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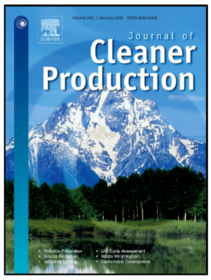


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# A Comprehensive Review of Industrial Symbiosis

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**Abstract**

Industrial symbiosis, which allows entities and companies that traditionally be separated, to cooperate among them in the sharing of resources, contributes to the increase of sustainability with environmental, economic and social benefits. Examples of industrial symbiosis have grown over the years with increasing geographic dispersion. Thus, through a comprehensive review of previous studies, this work aims to trace the trend of industrial symbiosis research and to map the existing case studies around the world, with a critical analysis of its impact. The analysis of the 584 selected publications allowed tracing the evolution of these according to their content and the type of article, as well as its distribution by journals. Based on the literature review, the main lines for research in industrial symbiosis are assessed, as well as an updated study of the published case studies is provided with emphasis on the location, type of industry and employed methodologies. Several challenges are then identified for future research. The results reveal the number of articles on industrial symbiosis has greatly increased since 2007 and China is the country with the largest number of publications and cases of industrial symbiosis, followed by the United States. The methods for quantifying impacts and analysing industrial symbiosis networks were the most widely used. The analysis of the published case studies allowed an overview of the industrial symbiosis in the world and showed that the potential for application is enormous, both in developed countries and in countries with developing economies, and although the most present economic activities in the synergies are associated with the manufacturing sector, the possibilities of industrial symbiosis are not restricted to these activities nor to the number of entities involved. The symbioses between industry and the surrounding community also have great potential for development with numerous advantages for both parties.

***Keywords:*** Industrial symbiosis, Case study, Industrial and urban symbiosis; Circular Economy; Sustainability;

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# 1. Introduction

The rise in industrialization and urbanization over recent years has led to an increase in carbon dioxide emissions (Dong et al., 2019; Liu and Bae, 2018), which are largely responsible for greenhouse gases. This increase has led to global warming, with adverse consequences for the environment and human health, as has been mentioned in the Intergovernmental Panel on Climate Change reports (IPCC, 2014). The increase in industrial and municipal solid waste and the increasing consumption of resources have also been highlighted as a consequence of the growth of industrialization and urbanization (Guan et al., 2019b, 2019a; Luzi et al., 2015; Minelgaitė and Liobikienė, 2019). However, the important role of industrialization for long-term economic growth has been recognized (Haraguchi et al., 2019). Thus, it is essential to find solutions which allow for the reduction of these negative effects, without jeopardizing economic growth.

The international agreements that have been established, ranging from the United Nations Framework Convention on Climate Change in 1992, currently ratified by 195 countries, to the most recent agreement reached in December 2015, the Paris Agreement, have greatly contributed to raising awareness of climate change issues and the search for sustainable solutions. These solutions are indispensable towards maintaining carbon dioxide emissions below the limits set in international agreements but also for the increasingly efficient use of resources. Industrial symbiosis has been shown to be a strong ally for the achievement of these objectives, without causing damage to the economic growth of the parties involved (Daddi et al., 2017; L. Dong et al., 2014; Fan et al., 2017; Martin and Harris, 2018), a fact also recognized by the European Commission, which has published several directives and communications mentioning the importance of industrial symbiosis (European Commission, 2018a, 2018b, 2018c).

The designation of industrial symbiosis has its genesis in biology in which symbiosis represents the "association of individuals of different species in a relationship where there is mutual benefit" (Schwarz and Steininger, 1997). This definition has been transposed to industries in which industrial symbiosis "engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" (Chertow, 2000). This definition is widely disseminated in the developing industrial ecological environment and research community (Albino et al., 2013). Posteriorly, industrial symbiosis was also identified as "a business opportunity and tool for eco-innovation" (Lombardi and Laybourn, 2012). Producing more without spending more energy or resources through cooperation is the ultimate objective pursued by the industrial symbiosis: companies that use by-products or waste from other companies. It is an effective method of “locking” the matter cycle and, therefore, to obtain a zero level of waste (Mantese and Amaral, 2018).

Often this concept appears associated with eco-industrial parks, because the concept of these parks is associated to the existence of a communities of companies, in which there is a sharing of resources, such as materials, energy, information, among others, with the aim of achieving economic, environmental and social gains (B. Huang et al., 2019; Liu et al., 2018b). The concept of industrial symbiosis is related to this definition, and it is not surprising that many of the existing eco-industrial parks have industrial symbiosis between firms. However, eco-industrial parks involve other characteristics besides industrial symbiosis, such as the use of renewable energies, the design of green buildings, among others, and in addition, when there are industrial symbiosis, they are almost always confined to the space of the park, and indeed industrial symbiosis can be triggered without the demand of the geographic proximity between the participants (Lombardi and Laybourn, 2012; Shi et al., 2010). Although proximity is a factor that facilitates the creation of synergies and reduces waste transportation costs, the reality is that there are examples in which symbiosis occur between more distant enterprises, such as in Tianjin, China (Shi et al., 2010; Yu et al., 2014b) and Choctaw in United States of America (Zhang et al., 2013).

Industrial symbiosis relationships have been fostered through a number of factors, such as saving resources, obtaining economic benefits, meeting environmental requirements such as reducing greenhouse gas emissions, scarcity of natural resources and reduction of waste that would otherwise stop at landfills and incinerators (Chertow and Ehrenfeld, 2012; Domenech et al., 2019; Mortensen and Kørnøv, 2019). Therefore, in order to meet these needs, industrial symbiosis has spread throughout the world with positive economic, environmental and social results (Geng et al., 2014; Guo et al., 2016; Martin and Harris, 2018; Park and Behera, 2015; F. Yu et al., 2015a, 2015b; Zhang et al., 2017). For example, in Sotenäs, Sweden, and even at an early stage, the industrial symbiosis network has allowed for the retention or creation of 20 jobs, the creation of 5 new companies as well as a reduction of approximately 59 million kg $CO_2$-eq emissions annually through resource sharing (Martin and Harris, 2018). In Kalundborg, Denmark with the replacement of groundwater with surface water, all symbiosis industries reduced the use of more than 30 million $m^3$ of groundwater, and in the period 1990-2002 due to the industrial symbiosis between the power plant and the refinery, of more than 7.6 million $m^3$ of surface water (Jacobsen, 2006). The implementation of urban industrial symbiosis in Guiyang, China allowed for a reduction of the urban carbon footprint by about 1090 thousand $tCO_2$ annually (Fang et al., 2017).

Since the earliest publications reporting on the case of Kalundborg in Denmark (Lowe and Evans, 1995; Schwarz, 1996; Schwarz and Steininger, 1997), one of the most successful cases of the application of industrial symbiosis and the most cited in literature, much research has been done not only to evaluate the impact that industrial symbiosis has had on the environment, the economy and society, but also on ways to increase the propagation of this practice and to understand and find solutions towards solving its vulnerabilities. Many of these studies have a practical application base, supported by their application to case studies. These are a crucial tool in order to increase the knowledge about industrial symbiosis, not only to validate proposed methods and structures, but also to analyse and serve to elucidate and draw lessons for future improvements (Eisenhardt, 1989; Yin, 2014).

Cases of industrial symbiosis have been growing over recent years and are scattered all over the world, whether in developed regions such as the United Kingdom, the United States of America and Japan, or in countries with developing economies, such as Thailand, Morocco and Algeria. In addition to diversity in terms of location, the case studies reported in literature also reflect the enormous variety in the size and types of activity involved in symbiosis. The two cases of industrial symbiosis studied in Västra Götaland in Sweden (Patricio et al., 2018) are examples of cases having few companies and little diversity, where one of the symbioses is developed between growers of mushrooms and farmers and the other between brewers and breeders. The case of Tianjin, China (Shi et al., 2010; Zhang et al., 2013) is one of the most varied of activities, involving a synergy of water and wastewater companies, thermal power plants, farms, pharmaceutical, paper, cement, automobiles and machinery industries, among others.

Given this wide variety of case studies, some publications have appeared with the aim of compiling and extracting lessons about the characteristics, the methodology, and the weaknesses of the network, among others and to use them as a basis for theories. In the same way, Chertow

(2000) used twelve cases of industrial symbiosis to illustrate the proposed taxonomy of five different material exchange types. Zhang et al. (2015a) also used some examples of industrial symbiosis cases to illustrate proposed theories and types of industrial parks based on these theories. Herczeg et al. (2018) with the aim of improving the understanding of supply chain collaboration in industrial symbiosis networks, combined the analysis of fifteen case studies with theoretical perspectives. Chertow and Ehrenfeld (2012) focused the study on the self-organizing industrial symbiosis using ten existing cases categorized according to the spatial scale where they were organized. Mathews and Tan (2011) described and compared nine case studies of industrial symbiosis to study their evolution and identify which are the drivers and inhibitors of the various synergy initiatives. Zhu and Ruth (2014) analysed the growth of the industrial symbiosis networks of sixteen cases, by characterizing them in terms of the number of companies involved, clusters and their institutional settings and analysed the impact of the promotional institutions. Also in the article by Kastner et al. (2015) some case studies were listed and classified according to the existing exchange. Chertow and Park (2011), by analysing the types of waste reused and the industries involved in these synergies in thirteen distinct cases of industrial symbiosis, proceeded to identify and categorize waste materials and types of industries with the potential to generate and use the various types of waste. Through this list it was possible to identify which categories of waste had the greatest links across different industries and therefore provide more potential for development. More recently, a study has been published which compiled the various cases of industrial symbiosis in Europe and through this mapping and the interviews conducted, analysed the main characteristics of the symbioses in Europe and the main drivers that lead companies to create such synergies (Domenech et al., 2019).

In spite of the existence of all these publications that somehow compiled and characterized the various cases of industrial symbiosis, the number of cases analysed in each article was reduced and in the publication where the number of cases was much higher, these were confined to a particular area. As a result, there was still a need for a publication that was more comprehensive and that compiled in a single article all published case studies without any restriction of characteristics or location.

In order to fill this gap in research, this article has as its main objective to compile the various cases of industrial symbiosis in the world and to perform an analysis concerning the location, types of economic activities involved in the synergies and the methods employed in the various studies. This analysis, besides comparing different characteristics, also has the objective of framing them in the different realities underlying each case, not only to trace future research paths, but also to improve the understanding of industrial symbiosis and to increase its usage. In addition, this article also aims to serve as a guide for the creation of new synergies, since this has been recognized by some authors (Grant et al., 2010; Patricio et al., 2018) highlighting the importance of the dissemination of cases of industrial symbiosis as a way to identify and promote new symbiosis opportunities, called relationship mimicking. In addition to these objectives, the article also intends to provide a quantitative view of the publications on industrial symbiosis and to trace the evolution of research on this theme, explaining its distribution by journals, content and type of article. Although there were some studies with quantitative evaluations, these were related to articles published until 2012 (Yu et al., 2014a), 2014 (Chertow and Park, 2016) and 2016 (M. Huang et al., 2019), and are therefore not currently up to date.

The remainder of this article is organized as follows. Section 2 presents the methodology that was adopted for the research and selection of publications, as well as how the objectives of the article guided the subsequent content analysis. In Section 3 the trend of research on industrial symbiosis is described and analysed. In addition to the analysis of the evolution of the number of publications, the distribution through journals and type of article is also presented and examined. The study of the distribution of publications by type of content and the analysis of published case studies involving their geographical distribution, type of industries involved in the symbiosis and methods used is performed in Section 4. Finally, in Section 5, a discussion about the material presented in the previous sections, as well as the limitations of the study carried out. The main conclusions and recommendations for future research are made in Section 6.

## 2. Methodology

To carry out the main purpose of this paper in providing a comprehensive review of previous studies on industrial symbiosis, several steps were conducted. As shown in Fig. 1, these can be summarized in three main ones, research, selection and analysis of the several articles, directly related to the objectives of a literature review, such as "identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners" (Fink, 1998). These steps were conducted in order to answer, on the one hand, the way in which the works published in this theme have evolved and how they are classified in the various aspects, and on the other hand, the distribution of case studies of industrial symbiosis around the world, their characteristics and the methods used.

For the accomplishment of the research of articles, it was necessary the establishment of the keywords and the choice of the academic databases. Thus, in order to identify the largest number of publications, the keyword used for the research was "industrial symbiosis" and no time interval was imposed. For the research of the various publications, the academic databases that comprise the publishers with the greatest number of articles published in this area were used, such as Elsevier, Wiley Online Library, Springer, Inderscience Online, IEEE Xplore, MDPI, Taylor & Francis Online, ACS Publications, SAGE Journals, Nature Research, Emerald Insight and Annual Reviews. The choice of using these publishers instead of the most usual databases, such as the Web of Science and Scopus, was due to the fact that after comparing the initial results of the research, it was concluded that some of the articles were not included in these. Also the number of publications obtained through the publishers was greater than in these two databases. The search resulted in 761 publications from Web of Science, 907 from Scopus and the total of publications obtained through the publishers was 2888, as shown in Fig. 1.

Included in this study were research articles, review articles, conference articles, book chapters and editorials. Although some of these publications were not peer-reviewed, they provided more information about existing industrial symbiosis cases that were not reported in peer-reviewed publications. The only exclusion criterion, in this first phase of research, was all articles that were not written in English.

The next step comprised the selection of the articles. Titles, abstracts and keywords were read in a first stage to analyse whether the article concerned with the theme of industrial symbiosis. If, after this reading, some doubts remained as to the inclusion of the articles for later content analysis, then the text was examined. This included not only the counting of the number of times the term industrial symbiosis appeared, but also reading the context in which they were inserted. That is, all articles those referred only to industrial symbiosis as an example, or mentioned only in the introduction to contextualize another concept or to distinguish concepts, without the study of this practice, were eliminated. The snowballing method (Bakker, 2010) was used to obtain additional articles, that is, the references cited in the papers analysed were used to search for more relevant publications, however, few emerged from this analysis, which may be indicative of the effectiveness of the initial research. A total of 584 articles resulted in the end of the entire research and screening process.

In order to obtain a quantitative representation of the distribution of publications and their evolution, the main data of the selected articles, such as the year of publication, the journal and the type of article (research, review, conference, book chapter and editorial) were collected. To map the industrial symbiosis and characterize the main activities and methods used in the various studies, the publications were analysed in two distinct phases. The first one consisted in categorizing the selected publications in terms of content type and the second consisted in a content analysis of all case studies in order to characterize and map the various initiatives of industrial symbiosis in the world. In the first phase of categorization, the publications were classified into three types: Theoretical, Review and Case Studies. However, during the analysis of the articles, it was concluded that many of the studies carried out looked at the potential of applying industrial symbiosis in new places and what the environmental and economic advantages could result from its application. Thus, these cases were not covered in the case studies, because although they related to a specific location and existing industries, they were not yet realized. Therefore, a new category, Potential Industrial Symbiosis was defined, in order to encompass these publications. In the Theoretical category are included theoretical and conceptual articles, as well as those that use models from mathematical functions, that is, modelling and simulation. The publications in which qualitative data was used, such as interviews, to study a case of existing industrial symbiosis were classified as Case Studies.

