleaner Production*, 174:807–820.

Valenzuela-Venegas, G., Salgado, J. C., and Díaz-Alvarado, F. A. (2016). Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection. *Journal of Cleaner Production*, 133:99–116.

van Beers, D., Corder, G., Bossilkov, A., and van Berkel, R. (2007). Industrial symbiosis in the Australian minerals industry - The cases of Kwinana and Gladstone. *JOURNAL OF INDUSTRIAL ECOLOGY*, 11(1):55–72.

Vera, J. R., Weintraub, A. A., Koening, M., Bravo, G., Guignard, M., and Barahona, F. (2003). A Lagrangian Relaxation Approach for a Machinery Location Problem in Forest Harvesting. *Pesquisa Operacional*, 23:111–128.

Vicuña, S., Garreaud, R., and McPhee, J. (2011). Climate change impacts on the hydrology of a snowmelt driven basin in semiarid Chile. *Climatic Change*, 105:469–488.

WANG, G., FENG, X., and Khim Hoong, C. (2014). Symbiosis Analysis on Industrial Ecological System. *Chinese Journal of Chemical Engineering*, 22(6):690–698.

Wen, Z. and Meng, X. (2015). Quantitative assessment of industrial symbiosis for the promotion of circular economy: a case study of the printed circuit boards industry in China's Suzhou New District. *Journal of Cleaner Production*, 90:211–219.

Xiao, Z., Cao, B., Sun, J., and Zhou, G. (2016). Culture of the stability in an eco-industrial system centered on complex network theory. *Journal of Cleaner Production*, 113:730–742.

Yang, H., Li, Y., Shen, J., and Hu, S. (2003). Evaluating waste treatment, recycle and reuse in industrial system: an application of the eMergy approach. *Ecological Modelling*, 160(1-2):13–21.

Yang, J., Chen, B., Qi, J., Zhou, S., and Jiang, M. (2012). Life-cycle-based multicriteria sustainability evaluation of industrial parks: a case study in China. *The Scientific World Journal*, 2012:9.

Yu, C., de Jong, M., and Dijkema, G. P. (2014). Process analysis of eco-industrial park development – the case of Tianjin, China. *Journal of Cleaner Production*, 64:464–477.

Yu, F., Han, F., and Cui, Z. (2015). Reducing carbon emissions through industrial symbiosis: a case study of a large enterprise group in China. *Journal of Cleaner Production*.

Zeng, Y., Xiao, R., and Li, X. (2013). A resilience approach to symbiosis networks of ecoindustrial parks based on cascading failure model. *Mathematical Problems in Engineering*, 2013.

Zhang, B. J., Xu, T., He, C., Chen, Q. L., and Luo, X. L. (2017). Material stream network modeling, retrofit and optimization for raw natural gas refining systems. *Journal of Cleaner Production*, 142:3419–3436.

Zhang, C., Zhou, L., Chhabra, P., Garud, S. S., Aditya, K., Romagnoli, A., Comodi, G., Dal Magro, F., Meneghetti, A., and Kraft, M. (2016). A novel methodology for the design of waste heat recovery network in eco-industrial park using techno-economic analysis and multi-objective optimization. *Applied Energy*, 184:88–102.

Zhang, L., Yuan, Z., Bi, J., Zhang, B., and Liu, B. (2010). Eco-industrial parks: national pilot practices in China. *Journal of Cleaner Production*, 18(5):504–509.

Zhao, M.-Y., Cheng, C.-T., Chau, K.-W., and Li, G. (2006). Multiple criteria data envelopment analysis for full ranking units associated to environment impact assessment. *International Journal of Environment and Pollution*, 28(3-4):448–464.

Zhu, J. and Ruth, M. (2013). Exploring the resilience of industrial ecosystems. *Journal of Environmental Management*, 122:65–75.

Zhu, L., Zhou, J., Cui, Z., and Liu, L. (2010). A method for controlling enterprises access to an eco-industrial park. *The Science of the total environment*, 408(20):4817–25.

Appendices

A. Appendix

A.1 Indicators

Table A.1: Indicators obtained though the research, and their dimension and criteria classification. Ec: economic - En: environmental - Sc: social; U; understanding - P: pragmatism - R: relevance - S: partial representation of sustainability.

Indicator name	**Definition**	**Dimen. of Sust.**	**U**	**P**	**R**	**S**	**Ref.**
Industrial chain extension	It measures the role of the candidate enterprise in improving existing EIP member businesses linkage through supplies or demands.	Ec	✓		✓		(Zhu et al., 2010)
Industrial chain coupling	It measures the level of coupling difficulty of the exchange of product, by-product and waste, water and energy, of the candidate enterprise.	Ec	✓	✓	✓		(Zhu et al., 2010)
Industrial chain adjustability	It measures by how much the candidate enterprise will improve the industrial chain adjustability.	Ec	✓	✓	✓		(Zhu et al., 2010)
Land carrying capacity	It measures whether an EIP can accommodate the demand of the candidate enterprise.	Ec	✓	✓	✓	✓	(Zhu et al., 2010)
Water carrying capacity	It measures the possibility of meeting the water demand of the candidate enterprise in an EIP.	En	✓	✓	✓	✓	(Zhu et al., 2010)
Energy carrying capacity	It measures the possibility of meeting the energy demand of the candidate enterprise in an EIP.	En	✓	✓	✓	✓	(Zhu et al., 2010)
Wastewater collection and treatment capacity	It measures whether the wastewater volume from the candidate firm exceeds the maximal treatment load of the existing plant.	En	✓	✓	✓	✓	(Zhu et al., 2010)
Wastes collection and central treatment capacity permit	It evaluates whether the park has enough capacity for wastes collection and central treatment to accept the wastes from the new member enterprise.	En	✓	✓	✓	✓	(Zhu et al., 2010)
COD environmental capacity	It evaluates whether the COD capacity of the park is enough to accommodate a new member firm.	En	✓	✓	✓	✓	(Zhu et al., 2010)
SO_2 environmental capacity	It measures the amount of SO_2 added to the park by a new firm and evaluates if the park SO_2 environmental capacity is enough.	En	✓	✓	✓	✓	(Zhu et al., 2010)
Park COD emission change rate %	It measures the contribution of new business to the total emission of COD in the park after the introduction of this.	En	✓	✓	✓		(Zhu et al., 2010)

Park SO_2 emission change rate %	It measures the contribution of new business to the total emission of SO_2 after the introduction of the new business.	En	✓	✓	✓		(Zhu et al., 2010)
Percent-added of park water productivity	It measures the growth rate of water production in the park after the introduction of the new business.	En	✓	✓	✓		(Zhu et al., 2010)
Percent-added of park energy productivity	It measures the growth rate of energy production in the park after the introduction of the new business.	En	✓	✓	✓		(Zhu et al., 2010)
Sustainable architecture design	It evaluates the sustainable construction design of the candidate enterprise through three aspect including sustainable energy, sustainable building materials and building placement.	En	✓	✓	✓		(Zhu et al., 2010)
Product eco-design	It evaluates the design for disassembly and recovery, and product data management, of the candidate enterprise.	En	✓		✓		(Zhu et al., 2010)
Green packing	It measures the level of green packaging of the candidate enterprise in both environmentally friendly packaging materials and green packaging design.	En	✓		✓		(Zhu et al., 2010)
Green transportation design	It evaluates the environment-oriented transportation facilities, mode and scheme, of the new member firm.	En	✓		✓		(Zhu et al., 2010)
Industrial value-added per unit area	It measures the economic value created by the candidate enterprise per unit of area.	Ec	✓	✓	✓		(Zhu et al., 2010)
Industrial value-added per capita	It measures the annual industrial value-added of enterprises and employees in total.	Ec	✓	✓	✓	✓	(Zhu et al., 2010)
Energy consumption per unit	It measures the energy efficiency of the candidate enterprise by calculating of all the energy and converting to the number of standard coal using means conversion coefficients.	En	✓	✓	✓		(Zhu et al., 2010)
Fresh water consumption per unit	It measures the efficiency of water use in production as well as the level of technology and equipment of the new member firm.	En	✓	✓	✓		(Zhu et al., 2010)
Recycling rate of industrial water	It evaluates the proportion of water recycled in the new member enterprise.	En	✓	✓	✓		(Zhu et al., 2010)
Recycling rate of industrial solid waste	It measures the level of material reused and recycled in the new firm.	En	✓	✓	✓		(Zhu et al., 2010)
Wastewater production per unit IVA	It measures the efficiency of production management of the candidate enterprise. It also evaluates water utilization efficiency.	En/Ec	✓	✓	✓	✓	(Zhu et al., 2010)
COD production per unit IVA	It measures the quality of wastewater and material utilization efficiency through the total annual production of COD per unit IVA.	En/Ec	✓	✓	✓	✓	(Zhu et al., 2010)
Wastes production per unit IVA	It measures the solid waste production in the candidate enterprise.	En/Ec	✓	✓	✓	✓	(Zhu et al., 2010)
Output rate of main material resources	It refers to the amount of production value in EIP generated from one unit of material.	Ec	✓	✓		✓	(Su et al., 2013)
Output rate of land	It refers to the amount of production value in EIP generated from one unit of land.	Ec/En	✓	✓		✓	(Su et al., 2013)
Output rate of energy	It refers to the amount of production value in EIP generated from one unit of energy.	Ec/En	✓	✓		✓	(Su et al., 2013)
Output rate of water	It refers to the amount of production value in EIP generated from one unit of water.	Ec/En	✓	✓		✓	(Su et al., 2013)

Energy consumption per unit of production value	It measures the efficient use of energy in a firm.	En	✓	✓	✓	✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Energy consumption per unit of production in the key industrial sector.	It measures the efficient use of energy in an the key industrial sector.	En	✓	✓		✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Water consumption per unit of production value	It measures the efficient use of water in a firm.	En	✓	✓	✓	✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Water consumption per unit of production in the key industrial sector	It measures the efficient use of water in an the key industrial sector.	En	✓	✓		✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Utilization rate of industrial solid waste	It measures the ratio of amount of recycled industrial solid waste to total amount of industrial solid waste generated.	En	✓	✓	✓	✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Reuse ratio of industrial water	It measures the amount of total reused wastewater for industrial purpose. It includes both recycled water reuse and cascaded water reuse	En	✓	✓	✓	✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Recycling rate of industrial wastewater	It measures the amount of total recycled industrial wastewater for industrial propose. It includes both treated domestic wastewater and industrial wastewater.	En	✓	✓	✓	✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Decreasing rate of industrial solid-waste generation	It measures the total amount of industrial solid waste for final disposal.	En	✓	✓	✓	✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Decreasing rate of industrial wastewater generation	It measures the total amount of industrial wastewater for final disposal.	En	✓	✓	✓	✓	(Su et al., 2013) (Geng et al., 2012) (Geng et al., 2009b)
Education and training in waste minimization methodology	It measure the amount of employees trained per annum.	Sc	✓	✓	✓	✓	(Phillips et al., 2006)
Resource acquisition	It measures obtaining external funds to from local clubs	Ec	✓	✓	✓	✓	(Phillips et al., 2006)
Forming local and regional partnerships	It measures networking through clubs with all key local and regional organizations.	Ec	✓	✓	✓	✓	(Phillips et al., 2006)
Geographical distribution of clubs	It measures clubs in each district and borough, especially those with high deprivation	Sc	✓	✓			(Phillips et al., 2006)
Long term vision	It measures exit strategies from projects in place so as to continue with new club development	Ec	✓		✓		(Phillips et al., 2006)
Environmental reporting	It measures success of club activities included in local and regional media as well as journals.	En	✓				(Phillips et al., 2006)
Companies adopting waste minimization	It measures the increase in number of trained companies (in waste treatment) per annum.	En	✓	✓		✓	(Phillips et al., 2006)
Resource efficiency	It measures reduction in resource use per unit of production, the increase in recycling, and re-use.	En	✓	✓	✓	✓	(Phillips et al., 2006)

Reduction in effluent and special waste	It measures the reduction in effluent and special waste produced.	En	✓	✓	✓	✓	(Phillips et al., 2006)
Increase company competitiveness	It measures the companies saving.	Ec	✓	✓	✓	✓	(Phillips et al., 2006)
Cost effective waste minimization clubs	It measure the cost saving of waste ratio of clubs	Ec	✓	✓	✓	✓	(Phillips et al., 2006)
Job creation	It measures new job created per annum by partnership.	Sc	✓	✓	✓	✓	(Phillips et al., 2006)
Direct energy consumption carbon footprint	It refers to emission from direct combustion of fossil fuels within the administrative boundary.	En	✓		✓	✓	(Dong et al., 2014b) (Dong et al., 2013)
Industrial process carbon footprint	It refers to emissions from chemical and physical reactions in the production process.	En	✓		✓	✓	(Dong et al., 2014b) (Dong et al., 2013)
Material carbon footprint	It refers to the indirect carbon footprint embodied in the input materials.	En	✓		✓	✓	(Dong et al., 2014b) (Dong et al., 2013)
Depreciation carbon footprint	It refers to the indirect carbon footprint embodied in the annual depreciation of fixed assets that support the production in the industrial park.	En	✓		✓	✓	(Dong et al., 2014b) (Dong et al., 2013)
Electricity and heat carbon footprint	It refers to the indirect carbon footprint embodied in the purchased electricity and heat out of the park.	En	✓		✓	✓	(Dong et al., 2014b) (Dong et al., 2013)
waste treatment carbon footprint	It refers to emissions caused during the treatment process of the wastes generated within the park.	En	✓			✓	(Dong et al., 2014b) (Dong et al., 2013)
Added industrial value per capita	It measures the annual added industrial production value per total employees at the end of the year.	Ec	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Growth rate of added industrial value	it measures the relative difference of added industrial value between two years.	Ec	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Energy consumption per added industrial value	It measures the energy consumption including coal, electricity, oil, and energy consumption for both heating and cooling.	En/Ec	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Fresh water consumption per added industrial value	It measures the industrial freshwater used for production and living within the enterprises, including the tap water and self-provided water (if the domestic wastewater is not blended with the industrial wastewater, then water consumption for living should no be included).	En/Sc	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Industrial wastewater generation per added industrial value	It measures the industrial wastewater generation, not including water obtained from cascading and domestic wastewater from resident living in the park	En/Ec	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Solid waste generation per added industrial value	It measures solid, semisolid, and high-density liquid waste, including smelt residues, fly ash, bottom ash, gangue, dangerous waste, gangue, and radioactive wastes.	En/Ec	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Industrial water reuse ratio	It measures the industrial reuse water, including water that is recycled or cascaded.	En	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Solid waste reuse ratio	It measures the industrial solid waste, including all kinds of non domestic, non dangerous solid wastes generated by industries.	En	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Middle water reuse ratio	It measures the recycled treated wastewater from wastewater treatment plants.	En	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)

COD loading per added industrial value	It measures the amount of COD loading, including COD loading both from companies and wastewater treatment plant.	En/Ec	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
SO_2 emission per added industrial value	It measures the amount of SO_2 emissions.	En/Ec	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Disposal rate of dangerous solid waste	It measures the dangerous industrial wastes, including those toxic and hazardous wastes ad defined by the environmental standards.	En	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Centrally provided treatment rate of domestic wastewater	It refers to the ratio of total amount of treated domestic wastewater to amount of domestic wastewater generation.	En	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Safe treatment rate of domestic rubbish	It refers to the ratio of total amount of safely treated domestic rubbish to total amount of domestic rubbish.	En	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Waste collection system	It refers to the existence of a waste collection system	En	✓		✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Centrally provided facilities for waste treatment and disposal	It refers to the existence of a environmental management system.	En	✓		✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Environmental management systems	It refers whether the park management should pass ISO 14001 certification and have an emergency response plan.	En	✓			✓	(Geng et al., 2009a) (Geng et al., 2008)
Extent of establishment of information platform	It indicates whether the park has established a comprehensive information platform.	En	✓			✓	(Geng et al., 2009a) (Geng et al., 2008)
Environmental report release	It refers to the existence of an environmental report release.	En	✓		✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Extent of public satisfaction with local environmental quality	It measures the degree satisfaction of the population of the whole park with local environmental quality.	Sc	✓	✓	✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Extent of public awareness degree with eco-industrial development	It measures the public awareness of the population park about eco-industrial development.	Sc	✓		✓	✓	(Geng et al., 2009a) (Geng et al., 2008)
Energy intensity	It measures the energy consumption efficiency. It relates the consumption to the output of the sector in monetary values	En	✓	✓	✓	✓	(Tolmasquim et al., 2001)
Emission intensity	It assess the ratio between CO_2 emissions of the industrial sector and its output value.	En	✓	✓	✓	✓	(Tolmasquim et al., 2001)
The specific emission	It relates the total CO_2 emissions to the energy consumption	En	✓	✓	✓	✓	(Tolmasquim et al., 2001)
Nodes	It measures the quantity of metabolic compartments, and also the size of network.	Ec		✓		✓	(Lu et al., 2012)
Links	It measures the quantity of metabolic direct flows or arcs.	Ec		✓	✓	✓	(Lu et al., 2012)
Link density	It measures the metabolic linking degree.	Ec		✓	✓	✓	(Lu et al., 2012)
Connectance	It measures the metabolic connectivity, also the proportion or realized direct pathways	Ec		✓	✓	✓	(Lu et al., 2012)
Mutualism index (MI)	It reflects the ratio of the number of positive and negative signs regard to mutualism relationships between components of a system.	Ec		✓	✓	✓	(Lu et al., 2012)
Synergism index (SI)	It quantifies the total magnitude of the positive and negative utilities, which assess the mutualism condition of a system in slightly different angles.	Ec		✓	✓	✓	(Lu et al., 2012)

Control index (CI)	It indicates the control utility and organization capability of the whole system. It can be employed to index the self-regulation of system metabolism.	Ec		✓	✓	✓	(Lu et al., 2012)
R/U	It indicates the ratio of renewable inputs to total used emergy.	Ec/En		✓	✓	✓	(Geng et al., 2014)
N/U	It indicates the ratio of nonrenewable inputs to total used emergy.	Ec/En		✓	✓	✓	(Geng et al., 2014)
I/U	It indicates the ratio of imported resources to total used emergy.	Ec/En		✓	✓	✓	(Geng et al., 2014)
Emergy yield ratio	It reflects the net economic benefit.	Ec		✓	✓	✓	(Geng et al., 2014)
Environmental loading ratio	It reflects the pressure of industrial activities on the local ecosystem.	En		✓	✓	✓	(Geng et al., 2014)
Emergy sustainability indicator	It reflects the sustainable level of on industrial park.	Ec/En		✓	✓	✓	(Geng et al., 2014)
Absolute emergy savings	It is the absolute emergy savings of nonrenewable resource, purchased resources, services associated with imported resource, and emergy of the total energy used due to the use of by-products among different firms within the same park.	Ec/En		✓	✓	✓	(Geng et al., 2014)
Relatives emergy savings	It is the ratio of avoided inputs through all the industrial symbiosis activities to total emergy inputs without related industrial symbiosis activities.	En		✓	✓	✓	(Geng et al., 2014)
Emdollar values of total savings	It represents the economic benefits of industrial symbiosis.	Ec		✓	✓	✓	(Geng et al., 2014)
Per capita industrial value added	It refers to industrial value added created by one employee of the industry park in one year.	Ec	✓	✓	✓	✓	(Bai et al., 2014)
Per land use industrial value added	It refers to land use of production facilities, warehouse and affiliated facilities in enterprises such as railways, ports and land for roads, not including land for open pit mine.	En/Ec	✓	✓	✓	✓	(Bai et al., 2014)
Total energy consumption intensity	It refers to energy such coal, electricity, oil and other energy consumption (including the production of heating and cooling energy) used for production and operations of the enterprise.	En	✓	✓	✓	✓	(Bai et al., 2014)
Fresh water consumption intensity	It refers to tap water and selfprepared water used for production and operations of the enterprises.	En	✓	✓	✓	✓	(Bai et al., 2014)
Ratio of industrial waste water utilization	It refers to the ratio reuse of water including recycling, multiple use and cascade use of water (including the reuse of disposed waste water) in the production of enterprises and to water used for production and operation of the enterprises.	En	✓	✓	✓	✓	(Bai et al., 2014)
Ratio of industrial solid waste utilization	It refers to the ratio of recycled, processed, circulated or exchanged solid waste from solid waste generated by industrial enterprises.	En	✓	✓	✓	✓	(Bai et al., 2014)
Waste water generation intensity	It refers to industrial value added created by the total amount of waste water by industrial enterprises in a year.	Ec/En	✓	✓	✓	✓	(Bai et al., 2014)
Solid waste generation intensity	It refers to industrial value added created by the total amount of solid waste generated by industrial enterprises in a year.	Ec/En	✓	✓	✓	✓	(Bai et al., 2014)
COD generation intensity	It refers to industrial value added created by the total amount of solid COD by industrial enterprises in a year.	Ec/En	✓	✓	✓	✓	(Bai et al., 2014)

SO_2 emission intensity	It refers to industrial value added created by the total amount of SO_2 by industrial enterprises in a year.	Ec/En	✓	✓	✓	✓	(Bai et al., 2014)
Direct Material Input (DMI)	It measures the direct input of materials for use in the economy, i.e. All materials which are of economic value and are used in production and consumption activities.	En	✓	✓	✓	✓	(Eurostat, 2001)
Total Material Input (TMI)	It measures the materials that are moved by economic activities but that do not serve as input for production or consumption activities.	En	✓	✓	✓	✓	(Eurostat, 2001)
Total Material Requirement (TMR)	It measures the total "material base" of an economy. It includes, in addition to TMI, the material flows that are associated to imports but that take place in other countries.	En	✓	✓	✓		(Eurostat, 2001)
Domestic Total Material Requirement (domestic TMR)	It measures the total of material flows originating from the national territory.	En	✓	✓	✓		(Eurostat, 2001)
Domestic Material Consumption (DMC)	It measures the total amount of material directly used in an economy.	En	✓	✓	✓	✓	(Eurostat, 2001)
Total Material Consumption (TMC)	It measures the total material use associated with domestic production and consumption activities, including indirect flows imported but less exports and associated indirect flows of exports.	En	✓	✓	✓	✓	(Eurostat, 2001)
Net Additions to Stock (NAS)	It measures the quantity of new construction materials used in buildings and other Infrastructure, and materials incorporated into new durable goods such as cars, industrial machinery, and household appliances.	En	✓		✓	✓	(Eurostat, 2001)
Physical Trade Balance (PTB)	It measure the physical trade surplus or deficit of an economy.	Ec	✓	✓	✓	✓	(Eurostat, 2001)
Domestic Processed Output (DPO)	It refers to the total weight of materials, extracted from the domestic environment or imported, which have been used in the "domestic economy", before flowing to the environment.	En		✓	✓	✓	(Eurostat, 2001)
Total Domestic Output (TDO)	It represents the total quantity of material output to the environment caused by economic activity.	En	✓	✓	✓	✓	(Eurostat, 2001)
Direct Material Output (DMO)	It represents the total quantity of material leaving the economy after use either towards the environment or towards the rest of the world.	En	✓	✓	✓	✓	(Eurostat, 2001)
Total Material Output (TMO)	It measures the total of material that leaves the economy.	En	✓	✓	✓	✓	(Eurostat, 2001)
DMI	It measures the amount of materials entering the system to be used and/or processed.	En	✓	✓	✓	✓	(Sendra et al., 2007)
TMR	It measures the total material requirement.	En	✓	✓	✓	✓	(Sendra et al., 2007)
DMIw	It measures the DMI per number of workers.	En	✓	✓	✓	✓	(Sendra et al., 2007)
TMRw	It measures the TMR per number of workers	En	✓	✓	✓	✓	(Sendra et al., 2007)
TWG	It measures the total waste generated by the system.	En	✓	✓	✓	✓	(Sendra et al., 2007)
TWGw	It measures the TWG per number of workers.	En	✓	✓	✓	✓	(Sendra et al., 2007)
Wp	It measure the production of the system per number of workers, i.e., the worker productivity.	Ec	✓	✓	✓	✓	(Sendra et al., 2007)
Eco-Ef	It is the percentage of DMI converted into product.	En	✓	✓	✓	✓	(Sendra et al., 2007)

Eco-In	It measures the tonnes of material input required to manufacture a tonne of product or the amount of raw material equivalent to a product.	En	✓	✓	✓	✓	(Sendra et al., 2007)
M-Inef	It is the amount of output to nature per unit of material processed.	En	✓	✓	✓	✓	(Sendra et al., 2007)
TWI	It measures the amount of water consumed by the system from own sources (domestic) and imported from supply system, shafts and rivers.	En	✓	✓	✓	✓	(Sendra et al., 2007)
TWWG	It measures the amount of wastewater generated by the system.	En	✓	✓	✓	✓	(Sendra et al., 2007)
TWIw	It is used to analyze the difference with the average of water consumption per inhabitant	En	✓	✓	✓	✓	(Sendra et al., 2007)
TEI	It is the amount of energy consumed by the system and subsystem, distinguished between energy generated domestically and imported energy.	En	✓	✓	✓	✓	(Sendra et al., 2007)
TEIw	It measures the TEI per number of workers.	En	✓	✓	✓	✓	(Sendra et al., 2007)
E-In	It is used to make different-sized system comparable.	En	✓	✓	✓	✓	(Sendra et al., 2007)
Net economic benefit (net value added)	It measures the annual added industrial production value.	Ec	✓	✓	✓	✓	(Park and Behera, 2014)
Raw material consumption indicator	It refers to the total weight of all materials that the company purchases or obtains from other sources including raw materials for conversion, other process materials, and pre-or semi-manufactures goods and parts.	Ec	✓	✓	✓	✓	(Park and Behera, 2014)
Energy consumption indicator	It measures the total energy consumption of a park.	En	✓	✓	✓	✓	(Park and Behera, 2014)
CO_2 emission indicator	It measure the GHG emissions resulting from fuel combustion, process reactions, and treatment processes.	En	✓	✓	✓	✓	(Park and Behera, 2014)
Eco-efficiency	It is a combination of economic and ecological performance, where it indicates the ratio of the net economic benefit to three environmental indicators.	Ec/En	✓	✓	✓	✓	(Park and Behera, 2014)
Air pollution	It includes particulate matter, volatile organic compounds, sulfur oxides, and nitrogen oxides.	En	✓	✓	✓	✓	(Chen et al., 2012a)
Water and solid waste pollution	In considers biochemical oxygen demand, chemical oxygen demand, and suspended solids,	En	✓	✓	✓	✓	(Chen et al., 2012a)
Resource use	It considers the tree major resources, water, land, and energy	En	✓	✓	✓	✓	(Chen et al., 2012a)
Health	It measures the quantities of air pollutants, water pollutants, and waste discharged by manufactories into the surrounding area.	En/Sc	✓	✓	✓	✓	(Chen et al., 2012a)
Quality of life	It measures the number of manufactories and traffic generated by them.	Ec/Sc	✓	✓	✓	✓	(Chen et al., 2012a)
Recycling of metals	It reflects reduced input of scarce materials from nature	En	✓	✓	✓	✓	(Pakarinen et al., 2010)
Waste and by-product utilization	It measures waste and by-product utilization as raw material in paper production.	En	✓	✓	✓	✓	(Pakarinen et al., 2010)
Fuel use	It measures the amount of total fuel used in the park.	En	✓	✓	✓	✓	(Pakarinen et al., 2010)
Restricting emissions of chemicals to nature by the recovery of process chemicals	It measures the amount of by-products reused to avoid emissions of certain substances.	En	✓	✓	✓	✓	(Pakarinen et al., 2010)

Decrease in hazardous substance emissions to the water	It measures the amount of chlorine, mercury, and others hazardous compounds emissions released to the water.	En	✓	✓	✓	✓	(Pakarinen et al., 2010)
Other emissions to the water	It measures the amount of suspended solids in the water, biological oxygen demand, and phosphorus and nitrogen load.	En	✓	✓	✓	✓	(Pakarinen et al., 2010)
Emissions to the air	It measures the amount of atmospheric emissions (CO_2, mercury, etc.).	En	✓	✓	✓	✓	(Pakarinen et al., 2010)
Recycling and waste treatment	It indicates whether exists a property waste management.	En	✓		✓	✓	(Pakarinen et al., 2010)
Extraction of wood and other resources	It measures the consumption of natural resources.	En	✓	✓	✓	✓	(Pakarinen et al., 2010)
Other area-consuming activities	It measures the amount of resources imported to industrial area.	En	✓	✓	✓	✓	(Pakarinen et al., 2010)
Health risks of the pollution	It describes the pollution level of the resources used by the humans like water.	En/Sc	✓	✓	✓	✓	(Pakarinen et al., 2010)
Renewable resources input (R)	It is the total energy and material driving a process that is derived from renewable sources.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Non-renewable inputs (N)	It is a resource that their use rate exceeds replacement rate.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Input from the economy (F)	It considers mainly energy resources, raw material, transportation costs, labor costs, management costs, maintenance costs, and depreciation.	Ec/En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Waste emergy (E_w)	It reflects the emergy of the service of disposing waste.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Recycled resource emergy (E_r)	It reflects the recovery emergy from waste.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
E-waste emergy (E_e)	It reflects the emergy of the service of disposing waste.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Output emergy (E_0)	It reflects the emergy of all the products.	Ec/En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Yield of industrial process (Y)	It measures the amount of local resources exploited.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Emergy economic efficiency index (EYR)	It measures the net benefit to the economy from an waste processing activity-that is, the amount of local resources exploited compared to the amount of emergy investment. It measures the capability of industrial processes to exploit local resources.	Ec/En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)

Emergy environmental efficiency index (ELR)	It is an indicator of the pressure of the process on the local ecosystem and can be considered a measure of the ecosystem stress due to production activity.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Emergy sustainability index (ESI)	It reflects the ability of a system to provide desired products or services with a minimum of environmental stress and a maximum profit.	En			✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Emergy recovery ratio (ERR)	It measures the ability of a system to recover energy and materials from waste.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Quotes for emergy recyclability (QER)	It measures the quotes for emergy recyclability, i.e., the total emergy recyclability available from waste.	En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Emergy-LCA index	It assesses the ratio of the economic emergy (emergy used to evaluate the economic situation) and the total environmental performance expressed in LCA results (the unit environmental impacts multiplied by the total quantity of e-waste).	Ec/En		✓	✓	✓	(Song et al., 2013) (Brown and Ulgiati, 1997) (Yang et al., 2003)
Virgin Material Savings (VMS)	It assess the environmental benefits, measuring the amount of reuse or recycle wastes in place of virgin material use.	En	✓	✓	✓	✓	(Chen et al., 2012b)
Operation Rate (OR)	It is the ratio of the amount of wastes treated in practice to the planned amount of treatment. It assess the operational performance of an eco-town.	En	✓	✓	✓	✓	(Chen et al., 2012b)
Symbiosis degree ($gamma_{ij}$)	It expresses the change rate of the main essential parameter of a symbiosis unit corresponding to the change rate of the main essential parameter of other unit. It indicates which unit has more influence on the other.	En/Ec		✓	✓		(WANG et al., 2014)
Symbiosis degree of individual element ($gamma_{si}$)	It expresses the change rate of the main essential parameter of a unit corresponding to the change rate of the main essential parameter of the symbiosis system. It provides a simple way to analyze the stability of a symbiosis system.	En/Ec		✓	✓	✓	(WANG et al., 2014)
Symbiosis degree of total element ($gamma_s$)	It indicates the correlation degree of the symbiosis units and the system.	Ec		✓	✓	✓	(WANG et al., 2014)
Symbiosis profit (E)	It measures the net profit from the symbiosis process of a system.	Ec		✓	✓	✓	(WANG et al., 2014)
Symbiotic consumption	It is the cost of perform the symbiosis and gain symbiosis profit.	Ec		✓	✓	✓	(WANG et al., 2014)
Ecological efficiency (EE)	It measures the overall efficacy of the production system regarding to environmental support and resources input.	Ec/En	✓	✓	✓	✓	(Jiang et al., 2010)
Resource use efficiency (RUE)	It is based on the overall resources including energy sources.	En	✓	✓	✓	✓	(Jiang et al., 2010)
Environmental emission intensity (EEI)	It indicates the waste emissions per unit of yield. This ratio is focused on the direct impacts from waste emissions.	En	✓	✓	✓	✓	(Jiang et al., 2010)