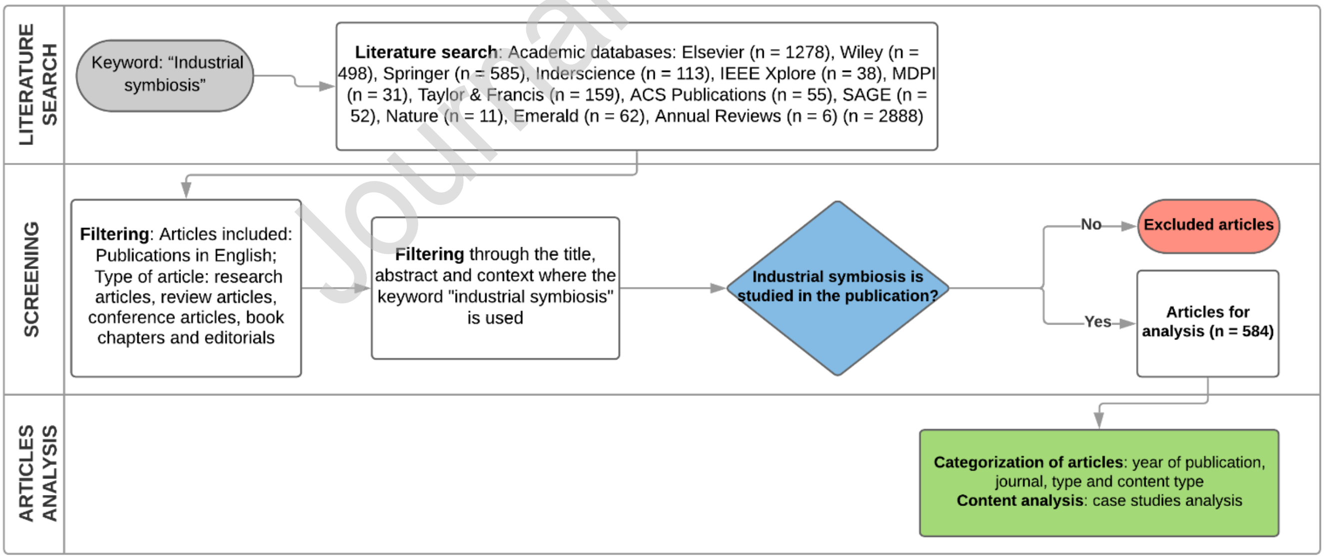


Fig. 1. Flow diagram of literature search and respective screening

## 3. Review of research trends

### *3.1. Evolution of the number of published articles*

After the research and application of the selection criteria set forth in the previous Section, the main data of the 584 articles selected were extracted in order to draw conclusions about the trend of research on industrial symbiosis. Fig. 2 shows the evolution of the number of articles published since 1995. It can be seen from the analysis of the figure that the number of articles has grown exponentially, revealing an increasing interest of the scientific community in this subject. This growth can be divided into two distinct periods, the first between 1995 and 2006, in which in the first years the number of articles remained almost constant, beginning to increase from 2004, however in this period the increase in the number of articles published was not very significant. In the second period between 2007 and the present year, there is a clear increase in the number of articles, from 20 in 2007 to 78 in 2018, reaching a maximum of 86 publications in 2017. And although in some years there has been a decrease in the number of publications, it is negligible compared to the considerable increase in the number of articles in subsequent years, reaching in 2014 and 2017 growth rates over the previous year of 88% and 72% respectively. It should be noted that the value of 2019 is provisional, since it refers to the first five months of the year, however given the large number of publications already verified; it is likely that by the end of the year the number of articles will exceed the value of the previous year.

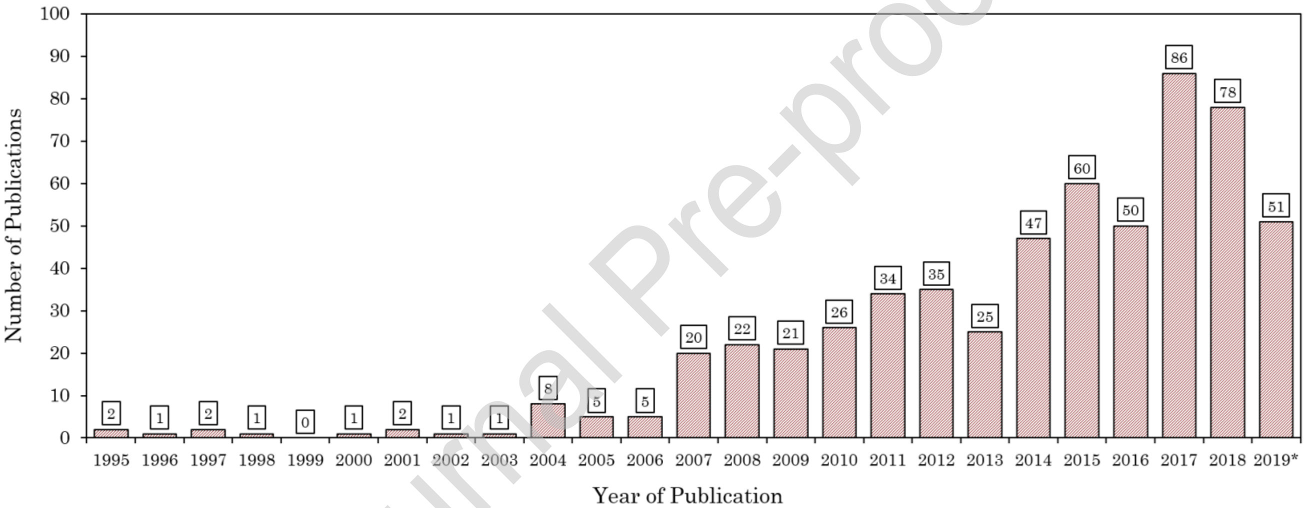


Fig. 2. Number of publications per year

This increase in the number of publications may be related with the development of European, national and regional programs and policies that have encouraged the practice of industrial symbiosis, as corroborated in the study by Chertow and Park (2016). The successful example of Kalundborg, so often cited in the literature (Domenech and Davies, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Valentine, 2016), may also be an important factor in the growing interest in industrial symbiosis and the consequent growth in the number of publications. As an example of success since 1972 and allied to the many studies that have demonstrated the numerous economic, environmental, and social benefits to companies and the surrounding community, it may have increased the interest in studying this practice.

### 3.2. *Contribution of journals in the evolution of published articles*

Selected articles were collected from 183 different sources, including journals, books and conference proceedings. However, as can be seen in Fig. 3, the distribution by journals is not uniform. In this figure it is possible to observe the distribution of articles by journals with the highest number of publications, at least 5, in the area of industrial symbiosis.

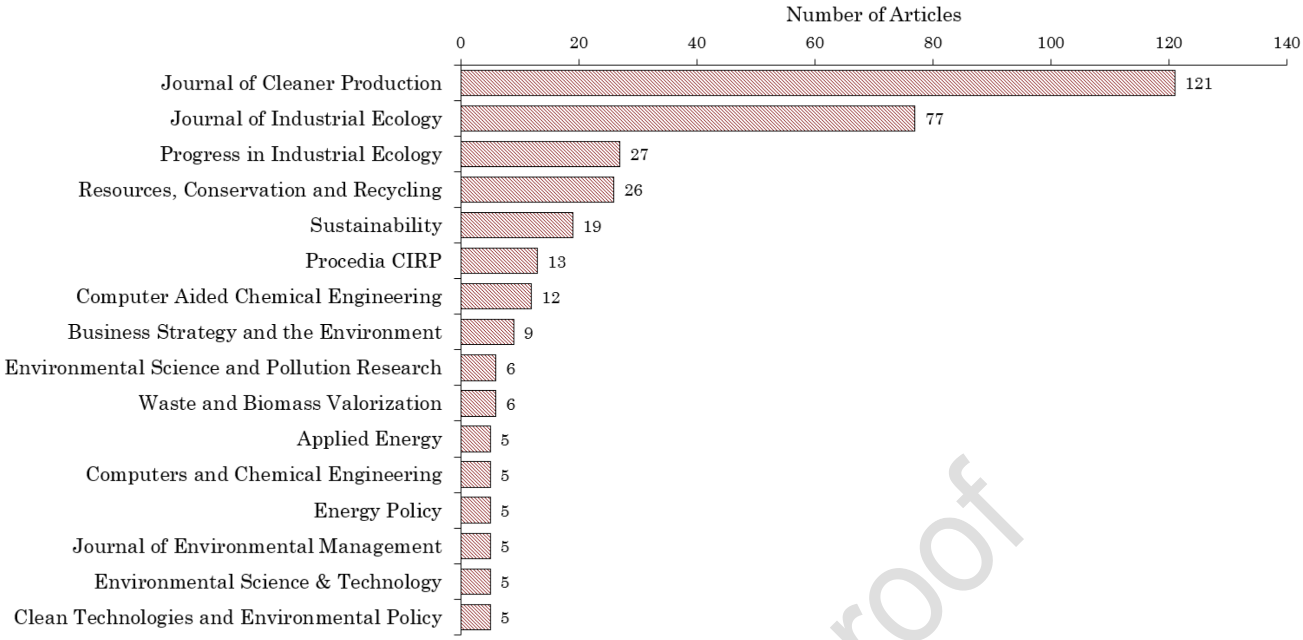


Fig. 3. List of journals with the highest number of articles published (at least 5 articles)

From Fig. 3, we can observe that the journals with the most publications are the Journal of Cleaner Production, with 121 articles, followed by the Journal of Industrial Ecology with 77 articles. In the universe of 183 sources, these 16 journals illustrated in the figure, corresponding to approximately 9% of the total, are responsible for 59% of all publications. While the two main journals, equivalent to 1.1% of all journals, books and conference proceedings, are responsible for 33.9% of the total articles, of which 20.7% are published in the Journal of Cleaner Production and 13.2% in the Journal of Industrial Ecology.

### 3.3. *Distribution of publications by article type*

The publications that resulted from the research and selection were grouped by article type, that is, research articles, review articles, conference articles, book chapters, and editorials, as illustrated in Fig. 4.

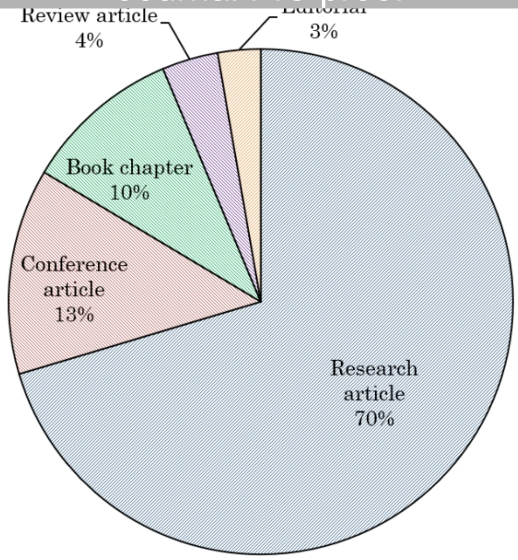


Fig. 4. Distribution of the number of publications by article type



Comparing the different types of publications, the research articles are those that stand out with a great difference compared to the other types, with a total of 411 articles. This is followed by conference articles with a total of 77, book chapters with 59, review articles with 21 and editorials with 16 publications in total.

Fig. 5 shows the evolution of the number of publications according to the type of articles. It is possible to analyse from the figure that, although the research articles are always preponderant over the other types, not always the proportion of the various types of articles in each year remains constant.

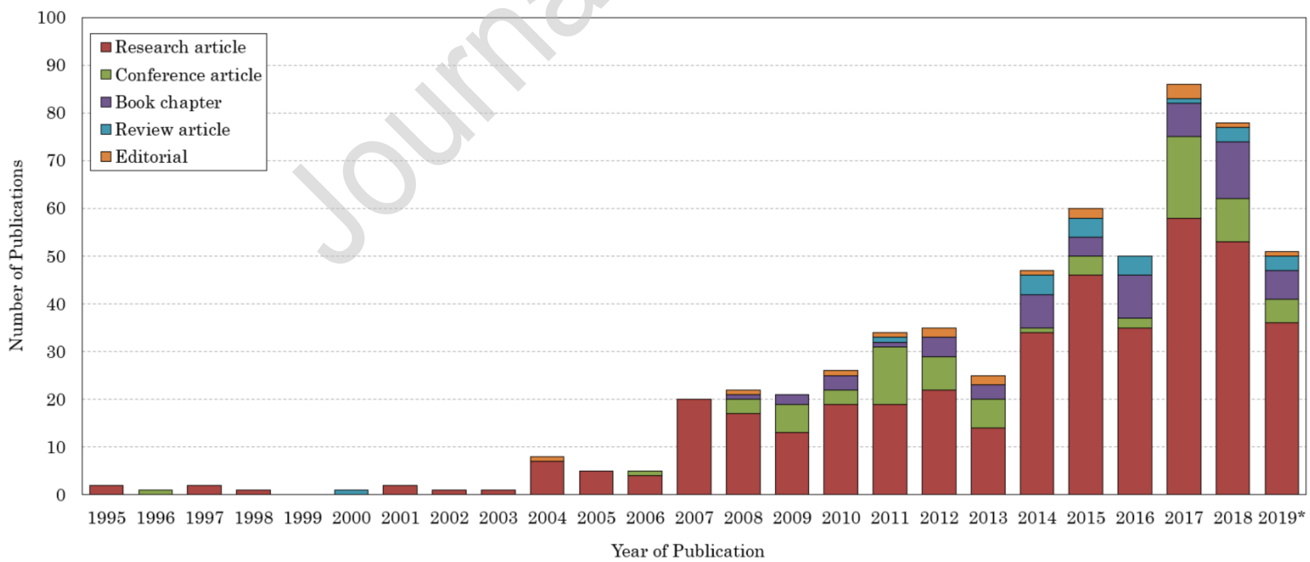


Fig. 5. Evolution of the number of publications by article type per year

Until 2003, and due to the small number of articles published, almost every year the research articles were the only ones to be published. Since 2004, the type of articles has become more diverse, nevertheless research articles continued to predominate over the others, with an average annual weight of 74.1% compared to the total published annually.

Regarding the maximum values obtained by the main types of articles, these have been verified in recent years, which illustrate the growing interest in industrial symbiosis. The research articles, as stated above, present the highest value of publications, reaching a maximum of 58 in 2017. Also in this year the conference articles reached a maximum of 17 and editorials a maximum of 3, while the other types of publications, reached the maximum values in dissimilar years. In 2018 book chapters peaked at 12 and review articles reached 4 publications in consecutive years from 2014 to 2016.

## 4. Analysis of case studies on industrial symbiosis

The next two sections focus on the analysis of content made to the various publications. In the first section, a broader analysis is carried out regarding the distribution and evolution of publications by content type. The following is an analysis of the various cases studies of industrial symbiosis found in the literature, where a characterization of the geographical distribution and type of activities involved in the symbiosis was carried out, as well as the methods that were used in the several studies.

### *4.1. Distribution of publications by content type*

During the detailed study of the selected articles on industrial symbiosis and with the aim of analysing the evolution of the research regarding the content of the publications, these were classified according to the content type. The categorization of selected publications was initially conducted according to three types of content: Review, Theoretical and Case Studies. However, during the analysis of the articles it was concluded that many of them were not included in any of these categories, and although they reported to a study of industrial symbiosis in a given location, they did not fit within the scope of the case studies. Thus, a new category, Potential Industrial Symbiosis was defined, with the aim of clarifying the division between content types and including all publications whose main focus was the analysis and description of potential industrial symbiosis.

#### *4.1.1. Distribution and evolution of publications by content type*

The selected articles on industrial symbiosis were carefully analysed and classified according to the type of content, whose distribution by categories, Review (R), Theoretical (T), Case Studies (CS) and Potential Industrial Symbiosis (PIS), is shown in Fig. 6.

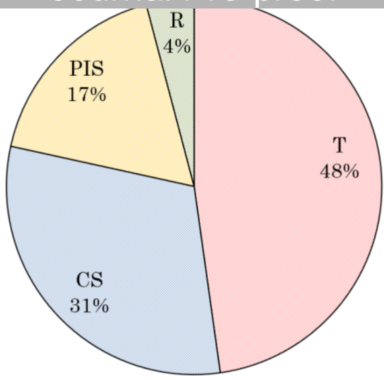


Fig. 6. Distribution of the publications by content type

From the analysis of the figure it is possible to conclude that the distribution of the publications by content type is quite different. Publications whose content is theoretical occupy the largest part of the universe of publications on industrial symbiosis. Of this category, a total of 279 articles were published, with a very wide and distinct scope. Some examples are the articles that dealt with methods (Valero et al., 2013), indicators (Couto Mantese and Capaldo Amaral, 2017; Felicio et al., 2016), approaches to quantify environmental performance (Martin et al., 2015) and analysis of symbiosis networks (Zeng et al., 2013). The study for the creation and development of industrial symbiosis was also the focus of many articles in this category. Articles in which quantification tools were developed to identify the best scenario for the implementation of industrial symbiosis (Brondi et al., 2018), in which platforms for collaboration and information sharing were studied and developed to facilitate the creation of synergies (Fraccascia and Yazan, 2018; Low et al., 2018), as well as the study of the best network configuration (Somoza-Tornos et al., 2018), are some of the examples.

The second content type most approached in industrial symbiosis publications are case studies, with 179 articles. The variety of these articles with regard to location, type of activities, methods used and formation and development of symbiosis is vast. Section 4.2 will provide a more detailed explanation of the case studies.

The potential industrial symbiosis corresponds to the third most published content in this area, with 102 articles. Although the core of this new category is the study of the industrial symbiosis that can be carried out, the scope of the publications included in this category is quite broad. Thus, publications with a narrower scope which focused on the study of new uses of by-products or waste in order to enhance industrial symbiosis were included. Examples of these publications were the study conducted for the potential recovery of platinum from waste thermocouples (Charles et al., 2018), and the study of the use of grape marc for the development of a bioadsorbent used for the removal of copper sulphate from water (Bustos et al., 2018). Publications with a broader scope were also included in this category, from publications that have studied the possibility of creating and developing industrial symbiosis around a specific industry, usually responsible for the production of a large number of wastes and by-products and therefore more attractive for the development of industrial symbiosis, to those who studied the potential transformation of an industrial park into an eco-industrial park with a major focus on industrial symbiosis. Examples of these publications are studies that have been developed to identify and evaluate industries capable of creating industrial symbiosis around nuclear plants in France (Leurent et al., 2018) and rubber industries in Kedah, Malaysia (Sharib and Halog, 2017), and the studies done in the industrial park of Salaise-Sablons in France (Ribeiro et al., 2018) and in the industrial city of Borg El-Arab in Egypt (ElMassah, 2018), which involved various types of industries with the aim of transforming the park where they are inserted into an eco-industrial park with various industrial symbiosis.

The lowest number of publications, 24 articles, is in the review content category. The subjects covered in these review publications are very diverse, ranging from the most comprehensive, in which a thorough study of previous publications is done, and from that analysis they establish categorization systems, identify the trends of the research carried out, as well as the possible evolutions (Chertow, 2000; Zhang et al., 2015a), to the most restricted in which although a thorough study of previous publications is done, it is more confined to the subject under analysis. Review articles that focus on a given region (Maes et al., 2011; Park et al., 2016) or waste (Gopinath et al., 2018), or methods and indicators (Neves et al., 2019a) or that study the role of policies for the development of industrial symbiosis (Jiao and Boons, 2014), or that study the role of information systems (van Capelleveen et al., 2018) and online social networks (Ghali et al., 2016) for the formation of new synergies are some of the examples of publications whose content is more focused.

The evolution of publications taking into account the content type is not always constant according to the evolution of the total publications, as shown in Fig. 7.

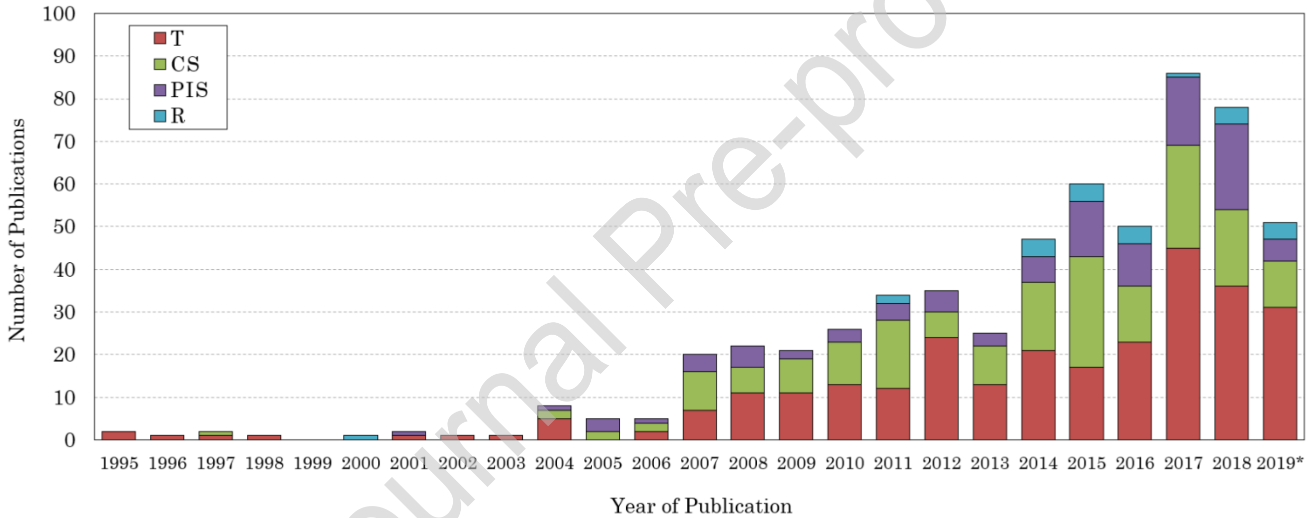


Fig. 7. Evolution of the number of publications by content type per year

Until 2003, the number of existing publications was very small and articles whose content is theoretical were predominant, representing until that year 73% of all publications. With the increase in the number of articles published on industrial symbiosis since 2004, the diversity of contents began to be noticed, but with few exceptions, publications whose content is theoretical dominated the annual publications, almost always accounting for about 50% of all publications. Articles whose contents are case studies accounted for a considerable portion of the total number of publications over the years, often occupying second place in annual publications. Furthermore, in 2007, 2011 and 2015 were the most published type of article. Since 2004, papers dealing with potential industrial symbiosis have been published regularly, and although their weight has varied over the years, there has been a clear increase since 2015. Of all content types, the ones that presented the greatest interregnum between publications were the review articles. However, since 2014 they have been published more regularly, reflecting the need to identify and analyse research trends.

### 4.2. *Analysis of case studies*

In order to map the existing industrial symbiosis case studies as well as the methods employed in the respective studies, the various publications were analysed. From this analysis it was possible to verify the enormous variety of cases of industrial symbiosis, not only in terms of location, but also in the size and industries involved, as illustrated, in a summarized form, in Table 1 where all these data were compiled. In Table A.1, in Appendix A, all this information is set out in more detail.

The case studies of industrial symbiosis reported in the literature cover several areas, such as, Europe, North America, Asia, Oceania, North Africa and South America. The order in which the various areas are organized refers to the year of publication, being sorted from the oldest to the most recent. Within each area, the regions were also organized in ascending order of publication year of the articles.

With the objectives of making the table more concise and analysing the economic activities present in the various cases of industrial symbiosis, it was decided to group the various activities into sections, defined according to the International Standard Industrial Classification of All Economic Activities, Revision 4 (ISIC, Rev.4). Recognized as an International reference classification, according to this, economic activities are subdivided into four levels in a hierarchical structure. However, in the table below the economic activities are established by the classification into sections, more comprehensive, belonging to the highest level and collected in alphabetical order. Of the 21 sections defined in the ISIC, 14 are present in the various cases of industrial symbiosis studied, being chosen to put in the table a more concise designation to enunciate the various sections. Thus, sections A: Agriculture, forestry and fishing, B: Mining and quarrying, C: Manufacturing, D: Electricity, gas, steam and air conditioning supply, E: Water supply; sewerage, waste management and remediation activities, F: Construction, G: Wholesale and retail trade; repair of motor vehicles and motorcycles, H: Transportation and storage, I: Accommodation and food service activities, L: Real estate activities, M: Professional, scientific and technical activities, N: Administrative and support service activities, O: Public administration and defence; compulsory social security and R: Arts, entertainment and recreation are included in the case studies.