Environmental loading ratio (ELR)	It represents the ratio of purchased and non-renewable emergy to locally free environmental emergy. It measures ecosystem stress due to excess exploitation of local non-renewable resources or investment from outside, compared with locally available renewable resources.	Ec/En		✓	✓	✓	(Geng et al., 2010b)
Emergy yield ratio (EYR)	It represents the ratio of total emergy used and exploited by the process to the emergy invested from outside the system. It measures the net benefit to the economy, namely the amount of local resources exploited derived from the investment amount. It measures the capability of industrial processes to exploit local resources.	Ec/En		✓	✓	✓	(Geng et al., 2010b)
RWCP	It refers to the ratio of waste collection within the prefecture.	En	✓	✓	✓	✓	(Ohnishi et al., 2012)
RPDP	It is the ratio of product delivery within the prefecture.	Ec	✓	✓	✓	✓	(Ohnishi et al., 2012)
PCF	It is the processing capacity of the facility.	Ec	✓	✓	✓	✓	(Ohnishi et al., 2012)
INWST	It measures the amount of industrial waste generated in the prefecture where the facility is located.	En/Sc	✓	✓			(Ohnishi et al., 2012)
HHWST	It measures the amount of household waste generated in the city where the facility is located.	En/Sc	✓	✓			(Ohnishi et al., 2012)
CPRI	It represents the capacity of steel, non-ferrous, and cement industries in the prefecture where the facility is located.	Ec	✓	✓			(Ohnishi et al., 2012)
DMAG	It indicates whether exists an agglomeration type.	En	✓		✓	✓	(Ohnishi et al., 2012)
DMCPL	It indicates whether exists a container/packaging recycling law.	En	✓		✓	✓	(Ohnishi et al., 2012)
DMHAL	It indicates whether exists a home appliance recycling law.	En	✓		✓	✓	(Ohnishi et al., 2012)
DMAML	It indicates whether exists a automobile recycling law.	En	✓		✓	✓	(Ohnishi et al., 2012)
DMFDL	It indicates whether exists a food recycling law.	En	✓		✓	✓	(Ohnishi et al., 2012)
RSET	It refers to the ratio of subsidies from the government.	Ec	✓	✓	✓	✓	(Ohnishi et al., 2012)
DMPRS	It indicates whether exists a waste collection support.	En	✓		✓	✓	(Ohnishi et al., 2012)
DMFS	It indicates whether exists a financial support from the municipality.	Ec	✓		✓	✓	(Ohnishi et al., 2012)
DMGP	It indicates whether exists a green purchase from the municipality.	Ec	✓		✓	✓	(Ohnishi et al., 2012)
DMWE	It indicates whether exists a waste exchange.	En	✓		✓	✓	(Ohnishi et al., 2012)
DMCOS	It indicates whether exists a Eco-Town committee.	Sc/En	✓				(Ohnishi et al., 2012)
RRCL	It measures the recycling rate in certain year in the city where the facility is located.	En/Sc	✓	✓	✓	✓	(Ohnishi et al., 2012)
Investment	It measures the amount of millions USD invested in a project.	Ec	✓	✓	✓	✓	(Behera et al., 2012)
Profit	It measures the amount of millions USD of benefit of both supplier and recipient.	Ec	✓	✓	✓	✓	(Behera et al., 2012)
Payback	It indicates the period of time required for a project to recover the money invested.	Ec	✓	✓	✓	✓	(Behera et al., 2012)
CO_2 reduction	It reflect the amount of CO_2 emissions that the project reduces.	En	✓	✓	✓	✓	(Behera et al., 2012)

Air pollutant reduction	It reflect the amount of SOx, NO_x and CO emissions that the project reduces.	En	✓	✓	✓	✓	(Behera et al., 2012)
Primary energy	It reflects the contribution of a material of a process to the primary energy.	En		✓	✓	✓	(Eckelman and Chertow, 2013b)
Greenhouse gas	It reflects the contribution of a process to greenhouse gas emissions.	En	✓	✓	✓	✓	(Eckelman and Chertow, 2013b)
Acidification	It reflects the contribution of a process to acidification of the environment.	En	✓	✓	✓	✓	(Eckelman and Chertow, 2013b)
Eutrophication	It reflects the contribution of a process to eutrophication of the environment.	En	✓	✓	✓	✓	(Eckelman and Chertow, 2013b)
Global warming potential (GWP)	It is the amount of greenhouse gas that a project produces.	En	✓	✓	✓	✓	(Chen et al., 2011)
Fossil fuel savings	It is the amount of fossil fuel replaced by other obtained as a by-product in a process.	En	✓	✓	✓	✓	(Chen et al., 2011)
Water consumption	It measures the amount of groundwater, surface water, cooling/waste water of a process or an industrial park.	En	✓	✓	✓	✓	(Jacobsen, 2006b)
CO_2	It measures the amount of CO_2 emissions saved by an industrial park.	En	✓	✓	✓	✓	(Jacobsen, 2006b)
SO_2	It measures the amount of SO_2 emissions saved by an industrial park.	En	✓	✓	✓	✓	(Jacobsen, 2006b)
NO_x	It measures the amount of NO_x emissions saved by an industrial park.	En	✓	✓	✓	✓	(Jacobsen, 2006b)
Abiotic resource depletion (resource use)	it reflects the depletion of nonrenewable resource.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Biotic resource depletion (resource use)	it is related to the use of species threatened with extinction.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Land use (resource use)	It represents the total land area used in different stage of the life cycle.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Global warming potential (GWP)	It represents total emissions of the greenhouse gases expressed relative to the global warming potential of CO_2.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Ozone depletion potential (ODP)	It indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and chlorinated (HCs) for depleting the ozone layer.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Acidification potential (AP)	It reflects the contributions of SO_2, NO_x, HCl, NH3, and HF to potential acid deposition.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Eutrophication potential (EP)	It is defined as the potential to cause over-fertilization of water and soil, which can result in increased growth of biomass.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Photochemical smog (PS)	It represents total emissions of different contributory species, primarily VOCs.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Human toxicity potential (HTTP)	It measures the human toxic releases to the three different media, i.e., air, water, and soil.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Ecotoxicity potential (ETP)	It measures toxic substances in water and soil.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Solid waste (SW)	It measures the amount of solid waste generated in the life cycle of a system.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Material intensity (MI)	It represents the sum of all materials used in the system.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Energy intensity (EN)	It represents the sum of the total amount of energy.	En	✓	✓	✓	✓	(Azapagic and Perdan, 2000)

Material recyclability (MR)	It shows a potential for the product to be recycled, either in the same or a different life cycle. It can be expressed as a percentage of the material that can potentially be recycled relative to the total amount of the material.	En	✓	✓			(Azapagic and Perdan, 2000)
Product durability (PD)	It represent the durability (period of time) of a product in relation with life cycle.	Ec	✓	✓			(Azapagic and Perdan, 2000)
Service intensity (SI)	it measures the degree to which the company has closed the loop in providing the service as opposed to only selling the product.	En		✓	✓	✓	(Azapagic and Perdan, 2000)
Environmental Management Systems (EMS)	It is a qualitative indicator which indicates whether in the company exists an environmental management system.	En	✓		✓	✓	(Azapagic and Perdan, 2000)
Environmental improvements above the compliance levels (ICL)	it expresses an average percentage decrease in environmental burdens for either prescribed substances, or substances that are of general environmental concern but are not legislated.	En	✓		✓		(Azapagic and Perdan, 2000)
Assessment of suppliers (AS)	It is a qualitative indicator which indicates whether the suppliers to have certain environmental features.	En	✓		✓	✓	(Azapagic and Perdan, 2000)
Value added (VA)	It is expressed as net operating profit of the company.	Ec	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Contribution to the gross domestic product (CGDP)	GDP is an aggregate measure of production equal to the sum of the gross values added of all participant in the industry. CGDP is expressed in terms of value added per functional unit.	Ec	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Expenditure on environmental protection (EP)	It represents an investment in the protection of the environment.	Ec	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Environmental liability (EL)	It expresses the costs that a company may have to pay if it is found liable for causing an environmental hazard.	Ec	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Ethical investments (ETI)	It represents assets invested in business activities that are considered to be ethical.	Ec/Sc	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Employment contribution (EM)	It represents the ratio of the number of employees per functional unit over an average number of people employed in the countries involved in the life cycle of an activity. Also it represents the number of employees per functional unit.	Sc	✓	✓	✓		(Azapagic and Perdan, 2000)
Staff turnover (ST)	It expresses the ratio of new employees to workforce made redundant by a company in a certain life cycle stage.	Sc	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Expenditure on health and safety (EHS)	It expresses the total expenditure on health and safety over the total number of employees, to give an investment in health and safety per employee.	Ec/Sc	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Investment in staff development (ISD)	It expresses the investment in training and continuing professional and personal development per employee.	Ec/Sc	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Stakeholder inclusion	It indicates whether the activities and performance of an organization have an impact in the local community, suppliers and business partners, civil society, natural environment, future generation and their defenders in to pressure groups.	Sc	✓		✓	✓	(Azapagic and Perdan, 2000)
Involvement in community projects	It is related to satisfaction of social needs. It shows the level of partnership that an organization develops with the community in which it operates.	Sc	✓	✓	✓	✓	(Azapagic and Perdan, 2000)

Income distribution (ID)	It shows an average distribution of wealth and could be expressed in term of income of the top 10% of employees per income of the bottom 10%.	Sc	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Work satisfaction (WS)	It represents the number of sick days or number of people "happy" with their job per employee.	Sc	✓	✓	✓	✓	(Azapagic and Perdan, 2000)
Satisfaction of social needs (SN)	It can be expressed as both quantitative and qualitative indicators. It is measured in terms of financial contributions of business to satisfying social needs. Contributions that cannot be measured in monetary terms can be included as a statement which describes the activity that contributed to satisfying a particular need and puts it in the context of the society to which the contribution has been made.	Ec/Sc	✓	✓	✓	✓	(Azapagic and Perdan, 2000)

A.2 Investment parameter calculation

The aim of the investment indicator is to measure the installing and piping (material of construction) costs, as a function of the length and the diameter of the pipes in an industrial network.

To achieve this goal, a linear and exponential dependence respect to the diameter of the pipe is used to estimate both costs. This assumption is based on Akbarnia et al. (2009), where the authors evaluate the design of a heat exchanger network, considering the installing and piping costs in addition to the energy and capital costs. They suppose a linear model for the installing cost and an exponential model for the piping cost. Through this assumption, they achieve an increasing in the accuracy of the global solution.

In this sense, both model are considered and adapted, expressing the investment of the pipeline as follows:

$$\text{Investment} = (a1D + a2) + be^{cD} \tag{A.1}$$

In this equation, the parameters $a1$ and $a2$ are the construction and installing cost coefficients per unit of pipe length; b, the pressure rating and material of construction coefficient per unit of pipe length; c, a dependent factor of the pipe diameter.

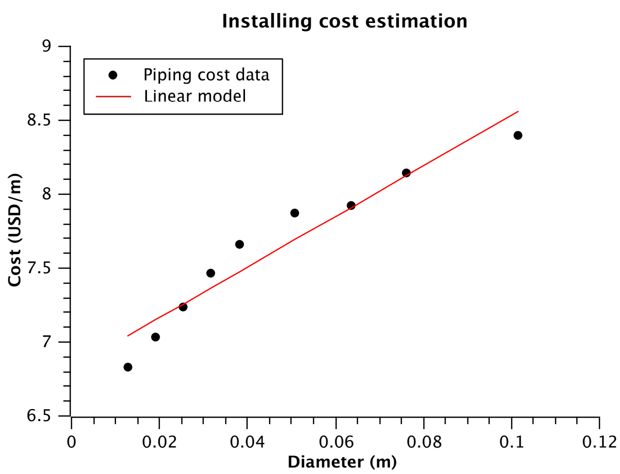
Since both costs are independents, they are separately fitted over their respective cost data (see Table A.2). It is worth to note that these data are based on Chilean costs since there is no information about Ulsan. Even though it may generate errors in the final value, they are considered in order to make a first approximation for this estimation.

In this sense, the data of the installing cost are fitted by means of a linear model, and the data of piping cost are fitted by means of an exponential model. Fig. A.1a and Fig. A.1b

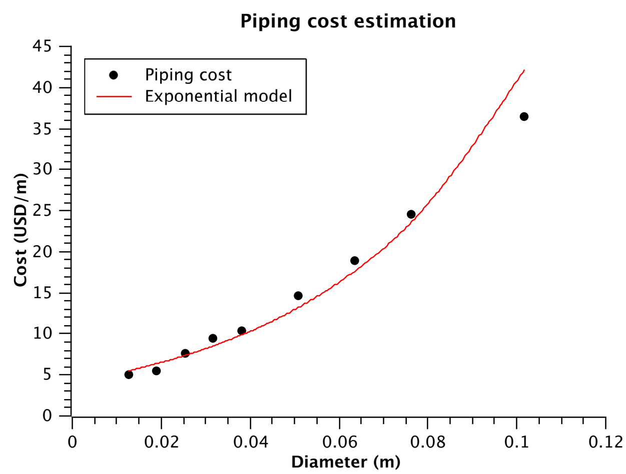
Table A.2: Data for the installing and piping cost according to the pipe diameter (information taken from CYPE Ingenieros (2018)). The displayed information is assuming a stainless steel pipe.

Diameter (m)	**Installing cost (USD)**	**Piping cost (USD)**
0.0127	6.83	4.98
0.01905	7.04	5.48
0.0254	7.24	7.61
0.03175	7.47	9.40
0.0381	7.66	10.41
0.0508	7.88	14.67
0.0635	7.93	18.88
0.0762	8.14	24.54
0.1016	8.40	36.46

show the data and resulting models for both costs. Table A.3 shows the resulting parameters and the respective coefficient of determination for each model.



(a) Data and resulting linear model for the installing cost.



(b) Data and resulting exponential model for the piping cost.

Table A.3: Resulting parameters and coefficients of determination for each model.

Model	**Parameters**		**Coefficient of determination (R^2)**
Installing cost $= a1D + a2$	a1	17.095	0.9246
	a2	6.82	
Piping cost $= be^{cD}$	b	4.1288	0.9767
	c	22.856	

With this information, finally, the investment indicator is defined as follows:

$$\text{Investment} = (17.095D + 6.82) + 4.1288e^{22.856D} \tag{A.2}$$

A.3 Pumping drop estimation

The aim of the pumping cost indicator is to measure the energy cost to pump the shared material through an industrial network. Since this information depends on the pressure drop along the pipe, an expression for this term is necessary.

It is worth to note that this pressure loss is the power needed to move the fluid within the pipe, which is supplied by the pump.

Assuming the pressure drop is only a consequence of the energy loss due to the friction of the fluid with the pipe, the Bernoulli equation is expressed as follows:

$$P_{pump} = \Delta H_f g \rho F_v \tag{A.3}$$

where P_{pump} is the pressure drop along a pipe; ΔH_f, the energy loss due to the friction of the fluid; g, the gravitational acceleration; ρ, the density of the fluid; and F_v, the volumetric flow of the fluid.

On the other hand, the Darcy-Weisbach equation gives an expression for the ΔH_f, as a function of the friction of a fluid along the pipe and its velocity. This equation is expressed as follows:

$$\Delta H_f = f \frac{L}{D} \frac{v^2}{2g} \tag{A.4}$$

where f is the friction factor, L is the length of the pipe, D is the diameter of the pipe, and v is the velocity of the fluid.

It is worth to note that this equation depends on the friction factor,f. In general, this term is determined from a graphical form, using the Reynolds number of the fluid and the relative effective roughness of the pipe. However, a mathematical expression is needed to define the pumping cost indicator.

Accordingly, an approximation of the Colebrook equation is used (Genić et al., 2011). This expression calculates the friction factor, f, as a function of the relative effective roughness height of the pipe, ε, and the Reynolds number, Re. The following expression shows the Moody's approximation for the Colebrook equation

$$f = 0.0055 \left[1 + \left(20000 \frac{\varepsilon}{D} + \frac{10^6}{Re} \right)^{1/3} \right] \tag{A.5}$$

where the Reynolds number is defined as $Re = \frac{\rho v D}{\mu}$, with μ the dynamic viscosity of the fluid.

Finally, gathering all the previously equations (from Eq. A.3 to Eq. A.5), the pressure drop can be calculated as follows:

$$P_{pump} = 0.0055 \left[1 + \left(20000\frac{\varepsilon}{D} + \frac{10^6\mu}{\rho v D}\right)^{1/3}\right] \frac{Lv^2}{2D}\rho F_v \tag{A.6}$$

It is worth to note that F_v is the volumetric flow of the fluid. In order to express theoretical power of the pump dependent on the mass flow, the following expression can be used:

$$F = F_v\rho \tag{A.7}$$

with F, the mass flow of the fluid.

A.4 Resulting publications of this work

Journal of Cleaner Production 133 (2016) 99–116

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection

Guillermo Valenzuela-Venegas [a, b], J. Cristian Salgado [b], Felipe A. Díaz-Alvarado [a, *]

[a] Departamento de Ingeniería Química y Biotecnología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Av. Beauchef 851, Piso 6-poniente, Grupo de Ingeniería Sistémica de Procesos y Sustentabilidad, 8370456 Santiago, Chile

[b] Process Modeling and Distributed Computing Lab, University of Chile, Beauchef 850, Santiago, Chile

ARTICLE INFO

Article history:
Received 3 October 2015
Received in revised form
19 March 2016
Accepted 18 May 2016
Available online 27 May 2016

Keywords:
Sustainability indicators
Eco-industrial parks
Sustainability assessment

ABSTRACT

A variety of indicators is available for assessing the economic, environmental, and social aspects of an Eco-industrial park (EIP). The managers of a sustainability assessment over these parks should overcome an important task at the beginning of the study: to select indicators.

To support this activity, the challenge is to list and classify a large set of sustainability indicators. Consequently, the main achievements of this article are a wide search and classification of sustainability indicators, and the development of four criteria to filter indicators when assessing an EIP. A literature search in ISI Web of Science's database is presented to explore feasible indicators. The definition of 249 indicators is provided in an annotated list.

An important difficulty to use these indicators is to select a proper subset. To deal with this selection, this work proposes four criteria constructed to be functional, clear, and adaptable to the application context. The proposed criteria are: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*. The 249 indicators have been filtered using the four criteria, and have been classified according to three dimensions of sustainability (social, environmental, and economic dimensions).

The four criteria provide a formal way to filter a large set of possible indicators, improving the mechanism for their selection. In order to illustrate their application to select suitable indicators for the assessment of EIPs, a hypothetical case is constructed on the basis of an industrial park in Kalundborg. The selected indicators meet the four criteria and the evaluation goal.

Focusing on sustainability dimensions, many of the integrated indicators are related to the economic and environmental dimensions. Nevertheless, few of them are related to social dimension. Therefore, to cover the main aspects of each dimension of sustainability, a combination of single and integrated indicators should be included in this assessment.

Finally, four recommendations are made to select proper indicators during the sustainability assessment of an EIP: start with a large set of possible indicators, as those presented herein, preselect those indicators linked to the objectives of the assessment, apply the four criteria for indicators choice, and prefer comparative indicators.

Contents

1. Introduction 100
2. Methods for searching indicators 101
3. Results: indicators for eco-industrial parks: selecting criteria, sustainability dimension, and classification 102
 3.1. Criteria for selecting indicators on EIPs 102
 3.2. Classification of EIP indicators 103
  3.2.1. Classification by criteria for indicators choice 103

* Corresponding author.
E-mail addresses: gvalenzu@ing.uchile.cl (G. Valenzuela-Venegas), felidiaz@ing.uchile.cl (F.A. Díaz-Alvarado).

http://dx.doi.org/10.1016/j.jclepro.2016.05.113
0959-6526/

3.2.2. Classification by dimensions of sustainability 103
4. Discussions 104
4.1. Applying the criteria for indicators choice over 249 indicators 104
4.1.1. Understanding 104
4.1.2. Pragmatism 104
4.1.3. Relevance 105
4.1.4. Partial representation of sustainability 105
4.2. Applying the criteria for indicators choice to an EIP in Kalundborg: hypothetical case 105
4.2.1. Defining the hypothetical case 105
4.2.2. Applying the criteria for indicators choice 105
4.3. Sustainability dimensions 106
4.4. Final considerations 107
5. Conclusions 107
Acknowledgments 108
Indicators 108
References 114

1. Introduction

Industrial Ecology (IE) is a field of study focused on the stages of the production processes of goods and services from a point of view of nature, trying to mimic a natural system by conserving and reusing resources (Chertow, 2008). It studies the interaction of industrial development with environmental, social, and industrial system of different scales and aims at increasing business success, preserving environment and taking into account the life of local community (Chertow, 2007; Frosch and Gallopoulos, 1989). A specific area of this field is the Industrial Symbiosis (IS), which "engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow, 2000). The main conception of the IS is to transform the wastes or by-products from the activity of a firm, into inputs of another by means of connections between them.

An industrial park can be classified as an Eco-Industrial Park (EIP) if the community of businesses cooperate with each other, sharing resources (PCSD, 1997). This type of industrial parks can receive their denomination of EIP because of different reasons, related with sharing materials, energy, or infrastructure. It's also possible to develop green infrastructure or foster scavenger companies in the park, so Industrial Symbiosis is one possible aspect of EIPs. The most accepted definition of an EIP (Lowe, 2001) proposes a community of businesses located together on a common property. These businesses seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues.

A precursor to EIPs is the regional industrial symbiosis at Kalundborg, Denmark, uncovered in 1990 and then described in the international press (Knight, 1990). The participants share water, wastewater facilities, steam, fuel, by-products and waste products, that become feedstock in other processes (Chertow, 2008). The benefits of the symbiosis for this industrial park and the surrounding community are (National Research Council, 1997):

- The significant reduction in energy consumption and coal, oil, and water use.
- The reduction in sulfur dioxide (SO_2) and carbon dioxide (CO_2) emissions and improved quality of effluent water.
- The transformation of traditional waste products such as fly ash, sulfur, and biological sludge, into raw materials for production.

On the other hand, many authors have measured the benefits of applying IS to different sustainability projects about enterprise management and city design, in order to reduce the carbon emissions. For example, in the work of Yu et al. (2015), the authors make a quantitative evaluation of the effects of IS performance on carbon emission reduction in Xinfa Group, a comprehensive large enterprise group in China. They compare a scenario with IS and other without IS, and obtain that the first one exhibits a decrease of the carbon emission by 11% compared with the second one. Other example is the application of IS to cities presented in Dong et al. (2014b). In this work, the authors study the CO_2 emissions reduction potential in IS projects in two cities of China, Jinan and Liuzhau. They design new scenarios to apply in the both real project, including energy network, waste plastics recycling, and others. They obtain that the total reduction potential amounts to 4000 thousands tCO_2/year and 2300 thousands tCO_2/year in Jinan and Liuzhau respectively. Based on the results, the authors propose several policies to promote IS model in China. Both examples mentioned above show that IS is an important tool to reduce the environmental impact and to achieve the sustainability. This behavior may be extended to other aspects (as social), to promote the sustainability further than environmental or economic dimension.

Benefits of applying IS to an industrial park are related to economic, environmental and social aspects (Azapagic and Perdan, 2000; Harlem, 1987), and they are focused on (i) to improve the profits and resilience of the companies, (ii) to reduce environmental impact, and (iii) to care about the life of people in local communities. Some of them are mentioned in the works of Dunn and Steinemann (1998) and Gibbs (2008). Economic benefits are reducing of waste disposal costs and decreasing of purchase of raw materials. The environmental achievements are a reduction of waste production and of exploitation rate of new resource inputs (Dunn and Steinemann, 1998). The social consequences of IS are not obvious, since increased company profitability will produce a trickle-down effect on local spending and on jobs to the benefit of the wider local population (Gibbs, 2008). Other social effects are related to life style and health in the surroundings of the EIP. While the effects of economic and environmental benefits are easy to measure because they are often assessed in an industrial context, the social effects require a suitably evaluation because they are difficult to quantify and are not usually assessed. Therefore, all the sustainability dimensions must be properly assessed in order to quantify the total effect of applying IS to an industrial park.

To choose the best EIP configuration, a measurement of sustainability is required to facilitate the comparison of different alternatives. An optimal EIP minimizes the negative impacts and maximizes the positives ones as a result of the activity of the park. However, how the social, environmental, and economic aspects of sustainability in an industrial park could be measured?

The answer comes from the quantitative sustainability indicators. Using this indicators it is possible to assess the effectiveness of an industrial park in terms of dimensions of sustainability development. This quantitative sustainability assessment of an EIP is necessary to ease the comparison between different configurations and to support decisions on its design. Some examples of these indicators are *Value Added* (economic), *Ozone Depletion* (environmental), and *Income Distribution* (social) (Azapagic and Perdan, 2000). There are also integrated indicators grouping two or more of these single indicators. For instance, Eco-efficiency includes one economic indicator and three environmental indicators (raw material consumption, energy consumption, and CO_2 emissions) (Park and Behera, 2014).

Other tools used to analyze and to assess the sustainability level of industry are Life Cycle Analysis (LCA) and Material Flow Analysis (MFA). LCA is an analytical tool for a systematic evaluation of the environmental impact of a product (or services) on its completely life cycle (Chertow, 2008; Curran, 1996). It offers a quantitative comparison between different alternatives of product design in order to analyze each of them and to select the best one. MFA is similar tool to LCA, and is based on methodically organized accounts in physical units and the principle of mass balancing (OECD, 2008; Sendra et al., 2007). The use of this tool can provide an integrated view of the economy and the environment; capture flows that are not used and produce a relevant impact; and reveal how flows of material shift among countries and within countries. It can analyze various scales of the industry (as shown in Fig. 1) with different instruments depending on the issue of concern and the goal of the assessment. Both tools are widely used in the assessment of industrial parks and EIPs (Chen et al., 2013; Dong et al., 2013; Sendra et al., 2007; Wen and Meng, 2015; Yang et al., 2012; Zhang et al., 2016) and use indicators to measure the activity of the actors.

On the other hand, there are many articles about IS and the dynamic organization of an EIP (Boons et al., 2011; Chertow, 2000, 2007, 2008, 2012) where the authors explain the bases and propose models of IS. There are also many examples about EIP projects, which mimic the development of the regional industrial symbiosis in Kalundborg (Baas, 2011; Behera et al., 2012; Côté and Cohen-Rosenthal, 1998; Geng et al., 2010a; Sokka et al., 2011; van Beers et al., 2007; Zhang et al., 2010). There are works related to the design of EIPs where the authors optimize economic, environmental, and social aspects of each park (recently Boix et al. (2015) wrote a complete review on this topic). However, to our knowledge there is no article focused on a wide repository of EIP indicators and their applicability to a quantitative assessment on the EIP sustainability. Besides other non-quantitative indicators could be useful to assess an EIP, this work covers quantitative indicators because of their wide application in sustainability assessment, and the suitability of this type of indicators to compare different EIP configurations or their progression in time (Azapagic and Perdan, 2000; Zhu et al., 2010).

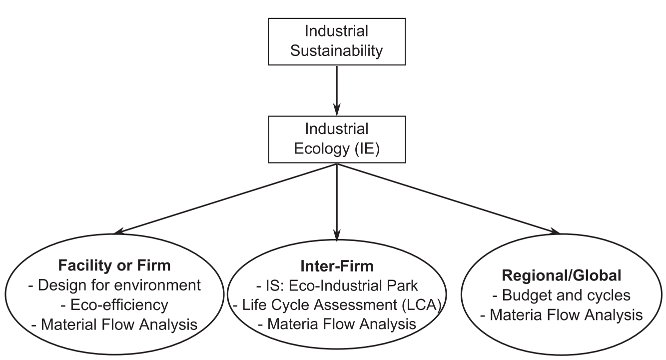


Fig. 1. Conceptual model of the Industrial Ecology level. IS transforms the wastes or by-products from a firm into inputs of another by means of connections between them. Information taken and modified from Chertow (2000).

An important difficulty to use indicators when assessing an EIP is to select a proper set among all possible indicators. To overcome this difficulty, the goals of this article are to develop criteria in order to construct suitable indicators, to build a database of single and integrated indicators, and to classify them focusing on the assessment of EIPs. An important challenge is to cover a wide set of indicators. Accordingly, the keywords for this search have to be wide. After finding these indicators, a set of filters are presented herein for their classification aiming at sustainability. Therefore, a broad search and the respective classification of sustainability indicators are presented as results to the readers.

First, we present the indicators that can be found in the literature and propose criteria to select or construct suitable indicators to assess an EIP. We also present two classifications of these indicators: the compliance with the criteria proposed herein and the covering of the three dimensions of sustainability. For studying the applicability of the four criteria to select suitable indicators, a hypothetical case is presented. After a critical analysis, the last section summarizes the desirable features for an indicator to assess an EIP.

Instead of using these four criteria, the managers could select the indicators for the assessment of an EIP based on their own experience. Nevertheless, the four criteria presented herein provide a formal way to filter a large set of possible indicators, improving the mechanism to select proper indicators.

Naturally, this is not the only strategy to filter variables. Is possible to perform a multiple criteria data envelopment analysis (MCDEA) (Zhao et al., 2006), addressing qualitative and quantitative criteria. MCDEA is used to rank the alternatives through the consideration of the relative membership degree of qualitative factors in quantitative data. However, this type of analysis requires data. The criteria developed in the present work assume a scenario where the data is not yet provided.

2. Methods for searching indicators

Sustainable indicators are essential to assess the effectiveness of an EIP regarding the axes of sustainable development (economic, environmental, and social dimensions) (Azapagic and Perdan, 2000; Harlem, 1987). These indicators have to capture the main characteristics of an EIP: to compare with other contexts and to support decisions concerning its configuration. The comparison of an EIP can be done with: (i) its historical performance, (ii) a new configuration of the same park, (iii) or other parks.

For a complete sustainability assessment, the indicators must quantify all impacts (internal, external, positives, and negatives) produced by the geographical location of firms and their connections through an industrial network.

This repository of indicators is based on publications registered in the ISI Web of Science (ISI-WoS). The keywords used in the search are subject to the following logic sentence: (indicator OR quantitative assessment) AND (“industrial park” OR “industrial symbiosis”). The search was performed over the abstract, title, and keywords of all publications in the database with the ISI-WoS searching engine. Through this search we found 51 articles published between 2000 and 2014.

The keywords used in the search are generic because we propose a wide search considering all the indicators used in assessments. The resulting indicators could include indicators with no relation to sustainability. However, the resulting indicators also include those sustainability indicators not presented as sustainability indicators in bibliography. Therefore, after processing the results, we classify the resulting indicators in the respective dimension of sustainability and the adjustment to the criteria for selection.

In order to achieve the goals of this article, these publications were filtered by document type, publication year, and topic. The works passing this filter are related to industrial assessment and provide a set of indicators. Thus, we exclude publications about dynamic organization of EIP, studies of diseases caused by proximity to an EIP, and other specific evaluations.

Finally, we consider 32 articles published between 2000 and 2014 in which industrial assessment is the main topic and which includes a set of indicators.

To propose criteria for indicators choice, is necessary to cover the context of the sustainability assessment. A review of criteria proposed in literature is performed in order to take into account previous efforts to guide the indicators selection. These criteria, proposed for a wide industrial context, will be adapted to the assessment of an EIP. This adaptation mainly considers the applicability of the criteria and their suitability to an industrial analysis of sustainability.

3. Results: indicators for eco-industrial parks: selecting criteria, sustainability dimension, and classification

3.1. Criteria for selecting indicators on EIPs

Sustainability indicators allow to assess economic, environmental and social aspects of a process, a company, the development of a product, a city, an industrial park, and others. When applied to an industrial park, those indicators must capture the main characteristics of a process from a specific angle of the sustainability assessment. They must reflect the negative and positive impacts resulting from the activity of an EIP, focusing on a specific dimension of evaluation.

To reflect those characteristics of an EIP, indicators must achieve minimum requirements because they are often oversimplified, they include only some important characteristics, or some of them are difficult to quantify or understand (Azapagic and Perdan, 2000). As a general framework, other authors (Azapagic and Perdan, 2000) have presented a standardization of industrial indicators for their application to companies and included the following characteristics for them:

- Simple and informative.
- Relevant to the three dimensions of sustainability.
- Generic for all industry and sector.
- Normalized by a certain value depending on the goal of the assessment.

To achieve the goal of the evaluation and to assess different scales of companies, the authors Azapagic and Perdan (2000) define three types of analysis: product-, process-, and company-oriented analyses. These analyses normalize indicators by a certain value or functional unit. The first one is related to products sharing the same function but made by different competitors. The second one refers to the operation and production of a plant. The last one is focused on the performance of a company or of its parts. Each analysis informs the levels of sustainability (Azapagic and Perdan, 2000).

Other alternatives are the risk analysis (Tixier et al., 2002) and exergy analysis (Dewulf and Van Langenhove, 2002) among other types of analysis. As the classification based on scale is related with the sustainability assessment of an EIP, this type of analysis will be adopted. Specifically, the process-oriented analysis allows to identify aspects to overcome within a set of connected processes.

Even though it's possible to avoid the scale classification, this logic allows to properly separate these analyses developed for different types of assessment, most of them oriented to single entities: single companies, single processes, or single products. An alternative analysis could have a systemic view based on the integration of processes or companies. However, this type of analysis could also be classified in the former scale-based categories because an integrated process is still a process, and the integration of companies can be considered a new entity with the characteristics of a larger company. In general, the scale-based classification of analyses is well adapted to the sustainability assessment in an industrial context.