**Table 1**
Industrial Symbiosis Application and Analysis Studies

| Country | Region | N. Enterprises | Activity | Method | Publication Year | Reference |
|---|---|---|---|---|---|---|
| **Europe** | | | | | | |
| Denmark | Kalundborg | 6/ 18 | Energy supply, Manufacturing, Agriculture, Water and waste and Public administration | On-site visits and interviews. Interdependencies analysis. Environmental and economic analysis. Social network analysis (SNA) and core-periphery structure analytical methods. Centrality indicators, centralization measures and small-world and scale-free effects. Disruptive scenarios and cascading effects. Input-output inoperability model, Fuzzy approach. Dependency and influence gain indexes. Stability analysis | 1997/ 2019 | (Branson, 2016; Chopra and Khanna, 2014; Domenech and Davies, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Kuznetsova et al., 2017; Valentine, 2016; Zhang and Chai, 2019; Zhang et al., 2013) |
| United Kingdom | Grangemouth | | Manufacturing, Energy supply and Water and waste | Technology transfer model adapted | 2004 | (Harris and Pritchard, 2004) |
| | Forth Valley | | Manufacturing, Energy supply and Water and waste | | | |
| | Humber | | Energy supply, Manufacturing, Agriculture and Water and waste | Direct observations, interviews and SNA | 2004/ 2016 | (Mirata, 2004; Velenturf, 2016) |
| | West Midlands | 167 | Manufacturing, Food service and Professional and scientific activities | Direct observations and interviews and conversations | 2004/ 2012 | (Mirata, 2004; Paquin and Howard-Grenville, 2012) |
| | England/ Scotland/ Wales | | | Geographic Information Systems software package | 2011 | (Jensen et al., 2011) |
| | Bristol | | Manufacturing | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| | Wissington | | Manufacturing | Interviews | 2014 | (Short et al., 2014) |
| | | | Transportation and storage | Interviews | 2015 | (Leigh and Li, 2015) |
| | | | Manufacturing, Water and waste and Professional and scientific activities | Interviews | 2018 | (de Abreu and Ceglia, 2018) |
| Sweden | Landskrona | >20 | Manufacturing, Water and waste, Agriculture, Transportation and storage and Public administration | Interviews | 2005 | (Mirata and Emtairah, 2005) |
| | Southern Sweden | | Manufacturing and Energy supply | Interviews | 2007 | (Wolf et al., 2007) |
| | Sundsvall-Timrå | | Manufacturing and Public administration | On-site observation and interviews | 2007 | (Wolf and Petersson, 2007) |
| | Mönsterås | | Manufacturing and Public administration | | | |
| | Östergötland | | Manufacturing and Energy supply | Planned and unplanned IS activities analysis | 2011 | (Baas, 2011) |
| | Händelö | 3 | Agriculture, Manufacturing, Energy supply, Water and waste and Public administration | Visits and interviews. Material and energy flows. Life cycle assessment (LCA), EPD 2008, energy allocation, system expansion and the 50/50 methods | 2011/ 2015 | (Martin, 2015; Martin et al., 2014; Martin and Eklund, 2011) |
| | Västra Götaland | 11 | Agriculture and Manufacturing | On-site visits and interviews | 2018 | (Patricio et al., 2018) |
| | Stenungsund | | Manufacturing | LCA and CML 2001 method. Cost-effectiveness analysis | 2018 | (Røyne et al., 2018) |
| | Sotenäs | 10 | Manufacturing, Agriculture and Water and waste | Interviews, consultation, LCA and socio-economic assessments | 2018 | (Martin and Harris, 2018) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Netherlands | Rotterdam | | Manufacturing, Agriculture, Sale and repair, Energy supply, residential areas and port | On-site visits and interviews. Role of organizations. Analysis of embeddedness and capabilities. Historical background and development analysis. Planned and unplanned IS analysis | 2007/ 2014 | (Baas, 2011; Baas and Boons, 2007; Baas and Huisingh, 2008; Baas and Korevaar, 2010a; Cerceau et al., 2014) |
| | Canal Zone of Zeeland | | Agriculture, Manufacturing, Water and waste and regional port authority | Interviews and event sequence analysis | 2013/ 2014 | (Boons et al., 2014; Spekkink, 2013) |
| | Zeeland | | Agriculture and Manufacturing | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| | Sloe Area and Canal Zone | | Agriculture, Manufacturing and Water and waste | Interviews and event sequence analysis | 2015 | (Spekkink, 2015) |
| | South of the Netherlands | | Agriculture, Manufacturing, Public administration and Professional and scientific activities | Interviews, brainstorming sessions, comparative analysis and visual analysis | 2019 | (Baldassarre et al., 2019) |
| France | Mèze | | Agriculture and Water and waste | On-site visits and interviews | 2007 | (Gibbs and Deutz, 2007) |
| | Marseille-Fos | | Energy supply | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| | Bazancourt-Pomacle | | Manufacturing | Interviews | 2015 | (Schieb et al., 2015) |
| | Dunkirk | 14 | Manufacturing, Energy supply, Water and waste, Agriculture and Construction | Site visits and interviews. Geographical system dynamics method and Causal Loop Diagrams | 2019 | (Morales and Diemer, 2019) |
| | | | Water and waste and local companies | Site visits, interviews, qualitative and quantitative model of the stakeholder value network approach | 2017 | (Hein et al., 2017) |
| Russia | Kola Peninsula | 9 | Mining and quarrying | Interviews, counterfactual method, eco-efficiency indicators and material flow analysis | 2007 | (Salmi, 2007) |
| Finland | Kuusankoski | | Manufacturing, Energy supply and Water and waste | Quantifiable indicators for the analysis of sustainability | 2010 | (Pakarinen et al., 2010) |
| | Kymenlaakso | | Manufacturing, Energy supply and Water and waste | On-site survey. Process, hybrid and input-output life cycle assessment approaches and LCIA-RECIPE method. LCA | 2010/ 2011 | (Mattila et al., 2010; Sokka et al., 2011b) |
| | Kouvola | 9 | Manufacturing, Energy supply and Water and waste | Interviews and LCA | 2011 | (Lehtoranta et al., 2011; Sokka et al., 2011a) |
| Portugal | Chamusca | | Water and waste, Manufacturing and Agriculture | Interviews, on-site visits and middle-out approach | 2010 | (Costa and Ferrão, 2010) |
| | Lisbon | 44 | Manufacturing, Sale and repair, Construction, Energy supply and Agriculture | Material Flow Analysis | 2015 | (Patrício et al., 2015) |
| | | | Manufacturing | Interviews, indicators and radar chart graph. Comparative analysis | 2019 | (Ferreira et al., 2019) |
| Austria | Styria | | Manufacturing, Sale and repair, Water and waste, Mining and quarrying, Energy supply and Public administration | SNA and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| Italy | Taranto | >15 | Manufacturing, Agriculture and Energy supply | Questionnaires | 2014/ 2016 | (Notarnicola et al., 2016, 2014) |
| | Venice, Veneto | | Manufacturing | Surveys data | 2015 | (Mannino et al., 2015) |
| | Prato, Tuscany | | Manufacturing | Interviews | 2015 | (Daddi et al., 2015) |
| | Ponterosso, Friuli-Venezia Giulia | | Manufacturing | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Ancona, Marche | | Manufacturing, Sale and repair, Professional and scientific activities, Food service and Administrative and support service | | | |
| | Abruzzo | | Manufacturing | On-site survey and questionnaires | 2017 | (Taddeo et al., 2017) |
| | S.Croce sull'Arno, Tuscany | | Manufacturing | LCA | 2017 | (Daddi et al., 2017) |
| Spain | Galicia | | Port-based industrial complexes | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| | | | Manufacturing | Interviews, indicators and radar chart graph. Comparative analysis | 2019 | (Ferreira et al., 2019) |
| Belgium | Antwerp | | Manufacturing and city | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| | Brussels | | Port-based industrial complexes | | | |
| | Koekhoven | | Energy supply, Agriculture, Professional and scientific activities, Manufacturing, Sale and repair, and Water and waste | Interviews, observations, field visits and dual-perspective framework application | 2016 | (Verguts et al., 2016) |
| Germany | | | Manufacturing | Simplified life cycle assessment model | 2015 | (Ammenberg et al., 2015) |
| Latvia | | | Manufacturing, Agriculture and Energy supply | Interviews. Integrated method for evaluation of the quality of industrial synergies | 2015 | (Rosa and Beloborodko, 2015) |
| | | | Manufacturing and Agriculture | | | |
| Denmark/ UK/ Portugal/ Switzerland | | | | Interviews and quantitative and qualitative descriptors | 2010 | (Costa et al., 2010) |
| **North America** | | | | | | |
| United States of America | Guayama, Puerto Rico | | Energy supply, Water and waste, Manufacturing and Construction | Field research, interviews, questionnaires and material flow analyses | 2005/ 2008 | (Chertow et al., 2008; Chertow and Lombardi, 2005) |
| | Barceloneta, Puerto Rico | 15 | Manufacturing, Agriculture and Water and waste | Field research and interviews. Material flow analyses. SNA. Congruence method | 2008/ 2011 | (Ashton, 2008, 2011, 2009; Chertow et al., 2008) |
| | Pennsylvania | | | Environmental assessment using the life cycle inventory databases of GREET and Ecoinvent | 2009 | (Eckelman and Chertow, 2009) |
| | Honolulu | 11 | Energy supply, Manufacturing, Water and waste, Mining and quarrying and Arts, entertainment and recreation | Interviews. Quantification of environmental and economic benefits. LCA | 2010/ 2013 | (Chertow and Miyata, 2010; Eckelman and Chertow, 2013) |
| | Kansas City | 9 | Manufacturing, Water and waste and Energy supply | Material flow network and mixed integer programming model | 2011 | (Cimren et al., 2011) |
| | Choctaw | | Manufacturing, Water and waste and Agriculture | SNA and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| | New York/ New Jersey | | Port-based industrial complexes | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| | Long Beach | | Ports and marinas | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| | North Dakota | | Manufacturing and Energy supply | Interviews and surveys. Stochastic mixed integer linear programming model and energy efficiency analysis | 2015 | (Gonela et al., 2015) |
| | Upper Valley | 2 | Manufacturing and Water and waste | Interviews | 2017 | (Krones, 2017) |
| | Chicago | | Manufacturing, Agriculture, Real estate activities, Professional and scientific activities and Water and waste | Measurements on-site and off-site, interviews, questionnaires and material flow analysis | 2018 | (Chance et al., 2018) |
| Canada | Sarnia-Lambton | | Manufacturing, Agriculture and Energy supply | Interviews | 2009 | (Bansal and Mcknight, 2009) |
| Mexico | Altamira- | 15 | Manufacturing | Interviews and on-site visits | 2019 | (Morales et al., 2019) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Tampico | | | | | |
| **Asia** | | | | | | |
| South Korea | Ulsan | 2/ 21/ 41 | Manufacturing, Water and waste, Energy supply, Sale and repair, metropolitan city and port-based industrial complexes | On-site visits and interviews. Analysis of the development of IS. Eco-efficiency evaluation. Eco-production strategy analysis. Assessment of economic, social and environmental benefits. GHG emissions based on the GHG protocol and LCA. Cut-off, avoidance impact, and 50/50 methods | 2006/ 2018 | (Behera et al., 2012; Cerceau et al., 2014; Kim et al., 2018b; Park and Behera, 2015, 2014; Park et al., 2008; Park and Park, 2014; Won et al., 2006) |
| | Yeosu | 27 | Manufacturing and Energy supply | Interviews, questionnaires and waste heat utilization network model | 2010 | (Chae et al., 2010) |
| | Banwol-Sihwa | | Manufacturing, Energy supply, and residential areas | Fieldwork and interviews | 2018 | (Yoon and Nadvi, 2018) |
| | | 596 | | Network analysis. Economic and environmental benefits analysis | 2019 | (Park et al., 2019) |
| China | Guigang | | Manufacturing, Water and waste, Energy supply and Agriculture | Interviews. SNA and core-periphery structure analytical methods. Robustness analysis and optimization of the network. Assessment of the vulnerability of symbiosis network based on the automatic control theory. Material flow analysis and comparative analysis | 2007/ 2018 | (Fang et al., 2007; Guo and Hu, 2011; Shi and Chertow, 2017; Q. Wang et al., 2018a, 2018b; Zhang et al., 2013; Zhu et al., 2007) |
| | Wudi County, Shandong province | 8/ 21 | Manufacturing, Mining and quarrying, Agriculture, Water and waste, Energy supply and living area | Eco-industrial development analysis. Environmental and economic analysis. SNA and core-periphery structure analytical methods. Centrality indicators, centralization measures and small-world and scale-free effects. Stability analysis. Ecological network analysis | 2007/ 2019 | (Fang et al., 2007; Guo and Hu, 2011; Wang et al., 2010; Zhang and Chai, 2019; Zhang et al., 2015b, 2013) |
| | Guiyang | | Manufacturing, Energy supply, Agriculture and urban areas | Eco-industrial development analysis. Hybrid model integrating an input-output approach and process-based inventory analysis. Carbon emissions analysis | 2007/ 2017 | (Fang et al., 2017, 2007) |
| | Nanning, Guangxi | | Manufacturing | On-site survey and Material flow analysis | 2008 | (Jianhua and Zhaohua, 2008; Yang and Feng, 2008) |
| | Dafeng | 5 | Agriculture and Manufacturing | Environmental and economic benefits analysis | 2010 | (Wang et al., 2010) |
| | Guangdong | 13 | Manufacturing and Energy supply | | | |
| | Tianjin | | Water and waste, Energy supply, Construction, Manufacturing, Agriculture, Administrative and support service, industrial, commercial and residential users and port-based industrial complexes | On-site visits and interviews. SNA and core-periphery structure analytical methods. Process analysis. Multicriteria decision analysis | 2010/ 2015 | (Cerceau et al., 2014; Qi and Wang, 2011; Shi et al., 2010; Yu et al., 2015, 2014b; Zhang et al., 2013) |
| | Tianjin Binhai | | Energy supply, Water and waste and Manufacturing | Interviews and Transition course analysis | 2011/ 2017 | (Li, 2011; Q. Wang et al., 2017) |
| | Suzhou | | Manufacturing, Water and waste and Energy supply | Field study and interviews. Energy-related GHG emissions using IPCC guidelines method. Substance flow analysis and resource productivity indicator | 2012/ 2015 | (L. Liu et al., 2012; Wen and Meng, 2015) |
| | Weifang | 2/ 11 | Mining and quarrying, Manufacturing, Energy supply, Water and waste and residential zone | Field research and interviews. Three-level approach. System dynamics method. Method of scenario analysis | 2012/ 2018 | (Cui et al., 2018; C. Liu et al., 2012; Liu et al., 2015) |
| | Liuzhou | 3 | Manufacturing and urban community | Surveys data. Hybrid physical input and monetary output model, co-benefit indicators and calculation of $CO_2$ emissions. Material flow analysis | 2013/ 2014 | (Dong et al., 2013a, 2013b; L. Dong et al., 2014) |
| | Jinan | 6 | Manufacturing and urban community | Questionnaire surveys and interviews. Material flow analysis and $CO_2$ emission reduction | 2013/ 2014 | (Dong et al., 2013b; L. Dong et al., 2014) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Changsha Huangxing | | Manufacturing, Agriculture and Water and waste | SNA, network connectedness analysis and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| | Shihezi | | Manufacturing, Agriculture and Water and waste | | | |
| | Wujing | | Manufacturing | | | |
| | Liaocheng | 16/ 27 | Manufacturing, Energy supply, Water and waste and Mining and quarrying | Laboratory data, field investigation and interviews. Energy-saving and financial indexes. Substance flow analysis. Carbon accounting methods. LCA. Network analysis method and SNA | 2014/ 2017 | (Han et al., 2017; Li et al., 2015; F. Yu et al., 2015a, 2015b) |
| | Shenyang | | Energy supply and Manufacturing | Interviews and meetings. Emergy analysis method and logarithmic mean divisia index method | 2014/ 2018 | (Dong et al., 2018; Geng et al., 2014) |
| | Ningbo | | Manufacturing | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| | Rizhao | 94 | Manufacturing | Questionnaires and interviews | 2015 | (F. Yu et al., 2015c) |
| | Jiangsu | 86 | Manufacturing and Energy supply | Interviews. Geographical information systems. Interconnected network model based on complex network theory | 2015 | (Li and Shi, 2015) |
| | Dalian | 7 | Water and waste, Manufacturing and Energy supply | Field research. Multicriteria decision analysis and process analysis approach. Emergy analysis and index decomposition analysis. LCA | 2015/ 2017 | (Yu et al., 2015; Zhang et al., 2017; Zhe et al., 2016) |
| | Jiayuguan | 26 | Manufacturing | Backward approach, substance flow analysis and substitution analysis method | 2016 | (Wu et al., 2016a) |
| | Midong | 18 | Manufacturing, Energy supply and Mining and quarrying | Interviews, questionnaires, material flow analysis and evaluation of benefits of IS | 2016 | (Guo et al., 2016) |
| | Shanghai Caohejing | 10 | Manufacturing | Site investigations | 2016 | (Huang et al., 2016) |
| | Gansu | 12 | Manufacturing | Bow-tie and risk index methods | 2017 | (Wu et al., 2017b) |
| | Hefei | | Energy supply and Manufacturing | On-site survey, interviews and emergy analysis | 2017 | (Fan et al., 2017) |
| | Qijiang | 17 | Manufacturing | Interviews, field trips, questionnaire-and simulation analysis on the cascading failure mode | 2017 | (Li et al., 2017; Li Sun et al., 2017) |
| | Wu'an | | Manufacturing, Energy supply, Mining and quarrying and Water and waste | On-site investigations, material flow analysis, $CO_2$ emission inventory and economic analysis | 2017 | (Cao et al., 2017) |
| | Yulin/ Ordos/ Jining | | Manufacturing | Field research, cascading failure model, network performance indicators, simulation and comparative analysis | 2017 | (D. Wang et al., 2017) |
| | Ordos | | Manufacturing | Lotka-Volterra population ecology model and interpolation fitting method | 2018 | (D. Wang et al., 2018) |
| | Gujiao | 38 | Mining and quarrying, Manufacturing, Water and waste and Energy supply | SNA | 2018 | (Song et al., 2018) |
| | Bohai Bay | | Energy supply, Manufacturing and Water and waste | Field surveys, interviews and meetings | 2018 | (Liu et al., 2018a) |
| | Northwestern China | | Manufacturing | Interviews, exergy analysis, life cycle GHG emissions assessment and water footprint analyses | 2018 | (Wu et al., 2018) |
| | Daqing | | Manufacturing and Energy supply | Questionnaires and field visit. Grey correlation analysis method. Eco-efficiency, economic, environmental and network indicators | 2019 | (Wang et al., 2019) |
| | | | Manufacturing | Interviews and substitution analysis method | 2015 | (Yu et al., 2015) |
| | | | Manufacturing and Energy supply | Exergy analysis. Energy and exergy efficiency, $CO_2$ emissions and overall performance indicators | 2016 | (Wu et al., 2016b) |
| | | | Manufacturing and Water and waste | Environmental, fracture and redundancy indexes, | 2017 | (Wu et al., 2017a) |

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|---|---|---|---|---|---|---|
| | | | | stability analysis method and probability method | | |
| Japan | Kawasaki | 5 | Manufacturing, Water and waste, community and port-based industrial complexes | Site visit and interviews. Material flow analysis. Life cycle $CO_2$ analysis method. Environmental and economic indicators. Hybrid life cycle assessment, material carbon footprint method, input-output analysis and emission coefficient. Emergy methods | 2009/ 2017 | (Cerceau et al., 2014; H. Dong et al., 2014; Dong et al., 2013b; Hashimoto et al., 2010; Ohnishi et al., 2017; Van Berkel et al., 2009a) |
| | 23 cities | | Eco-town | Questionnaires, influencing factors and performance indicators | 2012 | (Chen et al., 2012) |
| | Kitakyushu | | Manufacturing and Water and waste | SNA and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| | Osaka | | Energy supply, Manufacturing, Public administration and ports | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| India | Nanjangud | 12/ >14 | Manufacturing and Agriculture | Field surveys and interviews. Material flow analysis. SNA and statistical network correlation analyses | 2009/ 2012 | (Ashton and Bain, 2012; Bain et al., 2010, 2009) |
| | Tamil Nadu | | Manufacturing, Agriculture and Water and waste | Multi-objective mixed integer linear programming model and sensitivity analysis | 2019 | (Vimal et al., 2019) |
| Bangladesh | Sitakunda-Bhatiary | | Water and waste | Interviews | 2011 | (Gregson et al., 2011) |
| Thailand | Map Ta Phut | | Port-based industrial complexes | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| Singapore | Jurong Island | | Manufacturing, Transportation and storage and Energy supply | Online maps, workshop and survey | 2019 | (Yin and Lee, 2019) |
| | Ulu Pandan, and Clementi | | Water and waste and domestic and commercial buildings | | | |
| | Tuas, Tuas South, and Senoko | | Public administration and Water and waste | | | |
| | | | Food service and Manufacturing | | | |
| | | | Water and waste, Manufacturing, Energy supply, Agriculture, Construction and Arts, entertainment and recreation | | | |
| **Oceania** | | | | | | |
| Australia | Kwinana | 35 | Manufacturing, Agriculture, Energy supply, Construction, Water and waste and Mining and quarrying | Interviews. Integrated research programme and framework to facilitate IS | 2007/ 2013 | (Harris, 2007; MacLachlan, 2013; Van Beers et al., 2007) |
| | Gladstone | 7/ >8 | Manufacturing, Energy supply, Agriculture and Water and waste | Interviews and field survey. Qualitative tool for analysis of IS barriers | 2007/ 2015 | (Golev et al., 2015, 2014; Van Beers et al., 2007) |
| **North Africa** | | | | | | |
| Morocco | Jorf Lasfar | | Port-based industrial complexes | On-site visits and interviews | 2014 | (Cerceau et al., 2014) |
| Algeria | Bejaïa | | Manufacturing | | | |
| **South America** | | | | | | |
| Brazil | South-East | | Construction and Manufacturing | Indicators of quantitative data analysis and SWOT analysis | 2017 | (Freitas and Magrini, 2017) |

#### 4.2.1. Geographic distribution

Case studies of industrial symbiosis are scattered throughout the world, but this distribution is quite disparate, as illustrated in Fig. 8, where the distribution of the number of case study publications by country is represented. In addition to this asymmetry in the number of publications, the number of industrial symbiosis cases in each country, represented by the different divisions in each bar, is also indicative of the disparity between them.

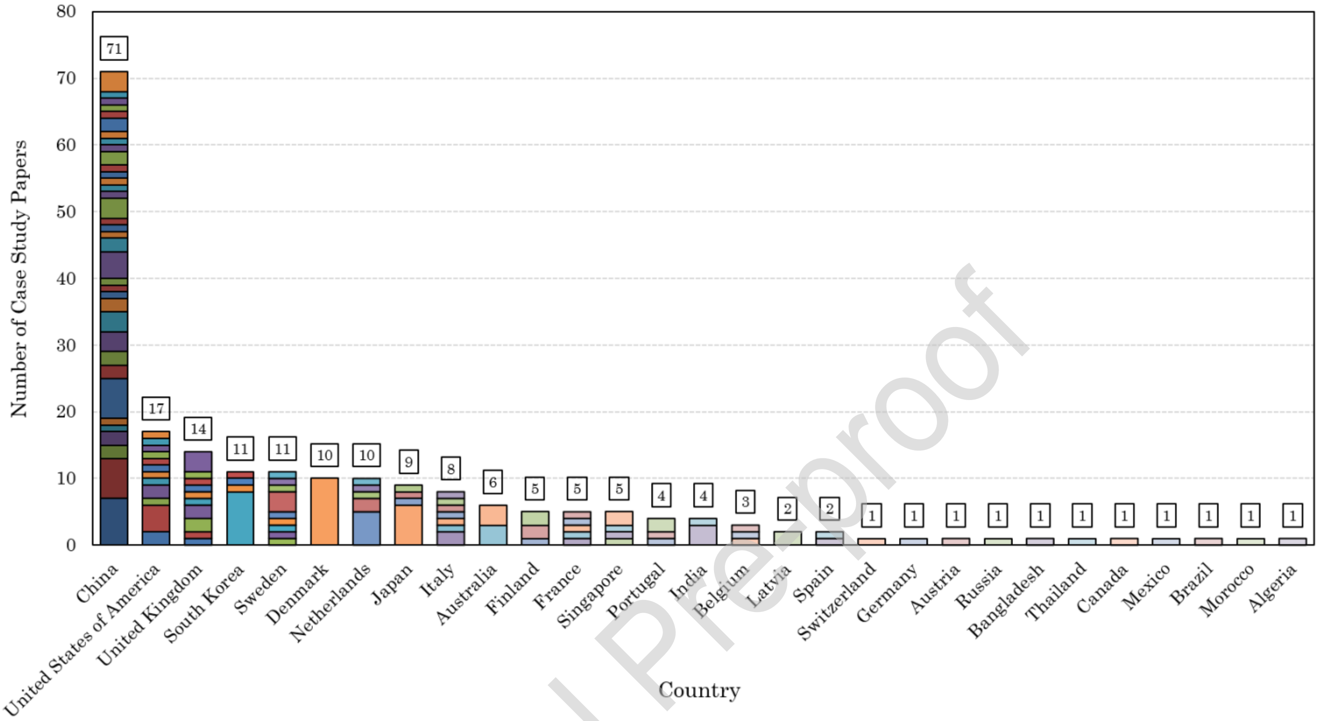


Fig. 8. Distribution of the number of case study publications by country

The area with the largest number of published case studies on industrial symbiosis is Asia with 102 studies corresponding to 49.0% of the total case study, followed by Europe with 78 studies and North America with 19 studies, corresponding to 37.5% and 9.1%, respectively. Oceania, North Africa and South America hold the remaining 4.4% of the total case study.

As shown in Fig. 8, China is the country with the largest number of case studies on industrial symbiosis accounting for 34% of all publications, value much higher than in the other countries and accounting for 70% of the total number of case studies published in Asia. It is also the country with the most cases of industrial symbiosis reported in the literature, with a total of 36. The number of studies on industrial symbiosis in China began to increase from 2014, peaking in 2017, a year in which the maximum value of publications on industrial symbiosis was also verified. The large number of industrial symbiosis and their dispersion across the country is greatly justified by the policies and plans that China has been implementing over the years. As a country with rapid economic growth, this has resulted in increased primary energy consumption, increased resource consumption and increased greenhouse gas emissions such as carbon dioxide, $CO_2$ (Fang et al., 2007; Liu et al., 2017). And since these emissions are much higher than those in other countries and with greenhouse gas emissions limitations set by the international community (Pao and Chen, 2019), China needed to implement policies and measures to counter this increase. Thus, over the years, China has implemented various measures, policies, research incentives, financial incentives, among others, that have been instrumental in the development of industrial symbiosis (Tao et al., 2015; Q. Wang et al., 2017). And although the plans that were established did not have the industrial symbiosis as the main objective, the fact of guiding the various measures for the circular economy and the development of eco-industrial parks, have made industrial symbiosis develop and China has thus played a key role in increasing synergies between enterprises. One of the measures that indirectly promoted the creation and development of industrial symbiosis and considered pioneering to change the paradigm of linear economy for the circular was the creation of a program, the National Pilot Circular Economy Zone Program, launched by the State Environmental Protection Administration in 2001, which considered the circular economy as fundamental to China's development (Mathews and Tan, 2011; Zhang et al., 2010). Another measure that had a major impact on the creation and development of industrial symbiosis was the China National Eco-industrial Park Demonstration Program launched in 2000 by the State Environmental Protection Administration (Shi et al., 2010), which developed the largest national network of eco-industrial parks and whose main objectives were to promote industrial symbiosis among companies, boost environmental management and encourage cleaner industrial practices in industrial parks (Shi et al., 2012; Yu et al., 2015). The number of approved parks has grown exponentially since its implementation. By November 2011, a total of 60 National Trial Eco-Industrials Parks had been evaluated and approved, being distributed in 15 National Demonstration Eco-Industrials Parks and 45 National Trial Eco-Industrials Parks (Shi et al., 2012; Zhang et al., 2010) and by 2017, 108 eco-industrial park projects had been approved by the Ministry of Environmental Protection of People's Republic of China for construction (Liu et al., 2017).

The first industrial park to be considered by the State Environmental Protection Administration of China as a national demonstration eco-industrial park was the Guitang Group, located in Guigang in 2001 (Guo and Hu, 2011; Liu et al., 2017). This group established by the state in the 50's is responsible for one of the largest sugar refineries in the country, and even before it was chosen as a demonstration park, industrial symbiosis was already common practice between the sugar refinery and the surrounding companies (Shi and Chertow, 2017; Zhu et al., 2007). For these reasons, it is not surprising that it is the third case most studied in the literature. In addition to this case, the Tianjin Economic-Technological Development Area in Tianjin was also the subject of these programs, being called as national pilot industrial area for circular economy in 2005 (Yu et al., 2014b) and was one of the first three national demonstration eco-industrial park (Shi et al., 2010; Yu et al., 2015). However, the proposals for industrial symbiosis creation date back to 2002, and in 2008, there were identified 81 symbiotic exchanges between companies located inside and outside Tianjin industrial area (Shi et al., 2010). For these reasons, it is not surprising that this area is the second region of China with more published case studies. The Lubei Group located in Wudi County, Shandong province, is also part of the national demonstration eco-industrial park, having been approved as such in 2003 (Guo and Hu, 2011) and is also one of the regions with the most published case studies.

In addition to these examples, there are others in China that are also included in the examples with the largest number of published case studies on industrial symbiosis, such as the examples of Xinfa Group in Liaocheng (Li et al., 2015; F. Yu et al., 2015a), the industrial city of Liuzhou (Dong et al., 2013b; L. Dong et al., 2014), and the Dalian Economic and Technological Development Area in Dalian (Yu et al., 2015; Zhe et al., 2016).

Apart from China, South Korea also occupies an important place in the number of industrial symbiosis case publications. Of the 11 cases published, 8 concern Ulsan Metropolitan City, which accounts for 73% of the total and among the various case studies analysed, is the second region with the most publications. This position is justified by the strong incentive of the government to conduct measures for the development of industrial symbiosis. These were accomplished through the National Eco-Industrial Park Development Program, designed for 15 years, to be developed in three distinct phases, beginning in 2005 that aimed to transform industrial parks into eco-industrial parks with a strong component in the development of industrial symbiosis (Behera et al., 2012; Park et al., 2008). This program was effectively determinant for the creation and development of industrial symbiosis, with at the end of 2014, 107 symbiosis projects in operation (Park et al., 2019). The industrial complexes of Mipo and Onsan, located in Ulsan, were chosen to be part of this program (Park and Behera, 2015; Park and Won, 2007), and are among the most advanced (Mathews and Tan, 2011), which also justifies the number of case studies in this region. However, even before the implementation of this program, Ulsan was already considered an important focus for Korea's industrial development. It contained in its industrial complex a huge number of companies, some of them of a very significant size, existing even before the program implementation, some already established synergy relations (Mathews and Tan, 2011).

Also in Japan, efforts have been made to reduce and manage waste more efficiently. In addition to the implemented recycling-oriented legislative framework, the Eco-Town program was set up in 1997 to reduce the amount of waste sent to landfills and to revitalize local industries (H. Dong et al., 2014; Van Berkel et al., 2009b). To this end, the government has provided funds to support projects that promote the achievement of these objectives. 26 Eco-Town Plans were approved during the ten years of operation (Chen et al., 2012; Van Berkel et al., 2009b). This program, together with the entry into force of legislation to promote recycling, and the provision of technology resources from the private sector, has enabled the development of industrial symbiosis and interaction between the industrial and urban areas, facilitated by the proximity between these two areas (Chen et al., 2012; Van Berkel et al., 2009b, 2009a).

India, despite showing significant growth in gross domestic product, still has many social problems, with high poverty rates and a very significant portion of the population without access to basic conditions, as well as population growth and rapid urbanization (Falebita and Koul, 2018; Gupta et al., 2019). The various initiatives that have been made to develop industrial symbiosis have proved fruitless, despite being a resource-scarce country (Bain et al., 2010). The lack of economic incentives and tax benefits, the lack of environmental legislation, the lack of financial resources and infrastructure are some of the barriers pointed to the development of circular practices and industrial symbiosis (Singh et al., 2018). However, in order to take advantage of the various resources, some relationships of industrial symbiosis that have emerged among self-organizing companies have been reported, such as the case of the Nanjangud Industrial Area (Bain et al., 2010).

Europe, as mentioned above, ranks second in the areas with more cases studies on industrial symbiosis. The European Union has played a very important role, both politically and practically, in enhancing practices that lead to sustainable development (Szopik-Depczyńska et al., 2017). The concept of circular economy in Europe dates from the 1970s, and since then several countries have adopted the concept (Bassi and Dias, 2019). The application of circular practices has been driven by various measures taken by the European Commission, which have been achieved through the publication of strategic documents, policies and programs with the provision of monetary support (Colombo et al., 2019; Fura et al., 2017; Szopik-Depczyńska et al., 2017). Industrial symbiosis has been mentioned in several communications and in the most recent publication of Directive 2018/851 on waste as important for more efficient use of resources and in which it encourages Member States to take measures to facilitate the application of this practice (European Commission, 2018b, 2015).

However, despite these incentives, the development of industrial symbiosis has proved to be disparate in the various countries of Europe, as a result of their economic development, but also the policies adopted in each country. The countries of North and North-West Europe account for the majority of published studies, corresponding to 72% of the total European studies. Leading the case studies is the United Kingdom with 14 studies, followed by Sweden, Denmark and the Netherlands with 11, 10 and 10 case studies, respectively. Most of these countries in northern and north-western Europe have been precursors in implementing policies that are in line with a more circular economy (Bassi and Dias, 2019), which has facilitated the spread of industrial symbiosis. In addition, existing economic conditions and the resilience to maintain sustainable development patterns even in the face of economic hardship, such as the major economic crisis in 2007-2008, have helped to drive the adoption of more sustainable practices (Domenech et al., 2019; Szopik-Depczyńska et al., 2017). In the United Kingdom, the increase in cases of industrial symbiosis is related to the policies and measures that have been implemented to encourage the development of industrial symbioses. Examples of these measures were the creation of more waste-oriented instruments, such as the Landfill Tax and the Waste Protocols Project, and the voluntary program launched by the United Kingdom government, the National Industrial Symbiosis Programme, to help companies find partners who could use their waste as raw materials, which made synergies between companies grow (Costa et al., 2010; de Abreu and Ceglia, 2018). In addition to this program, there have been others in Europe that have facilitated the development of industrial symbiosis, such as those in Italy, Finland, France, Denmark and Belgium (Domenech et al., 2019).

However, the existence of plans for the occurrence of industrial symbiosis relations is not essential. In many cases these arise spontaneously from a company initiative. The most published case study with 10 references in Kalundborg, Denmark is one such example. This emerged spontaneously in the 1960s between the four major industries and some companies outside the industrial area (Ehrenfeld and Gertler, 1997; Zhang and Chai, 2019). Over time, industrial symbiosis has developed not only to respond to the scarcity of resources, but also because of the economic and environmental benefits obtained by the companies involved in the synergies (Jacobsen, 2006; Valentine, 2016).

Some southern European countries, such as Portugal and Spain, while not having many reported cases of industrial symbiosis, have made an effort to promote more sustainable practices and to adopt programs for the promotion of industrial symbiosis (Costa and Ferrão, 2010; Ferreira et al., 2019). In the case of Portugal, in addition to the legislative amendment to transpose Directive 2008/98/EC on waste, a number of national plans have been established, in which not only the importance of industrial symbiosis is emphasized but also some measures to increase its implementation are defined (Neves et al., 2019b).

Initiatives to promote the creation of eco-industrial parks with the practice of industrial symbiosis in the United States date back to 1994, with funds available for the development of such projects (Chertow, 2000). And while some publications mention the creation of several eco-industrial parks in the United States (Chertow, 2000; Sakr et al., 2011), and that there are cases of industrial symbiosis scattered throughout the country (Chertow, 2000), publications on industrial symbiosis are few in number and most are not very recent. Some reasons have been cited as inhibitors of further development of industrial symbiosis (Neves et al., 2019c). The strong presence and involvement of the government was one of the reasons given for companies' reticence to start eco-industrial park projects (Heeres et al., 2004). Another reason is associated with existing regulations that make it difficult to create the industrial symbiosis relationship, especially the US Resource Conservation and Recovery Act where many wastes are defined as hazardous wastes (Gibbs and Deutz, 2007). The existing industrial symbioses are located in different regions. The largest number of studies were carried out in Barceloneta, Puerto Rico, an unincorporated territory of the United States, where the first industrial symbiosis date back to the end of the 1970s (Ashton, 2011, 2009), being the pharmaceutical companies, present in great number, the great responsible for the development of synergies between the different companies. The regions with the second largest number of case studies are Guayama in Puerto Rico and Honolulu where the existing industrial symbiosis are driven by the coal-fired power plant (Chertow and Miyata, 2010; Chertow and Lombardi, 2005), often considered as anchor tenant insofar as they are crucial for the creation and stimulation of the industrial symbiosis between the various companies.

In the case of Brazil, although the potential for applying industrial symbiosis has been recognized (Ometto et al., 2007; Santos and Magrini, 2018), practices associated with the circular economy and consequently with industrial symbiosis are still poorly developed (Oliveira et al., 2018). In addition, most of the waste produced is disposed of in landfills and although municipalities have high waste management expenditure, there has been no concern from them to correct this and invest in ways to reuse waste (da Silva, 2018).

#### *4.2.2. Type of industries involved in industrial symbiosis*

From the analysis of Table 1 and Table A.1, it is possible to conclude that the types of economic activities present in the industrial symbiosis are very disparate, which illustrates the immense possibilities of this type of practice. However, as shown in Fig. 9, the one which has a markedly higher weight is the manufacture, which according to ISIC is the section which comprises the activities involving the transformation of materials into new products.

It should be noted that Fig. 9 does not reflect the total number of companies involved in the symbiosis, because although the activities are listed in the publications, the number of companies involved and their distribution by type of activity is rarely mentioned. Thus the figure intends to illustrate the type of activities and the frequency with which they appear in the several industrial symbiosis case studies.


Fig. 9 – Number of occurrences of economic activities categories in the various case studies

The high presence of the manufacturing industries is justified by the volume of waste generated during their economic activity, but also by the capacity to absorb wastes and by-products and to incorporate them as raw material in their production processes. Within this section, the activities that are most often present in the industrial symbiosis are the chemical, cement, pulp and paper, and steel and iron industries and refineries. The first four industries are characterized by high energy consumption (Dong et al., 2013a; Man et al., 2018), thus representing great potential for measures to reduce resource consumption. The activities related to waste and water management and recycling also occupy a prominent place in cases of industrial symbiosis not only to establish the link between industries but also as an active part in the chain of transformation of waste into new products. The primary sector, in particular agriculture-related activities, is also often found in case studies, not only those directly related to crops, but also those associated with raising and breeding of animals.

Although the manufacturing section is the predominant one in most countries, as shown in Fig. 10, the weight of each activity varies depending on the case, also reflecting the economic reality characteristic of each country. With the exception of countries with few published case studies in the literature, such as Morocco, Algeria and Mexico, in which all companies belong to the manufacturing section, most countries have industrial symbiosis participants belonging to various types of activities. However, there is no direct relationship between the existence of many case studies in one country and the variety of sections. An example of this is China, which although it is the country with the largest number of cases, is not the one with a wider range of sections. The United States of America and Singapore with 12 and 4 distinct cases of industrial symbiosis, respectively, are those that present a greater diversity of economic activity classes, having participants in the synergies belonging to 9 different sections. It follows China with activities belonging to 7 distinct sections and in Europe with equal numbers, the United Kingdom, the Netherlands and Italy.

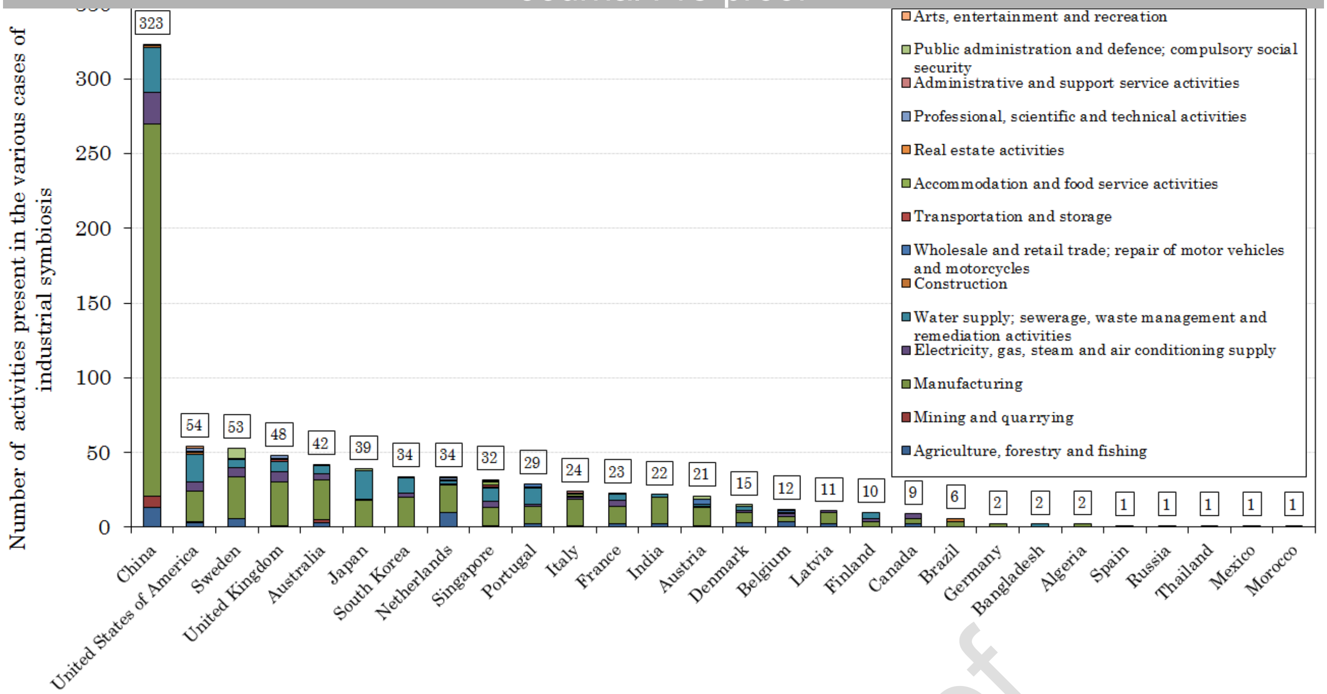


Fig. 10 – Distribution of the categories of economic activities existing in cases of industrial symbiosis by country

The chemical industries are among the most present in the various cases of industrial symbiosis, having played a key role in cases scattered throughout Europe, Asia, Australia and North America. The weight of these in the network of synergies varies greatly depending on the location. For example, in Grangemouth, in the United Kingdom, a region with a strong presence of the chemical and petrochemical industries (Harris and Pritchard, 2004), these have played a key role in boosting and creating industrial symbiosis. In other cases, although they have a less significant presence, they do play an important role in increasing sustainability. Thus, they have contributed to the reduction of wastes, as in the case of Kalundborg where the chemical company started to supply sludge and yeast slurry to farms (Branson, 2016), for the reduction of consumption of resources such as in Finland where chemical companies receive combustion gases and purified water from pulp and paper mill (Pakarinen et al., 2010) and for the substitution of petroleum products with others obtained from waste oils generated by the chemical and petrochemical industries, such as the Ulsan case (Behera et al., 2012).