Most of the articles referenced in this work can be classified as process-oriented analyses. The goal in this classification is to separate the attention points of the variety of feasible analyses, looking at the outputs, operations, or corporations. Regarding an EIP, the most important factors are the chemical/physical operations and the energy and mass input/output flows. Therefore, we considered a process-oriented analysis, since the performance of an EIP is mainly related with their operations and connections.

Ten years later, Zhu et al. (2010) reported four characteristics of EIP indicators to evaluate the incorporation of candidate companies to an EIP. They adopted the following criteria for selecting indicators (Zhu et al., 2010):

- Comprehensive: In choosing scale indicators, the indicators must consider various factors including capacity of an EIP to incorporate a new enterprise and the characteristics of an enterprise, e.g., resource use and pollutant production.
- Available: Indicators must be measurable and based on existing (easy to obtain) information.
- Relevant: Indicators must be relevant to the EIP development goal and to the long term strategy of participating companies.
- Practical: The measurement and monitoring of the indicators are practical and reliable given the available resources in the park and in companies. The value of the indicators must also be easy to obtain.

Taking the aforementioned criteria presented by Zhu et al. (2010), the *Availability* criterion can be discussed. Since the creation of an inventory is a complex and expensive work, the indicators with less complexity and less cost have an advantage. Nonetheless, is it important to have existing information? Existing information tend to be inaccurate and questionable, so industries measure their behavior with a specific scope. To our understanding, the key point in this criterion is the advantage of *easy-to-obtain* information, not the availability of existing information. Using the *Availability* criterion proposed by Zhu et al. (2010) with focus on existing information could impose a bias when selecting sustainability indicators, preferring those based on existing information instead of other *easy-to-obtain* options adjusted to the purpose of the study.

Most of the criteria proposed by Zhu et al. (2010) for selecting indicators for an EIP assessment are similar to the characteristics for industrial indicators presented by Azapagic and Perdan (2000). The main difference is the evaluation goal because the first one is based on product-, process-, and company-oriented analyses (generic case for industry), while the second one is only based on a process-oriented analysis (specific case for an EIP). Another difference is the selected criteria for defining proper indicators.

Since the criteria presented by Azapagic cover the generic case of an industrial analysis (product-, process- and company-oriented analyses) and the criteria reported by Zhu are process-oriented, we define new criteria more similar to the last ones. It is important to observe that the criteria by Zhu cannot be used directly in our scenario because they are only oriented towards the admissions of new members in an EIP.

The proposed new criteria are focused on selecting indicators to assess the EIP behavior. This new set is proposed combining the former criteria described by Azapagic and Zhu, and modifying some of them. This new reference to select indicators is constructed as follows.

We put forward three modifications on this base:

The first one (i) is to join *available* and *practical* features together, because both address calculation. This criterion will be called *pragmatism* and will comprise all the features of the aforementioned criteria.

Another modification (ii) concerns the feature *comprehensive*. We propose a modification to reflect the simplicity of the indicators as exposed by Azapagic and Perdan (2000). Accordingly, the meaning of the *understanding* criterion aims to simplicity instead of variety as the former *comprehensiveness* criterion by Zhu et al. (2010). The new criterion does not aim to wideness. It aims to previous formation of the personnel and the tuning of the indicator with this training. The original idea proposed by Zhu can now be represented in the combination of the concept *relevant*. Therefore, EIP indicators must present the following criteria: *understanding*, *pragmatism*, and *relevance*. An EIP indicator exhibits the criterion *understanding* if it is easy to understand (simple). It shows *pragmatism* if the characteristics are measurable by input–output flow data or surveys, and if its value is easy to obtain. The availability of information before the assessment is helpful but not critical, so its existence is not included in this criterion. An indicator shows *relevance* if it is engaged with the goals of both the EIP and firms.

The last modification to basic criteria (iii) is the addition of a new criterion, *partial representation of sustainability*, to state the proper representation of a dimension of sustainability by an indicator. All these definitions are shown in Table 1.

In Section 4 we focus the discussion on the performance of the indicators showed in Section 3.2 using the selected criteria as a filter.

3.2. Classification of EIP indicators

3.2.1. Classification by criteria for indicators choice

Several indicators have been used to evaluate the impact of an industrial park. For instance, in Lu et al. (2012), the authors assess the emissions of an EIP using a metabolic model and defining suitable indicators for this purpose. Other authors define considering energy performance (emergy and exergy) (Geng et al., 2010b; Jiang et al., 2010) or using Life Cycle Analysis (LCA) or hybrid-LCA strategies (Azapagic and Perdan, 2000; Chen et al., 2011).

At the beginning of a sustainability assessment, managers have to select indicators among all possible options. Different authors use a variety of indicators to evaluate the goals of EIPs or of companies. To ease the selection of indicators, a repository has been constructed through the search described in Section 2. Table 2 presents all the indicators used in these articles, including their definitions. Table 2 also presents an evaluation of the criteria defined in Section 3.1 for each indicator. Fig. 2 shows a histogram for each selection criterion, as a synthesis of the classification in Table 2. The green bars reflect the number of indicators meeting each criterion separately, and the red bars show the number of indicators classified according to each sustainability dimension. Additionally, single and integrated indicators are presented separately in order to analyze each category.

On the other hand, each indicator can also be classified according to its dimensions of sustainability (social, environmental or economic one). The following section is focused on this issue.

3.2.2. Classification by dimensions of sustainability

Sustainability dimensions are economic, environmental, and social. Indicators in Table 2 assess these dimensions and therefore they can be classified in these categories. Column *Dimen. of Sust*. in Table 2 shows this classification.

For assigning a category to an indicator we consider its main objective. Thus, if the main aspect assessed by the indicator is the use of resource, water, energy, by-product, and waste, it will be classified as environmental, even if this main aspect has also an economic or social impact. Recycling and reusing of material or energy will be also classified as environmental. An indicator will be considered as economic if it is related to the economic performance and capacities, or measures production efficiency. An indicator will be social if it is related to impacts on local community or workers of an EIP.

Some indicators, like ratios, assess more than one dimension. Examples of them are the *Chemical Oxygen Demand (COD) production per unit Industrial Value Added (IVA)* or the *ratio of industrial*

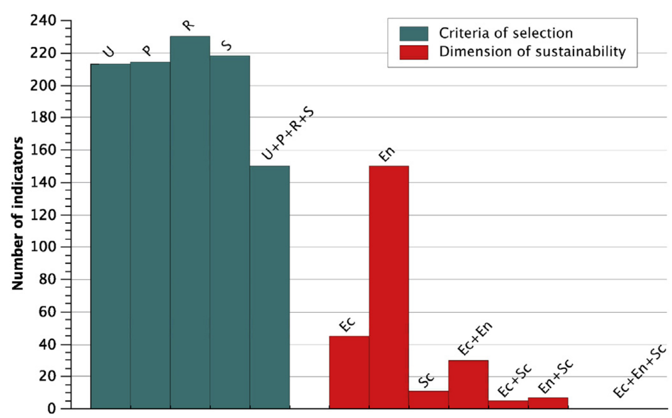


Fig. 2. Histogram of indicators by criteria of selection and sustainability dimension. U: Understanding; P: Pragmatism; R: Relevance; S: Partial Representation of Sustainability; Ec: Economic; En: Environmental; Sc: Social.

Table 1
Criteria for indicators choice and their description.

Criterion	Description
Understanding	An indicator must be easy to understand.
Pragmatism	An indicator must be measurable, its value has to be easy to obtain.
Relevance	An indicator must be relevant to the goal of EIP development and to enterprises' future.
Partial representation of sustainability	An indicator must properly represent one or more sustainability dimensions, allowing to compare configurations or historical progression of an EIP.

waste water utilization (Bai et al., 2014; Zhu et al., 2010). In these cases, we consider all the dimensions evaluated by the indicator.

Accordingly, an indicator can evaluate one or more dimensions of sustainability. The classification of an indicator as *single* or *integrated* refers to this issue. In both cases, the sustainability dimensions addressed in the assessment are informed in Table 2 including the number of dimensions in the corresponding column. In the case of integrated indicators, the dimensions included are separated by the character /. An indicator will be single if it evaluates only one dimension. Namely acidification potential (AP), which measures the contribution of SO_2, nitrogen oxides (NOx), hydrogen chloride (HCl), ammonia (NH_3), and hydrogen fluoride (HF) to potential acid deposition (Azapagic and Perdan, 2000), in essence it is an environmental indicator. On the other hand, if the indicator assesses two or more dimensions, it will be considered as an integrated indicator. An example is emergy-LCA index, which is a ratio of economic to environmental aspects (Brown and Ulgiati, 1997; Song et al., 2013; Yang et al., 2003). Fig. 2 shows a histogram for each sustainability dimension and their combination in integrated indicators. It is important to remark the counting in this histogram, because single and integrated indicators assessing environmental aspects have been counted separately in their respective bars: En, for single indicators; and Ec + En, En + Sc, for integrated indicators. The same separation is valid for the other sustainability dimensions.

4. Discussions

The total number of indicators studied on this article is 249. They have been classified using the four criteria selected in Section 3.1 and the dimensions of sustainability. The assessment managers should take into account the context of their application. This context could make a difference in the classification of indicators in our proposed categories. For instance, the availability of information or the formation of personnel could justify a change in *pragmatism* and *understanding* of an indicator, respectively.

As can be observed in Fig. 2, many indicators meet one of the four criteria, and only 150 meet all of them. Thus, some indicators are not suitable for assessing the activity of an EIP. Most of the rejected indicators need reserved information from companies, which is not easy to obtain. Other indicators were rejected because they were not directly understandable in an industrial context and demands a higher level of training for process managers than normal indicators.

Regarding the assessed dimension, the economic and environmental aspects have the largest number of single indicators (45 and 150 respectively), and only 11 are related to the social aspect. Integrated indicators have presented a similar distribution. There are many indicators evaluating the economic and environmental dimensions (30 indicators), and only a few of them are related to social aspects (5 economic-social and 7 environmental-social). On the other hand, there are no integrated economic-environmental-social indicators. The aforementioned distributions reflect the lack of indicators covering the social aspects and the need of constructing such indicators for the sustainability assessment of EIPs.

In the following sections the applicability of the four criteria over the indicators of Table 2 are analyzed in order to understand what indicators are included or excluded under each of them. A hypothetical case related to an EIP in Kalundborg is also presented for selecting sustainability indicators using these four criteria. After that, the classification using the sustainability dimensions over the set of indicators is studied and discussed. Finally, a general discussion related to the main characteristics of suitable indicators for the EIP sustainability assessment is presented.

4.1. Applying the criteria for indicators choice over 249 indicators

The proposed criteria for classifying the performance of EIP indicators are: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*. Indicators in Table 2 were filtered using these four criteria in order to simplify their further selection. The application of the four criteria is analyzed highlighting the attributes of the rejected indicators in each category. It is important to remark the flexibility of this filter. Each context of application could change the classification of indicators in three categories, because the *understanding*, *pragmatism*, and *relevance* depend on the context, because of the preparation of the personnel, availability of data, or measurement feasibility. These criteria also depend on the purpose, taking into account the goal of the assessment and the projected comparison after the analysis.

4.1.1. Understanding

In general terms, an indicator has been excluded from this category if its definition is hard to understand in an industrial context. Some indicators study the industrial interactions using a rationality based on metabolic pathways, as in biological networks. Thus, they were excluded according to the criterion of *understanding*. For instance, in Lu et al. (2012), the authors define a *mutualism index* to reflect the ratio of positive to negative mutualism relationships between entities. These type of indicators were excluded from this category, because it is necessary to manage the concept of mutualism in an industrial context for their application. Emergy is referred to the energy required to provide a given product or flow (Odum, 1996). All emergy-based indicators were excluded from this category because the use of emergy concept is not easy to understand in an industrial environment. An example is *Absolute emergy saving* (Geng et al., 2014) that uses the emergy concept to measure savings concerning, for instance, nonrenewable resources and purchased resources, resulting from sharing by-products between companies.

It is important to highlight the hypothesis sustaining this filter: It has been supposed the use of these indicators by process managers. Naturally, if the assessment is executed by professionals with environmental, economic, and social formation, the *understanding* criterion impose a less restrictive filter. The knowledge about indicators can be modified at any context with information available in measurement manuals (OECD, 2008).

4.1.2. Pragmatism

Some indicators are not easily measurable because they need a deep knowledge about the companies in the park. For instance *long term vision*, which needs information about projections and strategy of each company (Phillips et al., 2006). Since this information is not always available, all indicators exhibiting these characteristics were excluded under the criterion of *pragmatism*.

Among detailed analyses, LCA is probably the most important tool. It requires detailed data from companies participating in the production process, inside and outside the industrial park. The quality of information has to be guaranteed to support the analysis, so companies conduct audits. However, within a context, this information could be available or not. The necessary information to back up an LCA can already exist or its measurement can be possible. In both cases the related sustainability indicators are pragmatic. Nevertheless, the necessary information could be non-existent or impossible to be measured because of technical or economic reasons, turning the involved indicators in non-pragmatic. Consequently, the availability of information or its feasibility of measurement justify the classification of an indicator as pragmatic or not.

We supposed no detailed information is available when performing the assessment, so footprint-like indicators have been filtered because of the *pragmatism*. Is important to remark this classification is flexible and the *pragmatism* filter can change with the availability of information.

For instance, there are indicators using the carbon footprint to quantify the emissions. Although there are methodologies for measuring the carbon footprint, there is no warranty about the behavior of the companies in this area. Applying a carbon footprint with an LCA approach requires detailed information about companies and their providers from outside the park. This is a highly valuable approach. Nonetheless, its application is hard within the boundaries of an EIP. Since these indicators were proposed in a complete LCA approach, this class of indicators was excluded under the criterion of *pragmatism*. However, indicators applied under a Hybrid-LCA approach (Azapagic and Perdan, 2000) were accepted and, in this case, such indicators are considered pragmatic.

Other indicators reflect the presence or absence of specific institutions in the park. Even though this information is easy to obtain, it is not measurable using a continuous variable (continuous numerical space). Therefore, they were excluded under the criterion of *pragmatism* because they are only measurable with a binary variable (1 = presence; 0 = absence), and this class of variables were not fully integrable with other indicators during the sustainability assessment.

4.1.3. Relevance

The main units in the sustainability assessment of an EIP are firms and the EIP itself. A firm is the basic unit of an EIP and its activity causes economic, environmental, and social impacts on the whole park. Some indicators for sustainability work as black boxes instead of gray boxes over the EIP. A black box work as a simple input/output model of the whole park, while a gray box model includes information about partial steps (processes or firms). The representation of the complete activity of firms is impossible, and disregarding their existence is an oversimplification. As an example, we can analyze the indicator *output rate of land*, which measures the value generated in the EIP per unit of used land (Su et al., 2013). This sustainability indicator only takes into account a sustainability assessment of the whole EIP without focus on each participating company.

Another group of indicators is focused on products, without paying attention to firms or EIP performance. As an example, the indicator *product durability* reflects the durability of a product and is oriented to consumers. All these indicators were excluded under the criterion of *relevance*, because they do not aim to assess an EIP as proposed in Section 1. Relevant indicators allow to give feedback to companies in the EIP.

4.1.4. Partial representation of sustainability

Some of the indicators can be used to make a comparison between enterprises or products. However, some of them do not afford a comparison between the EIP and its history, or between different configurations of the park. Even though they make a suitable assessment for any sustainability dimension, these indicators do not achieve the second objective of the *partial representation of sustainability* criterion. For instance, the indicator *percent-added of park energy productivity*, can only be used to compare different firms incorporated in a park (Zhu et al., 2010).

Another set of indicators use characteristics of an industrial plant, when placed on different location. Therefore, this set of indicators was excluded from the *partial representation of sustainability* category because the comparison between firms in a park is not supported.

On the other hand, it is noteworthy that all indicators in Table 2 assess some dimension of sustainability, and thus they meet the first part of the definition of *partial representation of sustainability*.

4.2. Applying the criteria for indicators choice to an EIP in Kalundborg: hypothetical case

The formation of the regional industrial symbiosis in Kalundborg, Denmark, is attributed to an evolutionary progress of exchanges between firms, into a complex network of symbiosis interactions (Jacobsen, 2006). The main facilities in this regional integration are an oil refinery, a power station, a gypsum board facility, and a pharmaceutical company. Other firms have been located around these companies. The goal is to share ground water, surface water and wastewater, steam, fuel, and others by-products used as feedstock in other process (Chertow, 2000, 2008).

In order to evaluate the effectiveness of the criteria presented herein to select suitable indicators for the sustainability assessment of EIPs, we propose a set of indicators from Table 2 to assess the example from a subset of companies in Kalundborg. A hypothetical example is constructed, assuming the availability of some data and the goal of the EIP composed by:

- Novo Nordisk.
- Novozymes.
- Novo Nordisk & Novozymes Land Owner's Association.
- Novozymes Wastewater & Biogas.

These entities share energy (steam, warm condensate, and district heating), water (surface water, cleaned surface water, and waste water), and materials (ethanol waste and biomass) (Kalundborg-Symbiosis, 2015).

We remark the demonstrative purpose of this example. While the real case from Kalundborg is far more complex, the instance will be simplified to illustrate the applicability of the criteria presented in this work.

4.2.1. Defining the hypothetical case

Kalundborg is a regional industrial symbiosis where many companies share water, steam, by-products, or other resource, in order to increase the level of sustainability. Let's assume the following ideas to illustrate the application of the criteria for indicators choice, in the context of the aforementioned EIP composed by four participants:

- The main goals of this park are to reduce the main gases emissions (CO_2, NOx, and SO_2) and to increase the economic returns for each firms in the EIP.
- In this context, the achievement of the goals will be measured by a technical assistant from a Government department.
- This assistant has a basic academic training on process and environmental subjects.
- The available information to assess this EIP is a list of input/output flows of each industrial plant in the park.
- The goal of the assessment is to measure the main economic and environmental aspects of the park.

Now, based on the information and the four criteria previously identified, we propose a set of indicators to be checked by the assistant.

4.2.2. Applying the criteria for indicators choice

- **Understanding**: This criterion depends on who is assessing the EIP. In the example, the applicant has a basic academic training on process and environmental subjects. As the supposed applicants in the definition of the *understanding* criterion are professionals with analogous formation as the hypothetical applicant in the example, all the indicators classified as *understanding* on Table 2 may be used to assess this EIP in Kalundborg. For example, *CO_2 emission indicator*, *COD generation intensity*, *SO_2 emissions per added industrial value*, and *Net economic benefit*. In this case, the set of indicators has been reduced from 249 to 209.

- **Pragmatism**: This criterion depends on specific information, which reflects if the indicators are based on available or easy to obtain information. In the example, the available information is the input/output data of each firm in the park, therefore, only those indicators that measure characteristics using the input or output flow data are included. For instance, *Acidification*, *Air pollution*, *Direct Material Input*, and *Industrial value-added per capita*. The set of indicators has been reduced from 209 to 175.
- **Relevance**: This criterion considers the focus on the assessment and the goal of the evaluated park and firms. In the example, the goal of the EIP in Kalundborg considers the reduction of main emissions (CO_2, NOx, and SO_2) and the increase of economic return for all firms in the EIP. In this sense, the indicators as *Industrial value-added per capita*, *Increase company competitiveness*, *Park SO_2 emission change rate %*, *CO_2 emission indicator*, or *Eco-efficiency* may be used to assess these goals. The set of indicators has been reduced from 175 to 162.
- **Partial Representation of Sustainability**: This criterion considers the assessment of a sustainability dimension and the possibility of performing a comparison with the history of the EIP or with other feasible configurations. In the example, the indicators classified as environmental (En), economic (Ec), and those integrating both dimensions (En/Ec) are suitable for the assessment. The selected indicators have also allowed a comparison of the EIP performance with that of other feasible configurations or with its own performance in time. The set of indicators has been reduced from 162 to 131.

The application of the four criteria formalizes the indicators choice to assess the EIP. Despite the variety of economic and environmental indicators achieving the four criteria, they could be redundant. Thus, we selected the most representatives of each class to use them in the evaluation of the illustrative EIP in Kalundborg (see Fig. 3).

In Jacobsen (2006), the author uses a similar set of indicators to study the progress of the IS in the regional integration in Kalundborg: saving cost by substitutions; reduction of carbon dioxide, sulfur dioxide, and nitrogen dioxide emissions; and, heat saving and water consumption. In this work, Jacobsen also selects heat saving and water consumption as indicator, because he has specific information about the power plant in Kalundborg, and the goal of the assessment is to evaluate the symbiotic exchange between companies. In our case, we have only input/output flow data and the goals are to measure the main economic and environmental aspects of the park.

4.3. Sustainability dimensions

If the purpose is to optimize an EIP, then the problem grows rapidly in size with the number of indicators or objectives (Copado-Méndez et al., 2014; Díaz-Alvarado, 2015). In this context is preferable to have more dimensions of sustainability integrated in less indicators. This approach involves an oversimplification risk. Since this issue depends on the objective of the sustainability assessment, it was not considered in the criteria detailed in Section 3.1. The oversimplification risk has to be considered during the selection of indicators for the assessment.

The oversimplification risk comes from the selection of an integrated indicator instead of a set of single indicators. The integrated indicators could avoid details when compared with a set of single indicators. Other possible impact is the sensitivity difference between integrated or single indicators when describing real cases. For instance, assume we change the configuration of a park and a single indicator changes its value by 50%. Is this difference also represented by an integrated indicator? Is the reality well-captured by the single or the integrated indicator? Is important to remark the higher sensitivity of single indicators when compared to integrated indicators.

The desirable flexibility of single indicators to represent reality has a trade off with the increase of complexity. The level of detail is the cause of both. A proper set of indicators has to be pragmatic in

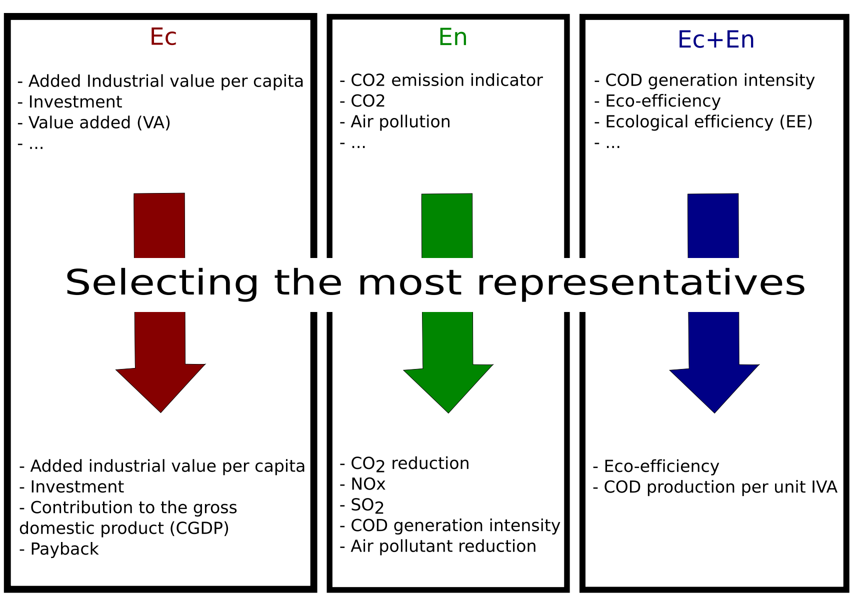


Fig. 3. Set of indicators proposed to assess the illustrative EIP in Kalundborg.

the sense of an approachable complexity, not sacrificing its relevance in terms of the flexibility to represent the reality.

Even though we found indicators meeting the four criteria, no indicator considers the three dimensions of sustainability. However, we found some indicators which covered two dimensions. For instance the ratio indicators measure the emission of certain pollutant divided by the added industrial value in products. In general, this type of integrated indicator takes into account an environmental characteristic of a system divided by an economic feature generated by the system. The most common environmental characteristics are resource consumption, generated emissions, reuse of by-product, water use or reuse, and amount of waste generated. The added industrial value is the most common economic characteristic. On the other hand, some indicators consider both economic and environmental characteristics as a measure of the energy required to provide a product or flow. An example is *emergy economic efficiency index*. It reflects the amount of local resource exploited compared to the amount of emergy investment (Brown and Ulgiati, 1997; Song et al., 2013; Yang et al., 2003). When used these indicators are not easy to classify into sustainability dimensions, because some of them commonly do not meet the criterion of *understanding*. The use of emergy concept is mainly associated with the energy. Then it should be considered as environmental, and its classification depends on the aim of the evaluation.

There are also integrated indicators known as Eco-efficiency indicators, which assess economic and environmental aspects as the ratio indicators. In general, they use the added industrial value divided by the sum of some characteristics measured by LCA.

The integrated indicators assess mainly economic and environmental aspects, and a few of them take into account the social dimension. There are two social integrated indicators applicable on EIPs: environmental-social and economic-social. The first one considers the specific emissions affecting the local community and the environment. For example, *health* indicator measures the air and water pollutant that could promote diseases as well as waste discharged by factories on the surrounding area (Chen et al., 2012a). The second one reflects an economic flow from companies to the local community or workers in the park. For instance, the indicator *expenditure on health and safety (EHS)* indicates the budget invested by an enterprise (an economic flow) in health and safety (social aspects) for its workers (Azapagic and Perdan, 2000).

Even though these integrated indicators meet the four criteria and assess two dimensions of sustainability, they do not cover all the factors related to a suitable social assessment. For instance, they do not evaluate the level of satisfaction of the surrounding population, the employment contribution of the enterprises, etc. In order to solve this lack of integrated indicators, single indicators may be considered. However, the use of these indicators must be aligned with the goal of the assessment and simplify the comparison between feasible configurations.

As integrated indicators do not cover the social dimension properly, single indicators included in Table 2 should be used in order to couple this topic in the analysis.

4.4. Final considerations

Many indicators classified in this article assess the sustainability dimensions and meet the four criteria. Even though there are plenty of them, the assessment coordinator must wonder if all these indicators are necessary to assess a park. The use of the indicators will depend on the park under evaluation. Not all of these indicators show a significant change when comparing different feasible configurations of a park. Another possibility for potential reduction is revealed if the Pareto dominance structure of different parks is preserved when certain indicator is absent (Brockhoff and Zitzler, 2006; Díaz-Alvarado, 2015). Thus, the selected indicators must be significant for the assessed parks to represent the change in their characteristics. The selection of significant indicators can be addressed with the Pareto dominance analysis (Brockhoff and Zitzler, 2006; Díaz-Alvarado, 2015), artificial neural networks (ANN) or genetic programming (GP) (Muttil and Chau, 2007).

On the other hand, the four criteria allow to select suitable indicators to evaluate EIPs but these indicators do not necessary assess the three sustainability dimensions (economic, environmental, and social). In Jacobsen (2006), the authors focused on a quantitative analysis of the economic and environmental performance of regional industrial symbiosis in Kalundborg. In order to measure these aspects, they used a set of economic and environmental indicators: saving cost by substitutions; reducing carbon dioxide, sulfur dioxide, and nitrogen dioxide emissions; and heat saving and water consumption. In this case, all these indicators pass the four criteria and therefore, they are suitable to evaluate the progress of the IS in the industrial park. Now, if we change the goal of the assessment and add a social analysis, the selected set of indicators would not be enough. In this case, this set will pass the four criteria. Nevertheless, they will not cover all the important aspects of social dimension, like investment of firms on near community and the job creations. Thus, to select a suitable set of indicators to assess EIPs, they should cover all the main aspects of the sustainability assessment and to achieve the four proposed criteria.

Finally, to select a suitable set of indicators during the sustainability assessment of an EIP, four recommendations are made: start with a large set of possible indicators, as those presented herein, preselect those indicators linked to the objectives of the assessment, apply the four criteria for indicators choice, and prefer comparative indicators.

5. Conclusions

In this work, we list a significant set of sustainability indicators in order to select a suitable subset to evaluate an EIP. Accordingly, four criteria were proposed to classify them all: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*. Under this classification, the excluded indicators use definitions difficult to understand in an industrial context, need a deep knowledge about companies in the park, only consider the EIP scale excluding the performance of the firms, or do not allow a comparison between feasible configurations of a park.

It is important to highlight the flexibility of the filter imposed by the criteria for indicators choice. Each context of application could change the classification of indicators in three of the four categories, because the *understanding*, *pragmatism*, and *relevance* depend on the context. From this point of view, the classification of indicators performed in this article can vary with the context. Future directions could report the most used indicators in the sustainability assessments of EIPs as an orientation to managers. This improvement should be translated to the *understanding* criterion, because the most applied indicators are also the most understood. We also suggest to develop a pathway of the historical progression of an EIP following the change in the value of some indicators. This pathway could be a reference to new successful cases of Eco-industrial parks.

Under a hypothetical case, a set of suitable indicators were selected to assess an illustrative EIP in Kalundborg. These indicators were: *added industrial value per capita*, *investment*, *contribution to the gross domestic product*, *payback*, *CO_2 reduction*, *NOx*, *SO_2*, *COD generation intensity*, *air pollutant reduction*, *Eco-efficiency*, and *COD production per unit of IVA*. They were selected by using the four criteria and choosing the most representative ones from this resulting set of indicators. All of them achieved the four criteria and met the goal of the evaluation.

On the other hand, indicators were also classified under the assessed dimension of sustainability: *single* for one dimension, and *integrated* for two or more dimensions. This classification showed an abundance of integrated indicators assessing economic and environmental dimensions, and a few of them are related to the social dimension. To solve this problem, single indicators may be considered.

In order to optimize an EIP, the integrated indicators are useful to reduce the number of indicators during the assessment. Classified indicators assess two dimensions of sustainability: economic-environmental, environmental-social, or economic-social. Single indicators should also been included because the integrated indicators related to the social dimension do not cover all the main aspects.

Finally, to construct or select suitable indicators for the sustainability assessment of EIPs, they have to meet the four criteria presented herein, cover the main goal of the assessment, be significant in comparing historical or feasible configurations, and take the complexity vs sensitivity trade-off into account.

Acknowledgments

Felipe A. Díaz-Alvarado wants to thank the funding from Program U-INICIA VID 2014 (UINICIA-2014-50138); University of Chile. He also appreciates the FCFM grant 2016 to Academic Insertion; University of Chile.

J. Cristian Salgado: This work was financed by grant 1130317 from Fondo Nacional de Ciencia y Tecnología (FONDECYT).

Guillermo Valenzuela-Venegas: This work was funded by the CONICYT-PCHA/Doctorado Nacional/2014-21140400.

Appendix. Indicators

Table 2
Indicators obtained though the research, and their dimension and criteria classification. Ec: economic – En: environmental – Sc: social; U; understanding – P: pragmatism – R: relevance – S: partial representation of sustainability.

Indicator name	Definition	Dimen. of sust.	U	P	R	S	Ref.
Industrial chain extension	It measures the role of the candidate enterprise in improving existing EIP member businesses linkage through supplies or demands.	Ec	✓		✓		Zhu et al. (2010)
Industrial chain coupling	It measures the level of coupling difficulty of the exchange of product, by-product and waste, water and energy, of the candidate enterprise.	Ec	✓	✓	✓		Zhu et al. (2010)
Industrial chain adjustability	It measures by how much the candidate enterprise will improve the industrial chain adjustability.	Ec	✓	✓	✓		Zhu et al. (2010)
Land carrying capacity	It measures whether an EIP can accommodate the demand of the candidate enterprise.	Ec	✓	✓	✓	✓	Zhu et al. (2010)
Water carrying capacity	It measures the possibility of meeting the water demand of the candidate enterprise in an EIP.	En	✓	✓	✓	✓	Zhu et al. (2010)
Energy carrying capacity	It measures the possibility of meeting the energy demand of the candidate enterprise in an EIP.	En	✓	✓	✓	✓	Zhu et al. (2010)
Wastewater collection and treatment capacity	It measures whether the wastewater volume from the candidate firm exceeds the maximal treatment load of the existing plant.	En	✓	✓	✓	✓	Zhu et al. (2010)
Wastes collection and central treatment capacity permit	It evaluates whether the park has enough capacity for wastes collection and central treatment to accept the wastes from the new member enterprise.	En	✓	✓	✓	✓	Zhu et al. (2010)
COD environmental capacity	It evaluates whether the *COD* capacity of the park is enough to accommodate a new member firm.	En	✓	✓	✓	✓	Zhu et al. (2010)
SO_2 environmental capacity	It measures the amount of SO_2 added to the park by a new firm and evaluates if the park SO_2 environmental capacity is enough.	En	✓	✓	✓	✓	Zhu et al. (2010)
Park *COD* emission change rate %	It measures the contribution of new business to the total emission of *COD* in the park after the introduction of this.	En	✓	✓	✓		Zhu et al. (2010)
Park SO_2 emission change rate %	It measures the contribution of new business to the total emission of SO_2 after the introduction of the new business.	En	✓	✓	✓		Zhu et al. (2010)
Percent-added of park water productivity	It measures the growth rate of water production in the park after the introduction of the new business.	En	✓	✓	✓		Zhu et al. (2010)
Percent-added of park energy productivity	It measures the growth rate of energy production in the park after the introduction of the new business.	En	✓	✓	✓		Zhu et al. (2010)
Sustainable architecture design	It evaluates the sustainable construction design of the candidate enterprise through three aspect including sustainable energy, sustainable building materials and building placement.	En	✓	✓	✓		Zhu et al. (2010)
Product eco-design	It evaluates the design for disassembly and recovery, and product data management, of the candidate enterprise.	En	✓		✓		Zhu et al. (2010)
Green packing	It measures the level of green packaging of the candidate enterprise in both environmentally friendly packaging materials and green packaging design.	En	✓		✓		Zhu et al. (2010)
Green transportation design	It evaluates the environment-oriented transportation facilities, mode and scheme, of the new member firm.	En	✓		✓		Zhu et al. (2010)
Industrial value-added per unit area	It measures the economic value created by the candidate enterprise per unit of area.	Ec	✓	✓	✓		Zhu et al. (2010)
Industrial value-added *per capita*	It measures the annual industrial value-added of enterprises and employees in total.	Ec	✓	✓	✓	✓	Zhu et al. (2010)
Energy consumption per unit	It measures the energy efficiency of the candidate enterprise by calculating of all the energy and converting to the number of standard coal using means conversion coefficients.	En	✓	✓	✓		Zhu et al. (2010)
Fresh water consumption per unit	It measures the efficiency of water use in production as well as the level of technology and equipment of the new member firm.	En	✓	✓	✓		Zhu et al. (2010)
Recycling rate of industrial water	It evaluates the proportion of water recycled in the new member enterprise.	En	✓	✓	✓		Zhu et al. (2010)
Recycling rate of industrial solid waste	It measures the level of material re-used and recycled in the new firm.	En	✓	✓	✓		Zhu et al. (2010)

Table 2 (*continued*)

Indicator name	Definition	Dimen. of sust.	U	P	R	S	Ref.
Wastewater production per unit IVA	It measures the efficiency of production management of the candidate enterprise. It also evaluates water utilization efficiency.	En/Ec	✓	✓	✓	✓	Zhu et al. (2010)
COD production per unit IVA	It measures the quality of wastewater and material utilization efficiency through the total annual production of *COD* per unit IVA.	En/Ec	✓	✓	✓	✓	Zhu et al. (2010)
Wastes production per unit IVA	It measures the solid waste production in the candidate enterprise.	En/Ec	✓	✓	✓	✓	Zhu et al. (2010)
Output rate of main material resources	It refers to the amount of production value in EIP generated from one unit of material.	Ec	✓	✓		✓	Su et al. (2013)
Output rate of land	It refers to the amount of production value in EIP generated from one unit of land.	Ec/En	✓	✓		✓	Su et al. (2013)
Output rate of energy	It refers to the amount of production value in EIP generated from one unit of energy.	Ec/En	✓	✓		✓	Su et al. (2013)
Output rate of water	It refers to the amount of production value in EIP generated from one unit of water.	Ec/En	✓	✓		✓	Su et al. (2013)
Energy consumption per unit of production value	It measures the efficient use of energy in a firm.	En	✓	✓	✓	✓	Su et al. (2013), Geng et al. (2012), Geng et al. (2009b)
Energy consumption per unit of production in the key industrial sector.	It measures the efficient use of energy in an the key industrial sector.	En	✓	✓		✓	Su et al. (2013)
Water consumption per unit of production value	It measures the efficient use of water in a firm.	En	✓	✓	✓	✓	Su et al. (2013)
Water consumption per unit of production in the key industrial sector	It measures the efficient use of water in an the key industrial sector.	En	✓	✓		✓	Su et al. (2013)
Utilization rate of industrial solid waste	It measures the ratio of amount of recycled industrial solid waste to total amount of industrial solid waste generated.	En	✓	✓	✓	✓	Su et al. (2013)
Reuse ratio of industrial water	It measures the amount of total reused wastewater for industrial purpose. It includes both recycled water reuse and cascaded water reuse	En	✓	✓	✓	✓	Su et al. (2013)
Recycling rate of industrial wastewater	It measures the amount of total recycled industrial wastewater for industrial propose. It includes both treated domestic wastewater and industrial wastewater.	En	✓	✓	✓	✓	Su et al. (2013)
Decreasing rate of industrial solid-waste generation	It measures the total amount of industrial solid waste for final disposal.	En	✓	✓	✓	✓	Su et al. (2013)
Decreasing rate of industrial wastewater generation	It measures the total amount of industrial wastewater for final disposal.	En	✓	✓	✓	✓	Su et al. (2013)
Education and training in waste minimization methodology	It measure the amount of employees trained per annum.	Sc	✓	✓	✓	✓	Phillips et al. (2006)
Resource acquisition	It measures obtaining external funds to from local clubs	Ec	✓	✓	✓	✓	Phillips et al. (2006)
Forming local and regional partnerships	It measures networking through clubs with all key local and regional organizations.	Ec	✓	✓	✓	✓	Phillips et al. (2006)
Geographical distribution of clubs	It measures clubs in each district and borough, especially those with high deprivation	Sc	✓	✓			Phillips et al. (2006)
Long term vision	It measures exit strategies from projects in place so as to continue with new club development	Ec	✓		✓		Phillips et al. (2006)
Environmental reporting	It measures success of club activities included in local and regional media as well as journals.	En	✓				Phillips et al. (2006)
Companies adopting waste minimization	It measures the increase in number of trained companies (in waste treatment) per annum.	En	✓	✓		✓	Phillips et al. (2006)
Resource efficiency	It measures reduction in resource use per unit of production, the increase in recycling, and re-use.	En	✓	✓	✓	✓	Phillips et al. (2006)
Reduction in effluent and special waste	It measures the reduction in effluent and special waste produced.	En	✓	✓	✓	✓	Phillips et al. (2006)
Increase company competitiveness	It measures the companies saving.	Ec	✓	✓	✓	✓	Phillips et al. (2006)
Cost effective waste minimization clubs	It measure the cost saving of waste ratio of clubs	Ec	✓	✓	✓	✓	Phillips et al. (2006)
Job creation	It measures new job created per annum by partnership.	Sc	✓	✓	✓	✓	Phillips et al. (2006)
Direct energy consumption carbon footprint	It refers to emission from direct combustion of fossil fuels within the administrative boundary.	En	✓		✓	✓	Dong et al. (2014a), Dong et al. (2013)
Industrial process carbon footprint	It refers to emissions from chemical and physical reactions in the production process.	En	✓		✓	✓	Dong et al. (2014a)
Material carbon footprint	It refers to the indirect carbon footprint embodied in the input materials.	En	✓		✓	✓	Dong et al. (2014a)
Depreciation carbon footprint	It refers to the indirect carbon footprint embodied in the annual depreciation of fixed assets that support the production in the industrial park.	En	✓		✓	✓	Dong et al. (2014a)
Electricity and heat carbon footprint	It refers to the indirect carbon footprint embodied in the purchased electricity and heat out of the park.	En	✓		✓	✓	Dong et al. (2014a)
waste treatment carbon footprint	It refers to emissions caused during the treatment process of the wastes generated within the park.	En	✓			✓	Dong et al. (2014a)
Added industrial value *per capita*	It measures the annual added industrial production value per total employees at the end of the year.	Ec	✓	✓	✓	✓	Geng et al. (2009a), Geng et al. (2008)
Growth rate of added industrial value	it measures the relative difference of added industrial value between two years.	Ec	✓	✓	✓	✓	Geng et al. (2009a)
Energy consumption per added industrial value	It measures the energy consumption including coal, electricity, oil, and energy consumption for both heating and cooling.	En/Ec	✓	✓	✓	✓	Geng et al. (2009a)
Fresh water consumption per added industrial value	It measures the industrial fresh water used for production and living within the enterprises, including the tap water and self-provided water (if the domestic	En/Sc	✓	✓	✓	✓	Geng et al. (2009a)

(*continued on next page*)

Table 2 (*continued*)

Indicator name	Definition	Dimen. of sust.	U	P	R	S	Ref.
	wastewater is not blended with the industrial wastewater, then water consumption for living should no be included).						
Industrial wastewater generation per added industrial value	It measures the industrial wastewater generation, not including water obtained from cascading and domestic wastewater from resident living in the park	En/Ec	✓	✓	✓	✓	Geng et al. (2009a)
Solid waste generation per added industrial value	It measures solid, semisolid, and high-density liquid waste, including smelt residues, fly ash, bottom ash, gangue, dangerous waste, gangue, and radioactive wastes.	En/Ec	✓	✓	✓	✓	Geng et al. (2009a)
Industrial water reuse ratio	It measures the industrial reuse water, including water that is recycled or cascaded.	En	✓	✓	✓	✓	Geng et al. (2009a)
Solid waste reuse ratio	It measures the industrial solid waste, including all kinds of non domestic, non dangerous solid wastes generated by industries.	En	✓	✓	✓	✓	Geng et al. (2009a)
Middle water reuse ratio	It measures the recycled treated wastewater from wastewater treatment plants.	En	✓	✓	✓	✓	Geng et al. (2009a)
COD loading per added industrial value	It measures the amount of *COD* loading, including *COD* loading both from companies and wastewater treatment plant.	En/Ec	✓	✓	✓	✓	Geng et al. (2009a)
SO_2 emission per added industrial value	It measures the amount of SO_2 emissions.	En/Ec	✓	✓	✓	✓	Geng et al. (2009a)
Disposal rate of dangerous solid waste	It measures the dangerous industrial wastes, including those toxic and hazardous wastes ad defined by the environmental standards.	En	✓	✓	✓	✓	Geng et al. (2009a)
Centrally provided treatment rate of domestic wastewater	It refers to the ratio of total amount of treated domestic wastewater to amount of domestic wastewater generation.	En	✓	✓	✓	✓	Geng et al. (2009a)
Safe treatment rate of domestic rubbish	It refers to the ratio of total amount of safely treated domestic rubbish to total amount of domestic rubbish.	En	✓	✓	✓	✓	Geng et al. (2009a)
Waste collection system	It refers to the existence of a waste collection system	En	✓		✓	✓	Geng et al. (2009a)
Centrally provided facilities for waste treatment and disposal	It refers to the existence of a environmental management system.	En	✓		✓	✓	Geng et al. (2009a)
Environmental management systems	It refers whether the park management should pass ISO 14001 certification and have an emergency response plan.	En	✓			✓	Geng et al. (2009a)
Extent of establishment of information platform	It indicates whether the park has established a comprehensive information platform.	En	✓			✓	Geng et al. (2009a)
Environmental report release	It refers to the existence of an environmental report release.	En	✓		✓	✓	Geng et al. (2009a)
Extent of public satisfaction with local environmental quality	It measures the degree satisfaction of the population of the whole park with local environmental quality.	Sc	✓	✓	✓	✓	Geng et al. (2009a)
Extent of public awareness degree with eco-industrial development	It measures the public awareness of the population park about eco-industrial development.	Sc	✓		✓	✓	Geng et al. (2009a)
Energy intensity	It measures the energy consumption efficiency. It relates the consumption to the output of the sector in monetary values	En	✓	✓	✓	✓	Tolmasquim et al. (2001)
Emission intensity	It assess the ratio between CO_2 emissions of the industrial sector and its output value.	En	✓	✓	✓	✓	Tolmasquim et al. (2001)
The specific emission	It relates the total CO_2 emissions to the energy consumption	En	✓	✓	✓	✓	Tolmasquim et al. (2001)
Nodes	It measures the quantity of metabolic compartments, and also the size of network.	Ec		✓		✓	Lu et al. (2012)
Links	It measures the quantity of metabolic direct flows or arcs.	Ec		✓	✓	✓	Lu et al. (2012)
Link density	It measures the metabolic linking degree.	Ec		✓	✓	✓	Lu et al. (2012)
Connectance	It measures the metabolic connectivity, also the proportion or realized direct pathways	Ec		✓	✓	✓	Lu et al. (2012)
Mutualism index (MI_x)	It reflects the ratio of the number of positive and negative signs regard to mutualism relationships between components of a system.	Ec		✓	✓	✓	Lu et al. (2012)
Synergism index (SI_x)	It quantifies the total magnitude of the positive and negative utilities, which assess the mutualism condition of a system in slightly different angles.	Ec		✓	✓	✓	Lu et al. (2012)
Control index (CI)	It indicates the control utility and organization capability of the whole system. It can be employed to index the self-regulation of system metabolism.	Ec		✓	✓	✓	Lu et al. (2012)
R/U	It indicates the ratio of renewable inputs to total used emergy.	Ec/En		✓	✓	✓	Geng et al. (2014)
N/U	It indicates the ratio of nonrenewable inputs to total used emergy.	Ec/En		✓	✓	✓	Geng et al. (2014)
I/U	It indicates the ratio of imported resources to total used emergy.	Ec/En		✓	✓	✓	Geng et al. (2014)
Emergy yield ratio	It reflects the net economic benefit.	Ec		✓	✓	✓	Geng et al. (2014)
Environmental loading ratio	It reflects the pressure of industrial activities on the local ecosystem.	En		✓	✓	✓	Geng et al. (2014)
Emergy sustainability indicator	It reflects the sustainable level of on industrial park.	Ec/En		✓	✓	✓	Geng et al. (2014)
Absolute emergy savings	It is the absolute emergy savings of nonrenewable resource, purchased resources, services associated with imported resource, and emergy of the total energy used due to the use of by-products among different firms within the same park.	Ec/En		✓	✓	✓	Geng et al. (2014)
Relatives emergy savings	It is the ratio of avoided inputs through all the industrial symbiosis activities to total emergy inputs without related industrial symbiosis activities.	En		✓	✓	✓	Geng et al. (2014)
Emdollar values of total savings	It represents the economic benefits of industrial symbiosis.	Ec		✓	✓	✓	Geng et al. (2014)
Per capita industrial value added	It refers to industrial value added created by one employee of the industry park in one year.	Ec	✓	✓	✓	✓	Bai et al. (2014)
Per land use industrial value added	It refers to land use of production facilities, warehouse and affiliated facilities in enterprises such as railways, ports and land for roads, not including land for open pit mine.	En/Ec	✓	✓	✓	✓	Bai et al. (2014)
Total energy consumption intensity	It refers to energy such coal, electricity, oil and other energy consumption (including the production of heating and cooling energy) used for production and operations of the enterprise.	En	✓	✓	✓	✓	Bai et al. (2014)
Fresh water consumption intensity	It refers to tap water and selfprepared water used for production and operations of the enterprises.	En	✓	✓	✓	✓	Bai et al. (2014)

Table 2 (*continued*)

Indicator name	Definition	Dimen. of sust.	U	P	R	S	Ref.
Ratio of industrial waste water utilization	It refers to the ratio reuse of water including recycling, multiple use and cascade use of water (including the reuse of disposed waste water) in the production of enterprises and to water used for production and operation of the enterprises.	En	✓	✓	✓	✓	Bai et al. (2014)
Ratio of industrial solid waste utilization	It refers to the ratio of recycled, processed, circulated or exchanged solid waste from solid waste generated by industrial enterprises.	En	✓	✓	✓	✓	Bai et al. (2014)
Waste water generation intensity	It refers to industrial value added created by the total amount of waste water by industrial enterprises in a year.	Ec/En	✓	✓	✓	✓	Bai et al. (2014)
Solid waste generation intensity	It refers to industrial value added created by the total amount of solid waste generated by industrial enterprises in a year.	Ec/En	✓	✓	✓	✓	Bai et al. (2014)
COD generation intensity	It refers to industrial value added created by the total amount of solid *COD* by industrial enterprises in a year.	Ec/En	✓	✓	✓	✓	Bai et al. (2014)
SO_2 emission intensity	It refers to industrial value added created by the total amount of SO_2 by industrial enterprises in a year.	Ec/En	✓	✓	✓	✓	Bai et al. (2014)
Direct Material Input (DMI)	It measures the direct input of materials for use in the economy, i.e. All materials which are of economic value and are used in production and consumption activities.	En	✓	✓	✓	✓	Eurostat (2001)
Total Material Input (TMI)	It measures the materials that are moved by economic activities but that do not serve as input for production or consumption activities.	En	✓	✓	✓	✓	Eurostat (2001)
Total Material Requirement (TMR)	It measures the total "material base" of an economy. It includes, in addition to TMI, the material flows that are associated to imports but that take place in other countries.	En	✓	✓	✓		Eurostat (2001)
Domestic Total Material Requirement (domestic TMR)	It measures the total of material flows originating from the national territory.	En	✓	✓	✓		Eurostat (2001)
Domestic Material Consumption (DMC)	It measures the total amount of material directly used in an economy.	En	✓	✓	✓	✓	Eurostat (2001)
Total Material Consumption (TMC)	It measures the total material use associated with domestic production and consumption activities, including indirect flows imported but less exports and associated indirect flows of exports.	En	✓	✓	✓	✓	Eurostat (2001)
Net Additions to Stock (NAS)	It measures the quantity of new construction materials used in buildings and other Infrastructure, and materials incorporated into new durable goods such as cars, industrial machinery, and household appliances.	En	✓		✓	✓	Eurostat (2001)
Physical Trade Balance (PTB)	It measure the physical trade surplus or deficit of an economy.	Ec	✓	✓	✓	✓	Eurostat (2001)
Domestic Processed Output (DPO)	It refers to the total weight of materials, extracted from the domestic environment or imported, which have been used in the "domestic economy", before flowing to the environment.	En		✓	✓	✓	Eurostat (2001)
Total Domestic Output (TDO)	It represents the total quantity of material output to the environment caused by economic activity.	En	✓	✓	✓	✓	Eurostat (2001)
Direct Material Output (DMO)	It represents the total quantity of material leaving the economy after use either towards the environment or towards the rest of the world.	En	✓	✓	✓	✓	Eurostat (2001)
Total Material Output (TMO)	It measures the total of material that leaves the economy.	En	✓	✓	✓	✓	Eurostat (2001)
DMI	It measures the amount of materials entering the system to be used and/or processed.	En	✓	✓	✓	✓	Sendra et al. (2007)
TMR	It measures the total material requirement.	En	✓	✓	✓	✓	Sendra et al. (2007)
DMIw	It measures the DMI per number of workers.	En	✓	✓	✓	✓	Sendra et al. (2007)
TMRw	It measures the TMR per number of workers	En	✓	✓	✓	✓	Sendra et al. (2007)
TWG	It measures the total waste generated by the system.	En	✓	✓	✓	✓	Sendra et al. (2007)
TWGw	It measures the TWG per number of workers.	En	✓	✓	✓	✓	Sendra et al. (2007)
Wp	It measure the production of the system per number of workers, i.e., the worker productivity.	Ec	✓	✓	✓	✓	Sendra et al. (2007)
Eco-Ef	It is the percentage of DMI converted into product.	En	✓	✓	✓	✓	Sendra et al. (2007)
Eco-In	It measures the tonnes of material input required to manufacture a tonne of product or the amount of raw material equivalent to a product.	En	✓	✓	✓	✓	Sendra et al. (2007)
M-Inef	It is the amount of output to nature per unit of material processed.	En	✓	✓	✓	✓	Sendra et al. (2007)
TWI	It measures the amount of water consumed by the system from own sources (domestic) and imported from supply system, shafts and rivers.	En	✓	✓	✓	✓	Sendra et al. (2007)
TWWG	It measures the amount of wastewater generated by the system.	En	✓	✓	✓	✓	Sendra et al. (2007)
TWIw	It is used to analyze the difference with the average of water consumption per inhabitant	En	✓	✓	✓	✓	Sendra et al. (2007)
TEI	It is the amount of energy consumed by the system and subsystem, distinguished between energy generated domestically and imported energy.	En	✓	✓	✓	✓	Sendra et al. (2007)
TEIw	It measures the TEI per number of workers.	En	✓	✓	✓	✓	Sendra et al. (2007)
E-In	It is used to make different-sized system comparable.	En	✓	✓	✓	✓	Sendra et al. (2007)
Net economic benefit (net value added)	It measures the annual added industrial production value.	Ec	✓	✓	✓	✓	Park and Behera (2014)
Raw material consumption indicator	It refers to the total weight of all materials that the company purchases or obtains from other sources including raw materials for conversion, other process materials, and pre-or semi-manufactures goods and parts.	Ec	✓	✓	✓	✓	Park and Behera (2014)
Energy consumption indicator	It measures the total energy consumption of a park.	En	✓	✓	✓	✓	Park and Behera (2014)
CO_2 emission indicator	It measure the GHG emissions resulting from fuel combustion, process reactions, and treatment processes.	En	✓	✓	✓	✓	Park and Behera (2014)
Eco-efficiency	It is a combination of economic and ecological performance, where it indicates the ratio of the net economic benefit to three environmental indicators.	Ec/En	✓	✓	✓	✓	Park and Behera (2014)
Air pollution		En	✓	✓	✓	✓	Chen et al. (2012a)

(*continued on next page*)

Table 2 (*continued*)

Indicator name	Definition	Dimen. of sust.	U	P	R	S	Ref.
	It includes particulate matter, volatile organic compounds, sulfur oxides, and nitrogen oxides.						
Water and solid waste pollution	In considers biochemical oxygen demand, chemical oxygen demand, and suspended solids,	En	✓	✓	✓	✓	Chen et al. (2012a)
Resource use	It considers the tree major resources, water, land, and energy	En	✓	✓	✓	✓	Chen et al. (2012a)
Health	It measures the quantities of air pollutants, water pollutants, and waste discharged by manufactories into the surrounding area.	En/Sc	✓	✓	✓	✓	Chen et al. (2012a)
Quality of life	It measures the number of manufactories and traffic generated by them.	Ec/Sc	✓	✓	✓	✓	Chen et al. (2012a)
Recycling of metals	It reflects reduced input of scarce materials from nature	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Waste and by-product utilization	It measures waste and by-product utilization as raw material in paper production.	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Fuel use	It measures the amount of total fuel used in the park.	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Restricting emissions of chemicals to nature by the recovery of process chemicals	It measures the amount of by-products reused to avoid emissions of certain substances.	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Decrease in hazardous substance emissions to the water	It measures the amount of chlorine, mercury, and others hazardous compounds emissions released to the water.	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Other emissions to the water	It measures the amount of suspended solids in the water, biological oxygen demand, and phosphorus and nitrogen load.	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Emissions to the air	It measures the amount of atmospheric emissions (CO_2, mercury, etc.).	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Recycling and waste treatment	It indicates whether exists a property waste management.	En	✓		✓	✓	Pakarinen et al. (2010)
Extraction of wood and other resources	It measures the consumption of natural resources.	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Other area-consuming activities	It measures the amount of resources imported to industrial area.	En	✓	✓	✓	✓	Pakarinen et al. (2010)
Health risks of the pollution	It describes the pollution level of the resources used by the humans like water.	En/Sc	✓	✓	✓	✓	Pakarinen et al. (2010)
Renewable resources input (R)	It is the total energy and material driving a process that is derived from renewable sources.	En		✓	✓	✓	Song et al. (2013)
Non-renewable inputs (N)	It is a resource that their use rate exceeds replacement rate.	En		✓	✓	✓	Song et al. (2013)
Input from the economy (F)	It considers mainly energy resources, raw material, transportation costs, labor costs, management costs, maintenance costs, and depreciation.	Ec/En		✓	✓	✓	Song et al. (2013)
Waste emergy (E_w)	It reflects the emergy of the service of disposing waste.	En		✓	✓	✓	Song et al. (2013)
Recycled resource emergy (E_r)	It reflects the recovery emergy from waste.	En		✓	✓	✓	Song et al. (2013)
E-waste emergy (E_e)	It reflects the emergy of the service of disposing waste.	En		✓	✓	✓	Song et al. (2013)
Output emergy (E_0)	It reflects the emergy of all the products.	Ec/En		✓	✓	✓	Song et al. (2013)
Yield of industrial process (Y)	It measures the amount of local resources exploited.	En		✓	✓	✓	Song et al. (2013)
Emergy economic efficiency index (EYR)	It measures the net benefit to the economy from an waste processing activity-that is, the amount of local resources exploited compared to the amount of emergy investment. It measures the capability of industrial processes to exploit local resources.	Ec/En		✓	✓	✓	Song et al. (2013)
Emergy environmental efficiency index (ELR)	It is an indicator of the pressure of the process on the local ecosystem and can be considered a measure of the ecosystem stress due to production activity.	En		✓	✓	✓	Song et al. (2013)
Emergy sustainability index (ESI)	It reflects the ability of a system to provide desired products or services with a minimum of environmental stress and a maximum profit.	En			✓	✓	Song et al. (2013)
Emergy recovery ratio (ERR)	It measures the ability of a system to recover energy and materials from waste.	En		✓	✓	✓	Song et al. (2013)
Quotes for emergy recyclability (QER)	It measures the quotes for emergy recyclability, i.e., the total emergy recyclability available from waste.	En		✓	✓	✓	Song et al. (2013)
Emergy-LCA index	It assesses the ratio of the economic emergy (emergy used to evaluate the economic situation) and the total environmental performance expressed in LCA results (the unit environmental impacts multiplied by the total quantity of e-waste).	Ec/En		✓	✓	✓	Song et al. (2013), Brown and Ulgiati (1997), Yang et al. (2003)
Virgin Material Savings (VMS)	It assess the environmental benefits, measuring the amount of reuse or recycle wastes in place of virgin material use.	En	✓	✓	✓	✓	Chen et al. (2012b)
Operation Rate (OR)	It is the ratio of the amount of wastes treated in practice to the planned amount of treatment. It assess the operational performance of an eco-town.	En	✓	✓	✓	✓	Chen et al. (2012b)
Symbiosis degree ($gamma_{ij}$)	It expresses the change rate of the main essential parameter of a symbiosis unit corresponding to the change rate of the main essential parameter of other unit. It indicates which unit has more influence on the other.	En/Ec		✓	✓		Wang et al. (2014)
Symbiosis degree of individual element ($gamma_{si}$)	It expresses the change rate of the main essential parameter of a unit corresponding to the change rate of the main essential parameter of the symbiosis system. It provides a simple way to analyze the stability of a symbiosis system.	En/Ec		✓	✓	✓	Wang et al. (2014)
Symbiosis degree of total element ($gamma_s$)	It indicates the correlation degree of the symbiosis units and the system.	Ec		✓	✓	✓	Wang et al. (2014)
Symbiosis profit (E)	It measures the net profit from the symbiosis process of a system.	Ec		✓	✓	✓	Wang et al. (2014)
Symbiotic consumption	It is the cost of perform the symbiosis and gain symbiosis profit.	Ec		✓	✓	✓	Wang et al. (2014)
Ecological efficiency (EE)	It measures the overall efficacy of the production system regarding to environmental support and resources input.	Ec/En	✓	✓	✓	✓	Jiang et al. (2010)
Resource use efficiency (RUE)	It is based on the overall resources including energy sources.	En	✓	✓	✓	✓	Jiang et al. (2010)
Environmental emission intensity (EEI)	It indicates the waste emissions per unit of yield. This ratio is focused on the direct impacts from waste emissions.	En	✓	✓	✓	✓	Jiang et al. (2010)
Environmental loading ratio (ELR)	It represents the ratio of purchased and non-renewable emergy to locally free environmental emergy. It measures ecosystem stress due to excess exploitation of local non-renewable resources or investment from outside, compared with locally available renewable resources.	Ec/En		✓	✓	✓	Geng et al. (2010b)

Table 2 (*continued*)

Indicator name	Definition	Dimen. of sust.	U	P	R	S	Ref.
Emergy yield ratio (EYR)	It represents the ratio of total emergy used and exploited by the process to the emergy invested from outside the system. It measures the net benefit to the economy, namely the amount of local resources exploited derived from the investment amount. It measures the capability of industrial processes to exploit local resources.	Ec/En		✓	✓	✓	Geng et al. (2010b)
RWCP	It refers to the ratio of waste collection within the prefecture.	En	✓	✓	✓	✓	Ohnishi et al. (2012)
RPDP	It is the ratio of product delivery within the prefecture.	Ec	✓	✓	✓	✓	Ohnishi et al. (2012)
PCF	It is the processing capacity of the facility.	Ec	✓	✓	✓	✓	Ohnishi et al. (2012)
INWST	It measures the amount of industrial waste generated in the prefecture where the facility is located.	En/Sc	✓	✓			Ohnishi et al. (2012)
HHWST	It measures the amount of household waste generated in the city where the facility is located.	En/Sc	✓	✓			Ohnishi et al. (2012)
CPRI	It represents the capacity of steel, non-ferrous, and cement industries in the prefecture where the facility is located.	Ec	✓	✓			Ohnishi et al. (2012)
DMAG	It indicates whether exists an agglomeration type.	En	✓		✓	✓	Ohnishi et al. (2012)
DMCPL	It indicates whether exists a container/packaging recycling law.	En	✓		✓	✓	Ohnishi et al. (2012)
DMHAL	It indicates whether exists a home appliance recycling law.	En	✓		✓	✓	Ohnishi et al. (2012)
DMAML	It indicates whether exists a automobile recycling law.	En	✓		✓	✓	Ohnishi et al. (2012)
DMFDL	It indicates whether exists a food recycling law.	En	✓		✓	✓	Ohnishi et al. (2012)
RSET	It refers to the ratio of subsidies from the government.	Ec	✓	✓	✓	✓	Ohnishi et al. (2012)
DMPRS	It indicates whether exists a waste collection support.	En	✓		✓	✓	Ohnishi et al. (2012)
DMFS	It indicates whether exists a financial support from the municipality.	Ec	✓		✓	✓	Ohnishi et al. (2012)
DMGP	It indicates whether exists a green purchase from the municipality.	Ec	✓		✓	✓	Ohnishi et al. (2012)
DMWE	It indicates whether exists a waste exchange.	En	✓		✓	✓	Ohnishi et al. (2012)
DMCOS	It indicates whether exists a Eco-Town committee.	Sc/En	✓				Ohnishi et al. (2012)
RRCL	It measures the recycling rate in certain year in the city where the facility is located.	En/Sc	✓	✓	✓	✓	Ohnishi et al. (2012)
Investment	It measures the amount of millions USD invested in a project.	Ec	✓	✓	✓	✓	Behera et al. (2012)
Profit	It measures the amount of millions USD of benefit of both supplier and recipient.	Ec	✓	✓	✓	✓	Behera et al. (2012)
Payback	It indicates the period of time required for a project to recover the money invested.	Ec	✓	✓	✓	✓	Behera et al. (2012)
CO_2 reduction	It reflect the amount of CO_2 emissions that the project reduces.	En	✓	✓	✓	✓	Behera et al. (2012)
Air pollutant reduction	It reflect the amount of SOx, NO_x and CO emissions that the project reduces.	En	✓	✓	✓	✓	Behera et al. (2012)
Primary energy	It reflects the contribution of a material of a process to the primary energy.	En		✓	✓	✓	Eckelman and Chertow (2013)
Greenhouse gas	It reflects the contribution of a process to greenhouse gas emissions.	En	✓	✓	✓	✓	Eckelman and Chertow (2013)
Acidification	It reflects the contribution of a process to acidification of the environment.	En	✓	✓	✓	✓	Eckelman and Chertow (2013)
Eutrophication	It reflects the contribution of a process to eutrophication of the environment.	En	✓	✓	✓	✓	Eckelman and Chertow (2013)
Global warming potential (GWP)	It is the amount of greenhouse gas that a project produces.	En	✓	✓	✓	✓	Chen et al. (2011)
Fossil fuel savings	It is the amount of fossil fuel replaced by other obtained as a by-product in a process.	En	✓	✓	✓	✓	Chen et al. (2011)
Water consumption	It measures the amount of ground water, surface water, cooling/waste water of a process or an industrial park.	En	✓	✓	✓	✓	Jacobsen (2006)
CO_2	It measures the amount of CO_2 emissions saved by an industrial park.	En	✓	✓	✓	✓	Jacobsen (2006)
SO_2	It measures the amount of SO_2 emissions saved by an industrial park.	En	✓	✓	✓	✓	Jacobsen (2006)
NO_x	It measures the amount of NO_x emissions saved by an industrial park.	En	✓	✓	✓	✓	Jacobsen (2006)
Abiotic resource depletion (resource use)	it reflects the depletion of nonrenewable resource.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Biotic resource depletion (resource use)	it is related to the use of species threatened with extinction.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Land use (resource use)	It represents the total land area used in different stage of the life cycle.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Global warming potential (GWP)	It represents total emissions of the greenhouse gases expressed relative to the global warming potential of CO_2.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Ozone depletion potential (ODP)	It indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and chlorinated (HCs) for depleting the ozone layer.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Acidification potential (AP)	It reflects the contributions of SO_2, NO_x, HCl, NH3, and HF to potential acid deposition.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Eutrophication potential (EP)	It is defined as the potential to cause over-fertilization of water and soil, which can result in increased growth of biomass.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Photochemical smog (PS)	It represents total emissions of different contributory species, primarily VOCs.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Human toxicity potential (HTTP)	It measures the human toxic releases to the three different media, i.e., air, water, and soil.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Ecotoxicity potential (ETP)	It measures toxic substances in water and soil.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Solid waste (SW)	It measures the amount of solid waste generated in the life cycle of a system.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Material intensity (MI)	It represents the sum of all materials used in the system.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Energy intensity (EN)	It represents the sum of the total amount of energy.	En	✓	✓	✓	✓	Azapagic and Perdan (2000)
Material recyclability (MR)	It shows a potential for the product to be recycled, either in the same or a different life cycle. It can be expressed as a percentage of the material that can potentially be recycled relative to the total amount of the material.	En	✓	✓			Azapagic and Perdan (2000)
Product durability (PD)	It represent the durability (period of time) of a product in relation with life cycle.	Ec	✓	✓			Azapagic and Perdan (2000)