The cement and steel and iron industries are of great importance in China and have contributed to the country's economic growth, but are both resource intensive and responsible for serious environmental problems such as greenhouse gas emissions (Cao et al., 2017; Gao et al., 2017; Zhu et al., 2019). Thus, it is not surprising that they are the target of many of the measures implemented to meet international requirements for the reduction of gas emissions, such as industrial symbiosis. Thus, by analysing the published case studies, most of the industrial symbiosis where these industries participate are located in China being scattered across several regions (Dong et al., 2018; Shi and Chertow, 2017; Q. Wang et al., 2018a; Wu et al., 2016a). The industrial symbiosis with this type of industries also occurs in other areas; however they have little expression compared with the case studies verified in China. In some parts of Europe, there are some examples where cement industries are part of the synergies, such as Kalundborg in Denmark (Domenech and Davies, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006), Rotterdam in the Netherlands (Baas and Boons, 2007; Baas and Korevaar, 2010b), Taranto in Italy (Notarnicola et al., 2016, 2014), among others. As for the steel and iron industry, it is much more concentrated in China, with fewer examples in other regions. However in Italy (Notarnicola et al., 2016, 2014), Japan (Dong et al., 2013b; Van Berkel et al., 2009a) and South Korea (Behera et al., 2012; Park and Behera, 2015), there are some of these cases.

The predominance of the paper industry in the case studies analysed also occurs in countries in Asia, such as China (Guo et al., 2016; Shi et al., 2010; Q. Wang et al., 2018a, 2018b; F. Yu et al., 2015c; Zhu et al., 2007), Japan (H. Dong et al., 2014; Dong et al., 2013b; Ohnishi et al., 2017; Van Berkel et al., 2009a) and South Korea (Behera et al., 2012; Park and Behera, 2015, 2014; Park et al., 2008), with the highest incidence in China. However, it is in Finland, a country with a long tradition in the pulp and paper industry, that it plays an essential role in the development of industrial symbiosis, around which all synergies with other companies are developed (Pakarinen et al., 2010; Sokka et al., 2011b).

One of the activities with the highest incidence in the case studies of industrial symbiosis are the power plants. Many authors have verified that this type of activity has the capacity to mobilize companies to create industrial symbiosis, functioning as an anchor (Chertow and Miyata, 2010; Korhonen, 2001). This concept, which is not unique to power plants, is referred to as anchor tenant (Chertow, 1998; Lowe, 1997), and has been widely used in the literature on industrial symbiosis, from the 1990s to the present day. It is based on the idea of a company capable of attracting and anchoring a network of companies not only for the supply of materials but also for the reuse of waste (Chertow, 2000, 1998; Lowe, 1997; Yoon and Nadvi, 2018). In the case studies analysed on industrial symbiosis, this concept was applied to different industries. Thus, the anchor tenants considered in the various case studies were a power plant in Honolulu, United States (Chertow and Miyata, 2010), a cement company in Kawasaki in Japan (Hashimoto et al., 2010), mining firms in Gujiao, China (Song et al., 2018), a pulp and paper mill in the region of Kymenlaakso in Finland (Lehtoranta et al., 2011; Pakarinen et al., 2010), and a combined heat and power plant in Händelö, Sweden (Martin and Eklund, 2011). However, in the development of industrial symbiosis, new anchor tenants may emerge, such as Guigang's example in China, in which the sugar manufacturing chain was initially the only driver of industrial symbiosis, and later the pulp and paper and combined heat and power units joined the network also as anchors (Shi and Chertow, 2017).

The diversity of industries in a given region can be seen as facilitating the creation of synergies (Mortensen and Kørnøv, 2019; Yu et al., 2014b). In the case studies analysed, the range of industries is very varied, and the diversity in each case study is very large. Thus, there are examples in which the diversity of industries involved in industrial symbiosis is reduced, such as the Västra Götaland Region of Sweden, where the industrial symbiosis are centred on two industries, beer production and mushroom farming (Patricio et al., 2018) and the case of North Dakota in the United States with the symbiosis between 1st generation bioethanol and combined heat and power plants (Gonela et al., 2015). And on the other hand, we have industrial symbiosis that are developed among a wide variety of industries, such as the example of Liaocheng in China where synergies occur between a wide variety of chemical and material production industries (Han et al., 2017; Li et al., 2015; F. Yu et al., 2015a, 2015b), the case of Kawasaki in Japan where there are symbiosis between the steel and iron, cement and paper industries together with different recycling companies (H. Dong et al., 2014; Hashimoto et al., 2010; Ohnishi et al., 2017; Van Berkel et al., 2009a), and the case of Ulsan in South Korea with synergies among chemical industries, steel industries, paper mill company, waste treatment companies, among others (Behera et al., 2012; Park and Behera, 2015, 2014; Park et al., 2008).

### 4.2.3. *Methods used in the analysis of case studies*

From the analysis of Table 1 and Table A.1, it is possible to verify that the methods used in the analysis of the case studies are very diverse and have been applied with very different objectives, such as quantification of environmental, economic and social impacts, analysis of the stability of the industrial symbiosis network, analysis of barriers to industrial symbiosis, evaluation of operational performance, among others.

#### 4.2.3.1. *Data collection*

The first step in any analysis of a case study is the collection of relevant information and data for further analysis. Thus, various strategies were conducted to achieve this goal, such as interviews (de Abreu and Ceglia, 2018; Morales et al., 2019; Patricio et al., 2018), site visits with investigations, data collection and research (Cerceau et al., 2014; Wu et al., 2018; Yu et al., 2015), questionnaires (Han et al., 2017; Qi and Wang, 2011; Wen and Meng, 2015), and meetings with experts, companies, government departments, and local stakeholders, conducted mostly in an informal way (Branson, 2016; Dong et al., 2018; Liu et al., 2018a). Of all these strategies, the semi-structured interviews were the most used (Hein et al., 2017; Lehtoranta et al., 2011; Velenturf, 2016), since they allow the interviewer to get answers to their questions and to validate their hypotheses, but also to discuss the subject more broadly.

#### 4.2.3.2. *Qualitative analysis*

In many of the case studies analysed, the collection of data and information on industrial symbiosis preceded the application of other methods, such as those used to quantify environmental and economic impacts (Gonela et al., 2015; Guo et al., 2016; L. Liu et al., 2012). However, in some cases, the approach to the case studies was more qualitative and only the methods related to the research and the obtaining of information and data on the industrial symbiosis were used. There are several examples of these case studies in the literature, as shown in Table 1, with very different objectives. One of the most common objectives is the study of industrial symbiosis in order to find the best ways to create and develop synergies between companies and maximize the benefits not only economic but also environmental. Thus the identification of barriers and drivers for the creation and development of synergies (Patricio et al., 2018; Valentine, 2016; Van Beers et al., 2007), the influence of policy instruments (Lehtoranta et al., 2011; Park et al., 2008) and programs (Mirata, 2004) in the development of industrial symbiosis and the development of approaches that would allow the evolution of an industrial symbiosis network (Wolf et al., 2007), are some of these examples. Also the evolution of industrial symbiosis (Mannino et al., 2015; Morales et al., 2019; Paquin and Howard-Grenville, 2012; Taddeo et al., 2017; Van Beers et al., 2007), the identification of future symbiosis (Notarnicola et al., 2016, 2014) and the comparative study between measures implemented in different case studies (Liu et al., 2018a) have been analysed in several publications.

One of the factors that may affect the creation and assessment of industrial symbiosis is the reluctance of some companies to provide quantitative information regarding their production process and waste generated since they are afraid of compromising their confidentiality. Thus, with the objective of overcoming this barrier, several studies have emerged that allow evaluating the industrial symbiosis in a qualitative way. One of these studies defined "exchange quality" evaluated through assessment categories such as geographic proximity, quality of environmental performance and quality of economic performance (Rosa and Beloborodko, 2015).

#### 4.2.3.3. *Environmental, economic and social analysis*

Many of the methods applied in the analysis of the case studies are related to the evaluation of the industrial symbiosis either at the environmental, economic or social level in order to assess the true impact of these practices on the participating companies, the population and the environment. To meet this objective, a number of methods and indicators have been used, some of which have a very broad field of application and not only industrial symbiosis (Eckelman and Chertow, 2013; Fan et al., 2017; L. Liu et al., 2012; Sokka et al., 2011a), while others have been developed specifically to evaluate this practice (Felicio et al., 2016; Rosa and Beloborodko, 2015; Trokanas et al., 2015). The dissemination of the benefits obtained by the industrial symbiosis can serve as a lever for the development of this practice, not only for companies but also for municipalities so that they create plans to encourage the creation and development of synergies. In the case studies analysed, the environmental impact was of all dimensions of sustainability, the most quantified, followed by the economic and social impact. The social dimension is the most difficult to quantify (Valenzuela-Venegas et al., 2016), which justifies being the dimension of sustainability less analysed in case studies of industrial symbiosis.

Several methods and indicators were used to quantify the environmental impact. The most used method was life cycle assessment, which allows quantifying potential environmental impacts throughout the life cycle (Daddi et al., 2017; Martin, 2015; Martin and Harris, 2018). In the various studies where it was used, it was possible to assess the environmental advantages of industrial symbiosis in comparison to non-symbiosis reference scenarios, such as the case centred on a pulp and paper manufacturing in Kymenlaakso, Finland (Sokka et al., 2011b), or the industrial cluster involving 11 companies in Honolulu County, Hawaii (Eckelman and Chertow, 2013) or in comparison with scenarios with various stages of development of industrial symbiosis such as the one performed at the Italian tannery cluster located in Tuscany (Daddi et al., 2017) or the one centred on the biofuel industry in Händelö, Sweden (Martin et al., 2014).

In addition to this method, the emergy analysis method was also used, which allows taking into account the contribution of the natural ecosystem to the development of synergies. There were several case studies where this method was employed (Dong et al., 2018; Fan et al., 2017; Geng et al., 2014). Two of the examples were carried out in Shenyang, China, where it was intended to analyse changes in environmental performance (Dong et al., 2018) and to evaluate the overall performance of industrial symbiosis, proposing various industrial symbiosis emergy indicators, such as absolute emergy savings, relative emergy savings from different resources, and emdollar values of total emergy savings (Geng et al., 2014).

Material flow analysis was also one of the most used methods in the case studies (Bain et al., 2010, 2009; Chance et al., 2018; Dong et al., 2013b; Guo et al., 2016; Hashimoto et al., 2010), with the main objective of analysing flows and stocks of materials, by-products, wastes, and resources. The exergy analysis method was also another of those used in industrial symbiosis cases (Wu et al., 2018, 2016b).

Due to the harmful effects of increasing greenhouse gases, the international community has imposed limitations on emissions of these gases by countries. Thus, many of the papers published on the quantification of environmental benefits of industrial symbiosis have focused on the quantification of greenhouse gas emissions (Cao et al., 2017; L. Dong et al., 2014; Fang et al., 2017; Jacobsen, 2006; Wu et al., 2016b; F. Yu et al., 2015a). China, where this issue is very relevant given the large volume of greenhouse gas emissions (Fang et al., 2007; Liu et al., 2017), has been the subject of several studies in which carbon emissions have been quantified. One of these studies used the methods based on the IPCC 2006 and the Greenhouse Gas Emission Accounting Methods and Reporting Guidelines (Trial) to account for carbon emissions (F. Yu et al., 2015a). Another example was the carbon footprint analysis in Guiyang, China (Fang et al., 2017) and its evolution over the years following the implementation of government programs. For this purpose a hybrid model was used that integrated the input-output approach and process-based inventory analysis. In Kawasaki, Japan, the reduction of carbon dioxide emissions was estimated by calculating annual $CO_2$ emissions, whose value depends on various parameters such as $CO_2$ emissions from the transport of raw materials, industrial and municipal waste to be recycled and to be disposed of, $CO_2$ emissions from cement production and $CO_2$ emissions due to the deposition of waste (Hashimoto et al., 2010).

In some case studies and in order to overcome some limitations inherent in the methods and improve the results obtained, some methods were combined. One of the examples was the study done in Kawasaki, Japan, in which the method for calculating carbon footprint was based on the hybrid model (H. Dong et al., 2014), from which the total lifecycle carbon footprint of an industrial park was calculated from six carbon footprints. Also in Kawasaki, a combination of the methods of material flow analysis, carbon footprint and emergy was used to evaluate the environmental consequences of industrial and urban symbiosis (Ohnishi et al., 2017).

In addition to the methods mentioned, indicators were also used to assess the impacts of industrial symbiosis. In order to evaluate the environmental impacts, the indicators used in the case study analyses were diverse, such as, for example, resource consumption reduction and waste emission reduction (Guo et al., 2016). In addition to these indicators, others have been proposed in the analysis of industrial symbiosis, such as "environmental gains", defined as the consumption or emission that a company can avoid with industrial symbiosis (Dong et al., 2013b), and indicators involving the quantification of energy consumption, exergy consumption and carbon dioxide emissions for the purpose of assessing the overall performance of a steel and iron industry network (Wu et al., 2016b).

Besides the environmental impact assessment, the economic consequences of industrial symbiosis were also evaluated in several case studies (Cao et al., 2017; Chertow and Miyata, 2010; Dong et al., 2013b; Guo et al., 2016; Jacobsen, 2006; Park et al., 2019; Wang et al., 2010), although the number of publications was smaller compared to environmental assessments. These evaluations were conducted in different ways. The use of indicators, such as cost saving of raw material purchase, cost saving of waste disposal, and sales income of waste (Chertow and Miyata, 2010; Guo et al., 2016), the combination of several parameters (reduction of direct costs, real investments and estimated return times) as a way of estimating the economic aspects of industrial symbiosis (Jacobsen, 2006), and the assessment of economic efficiency through the calculation of the gross benefit and dynamic investment payback period (Cao et al., 2017) were some of the forms used in case studies to quantify the economic consequences of industrial symbiosis. In addition to these, indicators have also been proposed in some publications, such as "economic gains", which are expressed in the revenue or costs avoided by a given company due to the reduction of raw materials, reduction of waste generation or the use of these (Dong et al., 2013b).

In the case studies analysed, most environmental and economic evaluations are carried out separately, but in one of the publications an eco-efficiency indicator was established to evaluate the performance of the industrial symbiosis located in Ulsan, South Korea (Park and Behera, 2014), which includes one economic indicator and three environmental indicators. In another publication and with the aim of also evaluating the industrial symbiosis in Ulsan, the environmental, economic and social benefits were estimated by calculating the payback period used to evaluate the economic component, the reduction of greenhouse gas emissions used to assess environmental benefits, and the increased employment and environmental quality as synonymous with social benefits (Park and Behera, 2015).