(*continued on next page*)

Table 2 (*continued*)

Indicator name	Definition	Dimen. of sust.	U	P	R	S	Ref.
Service intensity (SI)	it measures the degree to which the company has closed the loop in providing the service as opposed to only selling the product.	En		✓	✓	✓	Azapagic and Perdan (2000)
Environmental Management Systems (EMS)	It is a qualitative indicator which indicates whether in the company exists an environmental management system.	En	✓		✓	✓	Azapagic and Perdan (2000)
Environmental improvements above the compliance levels (ICL)	it expresses an average percentage decrease in environmental burdens for either prescribed substances, or substances that are of general environmental concern but are not legislated.	En	✓		✓		Azapagic and Perdan (2000)
Assessment of suppliers (AS)	It is a qualitative indicator which indicates whether the suppliers to have certain environmental features.	En	✓		✓	✓	Azapagic and Perdan (2000)
Value added (VA)	It is expressed as net operating profit of the company.	Ec	✓	✓	✓	✓	Azapagic and Perdan (2000)
Contribution to the gross domestic product (CGDP)	GDP is an aggregate measure of production equal to the sum of the gross values added of all participant in the industry. CGDP is expressed in terms of value added per functional unit.	Ec	✓	✓	✓	✓	Azapagic and Perdan (2000)
Expenditure on environmental protection (EEP)	It represents an investment in the protection of the environment.	Ec	✓	✓	✓	✓	Azapagic and Perdan (2000)
Environmental liability (EL)	It expresses the costs that a company may have to pay if it is found liable for causing an environmental hazard.	Ec	✓	✓	✓	✓	Azapagic and Perdan (2000)
Ethical investments (ETI)	It represents assets invested in business activities that are considered to be ethical.	Ec/Sc	✓	✓	✓	✓	Azapagic and Perdan (2000)
Employment contribution (EM)	It represents the ratio of the number of employees per functional unit over an average number of people employed in the countries involved in the life cycle of an activity. Also it represents the number of employees per functional unit.	Sc	✓	✓	✓		Azapagic and Perdan (2000)
Staff turnover (ST)	It expresses the ratio of new employees to workforce made redundant by a company in a certain life cycle stage.	Sc	✓	✓	✓	✓	Azapagic and Perdan (2000)
Expenditure on health and safety (EHS)	It expresses the total expenditure on health and safety over the total number of employees, to give an investment in health and safety per employee.	Ec/Sc	✓	✓	✓	✓	Azapagic and Perdan (2000)
Investment in staff development (ISD)	It expresses the investment in training and continuing professional and personal development per employee.	Ec/Sc	✓	✓	✓	✓	Azapagic and Perdan (2000)
Stakeholder inclusion	It indicates whether the activities and performance of an organization have an impact in the local community, suppliers and business partners, civil society, natural environment, future generation and their defenders in to pressure groups.	Sc	✓		✓	✓	Azapagic and Perdan (2000)
Involvement in community projects	It is related to satisfaction of social needs. It shows the level of partnership that an organization develops with the community in which it operates.	Sc	✓	✓	✓	✓	Azapagic and Perdan (2000)
Income distribution (ID)	It shows an average distribution of wealth and could be expressed in term of income of the top 10% of employees per income of the bottom 10%.	Sc	✓	✓	✓	✓	Azapagic and Perdan (2000)
Work satisfaction (WS)	It represents the number of sick days or number of people "happy" with their job per employee.	Sc	✓	✓	✓	✓	Azapagic and Perdan (2000)
Satisfaction of social needs (SN)	It can be expressed as both quantitative and qualitative indicators. It is measured in terms of financial contributions of business to satisfying social needs. Contributions that cannot be measured in monetary terms can be included as a statement which describes the activity that contributed to satisfying a particular need and puts it in the context of the society to which the contribution has been made.	Ec/Sc	✓	✓	✓	✓	Azapagic and Perdan (2000)

References

Azapagic, A., Perdan, S., 2000. Indicators of sustainable development for industry. Process Saf. Environ. Prot. 78, 243–261. http://dx.doi.org/10.1205/095758200530763. http://www.sciencedirect.com/science/article/pii/S0957582000708834.

Baas, L., 2011. Planning and uncovering industrial symbiosis: comparing the Rotterdam and Östergötland regions. Bus. Strategy Environ. 20, 428–440. http://dx.doi.org/10.1002/bse.735. http://doi.wiley.com/10.1002/bse.735.

Bai, L., Qiao, Q., Yao, Y., Guo, J., Xie, M., 2014. Insights on the development progress of national demonstration eco-industrial parks in China. J. Clean. Prod. 70, 4–14. http://dx.doi.org/10.1016/j.jclepro.2014.01.084. http://www.sciencedirect.com/science/article/pii/S0959652614001140.

van Beers, D., Corder, G., Bossilkov, A., van Berkel, R., 2007. Industrial symbiosis in the Australian minerals industry – the cases of Kwinana and Gladstone. J. Ind. Ecol. 11, 55–72.

Behera, S.K., Kim, J.-H., Lee, S.-Y., Suh, S., Park, H.-S., 2012. Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. J. Clean. Prod. 29–30, 103–112. http://dx.doi.org/10.1016/j.jclepro.2012.02.009. http://www.sciencedirect.com/science/article/pii/S0959652612000832.

Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S., 2015. Optimization methods applied to the design of eco-industrial parks: a literature review. J. Clean. Prod. 87, 303–317. http://www.sciencedirect.com/science/article/pii/S0959652614009627. http://dx.doi.org/10.1016/j.jclepro.2014.09.032.

Boons, F., Spekkink, W., Mouzakitis, Y., 2011. The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. J. Clean. Prod. 19, 905–911. http://dx.doi.org/10.1016/j.jclepro.2011.01.003. http://www.sciencedirect.com/science/article/pii/S0959652611000072.

Brockhoff, D., Zitzler, E., 2006. Are all objectives necessary? On dimensionality reduction in evolutionary multiobjective optimization. In: Runarsson, T., Beyer, H.-G., Burke, E., Merelo-Guervós, J., Whitley, L., Yao, X. (Eds.), Parallel Problem Solving from Nature – PPSN IX SE – 54, Lecture Notes in Computer Science, vol. 4193. Springer Berlin Heidelberg, pp. 533–542. http://dx.doi.org/10.1007/11844297_54. http://dx.doi.org/10.1007/11844297_54.

Brown, M., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51–69. http://dx.doi.org/10.1016/S0925-8574(97)00033-5. http://www.sciencedirect.com/science/article/pii/S0925857497000335.

Chen, B., He, G., Qi, J., Su, M., Zhou, S., Jiang, M., 2013. Greenhouse Gas Inventory of a typical high-end Industrial Park in China. Sci. World J. 2013, 7. http://dx.doi.org/10.1155/2013/717054.

Chen, C.-H., Liu, W.-L., Chiou, I.-J., Liaw, S.-L., 2012a. Methodology and system of total quantity and sustainability management for industrial parks. Environ. Eng. Sci. 29, 934–945. http://dx.doi.org/10.1089/ees.2011.0109.

Chen, X., Fujita, T., Ohnishi, S., Fujii, M., Geng, Y., 2012b. The impact of scale, recycling boundary, and type of waste on symbiosis and recycling. J. Ind. Ecol. 16, 129–141. http://dx.doi.org/10.1111/j.1530-9290.2011.00422.x.

Chen, X., Xi, F., Geng, Y., Fujita, T., 2011. The potential environmental gains from recycling waste plastics: simulation of transferring recycling and recovery technologies to Shenyang, China. Waste Manag. 31, 168–179. http://dx.doi.org/10.1016/j.wasman.2010.08.010 (New York, N.Y.). http://www.sciencedirect.com/science/article/pii/S0956053X10003958.

Chertow, M., 2008. Industrial ecology in a developing context. In: Clini, C., Musu, I., Gullino, M. (Eds.), Sustainable Development and Environmental Management SE – 24. Springer Netherlands, pp. 335–349. http://dx.doi.org/10.1007/978-1-4020-8229-0_24. http://dx.doi.org/10.1007/978-1-4020-8229-0_24.

Chertow, M., 2012. Industrial Symbiosis. http://www.eoearth.org/view/article/153824/.
Chertow, M.R., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Environ. 25, 313–337. http://dx.doi.org/10.1146/annurev.energy.25.1.313. http://www.annualreviews.org/doi/full/10.1146/annurev.energy.25.1.313.
Chertow, M.R., 2007. Uncovering industrial symbiosis. J. Ind. Ecol. 11, 11–30. http://dx.doi.org/10.1162/jiec.2007.1110. http://dx.doi.org/10.1162/jiec.2007.1110.
Copado-Méndez, P.J., Guillén-Gosálbez, G., Jiménez, L., 2014. MILP-based decomposition algorithm for dimensionality reduction in multi-objective optimization: application to environmental and systems biology problems. Comput. Chem. Eng. 67, 137–147. http://dx.doi.org/10.1016/j.compchemeng.2014.04.003. http://www.sciencedirect.com/science/article/pii/S0098135414001112.
Côté, R.P., Cohen-Rosenthal, E., 1998. Designing eco-industrial parks: a synthesis of some experiences. J. Clean. Prod. 6, 181–188. http://dx.doi.org/10.1016/S0959-6526(98)00029-8. http://www.sciencedirect.com/science/article/pii/S0959652698000298.
Curran, M., 1996. Environmental life-cycle assessment. Int. J. Life Cycle Assess. 1, 179. http://dx.doi.org/10.1007/BF02978949. http://dx.doi.org/10.1007/BF02978949.
Dewulf, J.P., Van Langenhove, H.R., 2002. Quantitative assessment of solid waste treatment systems in the industrial ecology perspective by exergy analysis. Environ. Sci. Technol. 36, 1130–1135. http://dx.doi.org/10.1021/es010140o. http://dx.doi.org/10.1021/es010140o.
Díaz-Alvarado, F.A., 2015. An example of pareto dominance for dimensionality reduction in multi-objective optimization. Comput. Chem. Eng. 79, 135–136. http://www.sciencedirect.com/science/article/pii/S0098135415001246.
Dong, H., Geng, Y., Xi, F., Fujita, T., 2013. Carbon footprint evaluation at industrial park level: a hybrid life cycle assessment approach. Energy Policy 57, 298–307. http://dx.doi.org/10.1016/j.enpol.2013.01.057. http://www.sciencedirect.com/science/article/pii/S0301421513000840.
Dong, H., Ohnishi, S., Fujita, T., Geng, Y., Fujii, M., Dong, L., 2014a. Achieving carbon emission reduction through industrial & urban symbiosis: a case of Kawasaki. Energy 64, 277–286. http://dx.doi.org/10.1016/j.energy.2013.11.005. http://www.sciencedirect.com/science/article/pii/S0360544213009675.
Dong, L., Gu, F., Fujita, T., Hayashi, Y., Gao, J., 2014b. Uncovering opportunity of low-carbon city promotion with industrial system innovation: case study on industrial symbiosis projects in China. Energy Policy 65, 388–397. http://dx.doi.org/10.1016/j.enpol.2013.10.019. http://www.sciencedirect.com/science/article/pii/S0301421513010410.
Dunn, B.C., Steinemann, A., 1998. Industrial ecology for sustainable communities. J. Environ. Plan. Manag. 41, 661–672. http://dx.doi.org/10.1080/09640569811353. http://dx.doi.org/10.1080/09640569811353.
Eckelman, M.J., Chertow, M.R., 2013. Life cycle energy and environmental benefits of a US industrial symbiosis. Int. J. Life Cycle Assess. 18, 1524–1532. http://dx.doi.org/10.1007/s11367-013-0601-5.
Eurostat, 2001. Economy-wide Material Flow Accounts and Derived Indicators: a Methodological Guide. Office for Official Publ.. of the Europ. Comm, Luxembourg.
Frosch, R.A., Gallopoulos, N.E., 1989. Strategies for manufacturing. Sci. Am. 261, 144–152. http://www.umich.edu/~nppcpub/resources/compendia/IEORpdfs/IEOR_Reading.pdf.
Geng, Y., Fu, J., Sarkis, J., Xue, B., 2012. Towards a national circular economy indicator system in China: an evaluation and critical analysis. J. Clean. Prod. 23, 216–224. http://dx.doi.org/10.1016/j.jclepro.2011.07.005. http://www.sciencedirect.com/science/article/pii/S0959652611002460.
Geng, Y., Liu, Z., Xue, B., Dong, H., Fujita, T., Chiu, A., 2014. Emergy-based assessment on industrial symbiosis: a case of Shenyang economic and technological development Zone. Environ. Sci. Pollut. Res. 21, 13572–13587. http://dx.doi.org/10.1007/s11356-014-3287-8. http://dx.doi.org/10.1007/s11356-014-3287-8.
Geng, Y., Tsuyoshi, F., Chen, X., 2010a. Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. J. Clean. Prod. 18, 993–1000. http://dx.doi.org/10.1016/j.jclepro.2010.03.003. http://www.sciencedirect.com/science/article/pii/S0959652610001034.
Geng, Y., Zhang, P., Côté, R.P., Fujita, T., Cote, R.P., 2009a. Assessment of the national eco-industrial park standard for promoting industrial symbiosis in China. J. Ind. Ecol. 13, 15–26. http://dx.doi.org/10.1111/j.1530-9290.2008.00071.x. http://dx.doi.org/10.1111/j.1530-9290.2008.00071.x.
Geng, Y., Zhang, P., Côté, R.P., Qi, Y., 2008. Evaluating the applicability of the Chinese eco-industrial park standard in two industrial zones. Int. J. Sustain. Dev. World Ecol. 15, 543–552. http://dx.doi.org/10.1080/13504500809469850. http://dx.doi.org/10.1080/13504500809469850.
Geng, Y., Zhang, P., Ulgiati, S., Sarkis, J., 2010b. Emergy analysis of an industrial park: the case of Dalian, China. Sci. Total Environ. 408, 5273–5283.
Geng, Y., Zhu, Q., Doberstein, B., Fujita, T., 2009b. Implementing China's circular economy concept at the regional level: a review of progress in Dalian, China. Waste Manag. 29, 996–1002. http://dx.doi.org/10.1016/j.wasman.2008.06.036 (New York, N.Y.). http://www.sciencedirect.com/science/article/pii/S0956053X08002432.
Gibbs, D., 2008. Industrial symbiosis and eco-industrial development: an introduction. Geogr. Compass 2, 1138–1154. http://dx.doi.org/10.1111/j.1749-8198.2008.00123.x. http://dx.doi.org/10.1111/j.1749-8198.2008.00123.x.
Harlem, B.G., 1987. Our Common Future. United Nations World Commission on Environment and Development (WCED), Rio de Janeiro.
Jacobsen, N.B., 2006. Industrial symbiosis in Kalundborg, Denmark – a quantitative assessment of economic and environmental aspects. J. Ind. Ecol. 10, 239–255. http://dx.doi.org/10.1162/108819806775545411.
Jiang, M., Zhou, J., Chen, G., 2010. Unified process assessment for resources use and waste emissions by coal-fired power generation. Commun. Nonlinear Sci. Numer. Simul. 15, 2723–2733. http://dx.doi.org/10.1016/j.cnsns.2009.10.009. http://www.sciencedirect.com/science/article/pii/S1007570409005280.
Kalundborg-Symbiosis, 2015. Diagram. http://www.symbiosis.dk/en/diagram. http://www.symbiosis.dk/en/diagram.
Knight, P., 1990. A rebirth of the pioneering spirit. Financial Times. http://medcontent.metapress.com/index/A65RM03P4874243N.pdfhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:A+rebirth+of+the+pioneering+spirit#0.
Lowe, E.A., 2001. Eco-industrial Park Handbook for Asian Developing Countries. Report to Asian Development Bank.
Lu, Y., Su, M., Liu, G., Chen, B., Zhou, S., Jiang, M., 2012. Ecological network analysis for a low-carbon and high-tech industrial park. Sci. World J. 2012.
Muttil, N., Chau, K.-W., 2007. Machine-learning paradigms for selecting ecologically significant input variables. Eng. Appl. Artif. Intell. 20, 735–744. http://www.sciencedirect.com/science/article/pii/S0952197606002028.
National Research Council, 1997. Examples of environmental design and management. In: The Industrial Green Game: Implications for Environmental Design and Management. The National Academies Press, Washington, DC, pp. 117–123. http://www.nap.edu/catalog/4982/the-industrial-green-game-implications-for-environmental-design-and-management.
Odum, H.T., 1996. Environmental Accounting. Wiley.
OECD, 2008. Measuring Material Flows and Resource Productivity. In: The OECD Guide, vol. I. http://www.oecd.org/environment/indicators-modelling-outlooks/MFA-Guide.pdf.
Ohnishi, S., Fujita, T., Chen, X., Fujii, M., 2012. Econometric analysis of the performance of recycling projects in Japanese Eco-Towns. J. Clean. Prod. 33, 217–225. http://dx.doi.org/10.1016/j.jclepro.2012.03.027. http://www.sciencedirect.com/science/article/pii/S0959652612001746.
Pakarinen, S., Mattila, T., Melanen, M., Nissinen, A., Sokka, L., 2010. Sustainability and industrial symbiosis. The evolution of a Finnish forest industry complex. Resour. Conserv. Recycl. 54, 1393–1404. http://dx.doi.org/10.1016/j.resconrec.2010.05.015. http://www.sciencedirect.com/science/article/pii/S0921344910001369.
Park, H.-S., Behera, S.K., 2014. Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks. J. Clean. Prod. 64, 478–485. http://dx.doi.org/10.1016/j.jclepro.2013.08.032. http://www.sciencedirect.com/science/article/pii/S0959652613005726.
PCSD, 1997. Presidents Council on sustainable development, eco-industrial park workshop. In: Eco-Industrial Park Workshop (October 17–18, 1996). Cape Charles, Virginia. http://clinton2.nara.gov/PCSD/Publications/Eco_Workshop.html#ii.
Phillips, P.S., Barnes, R., Bates, M.P., Coskeran, T., 2006. A critical appraisal of an UK county waste minimisation programme: the requirement for regional facilitated development of industrial symbiosis/ecology. Resour. Conserv. Recycl. 46, 242–264. http://dx.doi.org/10.1016/j.resconrec.2005.07.004. http://www.sciencedirect.com/science/article/pii/S0921344905001217.
Sendra, C., Gabarrell, X., Vicent, T., 2007. Material flow analysis adapted to an industrial area. J. Clean. Prod. 15, 1706–1715. http://dx.doi.org/10.1016/j.jclepro.2006.08.019. http://www.sciencedirect.com/science/article/pii/S0959652606003209.
Sokka, L., Pakarinen, S., Melanen, M., 2011. Industrial symbiosis contributing to more sustainable energy use – an example from the forest industry in Kymenlaakso, Finland. J. Clean. Prod. 19, 285–293. http://dx.doi.org/10.1016/j.jclepro.2009.08.014. http://www.sciencedirect.com/science/article/pii/S0959652609002868.
Song, Q., Wang, Z., Li, J., 2013. Sustainability evaluation of e-waste treatment based on emergy analysis and the LCA method: a case study of a trial project in Macau. Ecol. Indic. 30, 138–147. http://dx.doi.org/10.1016/j.ecolind.2013.02.016. http://www.sciencedirect.com/science/article/pii/S1470160X13000903.
Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: moving from rhetoric to implementation. J. Clean. Prod. 42, 215–227. http://dx.doi.org/10.1016/j.jclepro.2012.11.020. http://www.sciencedirect.com/science/article/pii/S0959652612006117.
Tixier, J., Dusserre, G., Salvi, O., Gaston, D., 2002. Review of 62 risk analysis methodologies of industrial plants. J. Loss Prev. Process Ind. 15, 291–303. http://www.sciencedirect.com/science/article/pii/S0950423002000086.
Tolmasquim, M.T., Cohen, C., Szklo, A.S., 2001. CO2 emissions in the Brazilian industrial sector according to the integrated energy planning model (IEPM). Energy Policy 29, 641–651. http://dx.doi.org/10.1016/S0301-4215(00)00141-5. http://www.sciencedirect.com/science/article/pii/S0301421500001415.
Wang, G., Feng, X., Khim Hoong, C., 2014. Symbiosis analysis on industrial ecological system. Chin. J. Chem. Eng. 22, 690–698. http://dx.doi.org/10.1016/S1004-9541(14)60084-7. http://www.sciencedirect.com/science/article/pii/S1004954114600847.
Wen, Z., Meng, X., 2015. Quantitative assessment of industrial symbiosis for the promotion of circular economy: a case study of the printed circuit boards industry in China's Suzhou New District. J. Clean. Prod. 90, 211–219. http://dx.doi.org/10.1016/j.jclepro.2014.03.041. http://www.sciencedirect.com/science/article/pii/S0959652614002625.
Yang, H., Li, Y., Shen, J., Hu, S., 2003. Evaluating waste treatment, recycle and reuse in industrial system: an application of the eMergy approach. Ecol. Model. 160, 13–21. http://dx.doi.org/10.1016/S0304-3800(02)00288-0. http://www.sciencedirect.com/science/article/pii/S0304380002002880.

Yang, J., Chen, B., Qi, J., Zhou, S., Jiang, M., 2012. Life-cycle-based multicriteria sustainability evaluation of industrial parks: a case study in China. Sci. World J. 9 http://dx.doi.org/10.1100/2012/917830. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3523585&tool=pmcentrez&rendertype=abstract.

Yu, F., Han, F., Cui, Z., 2015. Reducing carbon emissions through industrial symbiosis: a case study of a large enterprise group in china. J. Clean. Prod. 103, 811–818. http://www.sciencedirect.com/science/article/pii/S095965261400506X.

Zhang, L., Yuan, Z., Bi, J., Zhang, B., Liu, B., 2010. Eco-industrial parks: national pilot practices in China. J. Clean. Prod. 18, 504–509. http://dx.doi.org/10.1016/j.jclepro.2009.11.018. http://www.sciencedirect.com/science/article/pii/S0959652609003941.

Zhang, Y., Liang, K., Li, J., Zhao, C., Qu, D., 2016. Lca as a decision support tool for evaluating cleaner production schemes in iron making industry. Environ. Prog. Sustain. Energy 35, 195–203. http://dx.doi.org/10.1002/ep.12208.

Zhao, M.-Y., Cheng, C.-T., Chau, K.-W., Li, G., 2006. Multiple criteria data envelopment analysis for full ranking units associated to environment impact assessment. Int. J. Environ. Pollut. 28, 448–464. http://dx.doi.org/10.1504/IJEP.2006.011222. http://www.inderscienceonline.com/doi/abs/10.1504/IJEP.2006.011222.

Zhu, L., Zhou, J., Cui, Z., Liu, L., 2010. A method for controlling enterprises access to an eco-industrial park. Sci. Total Environ. 408, 4817–4825. http://dx.doi.org/10.1016/j.scitotenv.2010.06.035. http://www.sciencedirect.com/science/article/pii/S0048969710006406.

Antonio Espuña, Moisès Graells and Luis Puigjaner (Editors), Proceedings of the 27th European Symposium on Computer Aided Process Engineering – ESCAPE 27
October 1st - 5th, 2017, Barcelona, Spain
http://dx.doi.org/10.1016/B978-0-444-63965-3.50328-7

Resilience Study Applied in Eco-Industrial Parks

Guillermo Valenzuela-Venegas[a], Francisco Henríquez[a], Ludovic Montastruc[b], Marianne Boix[b] and Felipe A. Díaz-Alvarado[a*]

[a]*Departamento de Ingeniería Química y Biotecnología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Av. Beauchef 851, Piso 6-poniente, Grupo de Ingeniería Sistémica de Procesos y Sustentabilidad, 8370456 Santiago, Chile*
[b]*Université de Toulouse, Laboratoire de Génie Chimique U.M.R. 5503 CNRS/INP/UPS. 4 allée Emile Monso, 31432 Toulouse Cedex 4, France*
felidiaz@ing.uchile.cl

Abstract

An Eco-Industrial Park (EIP) is a community of businesses that seeks to reduce the global impact through material sharing.
Even though an EIP presents an environmental improvement when compared with a set of stand-alone industrial plants, the established connections among the industrial participants can propagate failures, and become in a source of risk. For this reason, this work proposes an indicator to follow the resilience of EIPs, which is constructed to be applied on the design phase of eco-industrial parks, by means of an optimization problem. This indicator is based on two aspects of an industrial network: its topology and its operative flexibility. These aspects are measured by two respective sub-indicators, Network Connectivity Index (NCI) and Flow adaptability index (ϕ). Both sub-indicators are integrated to compose a global resilience indicator.
Finally, we apply the resilience indicator over five illustrative cases in order to analyze its applicability, obtaining consistent results.

Keywords: Indicator; Resilience; Security; Eco-industrial parks.

1. Introduction

An Eco-industrial park (EIP) is a community of businesses located together on a common property, sharing materials, energy, or infrastructures. An EIP is motivated by the economic, environmental, and social improvements achieved through the collaboration among the firms within the park (Boix et al. (2015)). These relationships foster the implementation of Industrial Symbiosis (IS), which seeks to transform wastes, by-products or products of a firm into inputs of another one taking advantages of their own connections (Chertow (2000)).

An optimization problem can be formulated to design an EIP (Boix et al. (2015)). This formulation can back up decisions during the design phase of an EIP, formalizing the industrial planning to make the industrial development more sustainable.

In this context, there are several works regarding to propose a mathematical formulation in order to design an EIP (Boix et al. (2015)). Even though EIPs are largely studied in the literature, they suffer of reluctance from industries. Indeed, the potential industrial participants are often hard to convince due to security issues when connecting processes, because failures are also propagated through a network.

In computer science, a security or resilience factor is considered when defining a network so as to reduce its vulnerability. This measure takes into account the topology of the network, quantifying the damage done to the whole network when the most critical element (e.g. the element with the maximum number of connections) is removed (Matta et al. (2014)).

In the context of EIP design, if we obtain an optimal configuration on the basis of the three sustainability dimensions, the question is what would happen if a participant is removed from the park. A pending issue in this field is to plan the connections of a single plant considering the stability of the other participants and their flow requirements, specially during failures within the network. In consequence, a new objective can be defined during the design phase to improve the security of the network by increasing its resilience.

Chopra and Khanna (2012) propose four metrics to apply over EIPs, all of them sustained on a network theory approach (Chopra and Khanna (2012)). The goal of these metrics is to measure the impact of a disruptive event of a park, focusing on their most affected nodes. These metrics are related with two aspects of the resilience of an industrial network: its connectivity and its efficiency. The first one establishes how necessary is to use a node to connect with others, and the second one, measures the changes in the efficiency of the park when a disruptive event occurs. Even though the authors obtain good results when apply these measures over an example, they propose to work on the resilience or adaptability of a network. In this context, an important lack of this metric is the quantification of the minimum performance of the network to be functional.

The novelty of this work is to create an indicator to measure the resilience of an industrial network based on its topology and operative aspects. The main difference with previous efforts is the orientation of the proposed indicator to operative changes after a disruption. The construction of this indicator relies on graph representation and is developed to be used in an optimization problem oriented to design an eco-industrial parks. To illustrate the use of this index, we apply it over five application cases. Accordingly, the objectives of this paper are to propose a resilience metric over EIPs and to illustrate its use.

2. Resilience indicator

We adopt the definition from Fiksel (2003), where the authors define this concept as "the capability of the system to absorb disruptions before it changes its properties that control its functionality. This property allows an IS network to endure the impact of unforeseen event".

In this work, we consider a disruptive event as when a participant interrupts completely its activity. Therefore, if a disruptive event involves a participant, its associated connections (edges) disappear. In addition, since the network must continue operating, the other participants must modify the magnitude of their inputs and outputs to compensate the losses without important changes in its configuration (e.g. entering of a new participant).

Therefore, a resilience indicator must be focused on two aspects: (i) if the connections in the park are enough to withstand a disruptive event, and (ii) if the remaining participant can compensate the lost flows when a firm interrupts its activity.

For this purpose, the proposed resilience indicator measures two aspects of a network through the combination of two metrics: Network Connectivity Index (NCI) and Flow adaptability index (ϕ). The first one measures the number of connections among participants and the second one measures the capacity of the participants of the network to compensate the flow demand when a firm suffers a disruptive event.

To define the metrics, and to support its application the design phase of EIP though an optimization problem, we use a graph representation of the park (Aviso et al. (2010)). Accordingly, each participant of the park is represented by a node, and the connections by oriented edges. Based on this representation, we define the following terms and sets:

- N: Set of park participants.
- C: Number of connections among park participants.
- n: Number of participants in the network.
- IN_k: Set of participants that have an input into $k \in N$.
- OUT_k: Set of participants that have an output from $k \in N$.
- $Q_i^{min,in}$: Minimum input needed capacity for the participant $i \in N$ to operate.
- $Q_l^{max,in}$: Maximum input capacity of the participant $l \in N$.
- $Q_m^{max,out}$: Maximum output capacity of the participant $m \in N$.
- $F_{i,j}$: Magnitude of the flow between $i \in N$ and $j \in N$.
- ϕ_k: Flow sensitivity of the participant $k \in N$ in a network.
- NCI: Network Connectivity Index of a park.
- ϕ: Flow sensitivity of a park.

The goal of NCI is to measure if there are enough connections in a network to endure a possible disruption. In this sense, the more connections in the park, the better for the stability of the network, and NCI increases its value. The risk of isolation of the participants decreases with the grow of NCI.

The general idea of this metric is to set a maximum and a minimum number of connections of the network, and to establish its level of connectivity according to these values. We define the maximum number of connections as the maximum possible number of edges among participants (Eq. (1)); and the minimum number of connections, as the minimum number of edges to maintain the identity of the park (Eq. (2)). We assume that an EIP maintains its identity when each node has one connection at least. We define the corresponding NCI value associated to the maximum and minimum number of connections of a park. Then, if the network has C_m^{max} connections, $NCI(C_n^{max}) = 1$. Otherwise, if the network has C_m^{min} connections, $NCI(C_n^{min}) = 0$. With these values, and to simplify the calculation, we establish a linear function between both cases (Eq. (3)).

$$C_n^{max} = \frac{n(n-1)}{2} \quad (1) \qquad C_n^{min} = n - \left\lfloor \frac{n}{2} \right\rfloor \quad (2) \qquad NCI(n,C) = \frac{2(C - n + \lfloor \frac{n}{2} \rfloor)}{n^2 - 3n + 2\lfloor \frac{n}{2} \rfloor} \quad (3)$$

On the other hand, the goal of ϕ is to quantify the necessary flow to sustain the operation of the park by modifying the remaining flows after a disruption. In this sense, if the flow magnitudes in the park can change to compensate the activity interruption of a firm, the other participants can maintain their operation. Therefore, ϕ measures the flexibility of the park when a participant interrupts its activity and to determine if the other members can compensate this event through changes in their inputs and outputs.

Let k be the reference to a specific material being shared in the network. To determine the capacity of the park participants to absorb disruptive events (changes in the network), we consider that every plant has a security range for inlets and outlets, i.e. a maximum and minimum flow to operate. We define the maximum inlet and outlet capacity of a participant $k \in N$ as $Q_k^{max,in}$ and $Q_k^{max,out}$, and the minimum inlet capacity of a participant $k \in N$ as $Q_k^{min,in}$. Since we need to measure the change over the park when a participant interrupts its activity, we define the "total lack of flows related to a disruption in k", $\mathbb{L}_k$, as:

$$\mathbb{L}_k = \sum_{i \in OUT_k} \max\left\{0, Q_i^{min,in} - \sum_{m \in IN_i; m \neq k} F_{m,i} - \sum_{m \in IN_i; m \neq k}\left(Q_m^{max,out} - \sum_{w \in OUT_m; w \neq k} F_{m,w}\right)\right\}$$
$$+ \sum_{j \in IN_k} \max\left\{0, F_{j,k} - \sum_{l \in OUT_k; l \neq k}\left(Q_l^{max,in} - \sum_{v \in IN_l; v \neq k} F_{v,l}\right)\right\} \qquad \forall k \in N \qquad (4)$$

As NCI, we define the worst and the best cases to compensate the loosed flow, and establish a linear function between them. The worst case is defined when each participant is operating at full capacity: $\mathbb{L}_k$ is maximum. On the other hand, the best case is when the network can totally compensate the activity interruption of their participants: $\mathbb{L}_k$ is minimum. Establishing both cases, we define ϕ_k for the network affected by the interruption in the activity of the participant k (Eq. (5)). Accordingly, if the park is working at the worst case, $\phi_k(\mathbb{L}_k^{max}) = 0$; and if the park is working at the best case, $\phi_k(\mathbb{L}_k^{min}) = 1$. Finally, we apply ϕ_k over each participant and calculate its average, in order to simplify the calculation, obtaining the Flow adaptability index ϕ of the whole park (Eq. (6)).

$$\phi_k(\mathbb{L}_k) = 1 - \frac{\mathbb{L}_k}{\sum_{j \in IN_k} F_{j,k} + \sum_{i \in OUT_k} Q_i^{min,in}} \quad k \in N \qquad (5)$$

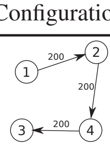
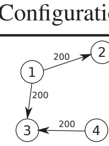
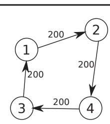
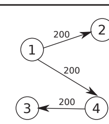
$$\phi = \frac{1}{n}\sum_{k \in N} \phi_k \qquad (6)$$

Finally, we define the resilience indicator as the average of NCI and ϕ.

3. Results and discussions

To analyze the applicability of the proposed indicator, we create four illustrative cases, where the connections among the participants are different in each of them (Table 1). Finally, to demonstrate the applicability of the proposed indicator to reality, we compose a new case considering all the previous examples, so as to address a new scenario with a higher complexity.

Table 1: Illustrative cases and their values of NCI, ϕ, and resilience indicator.

Example	Configuration	Results	Example	Configuration	Results
1		$\phi_1 = 0$ $\phi_2 = 0$ $\phi_3 = 0$ $\phi_4 = 0$ $\phi_{config.} = 0$ $NCI = 0.25$ $Resilience = 0.125$	3		$\phi_1 = 0.667$ $\phi_2 = 0.5$ $\phi_3 = 0.125$ $\phi_4 = 1$ $\phi_{config.} = 0.573$ $NCI = 0.25$ $Resilience = 0.441$
2		$\phi_1 = 0$ $\phi_2 = 0$ $\phi_3 = 0$ $\phi_4 = 0$ $\phi_{config.} = 0$ $NCI = 0.5$ $Resilience = 0.25$	4		$\phi_1 = 0$ $\phi_2 = 0.25$ $\phi_3 = 0$ $\phi_4 = 0.2$ $\phi_{config.} = 0.112$ $NCI = 0.25$ $Resilience = 0.181$
5	(Park)	$Resilience = 0.249$			

The first sub-indicator, NCI, considers the topology of a network, measuring the existence of connections in the park using the number of connections among the firms. Accordingly, if a network obtains a high NCI value, there are a lot of connections in the park, and therefore, the network does not loose connectivity when a disruptive event occurs. In contrast, if a network obtains a low NCI value, the park is weakly connected, and thus, the network has isolated participant during disruptions. This behavior can be seen on examples 1 and 2 (Table 1), where as the number of connection grows, the NCI increases its value. In the first example, if one participant interrupts its activity, it is highly probable that the network has isolated nodes. For instance, if the participant 2 interrupts its activity, participant 1 will loose connectivity. Conversely, in the example 2, since all participant have two connections, forming a closed loop, they will be always connected if any of them suffers a disruptive event. For example, if participant 2 interrupts its activity, the network maintains its connectivity. For this reason, the last configuration has the highest NCI value.

The second sub-indicator, ϕ, considers the performance of an industrial network, measuring the magnitude of the sharing flows and the feasibility of their substitution during disruptions. Therefore, if a network obtains a high ϕ value, the participants can endure the activity interruption of any of them, and therefore, the network can continue working.

We can observe on example 1, 3, and 4 (Table 1) the performance of this indicator, where the number of connections is kept constant ($NCI = 0.25$ for both of them), but the connected participant are changed. In the example 1, since all the participants obtain $\phi_k = 0$, they cannot be replaced, and therefore, the network cannot endure any disruptive event. In the example 4, the connection between participant 2 and 4 is changed for the connection between 1 and 4. This change makes modify the ϕ value of the network, suffering a little increase compared to the previous example. In this new configuration, participant 2 and 4 can be partially replaced for the other members when they suffer a disruptive event. In the example 3, the connection between participant 1 and 4 of the example 4 is changed for the connection between 1 and 3. In this new configuration, all the participant can be partially replaced by the other members, then ϕ of the network grows. This is because as some participants have more than one inputs or outputs, they do not depend just on one of them.

On the other hand, it is worth to note that the Flow adaptability index depends on the capacity of each firm to change the magnitude of its inputs and outputs, and on the connectivity of the participants. In consequence, ϕ depends on NCI.

An eco-industrial park is composed by a set of firms sharing different type of materials (e.g. water, biomass, oil, etc.). Each of these exchanges can be analysed through different sharing layers belonging to the same park, or by unconnected subsets within the park. In this context, two known examples in the literature are Kalundborg (Knight (1990)) and Ulsan (Behera et al. (2012)). In the first case, the industrial network is composed by different sharing layers, where the same set of firms share water, sludge, steam, among others; in the latter, there are different unconnected subsets of firms sharing different type of materials, as steam, waste oil, and zinc powder, among others. An illustrative example is provided with this logic. It considers a park composed by all the previous examples, sharing different type of material at once. We can estimate the resilience value in this context as the average of the individual resilience values of each sub-network (Table 1).

A better estimation of the resilience value of the whole park is proposed for further works, because the integration of multiple sharing layers or subsets can evolve from an average to another function, so as to improve the assessment of real industrial parks.

4. Conclusions

We propose an indicator to measure the resilience of an EIP and to support future application in optimization problems in the design phase of eco-industrial parks. This indicator is based on two characteristics of an industrial network: its topology and its operation. These aspects are measured by two sub-indicators: NCI and ϕ, respectively. The first one measures the number of connections in order to maintain the connectivity of the participants during a disruption event. The second sub-indicator measures the capacity of the participants to modify their flows and to replace the loosed ones when a disruptive event occurs. Both sub-indicators are integrated, composing a global resilience indicator.

The resilience indicator has been applied over five examples, where the number of connections and the orientation of them are modified. We obtain consistent results regarding both sub-indicators and the resilience indicator. It is important to remark the need to construct a good estimation of the resilience of a whole park, where different type of material is exchanged among the participants. Besides the number of connections conditions the resilience, their orientation has significant effects on the resilience indicator. It is important to remark that there is a dependence between ϕ and NCI, since the existence of a flow requires the existence of connections. In consequence, further work can be done to integrate ϕ and NCI so as to compose a resilience indicator.

Acknowledgments

G. Valenzuela-Venegas: This work was funded by the CONICYT-PCHA/Doctorado Nacional/2014-21140400. Felipe A. Díaz-Alvarado wants to thank the FCFM grant *Apoyo a la Inserción Académica* 2016; University of Chile.

References

Aviso, K., Tan, R., Culaba, A., 2010. Designing eco-industrial water exchange networks using fuzzy mathematical programming. Clean Technologies and Environmental Policy 12 (4), 353–363. URL http://dx.doi.org/10.1007/s10098-009-0252-1

Behera, S. K., Kim, J.-H., Lee, S.-Y., Suh, S., Park, H.-S., jul 2012. Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. JOURNAL OF CLEANER PRODUCTION 29-30, 103–112. URL http://www.sciencedirect.com/science/article/pii/S0959652612000832

Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S., 2015. Optimization methods applied to the design of eco-industrial parks: a literature review. Journal of Cleaner Production 87, 303–317. URL http://www.sciencedirect.com/science/article/pii/S0959652614009627

Chertow, M. R., nov 2000. INDUSTRIAL SYMBIOSIS: Literature and Taxonomy. Annual Review of Energy and the Environment 25, 313–337. URL http://www.annualreviews.org/doi/full/10.1146/annurev.energy.25.1.313

Chopra, S. S., Khanna, V., 2012. Toward a network perspective for understanding resilience and sustainability in industrial symbiotic networks. In: IEEE International Symposium on Sustainable Systems and Technology.

Fiksel, J., dec 2003. Designing Resilient, Sustainable Systems. Environmental Science & Technology 37 (23), 5330–5339. URL http://dx.doi.org/10.1021/es0344819

Knight, P., 1990. A rebirth of the pioneering spirit. Financial Times 14, 15.

Matta, J., Borwey, J., Ercal, G., 2014. Comparative Resilience Notions and Vertex Attack Tolerance of Scale-Free Networks. arXiv preprint arXiv:1404.0103, 1–9. URL http://arxiv.org/abs/1404.0103

Resilience Study Applied in Eco-Industrial Parks

Guillermo Valenzuela-Venegas [a], Francisco Henríquez [a], Ludovic Montastruc [b], Marianne Boix [b], Felipe Díaz-Alvarado [a]
[a] Departamento de Ingeniería Química y Biotecnología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Av. Beauchef 851, Piso 6-poniente, Grupo de Ingeniería Sistémica de Procesos y Sustentabilidad, Santiago, Chile.
[b] Université de Toulouse, Laboratoire de Génie Chimique U.M.R. 5503 CNRS/INP/UPS. 4 allée Emile Monso, 31432 Toulouse Cedex 4, France.

Abstract

An **Eco-Industrial Park (EIP)** is a community of businesses that seeks to reduce the global impact through material sharing.
Even though an EIP presents **an environmental improvement** when compared with a set of stand-alone industrial plants, **the established connections among the industrial participants can propagate failures**, and become in a source of risk.
For this reason, this work proposes an indicator to follow the **resilience of EIPs**, which is constructed to be applied on the design phase of eco-industrial parks, by means of an optimization problem. This indicator is based on two aspects of an industrial network: **its topology** and **its operative flexibility.** These aspects are measured by two respective sub-indicators, **Network Connectivity Index (NCI)** and Flow adaptability index (ϕ). Both sub-indicators are integrated to compose a global resilience **indicator.**
Finally, we apply the resilience indicator over five illustrative cases in order to analyze its applicability, obtaining consistent results.

Eco-Industrial Park and Industrial Symbiosis

- The **Industrial Symbiosis (IS)** seeks to **transform** wastes, by-products or products of a firm into inputs of another one taking **advantages of their connections** [Chertow, 2000].
- An **Eco-Industrial Park (EIP)** is a **community of businesses located together** on a common property, **sharing materials, energy, or infrastructures.** An EIP is motivated by the **economic, environmental, and social improvements** achieved through the collaboration among the firms within the park [Boix, 2015].

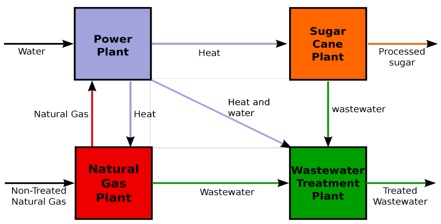
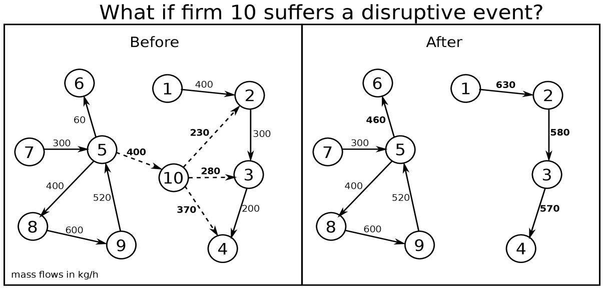


Figure 1: Example of an Eco-Industrial park.

Motivation of this work

- An EIP can be designed by the **formulation of an optimization problem**, obtaining improvements on the **sustainability dimension** [Boix, 2015].
- This formulation can **back up decisions** during the **design phase** of an EIP, formalizing the industrial planning to make the industrial development more sustainable.
- Even though EIPs are largely studied in the literature, they suffer of **reluctance from industries** to participate due to **security issues** when connecting processes, since **failures are also propagated** through the network.

What if firm 10 suffers a disruptive event?



- A pending issue in the design of EIPs is to plan the connections of a single plant considering the **stability** of the other participants and their **flow requirements**, specially during f**ailures within the network.**
- In consequence, **a new objective** can be defined **during the design phase** to **improve the security** of the network by increasing its **resilience.**

Objectives

- To **create** an indicator to **measure the resilience** of an EIP bases on its **topology** and **operative aspects.**
- To **illustrate** the use of the proposed indicator through examples.

The **difference** with previous efforts is the orientation of the proposed indicator to **operative changes after a disruptive event** and the consideration of the **participants response** in order to **endure the failure propagation.**

Notation

- **N**: Set of park participants.
- **C**: Number of connections among participants.
- **n**: Number of participants in the network.
- IN_k: Set of participants that have an input into k ϵ N.
- OUT_k: Set of participants that have an output from k ϵ N.
- $Q_i^{min,in}$: Minimum input needed capacity for the participant i ϵ N to operate.
- $Q_l^{max,in}$: Maximum input capacity of the
- $Q_m^{max,out}$: Maximum output capacity of the participant m ϵ N.
- $F_{i,j}$: Magnitude of the flow between i ϵ N and j ϵ N.
- ϕ_k: Flow adaptability index of the participant k ϵ N in a network.
- **NCI**: Network Connectivity Index of a park.
- **ϕ**: Flow adaptability index of a park.

Acknowledgments

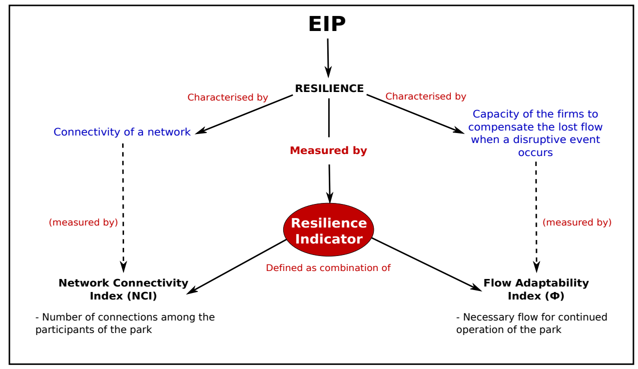
G. Valenzuela-Venegas: This work was funded by the CONICYT-PCHA/Doctorado Nacional/2014-21140400.
Felipe A. Díaz-Alvarado wants to thank the FCFM grant Apoyo a la Inserción Académica 2016; University of Chile.

Resilience Indicator

Definition of Resilience in EIP [Fiksel, 2003]:
"The capability of the system to absorb disruptions before it changes its properties that control its functionality. This property allows an IS network to endure the impact of unforeseen event."

- If a **disruptive event** ocurrs, the participant **interrupts completely** its activity, i.e., their associated **connections (edges) disappear.**
- In order **to compensate the losses**, the participants of an EIP **change their flows**, but the EIP **configuration is not altered** (e.g. entering of a new participant).

Structure of the Resilience Indicator



Network Connectivity Index (NCI)

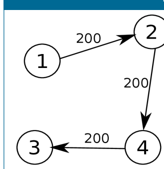
$$C_n^{max} = \frac{n(n-1)}{2} \qquad C_n^{min} = n - \left\lfloor \frac{n}{2} \right\rfloor \qquad NCI(n,C) = \frac{2(C - n + \lfloor \frac{n}{2} \rfloor)}{n^2 - 3n + 2\lfloor \frac{n}{2} \rfloor}$$

Flow Adaptability Index (ϕ)

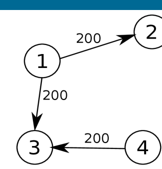
$$\mathbb{L}_k = \sum_{i \in OUT_k} \max\left\{0, Q_i^{min,in} - \sum_{m \in IN_i; m \neq k} F_{m,i} - \sum_{m \in IN_i; m \neq k} \left(Q_m^{max,out} - \sum_{w \in OUT_m; w \neq k} F_{m,w} \right) \right\}$$
$$+ \sum_{j \in IN_k} \max\left\{0, F_{j,k} - \sum_{l \in OUT_k; l \neq k} \left(Q_l^{max,in} - \sum_{v \in IN_l; v \neq k} F_{v,l} \right) \right\} \qquad \forall k \in N$$

$$\phi_k(\mathbb{L}_k) = 1 - \frac{\mathbb{L}_k}{\sum_{j \in IN_k} F_{j,k} + \sum_{i \in OUT_k} Q_i^{min,in}} \quad k \in N \qquad \phi = \frac{1}{n} \sum_{k \in N} \phi_k$$

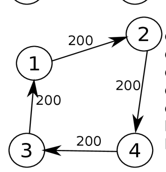
Illustrative examples



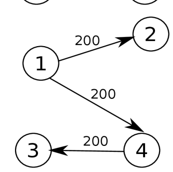
$\phi_1 = 0$
$\phi_2 = 0$
$\phi_3 = 0$
$\phi_4 = 0$
$\phi_{config} = 0$
NCI = 0.25
Resilience = 0.125



$\phi_1 = 0.667$
$\phi_2 = 0.5$
$\phi_3 = 0.125$
$\phi_4 = 1$
$\phi_{config} = 0.573$
NCI = 0.25
Resilience = 0.441



$\phi_1 = 0$
$\phi_2 = 0$
$\phi_3 = 0$
$\phi_4 = 0$
$\phi_{config} = 0$
NCI = 0.5
Resilience = 0.25



$\phi_1 = 0$
$\phi_2 = 0.25$
$\phi_3 = 0$
$\phi_4 = 0.2$
$\phi_{config} = 0.112$
NCI = 0.25
Resilience = 0.181

Resilience of a park
(considering the four previous examples) Resilience = 0.249

Conclusions and Future works

- The proposed indicator is based on the **topology** and **operation characteristics** of an industrial network, measured by two sub-indicators respectively: **Network Connectivity Index (NCI)** and **Flow Adaptability Index (ϕ).**
- This indicator is constructed to **support** future applications in **optimization problem** in the **design** phase of EIPs.
- A good estimation of the resilience of an EIP is needed in order to consider the exchange of different type of material among the participant.
- There is a dependence between phi and NCI, since the existence of a flow requires the existence of connections. So, future works can integrate both sub-indicators in order to create a resilience indicator.

References

- Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S. Optimization methods applied to the design of eco-industrial parks: a literature review. J. Clean. Prod. 87, 303–317 (2015).
- Chertow, M.R. INDUSTRIAL SYMBIOSIS: Literature and Taxonomy. Annu. Rev. Energy Environ. 25, 313–337 (2000).
- Fiksel, J. Designing Resilient, Sustainable Systems. Environ. Sci. Technol. 37, 5330–5339 (2003).

Journal of Cleaner Production 174 (2018) 807–820

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A resilience indicator for Eco-Industrial Parks

Guillermo Valenzuela-Venegas [a], Francisco Henríquez-Henríquez [a], Marianne Boix [b], Ludovic Montastruc [b], Fernando Arenas-Araya [a], Jenny Miranda-Pérez [a], Felipe A. Díaz-Alvarado [a, *]

[a] Department of Chemical Engineering, Biotechnology, and Materials, Faculty of Physical and Mathematical Sciences, Universidad de Chile, Av. Beauchef 851, Piso 6-poniente, Group of Sustainability and Process Systems Engineering, 8370456, Santiago, Chile

[b] Université de Toulouse, Laboratoire de Génie Chimique U.M.R. 5503 CNRS/INP/UPS, 4 allée Emile Monso, 31432, Toulouse Cedex 4, France

A R T I C L E I N F O

Article history:
Received 31 March 2017
Received in revised form
4 November 2017
Accepted 5 November 2017
Available online 7 November 2017

Keywords:
Indicator
Resilience
Eco-Industrial Park
Network

A B S T R A C T

An Eco-Industrial Park (EIP) is a community of businesses that seeks to reduce the global impact by sharing material. The connections among the industrial participants within this park improve the environmental performance of the industrial network. However, the connectivity also propagates failures. This risk is an important point of criticism and a barrier to industrial plants when evaluate their integration to an EIP. This paper proposes an indicator to follow the resilience of an EIP so as to improve the security of the whole system, considering the dynamic of the participants to endure a disruptive event. This metric could be used by decision-makers in order to include the resilience in the design phase of an EIP. Solving these security problems would expand the set of experiences of cleaner production, facilitating the integration of industrial processes. The proposed resilience indicator is based on two main characteristics of an industrial network: the number of connections among participants, and the capacity of each flow to change its magnitude when a participant suddenly stops sharing flows within the park. A network is separated in independent layers to quantify its flexibility when substituting flows. Each layer includes a single shared material. The resilience of a multi-layer park is then calculated as a weighted summation. This indicator is applied over two illustrative cases to study: Kalundborg, in Denmark; and Ulsan, in South Korea. These applications show consistent results when compared with reality. Although the proposed resilience indicator has been developed for material networks, it can be adapted to heat integration networks. In this case, special attention should be payed to physical constraints as minimal temperature gradients.

1. Introduction

An Eco-Industrial Park (EIP) is a community of businesses located together in a common property, sharing materials, energy, or infrastructures (Lowe, 2001). It is motivated by economic, environmental, and social improvements achieved through the collaboration among the firms within the park. These relationships foster the implementation of Industrial Symbiosis (IS), which seeks to transform wastes, by-products or products of a firm into inputs for another one taking advantage of their own connections (Chertow, 2000).

The benefits obtained by an EIP cover the three sustainability dimensions: economic, environmental, and social (Boix et al., 2015). The improvements are related to profitability and resilience, environmental impact reduction, and concern for local community next to the park (Valenzuela-Venegas et al., 2016). The magnitude of these benefits is associated to the configuration of an EIP, in other words, to connections among firms and their location. This configuration can be chosen by decision-makers at the design phase of EIPs.

One of the best-known examples of EIP is Kalundborg, in Denmark (Knight, 1990). It presents a regional symbiosis where the participants exchange water, heat and by-products (Chertow, 2008). The participants are firms, local community, and a lake (see Fig. 1). Each participant is considered in the design. Some of the benefits are reduction in carbon dioxide (CO_2) and in sulfur dioxide (SO_2) emissions; transformation of wastes into raw materials; reduction in coal, oil, and water flows; and heat reutilization as

* Corresponding author.
E-mail address: felidiaz@ing.uchile.cl (F.A. Díaz-Alvarado).

https://doi.org/10.1016/j.jclepro.2017.11.025

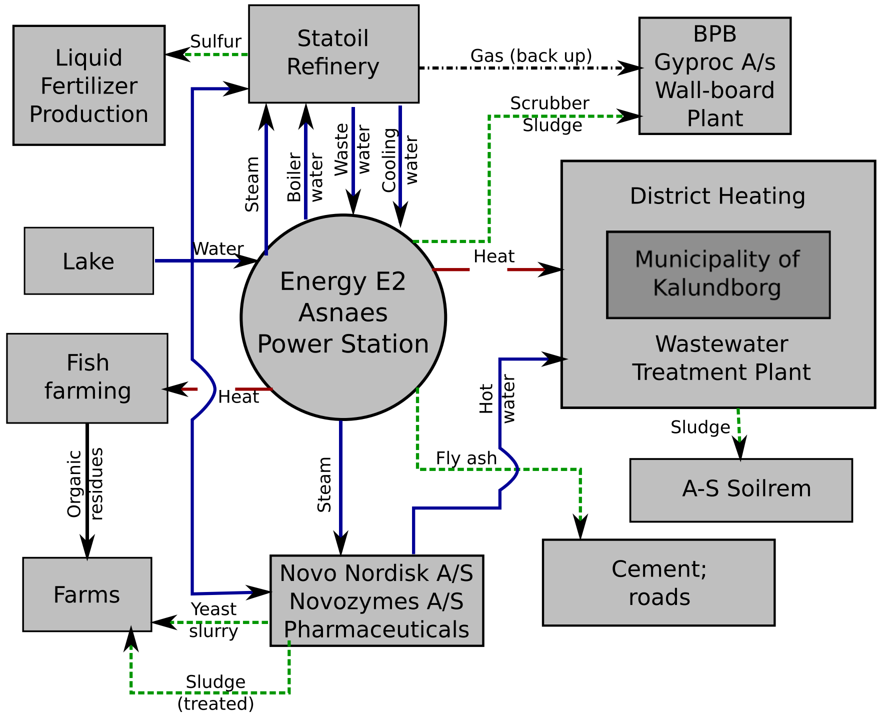


Fig. 1. Eco-Industrial Park in Kalundborg. Blue arrows indicate water exchanges, red arrows heat exchanges, and green arrows residue exchanges. Figure obtained from Chertow (2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

district heat for the local community (Chertow, 2000). All these flows produce changes on each sustainability dimension, obtaining remarkable improvements for each participant and for the entire park (Jacobsen, 2006).

To design an EIP focusing on their benefits, an optimization problem can be formulated (Boix et al., 2015). Using the solution of a nonlinear or mixed-integer nonlinear programming problem, it is possible to obtain an optimal network configuration (Biegler and Grossmann, 2004). This formulation can back up decisions during the design phase of an EIP, formalizing the industrial planning to make the industrial development more sustainable.

In this context, there are several works proposing a mathematical formulation to design an EIP. These efforts can be classified into three categories according to the type of exchanges among participants of the park (Tudor et al., 2007): water networks (e.g. Boix et al., 2011, 2012; Montastruc et al., 2013; Ramos et al., 2016; Rubio-Castro et al., 2011; Tiu and Cruz, 2017), energy networks (e.g. Chae et al., 2010; Kuznetsova et al., 2016; Liew et al., 2013), and material networks (e.g. Haslenda and Jamaludin, 2011; Tietze-Stöckinger et al., 2004; Zhang et al., 2017). Each of these formulations optimizes the configuration of an EIP with focus on one or more sustainability dimensions.

In the work of Lovelady and El-Halwagi (2009) the authors propose and solve a problem of water network design in order to minimize the total annualized cost using different strategies as recycling, reutilization, and separation. They compare this solution with the scenario of using only freshwater, and conclude that the recycling strategy is the most profitable. In Tiu and Cruz (2017), the authors propose a mathematical formulation to design a water network, simultaneously minimizing the economic and the environmental dimension through the reduction of piping, operating, freshwater, wastewater and treatment cost, and involving the volume and the quality of the water used in the EIP (Tiu and Cruz, 2017). They obtain a better result considering both sustainability dimension that just one of them. In Cimren et al. (2011), an optimization model over by-products in an industrial network is used to minimize economic and environmental indicators. This model is applied over an existing industrial network in USA and its solution is compared with a base case with no synergetic relationships among the companies. The resulting by-product network achieves the reduction on the costs and on the CO_2 emissions when is compared with the base case, illustrating the improvements offered by the design of an EIP using a mathematical formulation.

In all these examples the main objectives of the EIP design problems are focused on sustainability dimensions (Boix et al., 2015). Even though EIPs are largely studied in the literature, they suffer of reluctance from industries. Indeed, the potential industrial participants are often hard to convince due to security issues when connecting processes, because failures are also propagated through a network (Zeng et al., 2013). In this sense, how to convince industries to be included in an EIP? Is it always safe to connect processes? What if a company undergoes a stop in production?

In computer networks, a security or resilience factor is considered when defining a configuration. This focus allows to reduce the vulnerability of the whole network (Goel et al., 2004). This measure takes into account the topology of the network, in other words, the way the elements are connected in it. In general, this factor quantifies the damage done to the whole network when the most critical element (e.g., the element with the maximum number of connections) is removed (Matta et al., 2014). The aforementioned damage is commonly quantified by the number of compromised nodes after the failure of a single node within the network.

Following the same idea, after obtaining an optimal configuration in the context of an EIP design, the question is what would happen if a participant is removed from the park. A pending issue in this field is to design the connections of a single plant considering the stability of the other participants and their flow requirements, specially during failures within the network (Xiao et al., 2016; Zeng et al., 2013). A new objective during the design phase could be added to improve the security of the network by increasing its resilience.

The point is how to measure the resilience of the park during the design phase. In this sense, some authors define metrics in order to measure this characteristic (Chopra and Khanna, 2014; Li and Xiao, 2017; Xiao et al., 2016; Zeng et al., 2013; Zhu and Ruth, 2013). In Chopra and Khanna (2012, 2014), the authors propose four metrics to measure the resilience of an EIP, focused in two aspects of an industrial network: its connectivity and its efficiency (Chopra and Khanna, 2012, 2014). The general goal of these metrics is to measure the impact of a partial and complete disruption over the park and their participants, focusing on the most affected nodes and on the loss of efficiency of the park. In Li and Xiao (2017), the authors propose a methodology to measure the resilience of a network, analyzing their topological aspects (Li and Xiao, 2017). They explore the resilience from a topological approach, determining the main characteristics of a network and quantifying the importance of each participant through these characteristics. Additionally, the authors note the necessity to use the flows of the participant firms to better represent the real relationships in the park. Some works are focused on the cascading failure of the participants in a network, studying the responses of the firms after removing one of them. They base their analysis on the fact that if a critical component fails, it could lead to further participants decided to leave the network due to cascading failures (Zeng et al., 2013). In Xiao et al. (2016), the authors propose a model that can be used for more stable operation of an eco-industrial system (Xiao et al., 2016). To do this, they define two indicators respectively to assess two characteristics of an industrial network: its structural stability and its functional stability. The goal of the model is to measure the impact of the cascading failure, considering the decision of the firms to stay in or leave the park, i.e., the dynamic of the network after a disruptive event occurs.

All these works about resilience of an eco-industrial system are focused on the efficiency of the network from a topological point of view, or on the cascading failures phenomenon, considering the decision of the participant to stay in or leave the park. To the best of our knowledge, there are no works focusing on the dynamic of the participant of an EIP when a disruptive event occurs, considering the decision of the firms to absorb the consequences of this failure.

The present work aims at creating a resilience measure for EIPs, considering the decision of the participant to absorb possible disruptive events on them. This indicator is constructed to support its future application in an optimization problem, so as to design EIPs with an additional resilience-oriented objective. The goal of this metric is to determine if the connections are enough to maintain the identity of the park and to quantify the performance of the participants when a firm stops sharing flows, after changes in their input and output flows. Beside the resilience measure, this indicator is applied over two application cases in order to illustrate its use. The objectives of this paper are to define a resilience metric over EIPs and to apply this factor in existing EIPs.

After the present introduction, Section 2 explains the construction of the proposed indicator, and Section 3 illustrates its application by means of two examples. Section 4 presents the discussions about the application of the proposed indicator over the two illustrative examples, and about some improvements in its construction. Finally, Section 5 presents the conclusions of this work.

2. Definition of the resilience indicator

This section explains some considerations about the representation of an EIP to back up the definition of the Resilience Indicator.

The starting point is the definition of resilience from Fiksel (2003), where the authors define this concept as *the capability of the system to absorb disruptions before it changes its properties that control its functionality. This property allows an IS network to endure the impact of unforeseen event.*

This definition takes into account the capability of a network to face a disruptive event. In other words, resilience considers the adaptability of a network to withstand a disruptive event and to absorb their consequences. The present work considers a disruptive event when a firm interrupts its activity losing their inputs and outputs in the network.

Generally, from computer network studies, or other similar systems, the concept of resilience is focused on the number of connections. The most connected participant is identified as the critical node. When this node is removed from the network, the number of connections is detected (critical node), and the number of lost connections is quantified over the whole network comparing two scenarios: the base state, and the state where the critical element is not present (Matta et al., 2014).

When a participant interrupts its activity, the network losses connections (edges) and modifies its flows. Two effects are present in the network. After the disruption in the network, the remaining participants must compensate the flows they have lost. For instance, if a participant of a network interrupts its activity (see Fig. 2), its associated input and output flow would disappear (connections). The number of connections in the park changes. Since the network must continue working and producing, the remaining participants should modify the magnitude of their flows to compensate the losses without important changes in the network (entering of a new participant or creating new connections).

In view of the foregoing, the resilience measure has to detect these consequences and assess if the park could maintain its operation. The indicator has to focus on two aspects: (i) if the connectivity of the industrial network is enough to withstand a disruptive event and (ii) if the other firms can compensate the lost flows when a firm interrupts its activity.

The proposed resilience indicator measures two aspects of a network:

- The number of connections among participants, known as Network Connectivity Index (NCI).
- The capacity of the participants to compensate the flow demand when one participant interrupts its activity, or Flows adaptability index (ϕ).