Another case study that analysed the social and economic component was carried out in the Sotenäs region of Sweden, where quantitative and qualitative/semi-quantitative analyses were carried out to evaluate the social and economic dimensions (Martin and Harris, 2018). In the quantitative analysis, socioeconomic indicators were used, such as job retention or creation, number of new companies, potential revenue of sales of the network, visitors to the region due to the network, and savings on waste disposal transport. In qualitative/semi-quantitative analysis, some of the indicators used were improvement and strengthening of the local skill basis, impact on research and development, impact on sales values, and impact on operational efficiency (Martin and Harris, 2018).

#### *4.2.3.4. Network analysis*

The study of the industrial symbiosis network was also one of the topics most approached in the case studies analysed. This issue is of great importance, mainly because the companies involved in the symbiosis have to create a trustful link, since the operation of companies that receive waste depends in part on the flows of the issuing companies and their supply in sufficient quality and quantity. When there is a failure in this supply, it may compromise the operation of a company or the entire industrial symbiosis network (Chopra and Khanna, 2014; Q. Wang et al., 2018a). On the other hand, it is also important to understand the network structure of industrial symbiosis and how the interaction between the various actors takes place, because it has implications in the results of synergies, both in economic and environmental aspects (Domenech and Davies, 2011, 2009). In this way, by characterizing the network and its interactions, it is also possible to optimize them in order to improve the economic and environmental performance of the entire network. This optimization was done in a case study in Kansas City, Missouri (Cimren et al., 2011), in which using mathematical programming techniques it was possible to determine the ideal network in order to minimize the total cost or environmental impacts. And the optimization that was based on the profit maximization of the system was the one that allowed achieving greater benefits both in the reduction of the total cost, in the reduction of carbon dioxide emissions and reduction in wastes for landfill (Cimren et al., 2011). Knowledge of the network of synergies and their arrangement in the network, that is to say more central or in the periphery, also allows to improve symbiosis relations and to study ways to make it more stable over time (Zhang et al., 2013).

The most used method in the case studies to understand the network of industrial symbiosis was social network analysis (Ashton, 2008; Ashton and Bain, 2012; Domenech and Davies, 2011; Han et al., 2017; Shi and Chertow, 2017; Song et al., 2018; Velenturf, 2016; Zhang et al., 2013), whereby several associated concepts such as density, degree centrality, degree distribution, betweenness centrality, closeness centrality, compactness and degree of connectedness were determined. In addition to the symbiosis network characterization, some case studies analysed the behaviour of this network in the presence of some perturbations. Among them are studies that allowed the study of the resilience (Chopra and Khanna, 2014) and the robustness (Q. Wang et al., 2018a) of the network in the face of disruptive scenarios and the cascade effect that these could provoke. The vulnerability of the industrial symbiosis network was also evaluated based on the automatic control theory, a mathematical analysis method (Q. Wang et al., 2018b) and based on indicators, namely the vulnerability of an industrial symbiosis network and node betweenness (Li et al., 2017). However, the vulnerability of an industrial symbiosis network can also be affected by economic fluctuations. One of the case studies analysed this vulnerability, applying it to a symbiosis industrial coal network (D. Wang et al., 2017), and establishing for this purpose a cascade failure model with a weighted target network and design five network performance indicators.

#### *4.2.3.5. Other methods*

In addition to the methods mentioned in the previous sections, which comprise the most used in the analysis of industrial symbiosis, there are other methods and tools that were used. Among them, a qualitative tool that was proposed and applied to the case study in Gladstone, Australia (Golev et al., 2015), with the aim of analysing the barriers of industrial symbiosis, called industrial symbiosis maturity grid. In Japan, to evaluate the eco-town program, an environmental performance indicator and an operational performance indicator, the operating rate, which relates the amount of wastes treated with the planned ones (Chen et al., 2012) were calculated. Another example was the study carried out in the Suzhou region of China to evaluate the contribution of industrial symbiosis to the development of the circular economy, being used for this study the substance flow analysis with the resource productivity indicator (Wen and Meng, 2015).

### *4.2.4. Industrial and urban symbiosis*

Although the main focus of this review is the industrial part and the synergies that exist between the companies, this cannot be dissociated from the urban part that by proximity is often affected by the negative aspects of industrial zones, such as pollution. However, both the industrial and urban parts share some concerns with regard to sustainability, such as high resource consumption, increased greenhouse gas emissions, increased waste and cost of waste treatment (Dong et al., 2016; Simboli et al., 2017; Lu Sun et al., 2017). Thus, if in addition to the symbiosis between companies, these can be extended to the urban part, this can bring benefits to both parties and there is potential for the mitigation of some of the problems verified in the industrial and urban part. In the last years a number of scientific articles have been published which have focused on the symbiosis between industries and cities (Dong et al., 2017; Kim et al., 2018a; Ohnishi et al., 2017), with a more pronounced growth in recent years.

Some authors have used the term Urban Symbiosis (Ness and Xing, 2017; Van Berkel et al., 2009b, 2009a), referring to the use of waste produced in cities by adjacent industries in their industrial operations, either as an alternative to raw materials or as a source of energy, facilitated by the geographical proximity between them (Van Berkel et al., 2009b). This process differs from recycling, because the companies that receive these wastes are not the usual waste treatment and recycling centres, that is, they are companies that normally would not receive this type of waste nor would use it as raw material in their process productive. The term

Industrial and Urban Symbiosis (also called Urban and Industrial Symbiosis) has also appeared in several publications when the symbiosis comprises the industrial symbiosis and synergies between the industrial and urban zone (Kurdve et al., 2018; Van Berkel et al., 2009b). In other publications, this term has been used when waste generated by the urban area is used by industries as alternative raw materials or source of energy and in turn the industries provide the urban areas with heat wastes resulting from their operation (Dou et al., 2018; Fang et al., 2017).

The performance of the industrial and urban symbiosis has been studied by several authors (Dong et al., 2013b; Ohnishi et al., 2017; Van Berkel et al., 2009a) with the objective of evaluating the real impact of this practice in industry and in the cities and if its application proves to be an effective measure to achieve environmental and economic advantages. From the studies carried out it was possible to conclude that this practice has provided economic benefits (Afshari et al., 2018; Dong et al., 2013b) and environmental benefits such as saving of resources and raw materials (Dong et al., 2013b; Ohnishi et al., 2017), the reduction of carbon dioxide emissions (Dong et al., 2016; Ohnishi et al., 2017), and the reduction of wastes sent to landfills and incineration (Cao et al., 2017; H. Dong et al., 2014; Van Berkel et al., 2009a). And although in some cases the costs of creating symbiosis are high, for example in the exchange of waste heat and energy between industries and communities that requires the construction of necessary infrastructure, and in addition to these costs there is also the uncertainty of supplying these wastes in sufficient quantity and quality to meet the needs of communities, which may lead some industries and the community to retreat, but according to some studies (Afshari et al., 2018; Fang et al., 2017) the final balance is positive, with environmental and economic benefits. Some of the advantages listed are crucial for some countries, such as for China, as allied to highly industrialized areas and industries with high energy consumption and large carbon dioxide emissions, such as the iron and steel industry and the cement industry (Dong et al., 2013a; L. Dong et al., 2014), also has areas with a lot of population (Cao et al., 2017; Dong et al., 2017) which greatly increases the amount of household waste. In this case, the possibility of creating a symbiosis between these industrial sectors and the urban zone can mitigate some of the problems characteristic of highly industrialized and populated areas.

One of the examples of the studies carried out to evaluate the impacts of industrial and urban symbiosis was the case of Guiyang, China, where several synergies were measured. Regarding industrial and urban symbiosis, this was characterized by two types of flows, solid and energy waste. That is, municipal solid waste was used as a source of energy by the steel and iron industry and this provided residual heat to urban areas (Fang et al., 2017). In addition to resource saving, these synergies have led to the reduction of carbon footprint and reduction of urban waste disposal in landfills and incinerators (Fang et al., 2017). Jinan, also located in China, was another example that allowed the achievement of these environmental benefits by the steel and iron industry and adjacent community (Dong et al., 2013b; L. Dong et al., 2014). In this industrial and urban symbiosis, the steel and iron industry received, in its production process, waste steel and waste water from the urban zone and provided surplus steam to the community.

Japan was one of the countries that invested in the creation of industrial symbiosis and industrial and urban symbiosis, creating the Japan's Eco-Town Program applied to 26 cities that were designated as national eco-towns. Initiated in 1997, its main objective was to use industrial, municipal and commercial waste in industrial applications and arose from the need to boost the economy and reduce waste disposal, since the area available for this purpose was reduced to the amount of waste deposited at the launch of this program (Van Berkel et al., 2009b). One of the cities included in this program was Kawasaki City, whose formal approval of Eco-Town Status occurred at the launch of the program in 1997, being one of the first four cities to be approved with this statute (Van Berkel et al., 2009b, 2009a). With the participation of nine companies, municipal waste collection and wastewater treatment centers and a group of industrial and commercial waste management companies, it was possible to conduct wastes generated by communities and industries to be incorporated into productive processes of various industries, used either as alternative fuels or as alternatives to raw materials, removing a considerable amount of waste from refuse and incineration (H. Dong et al., 2014; Dong et al., 2013b; Van Berkel et al., 2009a). In addition to this environmental advantage, others were obtained due to these synergies, such as saving resources and raw materials, reducing carbon emissions, and economic gains (H. Dong et al., 2014; Dong et al., 2013b; Ohnishi et al., 2017).

Although much of these examples are more recent, industrial and urban symbiosis has been taking place for a number of years. An example is the municipality of Köping, Sweden, where the symbiosis network dates back to the 1980s, where excess heat produced by local industries was used for district heating, and this power grid has recently been extended to three municipalities in the Västra Mälardalen region (Kurdve et al., 2018).

In addition to the existing examples, there is great potential for the growth of these symbiosis, and many studies have been published with the aim of assessing the feasibility and the impact that new industrial and urban symbiosis have in the industries and communities. One of the examples was the assessment of the environmental impacts that the expansion of industrial and urban symbiosis would have in Liuzhou, China (Dong et al., 2017; Lu Sun et al., 2017). With this study, as in the case of existing symbiosis, it was possible to conclude that the new synergies would enable reductions in carbon dioxide emissions, consumption of raw materials and waste disposal. Another of the examples was the study carried out in Ulsan, South Korea, to evaluate the environmental and economic benefits that could be obtained through industrial and urban symbiosis based on the demand and supply of high and low-grade waste heat by the industrial area and/or urban area (Kim et al., 2018a).

## 5. Discussion

Through an extensive review of the existing literature on industrial symbiosis, this article aimed to reach two main objectives, to trace the tendency of the evolution of the publications about this practice and to map the case studies characterizing them as to the main activities involved in the symbiosis and methods used in the analyses. Based on the research and selection of publications, it was possible to verify the growing importance of this theme, due to its contribution to increasing sustainability in its three dimensions, environmental, economic and social, bringing innumerable advantages to companies and communities, such as reduction of the consumption of raw materials, energy and natural resources, reduction of greenhouse gas emissions, reduction of waste sent to landfills and incinerators, reduction of costs with the purchase of raw materials, reduction of landfill costs and treatment of waste, revenue from the sale of waste and creation of jobs. These results can be interpreted as opportunities for decision-makers in companies and governments to continue their efforts to create and develop industrial symbiosis. From the analysis to the various cases of industrial symbiosis reported in the literature, it was possible to conclude that the drivers for the development and creation of synergies can be several, as illustrated by some concrete examples in Table 2. The economic motives are the most frequent ones in the initiatives taken by the companies for the creation of industrial symbiosis relations. Whether on its own initiative or through associations organized by companies that support the search for partners for synergy networks, the reasons why companies are driven to achieve symbiosis relationships are economic profits or increased competitiveness or on the other hand they are intended to avoid costs with taxes or waste treatment and disposal. Environmental and social reasons are most often found as driving the action of governments to promote industrial symbiosis. Reducing waste, reducing greenhouse gas emissions and increasing job creation are some of the reasons why governments have created plans and measures to encourage the creation and development of synergies and to apply additional taxes to penalize companies that do not implement sustainability measures and to dissuade them from sending waste to landfills and incinerators.

**Table 2**
Needs that triggered the creation of industrial symbiosis and how they were materialized

| Region / Needs that triggered industrial symbiosis | How was materialized | References |
|---|---|---|
| Västra Götaland, Sweden<br>- Increase economic gains<br>- Creation of new business opportunity<br>- Improve environmental performance<br>- Avoid/reduce disposal costs<br>- Reduce cost for virgin material<br>- Marketing reasons | The industrial symbiosis was initiated by several micro, small and medium enterprises dedicated to the mushrooms production and beer production, which without the help of external institutions, sought the potential users of their residues. In the case of mushroom production the main by-products were used as fertilizers by the producers or local farmers. In brewing, the spent grains were used by animal breeders and the waste yeast is used as horse feed | (Patricio et al., 2018) |
| Kalundborg, Denmark<br>- Saving water resources due to the region's large groundwater deficit | Since the 1960s several industrial symbiosis projects involving cooperation between the various water consuming industries have been developed. The strategies have been to replace groundwater by surface water in the most water-consuming industries, to diversify external water sources and reduce internal water consumption in industries and to improve surface water to drinking water quality and to import groundwater from adjacent regions to the Kalundborg region | (Domenech and Davies, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006) |
| Kuusankoski, Finland<br>- Increase economic growth<br>- Increase production so as to respond to export growth, driven by increased demand for paper, which began in 1874 | Between 1872 and 1913 the symbiosis began to be developed between hydropower plant, forest ecosystem and pulp and paper mill, with linear flows of material and energy. Subsequently the symbiosis expanded, the numbers of participants increased and have developed an industrial symbiosis composed of power plants, chemical manufacturing plants, waste management facilities and sewage treatment plants operate around a pulp and paper mill, considered as an anchor tenant | (Pakarinen et al., 2010) |
| Grangemouth, United Kingdom<br>- Improving the competitiveness of the local chemical industry<br>- Creating further jobs<br>- Reduction of waste volumes<br>- Increased sustainability due to public and community pressure | Company attraction for the region, by the organization that exists in the region formed by major companies at Grangemouth, the Local Enterprise Council, Forth Ports, and Falkirk District Council, offering for this brownfield sites, which have water, electricity and steam utilities, waste management, storage and emergency services, and employee training centre for sustainability | (Harris and Pritchard, 2004) |
| Dunkirk, France<br>- Mitigate the negative effects of industrialization, especially air pollution<br>- Improvement of the quality of life | A shared territorial action plan which promoted the implementation of industrial symbiosis | (Morales and Diemer, 2019) |
| South of the Netherlands<br>- Create space for new greenhouses<br>- Creation of a cluster that | The industrial symbiosis was initiated by the local government, represented by a coalition between the Local Province, Local Municipality and the Local Port Authority. Subsequently joined an existing large industrial company in the zone to create a small | (Baldassarre et al., 2019) |

| | | |
|---|---|---|
| would contribute to the sustainable development of the region by creating new jobs and by reducing emissions and local waterways | company to manage the cluster of industrial symbiosis. It operates the infrastructure that collects and distributes waste heat and CO2 from the industrial company to greenhouse farming in nearby areas | |
| Kawasaki, Japan<br>- Need to boost economy and revitalize local industries<br>- Reducing waste deposition, since the area available for this purpose was reduced to the amount of waste deposited | Through a national initiative, inaugurated in 1997, the Japan's Eco-Town Program was created and applied to 26 cities that were designated as national eco-towns, where the creation of industrial symbiosis and industrial and urban symbiosis was promoted. Kawasaki was one of the first cities included in this program. With the participation of nine companies, municipal waste collection and wastewater treatment centres and a group of industrial and commercial waste management companies, it was possible to conduct wastes generated by communities and industries to be incorporated into productive processes of various industries, used as alternative fuels or as alternatives to raw materials, removing a considerable amount of waste from landfill and incineration. | (H. Dong et al., 2014; Van Berkel et al., 2009b, 2009a) |

Whether in creating synergies or in its operation or expansion, a number of challenges are put to companies so that the industrial symbiosis develops successfully and provides benefits to all parties. When creating new symbiosis, companies have to develop a trust bond so that the supply of waste and resources is assured in sufficient quantity and quality for the operation of the receiving companies. Often this confidence is facilitated by the closeness of companies, as happened in Kalundborg (Domenech and Davies, 2011). However, the challenge for companies increases substantially when symbiosis involves the sharing of utilities, such as water and heat, in which, in addition to the large initial investment in infrastructures, the risk of supply variability is greater in these cases with a greater impact on the functioning of companies, so it is not surprising that from the case studies analysed the sharing of waste is more frequent than the sharing of utilities. Furthermore, the way the symbiosis network is built can also cause some problems for companies, especially if there is a failure of a supply. And this impact is greater the more central, with greater responsibility for the synergies and with greater number of connections is the company in which the failure occurs, as was studied for Kalundborg (Chopra and Khanna, 2014) and Guigang (Q. Wang et al., 2018a). For these cases, and in order to minimize the impact of these failures, the introduction of new symbiosis may prove to be an excellent opportunity to increase the economic benefits and reduce the vulnerability of the symbiosis network. For example, through the study of the evolution of the network of industrial symbiosis in Kalundborg, it was concluded that the increase of synergies by different industries with similar exchanges had allowed the reduction of vulnerability of the network, since if any node were removed, the network had the capacity to adapt since there were alternatives to this synergy (Chopra and Khanna, 2014). The inclusion of a company and the synergies developed between it and non-core nodes proved to be fundamental to increase the robustness of an existing industrial symbiosis network in Guigang, China, since it allowed to reduce dependence on the network and to reduce the possibility of collapse if the company considered nuclear failed (Q. Wang et al., 2018a).