The resilience indicator is defined as a combination of both metrics, the Network Connectivity Index and Flows Adaptability Index. Fig. 3 shows the structure of this indicator, remarking how it is constructed by two sub-indicators and what characteristics of the resilience, in the context of EIP, it measures.

The following subsection explains the mathematical representation used in the definition for both metrics.

2.1. Mathematical representation of an EIP

An EIP is a set of firms where the participants can share different elements such as material and energy. To facilitate the design and the analysis of these parks, the information about flows can be separated in order to compose a network for each shared component (see Fig. 4a). With this in view, the design of an EIP can be approached by a succession of sub-designs, each of them related to a single material or energy. In such sub-design, the exchange network is defined by the connections between the participants and their respective flows. During this work, an exchange network associated with a single component (e.g. water) is a *layer*.

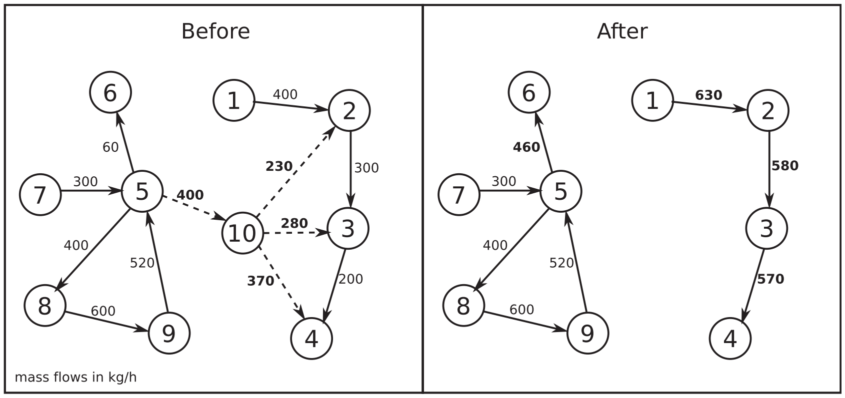


Fig. 2. Consequences over an eco-industrial park when one of their participants stops its activity. The dotted arrows show the affected connections; and the numbers in bold, the modified flows.

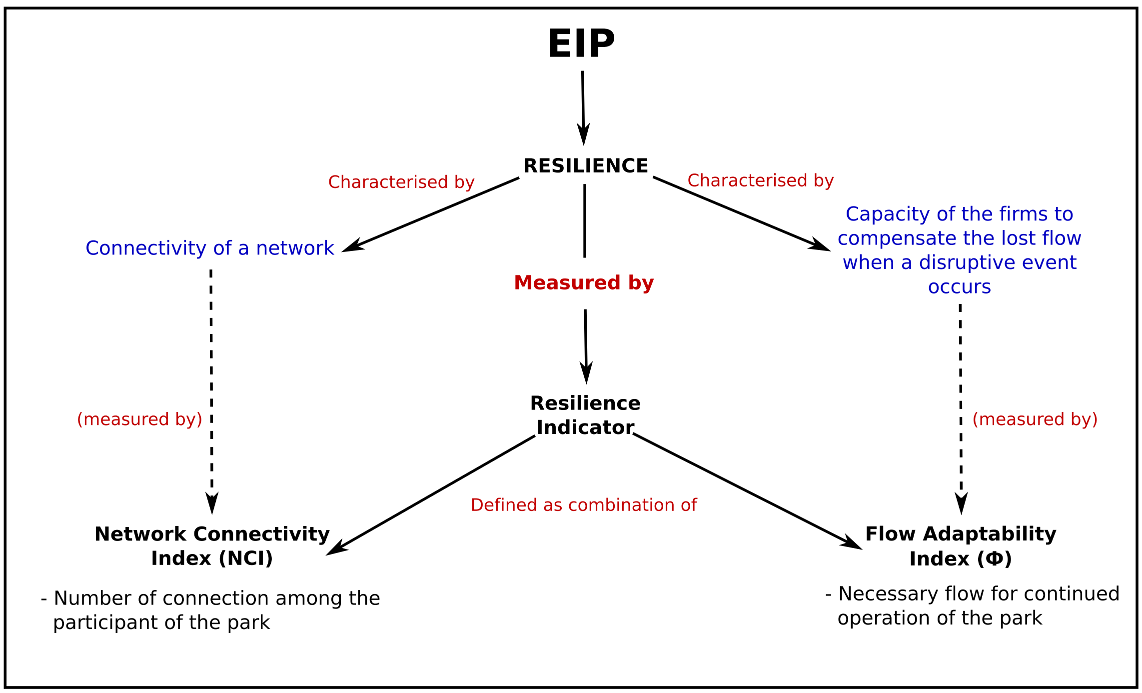


Fig. 3. Main characteristics of the resilience applied in an EIP, and structure of the proposed resilience indicator to measured it.

Each exchange network can be designed through mathematical optimization tools, deciding connections and allocations of each participant (Boix et al., 2011). These tools use a mathematical representation to formulate the optimization problem. These representations are graphs, where the participants of the park are represented by nodes; and the connections, by oriented edges (see Fig. 4b). This representation is adopted in order to define each metric and the resilience indicator of an EIP.

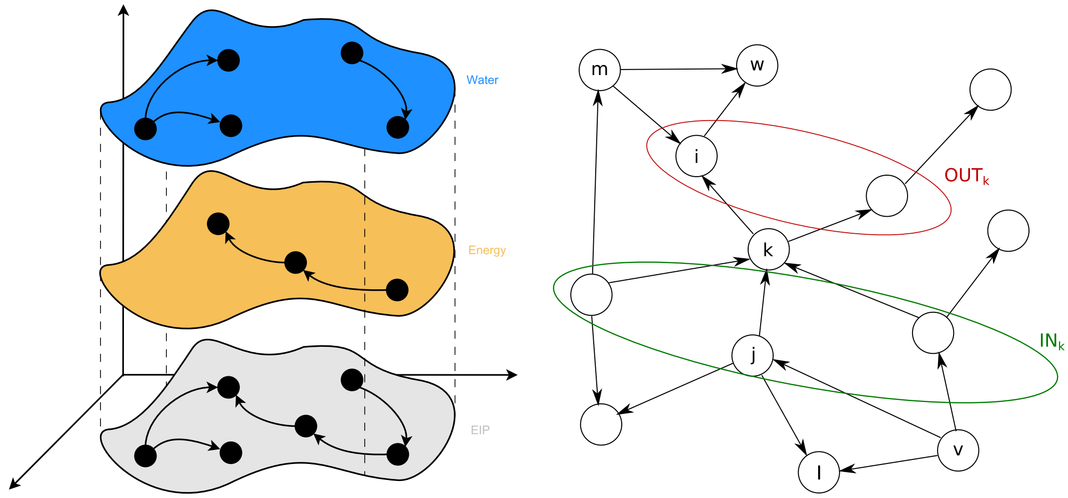
Due to the aforementioned points, the following terms and sets are defined:

- N: Set of park participants.
- C: Number of connections among park participants.
- n: Number of participants, $n = |N|$.[1]
- L: Set of layers in the park.
- $|L|$: Number of layers in the park.
- IN_k: Set of participants that contribute an input into $k \in N$.
- OUT_k: Set of participants that have an output from $k \in N$.
- $Q_l^{max,in}$: Maximum input capacity of the participant $l \in N$.
- $Q_i^{min,in}$: Minimum input capacity needed for the participant $i \in N$ to operate.
- $Q_m^{max,out}$: Maximum output capacity of the participant $m \in N$.
- $F_{i,j}$: Magnitude of the flow between $i \in N$ and $j \in N$.
- ϕ_k: Flow sensitivity of the participant $k \in N$ in a network.
- $\phi_k^{layer_r}$: Flow sensitivity of the participant $k \in N$ in the layer $r \in L$ of the park.
- NCI: Network Connectivity Index of a park.
- ϕ: Flow sensitivity of a park.

2.2. Network Connectivity Index

As in a computational network, in an EIP the connections among

[1] $|\cdot|$:cardinality of a set.



(a) Mathematical representation of different layers in a park.

(b) Mathematical representation of a network in a single layer.

Fig. 4. Representation of an EIP through a multi-layer scheme and directed graphs.

participant are important because they follow the existing exchanges within the network. In this sense, if one participant interrupts its activity, their surrounding connections are infeasible while the disruption persists. With a larger number of connections in the park, the network has greater possibilities to endure changes in its configuration because it will be able to keep its connectivity when a participant interrupts its activity. When a park has a lower number of connections, a disruptive event in a company can isolate others.

The Network Connectivity Index (NCI) aims at quantifying connections in a park and at measuring the endurance of the whole network against a possible disruption. The main focus of NCI is the configuration of the park: its topology. In this sense, if the park is completely connected and a disruptive event occurs, other firms will not be isolated and would have other options to compensate their losses. In this situation, the park maintains its identity. Conversely, if the network has only one connection between each participant and one of them interrupts its activity, the park is divided. This metric defines the connectivity level as a reference to a maximum and minimum number of connections in the network.

It is important to remark the absence of orientation in this measure. The NCI takes into account the complexity of the network, but other aspects as orientation and flows will be considered in other metric (flows adaptability index). Since an EIP can be configured as a multi-layer park, to count the number of connection, all the participants are considered in a unique layer, no matter what they are sharing. If between two nodes there are more than one connection, just one of them is considered. For example, if two participants (nodes) are connected in a direct or reverse direction (from A to B or from B to A), the NCI considers a unique connection (edge).

2.2.1. Minimum number of connections (C_n^{min})

The minimum number of connections of an EIP is defined as the minimum number of edges necessary to constitute a park. A basic assumption in this logic is that an EIP maintains its identity if each node has at least one connection.

In this definition, the following scenarios are possible:

- If the park has three node, $n = 3$ (see summary Table 1), the minimum number of connection to maintain the participants connected, without identity loss (node isolation), is $C_3^{min} = 2$.
- If a new node is added to the last configuration, $n = 4$, it is possible to create three new connections: one to each existing node. As the goal is to calculate the minimum number of connections, it is possible to consider only one of them. The minimum number of connection for $n = 4$ would be 3. However, there is a possibility to reduce this value with no isolated nodes. In this case, it is possible to separate the network in two subsets (see summary Table 1). The minimum number of connection for $n = 4$ is $C_4^{min} = 2$.

It is worth to note that the case with two or less nodes is not considered because they do not constitute an EIP, where the collaboration among three firms is required (Chertow, 2008).

Table 1 shows a summary of the minimum number of connections C_n^{min} for different number of nodes n. From this table and the above progression, it is possible to infer the following for the minimum case: (i) if n is even, every node has a unique edge; and (ii) if n is odd, one node has two edges and the remaining nodes have a single edge.

The equation for the minimum number of connection C_n^{min} for n nodes is expressed as follows:

$$C_n^{min} = n - \lfloor n/2 \rfloor \quad (1)$$

where x is the operation floor, which is the largest integer less than or equal x.

2.2.2. Maximum number of connections (C_n^{max})

The maximum number of connections (C_n^{max}) in a park of n participants is defined as the larger number of edges among participants. In this sense, the following procedure is necessary to define C_n^{max}:

- Considering a participant in a park composed by n members (p_1, where $p_1 \in N$), its maximum number of connections is $n - 1$.
- For another participant (p_2, where $p_2 \in N$), the maximum number of connections without the considered connection in

Table 1
Maximum (C_n^{max}) and minimum number of connections (C_n^{min}) among nodes in a park.

Number of nodes (n)	Minimum number of connections (C_n^{min})	Maximum number of connections (C_n^{max})
3	2	3
4	2	6
5	3	10
6	3	15
7	4	21
8	4	28
9	5	36
10	5	45

the above scenarios is $n-2$. This is because the connections have been considered unoriented.

- Following this logic, the maximum number of connection for the participant p_k, where $p_k \in N$ (without the considered connection), will be $n-k$.
- The maximum number of connections in a park with n participants is obtained by the following summation:

$$C_n^{max} = \sum_{k \in N} n - k \quad (2)$$

$$C_n^{max} = \frac{n(n-1)}{2} \quad (3)$$

To illustrate this point: if the network is composed by 3 nodes, the maximum number of connections is 3; if the network is composed by 4 nodes, the maximum is 6. Table 1 shows a summary of C_n^{max} for different number of nodes in a network.

2.2.3. Definition of Network Connectivity Index (NCI)

Establishing the maximum and minimum number of connections in a park, it is possible to define the Network Connectivity Index (NCI) associated with each of them. If the network has the maximum number of connections, C_m^{max}, then, $NCI(C_n^{max}) = 1$. If the network has the minimum number of connections, C_m^{min}, then the $NCI(C_n^{min}) = 0$. With these values, a linear function between both cases (see Fig. 5) allows to interpolate other cases. It is worth to remark the use of a linear function in order to simplify the definition of NCI. In future works, it could be changed according to properly represent the behavior of this characteristic between these two points.

The NCI is defined as follow:

$$NCI(n, C) = \frac{2\left(C - n + \lfloor \frac{n}{2} \rfloor\right)}{n^2 - 3n + 2\lfloor \frac{n}{2} \rfloor} \quad (4)$$

where C is the number of connections of the network (edges) and n is the number of participants of the network (nodes). It is worth noting that NCI is an adimensional index and indicates the connection level of a configuration network with n participants according to its maximum and its minimum number of connections.

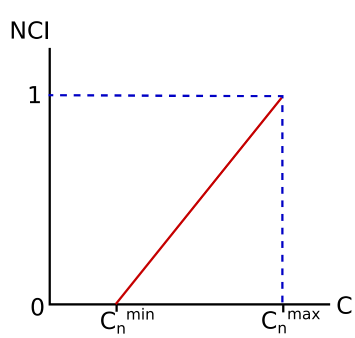


Fig. 5. Defined linear function between minimum and maximum cases for NCI.

This section has presented the construction of the Network Connectivity Index, which seeks to quantify the connection level of a park through the number of its connections. This index sets the maximum and the minimum number of possible connections, and establishes the level of connections of the park configuration. So, if $NCI = 1$, it means that the park is completely connected and can endure a firm activity interruption (see Fig. 6a). Conversely, if $NCI = 0$, it means that some participants are isolated when a disruptive event occurs (see Fig. 6b).

2.3. Flows adaptability index (ϕ)

After constructing the NCI in the above section, it remains to present the quantification of the Flows Adaptability Index (ϕ) in order to compose a resilience metric, which represents the necessary flow magnitude for the continued operation of a park if a disruptive event occurs.

The goal of this metric is to quantify if the flows and the participant capacities of the park are enough to compensate a disruptive event. This metric must quantify the necessary flow to sustain the operation of the park and the flexibility of the network to modify the remaining flows consequently.

Oriented connections were considered to quantify ϕ because the flows under study imply mass or energy transfer from one participant to another. The measure is based on demands from the nodes and their provisions before and after the disruptive event.

When a participant of a park interrupts its activity, its inputs and outputs disappear. These flows are also inputs for and outputs from other participants which need them to maintain their operations. The magnitude of other inlets and outlets in the surrounding nodes must change to compensate this loss during this event. With this purpose, a security range has been considered for every plant: a minimum and a maximum flow to operate. These values are defined for the inlets and outlets of every node. The inlet and outlet capacities for each participant k were defined as $Q_k^{max,in}$ and $Q_k^{max,out}$ respectively, with $k \in N$. It is also necessary to define the sets IN_k and OUT_k to include the nodes connected with $k \in N$ through an input or output of k, respectively (see Fig. 7).

Since the flows of the participants of a network have different magnitude and quality, they are not easily replaceable. To substitute these flows, the new ones have to comply the same characteristics of the original. To simplify this behavior, it is possible to assume that all the flows can be substituted by any inlets or outlets in a layer of the network, i.e., all the flows comply the requirements about quality if they belong to the same layer.

It should be noted that the terms defined in the following sections refer to a unique layer. Since an EIP can be configured by different layers, an extended definition will be provided in section 2.3.4 for a park with multiple layers.

2.3.1. Defining changes over the elements in the set IN_k after a disruptive event in node k

When a participant $k \in N$ interrupts its activity, all its input flows $F_{j,k} \forall j \in IN_k$ are lost (see Fig. 7). To ensure the continuous operation of the park, each of these flows has to be redistributed in the remaining outputs of the affected firms $j \in IN_k$, i.e. in $l \in OUT_j \backslash \{k\}$. The feasibility of this change depends on the capacity of each firm receiving the additional flow and its committed capacity. This value is defined as *the inlet available capacity for the participant l*, denoted

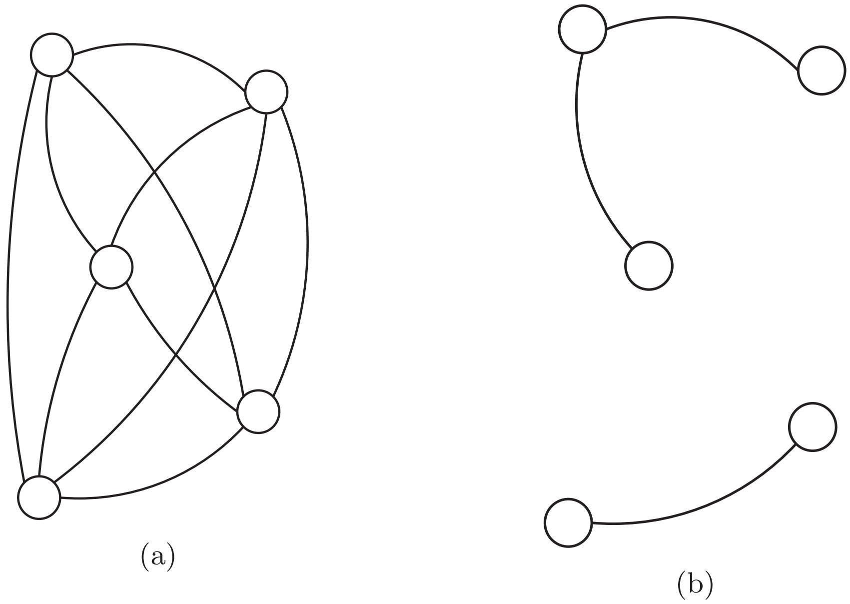


Fig. 6. Maximum and minimum cases for the Network Connectivity Index (NCI) considering five participants: 6a maximum case, and 6b minimum case.

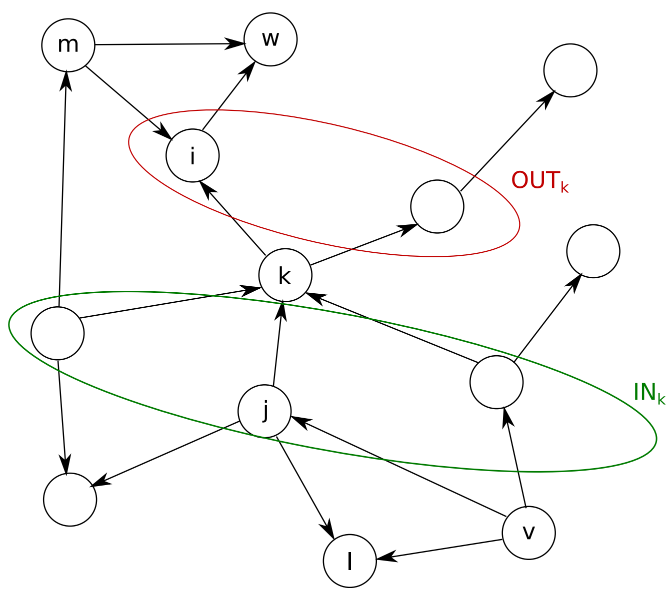


Fig. 7. An Industrial network with their participants and connections.

as:

$$Q_l^{in} = \left(Q_l^{max,in} - \sum_{v \in IN_l; v \neq k} F_{v,l} \right) \quad \text{with } l \in \text{OUT}_j \backslash \{k\} \tag{5}$$

It is worth to note that Q_l^{in} is minimum when l is working at maximum capacity ($\sum_{k \in IN; v \neq k} F_{v,l} = Q_l^{max,in}$). Conversely, Q_l^{in} is maximum when $F_{j,l}$ is the unique inlet of node l ($\sum_{k \in IN; v \neq k} F_{v,l} = F_{j,l}$).

The *total output available capacity for the participant* $j \in IN_k$ *when* k *interrupts its activity* is:

$$Q_{j-k}^{out} = \sum_{l \in OUT_k; l \neq k} Q_l^{in} \quad \text{with } j \in IN_k \tag{6}$$

Calculating this term, the feasible increase in the outputs of $j \in IN_k$ its inferred to compensate the lost flow $F_{j,k}$. To compare both values and to determine if this capacity is greater or equal to the lost flow, the definition of *the lack of flow for the participant j when k interrupts its activity* is provided as:

$$\mathscr{L}_{j-k}^{in} = \max\left\{0, F_{j,k} - Q_{j-k}^{out}\right\} \quad \text{with } j \in IN_k \text{ and } k \in N \tag{7}$$

This term is 0 if the park can compensate the lost flow of the participant j when k interrupts its activity; or it takes the magnitude of the flow to compensate the loss.

2.3.2. Defining changes over the elements in the set OUT_k *after a disruptive event occurs in node k*

As in the previous case, when a participant $k \in N$ interrupts its activity, all their outputs $F_{k,i} \forall I \in OUT_k$ are lost (see Fig. 7). To ensure the continued and normal operation of the park, each of these flows has to be compensated increasing the remaining inputs of the affected firms $i \in OUT_k$, i.e. $m \in IN_k \backslash \{k\}$. The feasibility of this substitution of flows depends on the capacity of each firm receiving the increased flow and its committed capacity. With this focus, *the outlet available capacity for the participant l* is defined as:

$$Q_m^{out} = \left(Q_m^{max,out} - \sum_{w \in OUT_m; w \neq k} F_{m,w} \right) \quad \text{with } m \in IN_i \backslash \{k\} \tag{8}$$

It is important to note that Q_m^{out} is minimum when m is working at its maximum capacity ($\sum_{w \in OUT_m; w \neq k} F_{m,w} = Q_m^{max,out}$). The available capacity of m is maximum when $F_{m,i}$ is the unique outlet of node m ($\sum_{w \in OUT_m; w \neq k} F_{m,w} = F_{m,i}$).

Then, the *total input available capacity for the participant* $i \in OUT_k$ *when k interrupts its activity* is:

$$Q_{i-k}^{in} = \sum_{m \in IN_i; m \neq k} Q_m^{out} \tag{9}$$

Calculating this term, the feasible increase in the inputs of $i \in OUT_k$ is inferred to compensate the lost flow $F_{k,i}$.

In the situation after disruption, it is not necessary to share the same flow than before to maintain the participant i in operation. Plant i can operate at its minimum capacity. It is necessary to define *the minimum capacity of i to continue its operation*, $Q_i^{min,in}$. This value depends on the security factor of each participant and complies with $Q_i^{min,in} \le \sum_{m\in IN_i} F_{m,i}$. Since after the disruption the participant i is working at its minimum capacity and has lost one input, the minimum flow necessary to feed is $Q_i^{min,in} - \sum_{m\in IN_i; m\neq k} F_{m,i}$. It is important to highlight that if this value is negative or zero, the minimum capacity is already satisfied by the remaining inlets and it is not necessary to increase other flows.

In view of the above, it is deemed necessary to compare $Q_i^{min,in} - \sum_{m\in IN_i; m\neq k} F_{m,i}$ and Q_{i-k}^{in} so as to determine if this capacity is equal or greater than the minimum required flow. For this purpose, *the lack of flow for the participant i when k interrupts its activity* is denoted as:

$$\mathscr{L}_{i-k}^{out} = \max\left\{0, Q_i^{min,in} - \sum_{m\in IN_i; m\neq k} F_{m,i} - Q_{i-k}^{in}\right\} \quad \text{with } i\in OUT_k \text{ and } k\in N \tag{10}$$

This term is 0, if the park can compensate the lost flow of the participant i when k interrupts its activity; or it will take the magnitude of the minimum flow to compensate the loss.

2.3.3. Defining the flows adaptability index

Using the aforementioned values, the required flow to compensate the absence of one participant in the park is calculated. It is worth noting that both metrics, $\mathscr{L}_{j-k}^{in}$ and $\mathscr{L}_{i-k}^{out}$, identify the participant that interrupts its activity and just one of their inputs and outputs respectively. To calculate the total required flow associated with the activity interruption of a participant, consider the summation of $\mathscr{L}_{j-k}^{in}$ over all the inputs ($j\in IN_k$) and also consider the summation of $\mathscr{L}_{i-k}^{out}$ over all the outputs ($i\in OUT_k$). The combination of both summations takes account of the necessary flow to compensate the disruption over k.

The *total lack of flows related to a disruption in k* is defined as:

$$\mathscr{L}_k = \sum_{j\in IN_k} \mathscr{L}_{j-k}^{in} + \sum_{i\in OUT_k} \mathscr{L}_{i-k}^{out} \quad \forall k\in N \tag{11}$$

Using this term, the total required flow to compensate the activity interruption of a network participant is obtained. In the same way as the NCI, the worst and the best scenarios were taken to establish a linear function between them in order to simplify the calculation.

The worst scenario for the park is when the network and their participants are working at their full capacity, i.e. when $\mathscr{L}_k$ is maximum: $Q_{j-k}^{out} = Q_{i-k}^{in} = 0$. $\mathscr{L}_k$ would be:

$$\mathscr{L}_k^{max} = \sum_{j\in IN_k} F_{j,k} + \sum_{i\in OUT_k} Q_i^{min,in} \tag{12}$$

The best scenario for the park is when the network can totally compensate the activity interruption of one of its participants. In this scenario, $\mathscr{L}_k$ is minimum: $Q_{j-k}^{out} \ge F_{j,k} \wedge Q_{i-k}^{in} \ge Q_i^{min,in} \Rightarrow \mathscr{L}_{j-k}^{in} = \mathscr{L}_{i-k}^{out} = 0$. Then, $\mathscr{L}_k$ would be:

$$\mathscr{L}_k^{min} = 0 \tag{13}$$

Establishing these worst and best scenarios for the park, the flows adaptability index ϕ_k is defined for the network affected by the interruption in the activity of the participant k. If the park is working at the worst scenario, $\phi_k(\mathscr{L}_k^{max}) = 0$; if the park is working at its best scenario, $\phi_k(\mathscr{L}_k^{min}) = 1$. With these values, the following linear function is created to quantify intermediate cases (see Fig. 8):

$$\phi_k(\mathscr{L}_k) = \phi_k\left(\mathscr{L}_k^{max}\right) - \left(\phi_k\left(\mathscr{L}_k^{min}\right) - \phi_k\left(\mathscr{L}_k^{max}\right)\right)\left(\frac{\mathscr{L}_k - \mathscr{L}_k^{max}}{\mathscr{L}_k^{min} - \mathscr{L}_k^{max}}\right) \tag{14}$$

$$\phi_k(\mathscr{L}_k) = 1 - \frac{\mathscr{L}_k}{\sum_{j\in IN_k} F_{j,k} + \sum_{i\in OUT_k} Q_i^{min,in}} k\in N \tag{15}$$

This equation can apply over each participant k of the park. In order to obtain a measure over the whole park, the average of this metric is calculated over all the participants under analysis:

$$\phi = \frac{1}{n}\sum_{k\in N} \phi_k \tag{16}$$

It is important to remark that the value of ϕ belongs to the interval $[0,\ 1]$. This is useful for a further combination with NCI. Since the average complies with this requirement, this function is applied to calculate the flows adaptability index of the whole park.

2.3.4. Final considerations about flows adaptability index

As mentioned before, an eco-industrial park is characterized by a complex network where different materials or energy are shared, composing different exchange networks. These different networks can be separated into layers. Since the flows adaptability index measures the required flow to compensate the loss of a participant in a specific exchange network, ϕ has to consider this fact.

ϕ can be calculated for each layer. Onwards, a superscript under ϕ will indicate the considered layer. The flows adaptability index for the specific layer r is calculated as:

$$\phi^{layer_r} = \frac{1}{n}\sum_{k\in N} \phi_k^{layer_r} \tag{17}$$

The flows adaptability index for the whole park is constructed covering all the layers in the set L:

$$\phi(park) = f\left(\phi^{layer_1}, \phi^{layer_2}, \phi^{layer_r}\right) \text{with } r\in \mathrm{L} \tag{18}$$

To simplify the notation, a linear combination of layers is

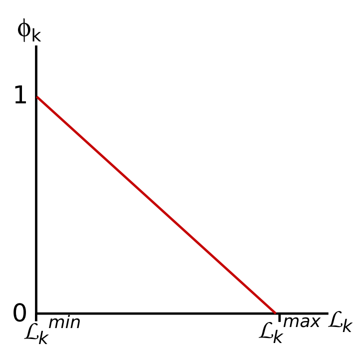


Fig. 8. Defined linear function between the worst and the best case for ϕ_k.

considered. The weights in the summation are all identical. The index is defined as:

$$\phi(park) = \frac{1}{|L|}\sum_{r\in L}\phi^{layer_r} \tag{19}$$

2.4. Resilience indicator

NCI and ϕ have been conceived to measure, respectively, the connectivity of a park and its capacity to endure a disruptive event by replacing flows. Both characteristics are important to assess the resilience of a park. The following equation is proposed so as to define a resilience indicator:

$$Resilience = a\cdot NCI + (1-a)\cdot\phi \tag{20}$$

where a and $1-a$ indicate the importance of each characteristic: the connectivity of a park, measured by NCI, and the capacity of the park to endure a disruptive event by replacing flows, measured by ϕ. The same importance is proposed for both aspects, that is: $a = 0.5$. This decision should be taken by the stakeholders of the park. Further developments in this line could be done so as to adapt this combination to reality. A feasible route to address this issue is to apply a multi-criteria decision-making tool. The resilience indicator is defined as:

$$Resilience = 0.5\cdot NCI + 0.5\cdot\phi \tag{21}$$

3. Application of the resilience indicator over case studies

In order to analyze the applicability of the proposed resilience indicator, consider two illustrative cases based on two particular EIPs: Kalundborg, in Denmark (see Fig. 9), and Ulsan, in South Korea (see Fig. 10). The application of the indicator is addressed in a single layer within both EIPs; and the study of multiple layers is covered in the case of Ulsan EIP. A brief explanation about each EIP is presented below, as an introduction to the illustrative cases.

3.1. Defining the illustrative cases

3.1.1. Kalundborg EIP, Denmark

The most renowned EIP in the literature, Kalundborg is characterized by the sharing of water, steam, by-products, and heat (Chertow, 2008). The most remarkable members are: an oil refinery, an energy plant, a cement plant, a pharmaceutical process, the lake Tissϕ, and the municipality of Kalundborg (see Fig. 1). The Kalundborg's EIP was originated by an integrated planning driven by the municipality and the participant companies. The plan takes into account the local community and the lake (Kalundborg Symbiosis, 2015). The main benefits obtained by the park are the improvement in resource efficiency and the economic utilities of the firms (Jacobsen, 2006).

3.1.2. Ulsan EIP, South Korea

Ulsan is located in the southeast of South Korea. This city has many important industrial complexes at a national and regional level. Among these complexes, two of them are analyzed: Ulsan-Mipo and Onsan. These Complexes employ 100,000 workers and cover 63,256 km^2 of the territory (Behera et al., 2012).

In 2005 started the implementation of a government initiative in the Mipo/Onsan complex, focused on the development of an EIP in the region. This program established the *Ulsan EIP center* in 2007, aiming at sharing materials and energy within the network. There are 33 exchanging flows among the firms operating in this EIP, which includes 41 companies. The main benefits obtained by this exchanges are related to reduce the CO_2 emissions and other gaseous pollutants, and to increase the economic utilities of the companies (Behera et al., 2012).

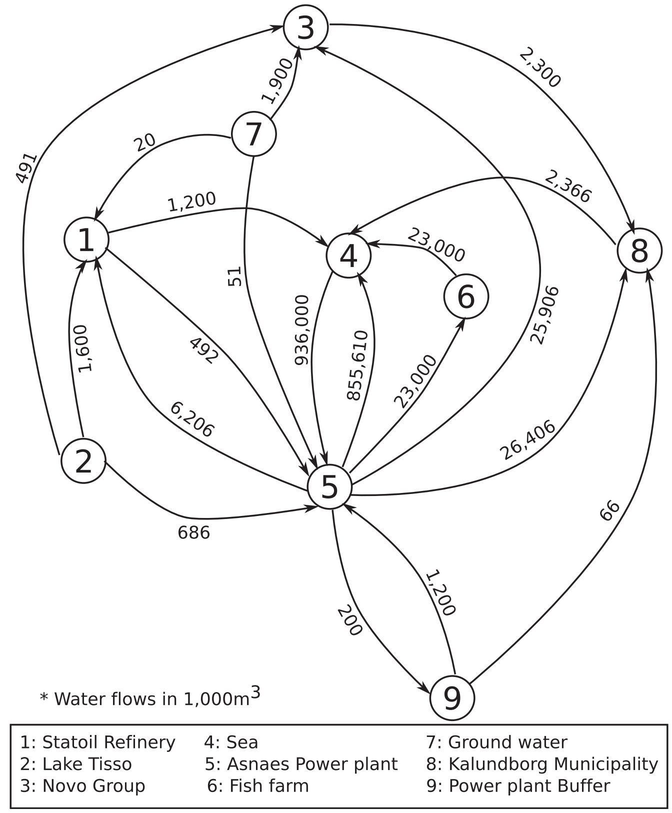


Fig. 9. Water Network in Kalundborg (information taken from Jacobsen (2006)).

3.1.3. Case 1: application of the resilience indicator on networks with a unique layer

To study the applicability of the resilience indicator on networks with a unique layer, consider the Kalundborg and Ulsan networks. In Kalundborg, the focus of the analysis is on the water network (see Fig. 9); in Ulsan, the steam network is the subject of analysis (see Fig. 11). In the latter case, the steam network was considered as a conventional material network, with no constraints on the temperature requirements of the participants. It is worth remarking the base to calculate: the data used to describe the connections and flows depend on the available information. The first and second rows of Table 2 show a summary about the values obtained for the resilience indicator, NCI, and ϕ in both networks. The plots in Fig. 12a and Fig. 12b show a comparison among the participants of the respective networks with focus on ϕ.

The main goal of the case studies is to illustrate the application of the Resilience Indicator. This exercise also shows a significant difference between these networks: the value of the Resilience Indicator is higher in the Kalundborgs water network, and the difference is mainly due to the network structure. The reader can appreciate the value of NCI for the Ulsans steam network, which is significantly lower than the NCI for Kalundborgs water network. The point is how these networks would been configured if the Resilience Indicator was applied at the design phase. To our understanding, the Ulsans steam network can improve its resilience

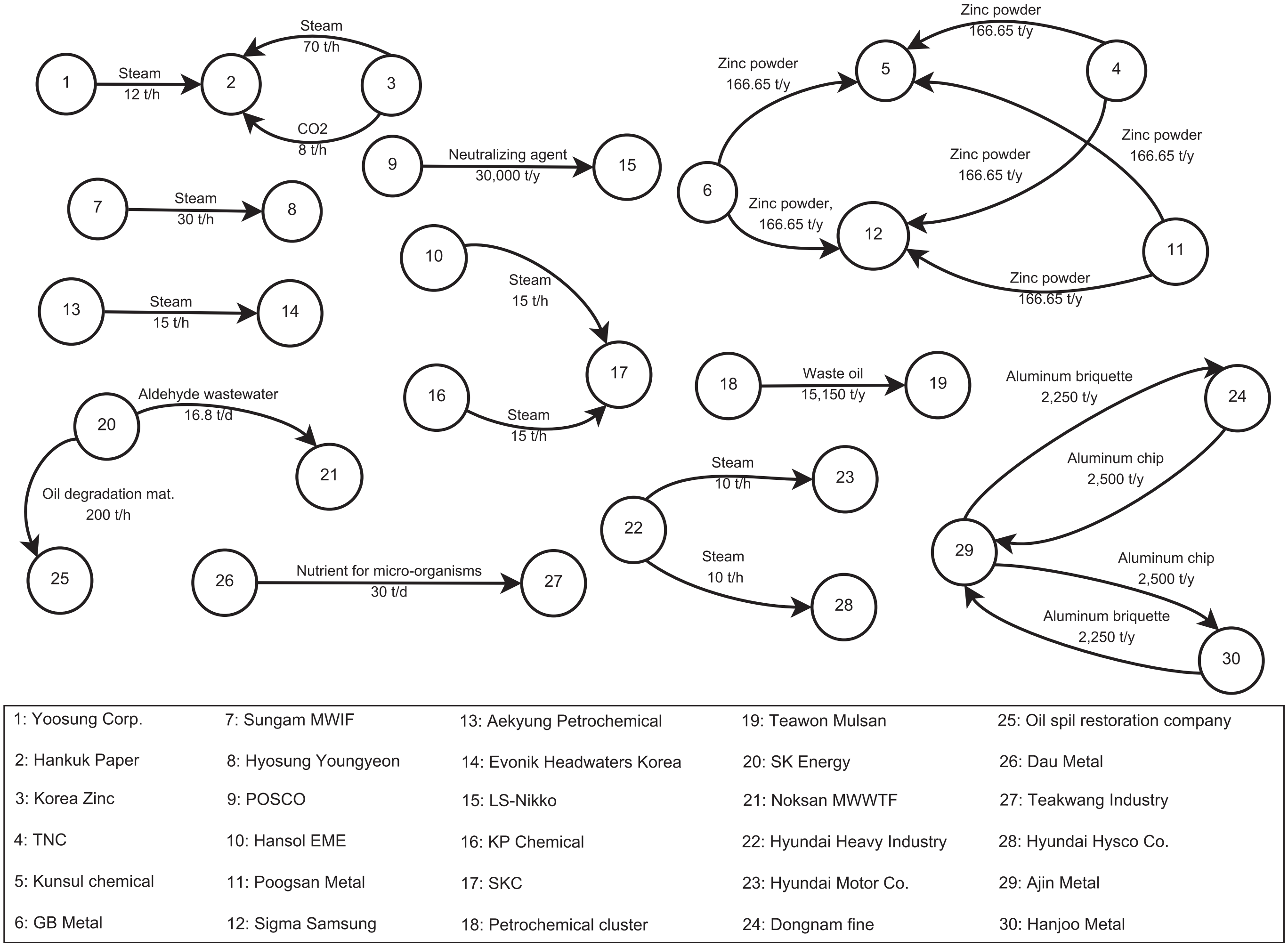


Fig. 10. Network in Ulsan (information taken from Behera et al. (2012)).

with this consideration.

3.2. *Case 2: application of the resilience indicator over an EIP with multiple layers*

The variety of material exchanges in Ulsan EIP (see Fig. 10) were considered to study the application of the resilience indicator over an EIP with multiple layers. Regarding the information available on the literature, the analysis take into account 8 material exchanges among the firms in the park: steam, zinc powder, oil, neutralizing agents, aldehyde, nutrients for microorganism, aluminum, and carbon dioxide. Each of them forms a layer in the EIP. The third row of Table 2 shows the results obtained for the resilience indicator, and the respective values for NCI and ϕ. Table 3 shows a comparison among the participants of each layer, with focus on their Flows Adaptability Index.

Extending the analysis of the Ulsan steam network in the previous section to the whole Ulsan EIP, the Resilience is low mainly because of the value of NCI. The structure of the Ulsan EIP has many subsystems: non-connected sub-parks. Although this structure is functional to share materials and energy among neighbors, the concept of EIP is not fully developed in the sense of connectivity, and the structure of the park is not as safer as highly connected parks (e.g. Kalundborg). An early application of the Resilience Indicator at the design phase can improve the capacity of the whole park to overcome disruptions, and allow decision-makers to measure and compare different alternatives in this field.

4. Discussions

This paper presents an indicator to measure the resilience of an eco-industrial park. This index considers the connectivity of a network and the capacity of the participants to endure a disruptive event. These aspects have been quantified with two sub-indicators: the Network Connectivity Index (NCI) and the Flows Adaptability Index (ϕ), respectively. The resilience indicator has been applied to real cases and after this exercise is possible to analyze the performance of the metric.

As defined before, the resilience indicator depends on two indexes: the Network Connectivity Index (NCI) and the Flows Adaptability Index (ϕ). The first one is a topologic measure of a network, measuring the number of connections among EIP participants. This characteristic is not exclusive to an industrial context since it is present in every network. The NCI reports the existence of a connection between two members of a network.

If a network obtains a high NCI value (near to 1 or 100%) there are many connections among the network participants. If a participant interrupts its activity, other participants in the network will remain connected. It is possible to appreciate this behavior in the water network of Kalundborg (see Fig. 9). This network

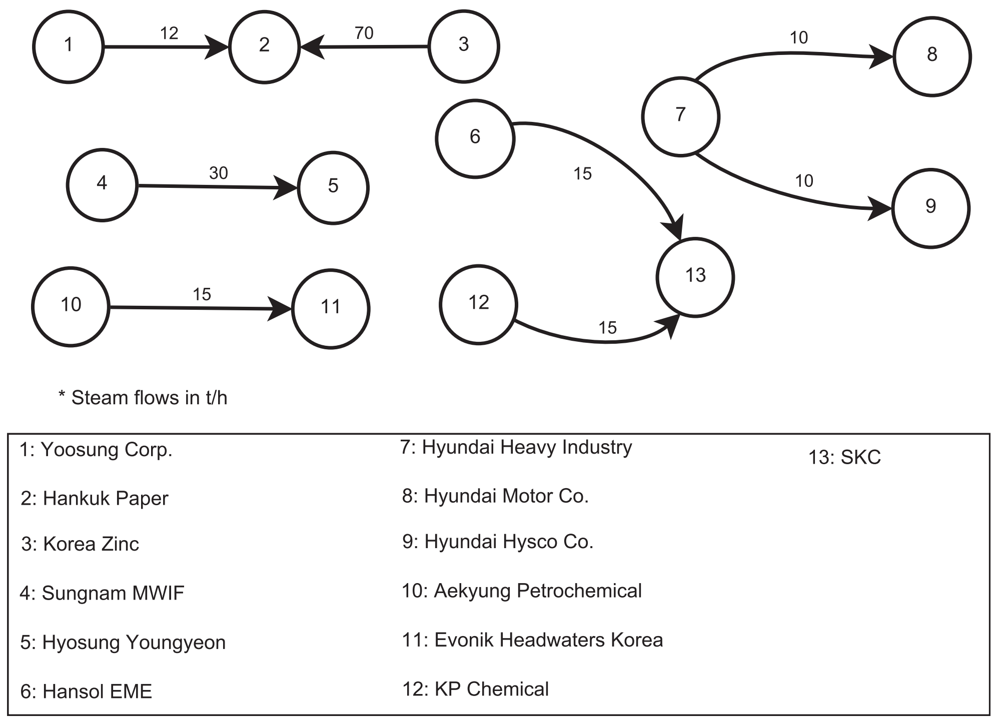


Fig. 11. Steam network of Ulsan (obtained from Behera et al. (2012)).

Table 2
Resilience Indicator applied over case studies. The values of NCI and ϕ are also shown.

Case study	NCI (%)	ϕ (%)	Resilience (%)
Kalundborg water network	39	86	62
Ulsan steam network	1	17	10
Ulsan EIP (multilayer)	1	18	10

obtained a NCI value of 39%, which is high compared with the other cases. In this case, by removing the most connected participant (plant 5: Asnaes Power Plant) the remaining participants will be still connected through the remaining lines.

If NCI has a near-zero value the network is weakly connected. If a participant disappears from the network there will be isolated members. In the Ulsan steam network (see Fig. 11), a NCI value of 1% is obtained. This value means that if a participant disappears (e.g. participant 2), some members of the network will be unconnected and part of the network is lost.

One goal of a resilient network is to maintain the connectivity in the remaining network when a member interrupts its activity. In this sense, the NCI takes into account this property. The values obtained in both cases are consistent with the described reality.

The second index used to construct the resilience indicator, ϕ, is

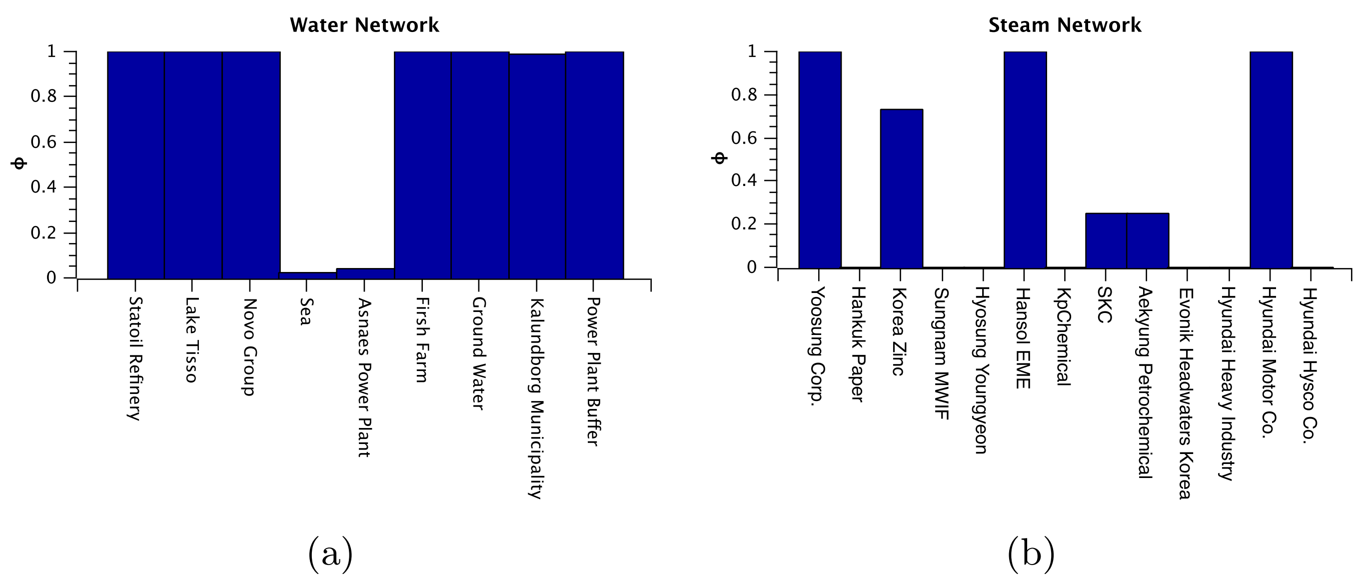


Fig. 12. Flows adaptability index of each participant in a layer of the illustrative cases: 12a Water Network in Kalundborg EIP, and 12b Steam Network in Ulsan EIP.

Table 3
Flows adaptability index for participants into each layer of Ulsan EIP.

Steam Network	Zinc Powder Network	Oil Network	Neutralizing Agents Network	Aldehyde Wastewater Network	Nutrient for Micro-organism Network	Aluminum Network	Carbon Dioxide Network
$\phi_1 = 1$	$\phi_4 = 1$	$\phi_{18} = 0$	$\phi_9 = 0$	$\phi_{20} = 0$	$\phi_{26} = 0$	$\phi_{24} = 0.52$	$\phi_2 = 0$
$\phi_2 = 0$	$\phi_5 = 0.75$	$\phi_{19} = 0$	$\phi_{15} = 0$	$\phi_{21} = 0$	$\phi_{27} = 0$	$\phi_{29} = 0$	$\phi_3 = 0$
$\phi_3 = 0.73$	$\phi_6 = 1$	$\phi_{20} = 0$				$\phi_{30} = 0.52$	
$\phi_7 = 0$	$\phi_{11} = 1$	$\phi_{25} = 0$					
$\phi_8 = 0$	$\phi_{12} = 0.75$						
$\phi_{10} = 0$							
$\phi_{13} = 0$							
$\phi_{14} = 0$							
$\phi_{16} = 0$							
$\phi_{17} = 0$							
$\phi_{22} = 0$							
$\phi_{23} = 0.25$							
$\phi_{28} = 0.25$							

a measure of the network performance. This index focuses on the magnitude of the sharing flows and the feasibility of their substitution during disruptions. This characteristic is fundamental in an industrial context and constitutes a difference with other kind of networks. If a network obtains a high value of ϕ the participants can endure the absence of any member suffering a disruptive event. For example, a $\phi = 86\%$ is obtained in the water network of Kalundborg. This value means that if a network participant interrupts its activity (e.g. the Power Buffer Plant) (see Fig. 12a), other members can take over the lost inputs and outputs. This attribute allows the other members to maintain their operations.

If the network obtains a low ϕ the members within the network will not be able to supply the lost flows. The park could not continue its operation. For example, a $\phi = 17\%$ is obtained in the Ulsan steam network. In this case, if the network loses a participant, for instance Korea Zinc (see Fig. 12b), a participant as Yoosung Corp. cannot change the magnitude of its flows because the defined capacity is not enough to completely endure this event.

Another goal of a resilient network is to endure any disruptive event by modifying the magnitude of its flows. The values obtained for ϕ are fair with the described cases.

An assumption considered over this sub-indicator is regard to the quality (composition) of the substituted flows. To simplify the calculation, consider that all the flows can be substituted by others in a layer of a network no matter the different compositions of them. Since in the reality the quality of the flows is important in order to comply with the requirements of the participants, this aspect can be considered in ϕ through the use of different layers. If a set of firms need to comply with certain requirements about flow composition, they can be separated in a different layer and to obtain an additional ϕ^{layer_r}. In this way, the quality of the flows is considered in the flow adaptability index.

It is worth noting that the value of ϕ will depend on the capacity of each firm to change the magnitude of its inputs and outputs. ϕ also depends on the connectivity. For instance, in the last example, if Hankuk Plant interrupts its activity the remaining participants will not be able to endure this event, because the affected members do not have more connections than the lost ones (see Fig. 11).

The question is whether both factors are independent. As noticed before, ϕ depends on the connections. ϕ depends on NCI. This dependence is sustained on a physical fact: every flow of a certain material requires an existing connection in the network. The aforementioned idea is not reversible, and the existence of a connection does not imply a specific material sharing. The existence of a connection allows the sharing of one material or more. Nevertheless, it is possible to have a physical connection with no sharing flow. NCI does not depend on ϕ.

The proposed resilience indicator is a weighted sum of both indexes: NCI and ϕ. If one of them has a higher influence over the reality it should have more importance in the equation. The same weights were assumed as a first approximation. NCI includes topological characteristics of a network, while ϕ is related to operative aspects which is supported by its topology. A pending issue is to define specific weights to represent the global resilience in an industrial network. This definition could be constructed on the basis of a comparative analysis of many application cases. An idea to guide this definition is to state what is more important to the resilience of an industrial network: topology or operation.

The resilience indicator was created to be applied over EIPs sharing different materials, i.e. parks with multiple layers. This characteristic is captured by ϕ through the weighted sum of single layers (ϕ^{layer_r}). To simplify the notation, it was assumed that each layer had the same specific weight (see Eq. (19)). In other words, all these layers have the same importance for the EIP. As can be seen in the second illustrative case, Ulsan EIP, there is a subset of layers with ϕ^{layer_r} equal to 0 (see Table 3). This situation results in a low value of ϕ for the whole park (18%). Even though this assumption could be correct, it is a pending issue to properly describe the importance of each layer. To cover this point, the number of participants in a single layer or the criticality of a shared material could indicate the relative importance of a layer. As illustrated in Fig. 10, there are many layers with different number of participants.

Regarding the resilience indicator, even though it was created with the goal to measure resilience over eco-industrial parks, it can be applied over any system where the participants share materials, e.g. industrial parks, regional integrations, and eco-cities.

The adopted definition of resilience considers the withstanding capacity to undergo a disruptive event. During this work, a disruptive event was assumed as a complete interruption in the activity of a network participant. However, when an industrial plant suffers a disruptive event, it is not always complete. Sometimes this event is partial. Even though the proposed indicator does not consider this aspect, it could be modified so as to consider the partial activity interruption of a participant. Since this characteristic is related with the operation of a participant, the flows adaptability index has to be modified. In Eqs. (7) and (10) it is possible to add a term representing this partial activity interruption as follows:

$$\mathscr{L}^{in}_{j-k} = \max\left\{0, F_{j,k} - p^{in}_k Q^{out}_{j-k}\right\} \quad \text{where } j \in IN_k \text{ and } k \in N \tag{22}$$

$$\mathscr{L}^{out}_{i-k} = \max\left\{0, Q^{min,in}_i - p^{out}_k Q^{in}_{i-k}\right\} \quad \text{where } i \in OUT_k \text{ and } k \in N \tag{23}$$

In this equation, p^{in}_k and $p^{out}_k \in [0,\ 1]$ are the factors representing the partial stop of a firm for its input and output flows, respectively. These factors are defined as 1 when a firm completely stops its operation.

Another aspect to discuss is the probability of disruptions. The definition of resilience considers that every participant has the same risk to suffer a disruptive event. However, the reality is different: there are firms with highly effective prevention programs to avoid stops in production while other ones are unstable. This fact can be translate into a probability of suffering a disruptive event. This value could be estimated taking into account the history of each participant. To consider this probability in the resilience indicator, the flows adaptability index should be modified since the disruption probability is an operative characteristic of each firm. As shown in Eq. (17), this index is applied over each firm and averaged to calculate ϕ^{layer_r}. This average can be replaced by a weighted sum, where the weights are calculated over respective disruption probabilities.

The configuration of an EIP can be based on sharing material or energy in a network. For example, in the steam network of Ulsan (see Fig. 11), even though the main focus is material sharing, it is also important the temperature since the participants could need to comply with certain operational requirements to work. The resilience indicator should also consider the case of energy networks. In this work the resilience indicator is conceived for material networks, based on its connections and sharing flows. Beside analogous characteristics from energy networks, it is deemed necessary to include the temperature of each flow as a constraint to sharing and substitution of flows during disruptions. These constraints come from heat transfer gradients. Since the indicator herein proposed has considered the connections and the flows of a network, it is adapted to measure the resilience of material networks. The extension of this indicator to consider temperatures, or the development of a new resilience indicator for heat transfer networks, can be addressed in further work.

5. Conclusions

The previous sections have proposed a resilience indicator to assess EIPs. This indicator is based on two important aspects of an industrial network: its topology and its operation. These main ideas sustain the creation of two sub-indicators oriented to measure the connectivity and flexibility of flows, respectively.

The novelty of the proposed indicator lies into consider the dynamic of the assessed eco-industrial park after one of their participants suffers a disruptive event, taking into account the decision of the remaining firms to modify their input and output flows to absorb this perturbation and to prevent the fault propagation on the park. The resilience indicator is constructed to support the evaluation of multi-layer park, where more than one material is shared.

The resilience indicator has been created for both assessing and designing eco-industrial parks. The design phase can be addressed with optimization tools. In this context, the resilience indicator can be included in a multi-objective formulation. The objectives of this formulation can also cover environmental, social, and economic dimensions of the sustainability, so as to improve the performance of the whole park by design.

The proposed indicator has been applied over two illustrative cases based on two known EIPs: Kalundborg, in Denmark; and Ulsan, in South Korea. The application over these parks shows a significant potential in Ulsan EIP to improve its resilience, which is conditioned by the structure of the park.

There is a possible improvement in this development: the defined sub-indicators are not independent. This dependence is sustained on physics, because the existence of a flow requires a connection. This idea backs up the dependence of ϕ on NCI. This limitation can be overcome in the future by calculating the resilience indicator through a weighted sum of NCI and ϕ. The specific weighs must be properly defined taking into account the aforementioned dependence, since one of them may be overestimated. Industrial stakeholders should define which aspect is more important in the network: topology or operation.

In the future, the resilience indicator can be modified in order to capture a more realistic behavior of an EIP, where some firms are most likely to suffer a disruptive event or they have contingency plans in this situations. For example, the indicator can consider partial disruptive events over the participants of the park. It is also possible to include the probability of each firm to suffer a disruptive event. Since both of them are related to operative aspects, these changes could be addressed by modifying ϕ.

The proposed indicator measures the resilience of material network, taking into account connections and flows among the participants. Since an EIP can be configured to share material or / and energy, the extension of this indicator to heat transfer networks is proposed for further work.

Acknowledgments

Felipe A. Díaz-Alvarado wants to thank the FCFM grant *Apoyo a la Inserción Académica* 2016; University of Chile. This project was financed by *CONICYT/FONDECYT de Iniciación en Investigación/2017-11170042*.

Guillermo Valenzuela-Venegas: This work was funded by the *CONICYT-PCHA/Doctorado Nacional/2014-21140400*.

References

Behera, S.K., Kim, J.H., Lee, S.Y., Suh, S., Park, H.S., 2012. Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. J. Clean. Prod. 29–30, 103–112. https://doi.org/10.1016/j.jclepro.2012.02.009. www.sciencedirect.com/science/article/pii/S0959652612000832.

Biegler, L.T., Grossmann, I.E., 2004. Retrospective on optimization. Comput. Chem. Eng. 28, 1169–1192. https://doi.org/10.1016/j.compchemeng.2003.11.003. www.sciencedirect.com/science/article/pii/S0098135403003089.

Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S., 2015. Optimization methods applied to the design of eco-industrial parks: a literature review. J. Clean. Prod. 87, 303–317. https://doi.org/10.1016/j.jclepro.2014.09.032. www.sciencedirect.com/science/article/pii/S0959652614009627.

Boix, M., Montastruc, L., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., 2011. A multiobjective optimization framework for multicontaminant industrial water network design. J. Environ. Manag. 92, 1802–1808. https://doi.org/10.1016/j.jenvman.2011.02.016. www.sciencedirect.com/science/article/pii/S030147971100065X.

Boix, M., Montastruc, L., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., 2012. Industrial water management by multiobjective optimization: from individual to collective solution through eco-industrial parks. J. Clean. Prod. 22, 85–97. https://doi.org/10.1016/j.jclepro.2011.09.011. www.sciencedirect.com/science/article/pii/S0959652611003428.

Chae, S.H., Kim, S.H., Yoon, S.G., Park, S., 2010. Optimization of a waste heat utilization network in an eco-industrial park. Appl. Energy 87, 1978–1988. https://doi.org/10.1016/j.apenergy.2009.12.003. www.sciencedirect.com/science/article/pii/S0306261909005261.

Chertow, M., 2008. Industrial ecology in a developing context. In: Clini, C., Musu, I., Gullino, M. (Eds.), Sustainable Development and Environmental Management SE - 24. Springer Netherlands, pp. 335–349. https://doi.org/10.1007/978-1-4020-8229-0_24.

Chertow, M.R., 2000. INDUSTRIAL SYMBIOSIS: literature and taxonomy. Annu. Rev. Energy Environ. 25, 313–337. https://doi.org/10.1146/annurev.energy.25.1.313. www.annualreviews.org/doi/full/10.1146/annurev.energy.25.1.313.

Chopra, S.S., Khanna, V., 2012. Toward a network perspective for understanding resilience and sustainability in industrial symbiotic networks. In: IEEE International Symposium on Sustainable Systems and Technology. https://doi.org/10.1109/ISSST.2012.6227987.

Chopra, S.S., Khanna, V., 2014. Understanding resilience in industrial symbiosis networks: insights from network analysis. J. Environ. Manag. 141, 86–94. https://doi.org/10.1016/j.jenvman.2013.12.038.

Cimren, E., Fiksel, J., Posner, M.E., Sikdar, K., 2011. Material flow optimization in by-

product synergy networks. J. Ind. Ecol. 15, 315–332. https://doi.org/10.1111/j.1530-9290.2010.00310.x.
Fiksel, J., 2003. Designing resilient, sustainable systems. Environ. Sci. Technol. 37, 5330–5339. https://doi.org/10.1021/es0344819.
Goel, S., Belardo, S., Iwan, L., 2004. A Resilient Network that Can Operate under Duress: to Support Communication between Government Agencies during Crisis Situations. https://doi.org/10.1109/HICSS.2004.1265312.
Haslenda, H., Jamaludin, M., 2011. Industry to Industry By-products Exchange Network towards zero waste in palm oil refining processes. Resour. Conserv. Recycl. 55, 713–718. https://doi.org/10.1016/j.resconrec.2011.02.004. www.sciencedirect.com/science/article/pii/S092134491100036X.
Jacobsen, N.B., 2006. Industrial symbiosis in Kalundborg, Denmark - a quantitative assessment of economic and environmental aspects. J. Ind. Ecol. 10, 239–255. https://doi.org/10.1162/108819806775545411.
Kalundborg Symbiosis, 2015. Kalundborg Symbiosis Is the World's First Working Industrial Symbiosis. www.symbiosis.dk/en.
Knight, P., 1990. A rebirth of the pioneering spirit. Financ. Times 14, 15.
Kuznetsova, E., Zio, E., Farel, R., 2016. A methodological framework for Eco-Industrial Park design and optimization. J. Clean. Prod. 126, 308–324. https://doi.org/10.1016/j.jclepro.2016.03.025. www.sciencedirect.com/science/article/pii/S0959652616300853.
Li, X., Xiao, R., 2017. Analyzing network topological characteristics of eco-industrial parks from the perspective of resilience: a case study. Ecol. Indic. 74, 403–413. https://doi.org/10.1016/j.ecolind.2016.11.031. linkinghub.elsevier.com/retrieve/pii/S1470160X16306689.
Liew, P.Y., Wan Alwi, S.R., Varbanov, P.S., Manan, Z.A., Klemeš, J.J., 2013. Centralised utility system planning for a total site heat integration network. Comput. Chem. Eng. 57, 104–111. https://doi.org/10.1016/j.compchemeng.2013.02.007. www.sciencedirect.com/science/article/pii/S0098135413000549.
Lovelady, E.M., El-Halwagi, M.M., 2009. Design and integration of eco-industrial parks for managing water resources. Environ. Prog. Sustain. Energy 28, 265–272. https://doi.org/10.1002/ep.10326.
Lowe, E.A., 2001. Eco-industrial Park Handbook for Asian Developing Countries. Technical Report. Asian Development Bank. indigodev.com/ADBHBdownloads.html.
Matta, J., Borwey, J., Ercal, G., 2014. Comparative Resilience Notions and Vertex Attack Tolerance of Scale-free Networks. CoRR abs/1404.0103, pp. 1–9. arXiv: arXiv:1404.0103v1. arxiv.org/abs/1404.0103.
Montastruc, L., Boix, M., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., 2013. On the flexibility of an eco-industrial park (EIP) for managing industrial water. J. Clean. Prod. 43, 1–11. https://doi.org/10.1016/j.jclepro.2012.12.039. www.sciencedirect.com/science/article/pii/S0959652612006956.
Ramos, M.A., Boix, M., Aussel, D., Montastruc, L., Domenech, S., 2016. Water integration in eco-industrial parks using a multi-leader-follower approach. Comput. Chem. Eng. 87, 190–207. https://doi.org/10.1016/j.compchemeng.2016.01.005.
Rubio-Castro, E., Ponce-Ortega, J.M., Serna-González, M., Jiménez-Gutiérrez, A., El-Halwagi, M.M., 2011. A global optimal formulation for the water integration in eco-industrial parks considering multiple pollutants. Comput. Chem. Eng. 35, 1558–1574. https://doi.org/10.1016/j.compchemeng.2011.03.010. www.sciencedirect.com/science/article/pii/S0098135411001001.
Tietze-Stöckinger, I., Fichtner, W., Rentz, O., 2004. A model to minimize joint total costs for industrial waste producers and waste management companies. Waste Manag. Res. 22, 466–476. https://doi.org/10.1177/0734242X04048522. wmr.sagepub.com/content/22/6/466.abstract.
Tiu, B.T.C., Cruz, D.E., 2017. An MILP model for optimizing water exchanges in eco-industrial parks considering water quality. Resources. Conserv. Recycl. 119, 89–96. https://doi.org/10.1016/j.resconrec.2016.06.005. linkinghub.elsevier.com/retrieve/pii/S0921344916301422.
Tudor, T., Adam, E., Bates, M., 2007. Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): a literature review. Ecol. Econ. 61, 199–207. https://doi.org/10.1016/j.ecolecon.2006.10.010. www.sciencedirect.com/science/article/pii/S0921800906005453.
Valenzuela-Venegas, G., Salgado, J.C., Díaz-Alvarado, F.A., 2016. Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection. J. Clean. Prod. 133, 99–116. https://doi.org/10.1016/j.jclepro.2016.05.113. linkinghub.elsevier.com/retrieve/pii/S0959652616305856.
Xiao, Z., Cao, B., Sun, J., Zhou, G., 2016. Culture of the stability in an eco-industrial system centered on complex network theory. J. Clean. Prod. 113, 730–742. https://doi.org/10.1016/j.jclepro.2015.11.096. linkinghub.elsevier.com/retrieve/pii/S0959652615018272.
Zeng, Y., Xiao, R., Li, X., 2013. A resilience approach to symbiosis networks of ecoindustrial parks based on cascading failure model. Math. Problems Eng. 2013, 1–11. https://doi.org/10.1155/2013/372368.
Zhang, B.J., Xu, T., He, C., Chen, Q.L., Luo, X.L., 2017. Material stream network modeling, retrofit and optimization for raw natural gas refining systems. J. Clean. Prod. 142, 3419–3436. https://doi.org/10.1016/j.jclepro.2016.10.124. linkinghub.elsevier.com/retrieve/pii/S0959652616317553.
Zhu, J., Ruth, M., 2013. Exploring the resilience of industrial ecosystems. J. Environ. Manag. 122, 65–75. https://doi.org/10.1016/j.jenvman.2013.02.052. linkinghub.elsevier.com/retrieve/pii/S0301479713001503.