The case studies on industrial symbiosis represent a considerable part of the publications on this subject, revealing the pertinence of this type of article to the knowledge of industrial symbiosis, not only to validate proposed methods and frameworks, but also to be analysed and serve to elucidate and draw lessons for future improvements. The review of publications on industrial symbiosis showed the huge diversity of case studies, in terms of location, industries involved in the synergies, and in the methods employed. From the analysis done to the case studies, it was possible to conclude that there are cases spread all over the world, with China having the highest incidence of studies on industrial symbiosis, justified by the growing concern about the reduction of greenhouse gases, due to the strong presence of industries characterized by high energy consumption and large carbon dioxide emissions and due to the limitations of emissions set by the international community. And while there is a greater tradition of implementing sustainability promotion measures in Europe, China has made an effort to contain greenhouse gas emissions by implementing a number of policies and programs that curb the negative effects of rapid industrialization and urbanization that have occurred in recent years. In addition, China being a developing economy country, presents a lower economic and social level, and it is therefore imperative to become more efficient, which has resulted in several programs to accelerate growth and to use resources efficiently, such as those to stimulate the circular economy and consequently industrial symbiosis. Although China, Brazil, India and South Africa are all developing countries, the number of industrial symbiosis in China is undoubtedly higher than in other countries. How countries are organized can contribute to this difference, while China has a more centralized planning, the other countries present more heterogeneous, disorganized and more unstable social scenarios.

As for the type of industry, it is concluded that the chemical industry, cement industry, paper industry, steel and iron industry, power plant, and refineries are those that appear most frequently in industrial symbiosis. The fact that the refineries, iron and steel, pulp and paper, and chemicals industries are most involved in industrial symbiosis can be explained by the high overall industrial final energy consumption of these industries, as well as being responsible for a large proportion of carbon dioxide emissions (Napp et al., 2014), which encourages measures to make them more efficient and to reduce the negative effects of the process.

The study by Jensen (2016) and more recently the study by Domenech et al. (2019) have revealed that the diversity of industries is a crucial factor in the development of industrial symbiosis. However, in addition to cases where there is great diversity, for example in Landskrona, Sweden (Mirata and Emtairah, 2005) and Kwinana in Australia (Van Beers et al., 2007), symbiosis has also been found in many places where diversity is reduced, for example in Västra Götaland in Sweden (Patricio et al., 2018) and North Dakota in the United States (Gonela et al., 2015). It was also concluded that the predominance of a particular type of industry could enhance the initiation of synergies, for example the pulp and paper industry in Kymenlaakso in Finland (Sokka et al., 2011b) and the chemical and petrochemical industries in Grangemouth, in the United Kingdom (Harris and Pritchard, 2004).

The methods used to quantify the impacts of industrial symbiosis were the most widely used and were very diverse, being the life cycle assessment the most used in these assessments, and the environmental dimension was the most analysed, followed by the economic one. The predominance of environmental impact assessment can be explained by growing concerns about climate change, the urgency of reducing greenhouse gas emissions, the need to conserve natural resources and the consequent increase in environmental policies that have been applied. Interest in the assessment of economic impacts can be justified by the fact that companies are often driven to create synergies because of the economic benefits they can derive from them and are therefore an important impact to be assessed.

This literature review presents some limitations, associated with the methodology used for the research of publications. By limiting the search to articles written solely in English, some relevant publications may have been omitted. Another limitation relates to the data source used, that is, only research articles, conference articles, book chapters and editorials obtained through publishers have been used, however there must be more cases of industrial symbiosis scattered around the world that are not reported in this manner such as reports or public documents. Subsequently a more extensive research, such as an online survey or research with facilitators of industrial symbiosis could have provided more case studies.

## 6. Conclusions

Finding solutions that limit resource consumption and greenhouse gas emissions is essential to ensure sustainable economic growth. Industrial symbiosis has proved to be a strong ally for the achievement of environmental, economic and social objectives, evidenced by the growing number of publications on this subject, especially since 2007. From the analysis of the 584 published articles, it was possible to conclude that most of them were concerned with the analysis of industrial symbiosis case studies, whether were already implemented or with potential to be developed. Thus, one of the objectives of this extended review of industrial symbiosis was to map the existing case studies, with analysis of the location, type of activity and methods used in the analyses, in order to serve as a guide to foster new symbiosis opportunities. In Europe and Asia, notably China, it was where there was a higher prevalence of industrial symbiosis, justified by the implementation of public policies. However, in North America, Oceania, North Africa and South America it was possible to find cases of symbiosis. The manufacturing sector was the one that presented the highest prevalence in the industrial symbiosis relations, due to the wastes generated but also in the capacity of integrating wastes and by-products into the production cycle. Within this section, the chemical, cement, paper and steel and iron industries and the refineries are the most present. Power plants and waste and wastewater companies were also part of a large number of industrial symbiosis cases. Although the diversity of economic activities does not cease in these statements, there are many more present in the various cases. However, there was no direct link between the existence of many case studies in one country and the variety of sections of economic activity.

The review also emphasized that the methods used to quantify the impacts and to analyse the network of industrial symbiosis were the most used in the analysis of the case studies. The methods used to quantify the impacts of industrial symbiosis were very diverse, being the life cycle assessment the most used in these assessments, and the environmental dimension was the most analysed, followed by the economic one. Another of the conclusions drawn from the analysis of the case studies concerns the growth of studies conducted on industrial and urban symbiosis. Although some synergies between industries and cities date back to the 1980s, it has only been in recent years that the number of publications has expanded further. However, this type of synergy has great potential for growth, because with urban development, populations are closer to industrial areas and need to increase sustainability due to high energy consumption and waste production with significant increases in landfills and incinerators.

As previously mentioned, knowledge of the existing cases of industrial symbiosis can foster new synergies through relationship mimicking, that is, knowledge of success cases can lead to similar organizations applying the same concept. Although this article has contributed to an increase in the knowledge of existing cases in the world by compiling into one single publication the various published case studies, it does have some limitations, as stated in the previous section. Thus, one of the recommendations for future work would be to provide greater knowledge of existing cases. For this purpose, it would be important to use other types of sources, not only scientific publications in order to collect more information about cases of industrial symbiosis. In this sense, online research and research with local authorities, industrial associations, and associations that coordinate industrial symbiosis could provide a better understanding of existing cases.

Although the industrial symbiosis is spread all over the world, in some regions the number of cases reported in the publications is very small, for example in Canada, Mexico, Brazil, among others. Thus, future research could deepen the knowledge about the industrial symbiosis in these places. On the one hand investigate whether there are more cases of symbiosis, and on the other hand evaluate the potential of new synergies, i.e. to assess local reality in terms of existing industries, legislation, and other constraints, and to study the best ways of disseminating these practices in those locations. Future research is also needed to make a greater comparison of case studies in different countries with industrial symbiosis with different levels of development, in order to draw conclusions about the reasons for this development and the surrounding reality of each one and how this translates into drivers and barriers to development.

The case studies reported in literature, whether confined to a small number of stakeholders or those involving hundreds of entities, are mostly success stories. These can, therefore, be translated into a greater or lesser benefit for the environmental and economic results having a variable impact on the companies involved. However, even though these studies are essential for assessing the impact of industrial symbiosis and for collecting very important lessons in order to foster new synergies and develop existing ones, the lessons that can be drawn from failed cases are equally important. Understanding if there were external constraints, such as the economic situation of the region or country where the industrial symbiosis develops or if the failure was in the network itself and to understand the reasons for this failure, can be a very valuable source of information to better understand symbiosis and eventually prevent similar situations in other networks. Thus, there is a great potential for research in this field, and although a study has been carried out to analyse the reasons that led to the decline of symbiosis in Porto Marghera, Italy (Mannino et al., 2015), this is still insufficient.

The expansion of industrial symbiosis to the surrounding communities has also revealed a strong ally for the reduction of carbon dioxide emissions and the amount of waste sent to landfills and incinerators. However, the published studies are still small in view of the great potential of these synergies. Thus, future research on industrial and urban symbiosis is essential, not only to quantify the impacts and improve existing synergies, but also to foster the creation of new symbioses. Thus, the economic viability of the construction of structures for the industry to supply the urban part of residual heat or studies to evaluate the integration of urban waste in the productive process of several industries, are some of these examples.

Contrary to environmental and economic indicators, social indicators are translated by some subjectivity and complexity, and data for their quantification are more difficult to obtain (Hutchins et al., 2019; Ibáñez-Forés et al., 2019; Kühnen and Hahn, 2018). Moreover, another barrier that can be placed in determining the social impact of industrial symbiosis is to dissociate the effects of this practice with other measures that may be taken in the community and also increase the social benefit. As for example the improvement of the quality of the air can be boosted by the industrial symbiosis but also could have occurred other measures that have contributed to this improvement. Thus, it is not surprising that in the case studies analysed, the social component is the least studied. However, this component may be very important for the development of industrial symbiosis, since if the surrounding community and regional governments are aware of the advantages of these synergies, they can become active agents in the development of industrial symbiosis. Thus, future research is needed to study the impacts on society derived from this practice. For example, quality of life, translated by better social and economic conditions, spending on health, employment and income, improvement of roads and accesses can be developed to assess the impacts of industrial symbiosis in the surrounding communities. In addition, research should also focus on ways to measure them and how to decouple the effects of industrial symbiosis from other measures that are taken to increase sustainability and it would also be important to assess which factors are most valued by the surrounding populations.

Another future active area of research would be the development of indicators or methods, aimed at industrial symbiosis, which would allow quantifying the impacts of the three dimensions of sustainability, environmental, economic and social. Although there are several studies that have encompassed these three dimensions, they are not aimed at industrial symbiosis. In addition, encompassing the environmental, economic and social components has entailed some difficulties, such as the integration of qualitative and quantitative indicators in the same evaluation framework (Schoubroeck et al., 2018), the possibility of considering several objective functions simultaneously in the optimization studies (Boix et al., 2015), and the difficulty of integrating the social component with the other dimensions, since it is more related to the practices of an organization and not to the unit processes (Petit et al., 2018). Thus, future research would be necessary to overcome these barriers and to define a specific indicator for industrial symbiosis that would allow to quantify the total impact of this practice on companies, the environment and society and that allows the comparison of industrial symbiosis in different realities, that is, different characteristics of the network and taking into account the particularities of the region where it develops. Future research is also need to develop the integration of these indicators or methods with decision-making methods in order to serve as a tool in the final decision-making process.

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## Appendix A

**Table A.1**
Industrial Symbiosis Application and Analysis Studies

| Country | Region | N. of Enterprises | Activity | Method | Publication Year | Reference |
|---|---|---|---|---|---|---|
| **Europe** | | | | | | |
| Denmark | Kalundborg | | Coal-fired power plant, oil refinery, maker of pharmaceuticals and enzymes, plasterboard manufacturer, district heating, fish farms, neighbouring farms, and cement and road aggregate producers | Evolution and interdependencies analysis | 1997 | (Ehrenfeld and Gertler, 1997) |
| Denmark | Kalundborg | | Power plant, oil refinery, biotech and pharmaceutical company, producer of plasterboard, soil remediation company, fish farm, public wastewater treatment, fertilizer company, municipality, farmers, and cement industry | Qualitative key-informant interviews, environmental effects analysis, cogeneration effect, net reduction of emissions, and economic benefits estimation | 2006 | (Jacobsen, 2006) |
| Denmark | Kalundborg | | Power station, two major chemical companies, plaster board manufacturer, soil remediation company, refinery, the municipality, farmers, fishing factory, cement companies, and some material recycling companies | Site-visit, face-to-face interviews, and short communications. Social Network Analysis | 2011 | (Domenech and Davies, 2011) |
| Denmark | Kalundborg | | Liquid fertilizer, refinery, fish farm, power plant, gypsum board plant, cement plant, biopharmaceutical plant, Kalundborg City, recovered nickel and vanadium, farm, and specialist in remediation of soil contaminated | Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| Denmark | Kalundborg | 6 | Power plants, oil refinery, pharmaceutical company, the district municipality, and fish farm | Network analysis; network metrics: degree centrality, betweenness centrality, stress centrality and network efficiency; hypothetical disruptive scenarios; cascading effects; social network analysis and visualization software | 2014 | (Chopra and Khanna, 2014) |
| Denmark | Kalundborg | | Power station, two major chemical companies, plasterboard manufacturer, soil remediation company, refinery, municipality, farmers, fishing | On-site visits, interviews and meetings with experts | 2016 | (Branson, 2016) |

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| | | | factory, waste water treatment, cement company, and some material recycling companies | | | |
| Denmark | Kalundborg | | Insulin production, enzymes production, oil refinery, coal-fired power plant, wallboard manufacture, biofuel producer, Kalundborg's municipal waterworks, soil remediation and recovery company, fertilizer industry, waste management company, cement industry, wastewater treatment, nickel industry, purification plant, farms, fish farms, and pig farms | On-site visits, interviews, and follow-up enquiries | 2016 | (Valentine, 2016) |
| Denmark | Kalundborg | | Refinery, power plant, biotech and pharmaceutical company, producer of plasterboards, biotechnology company, soil remediation and recovery company, waste treatment company, fertilizer industry, cement industry, fish farms, farms and Kalundborg municipality | Questionnaire for experts, input-output inoperability model, Fuzzy approach, dependency index, and influence gain index | 2017 | (Kuznetsova et al., 2017) |
| Denmark | Kalundborg | 18 | Biomass refinery, refinery, fertilizer industry, plasterboards manufacturer, waste management company, energy company, farms, fish farms, cement industry, nickel-vanadium industry, pig farms, pharmaceutical and biotechnology company, fresh water provider, district heating distribution and wastewater treatment company, purification plant, and wastewater treatment company | Social network analysis. Densities. Centrality indicators: degree and relative degree centrality, betweenness and relative betweenness centrality, and closeness and relative closeness centrality. Centralization measures: degree, betweenness, and closeness centralization. Small-world and scale-free effects: average clustering coefficient, average path length, and power law distribution of degree. Stability analysis: network fragmentation degree. Comparative analysis | 2019 | (Zhang and Chai, 2019) |
| United Kingdom | Grangemouth | | Biotechnology company, active ingredient manufacture, refinery, gas supplier, water effluent treatment, de-watering/drying company, combined heat and power plant, petrochemical company, plastics and rubber industry, chemical industry, and plastics-chemical industry | Technology transfer model adapted with the idea of industrial ecology as a learning process | 2004 | (Harris and Pritchard, 2004) |
| United Kingdom | Forth Valley | | Energy company, refinery, chemical industry, paper mill, oil and gas company, cement manufacturer, and waste processor | Technology transfer model adapted with the idea of industrial ecology as a learning process | 2004 | (Harris and Pritchard, 2004) |
| United Kingdom | Humber | | Bioenergy sector: fuel producer, energy intensive company, farmers, specialist recycler, and steam | Semi-structured interviews and Social network analysis | 2016 | (Velenturf, 2016) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | producer | | | |
| United Kingdom | Humber | | Bio-Diesel production, plaster board manufacturer, chemical industry, refineries, water treatment chemicals, food and fish processing, wastewater treatment, local farms, pet food, and furniture production | Direct observations, and in-person and telephone interviews | 2004 | (Mirata, 2004) |
| | West Midlands | | Local food processors and restaurants, bio-fuel production, automotive industry, and horticultural research institute | | | |
| United Kingdom | West Midlands | 167 | | In-depth interviews, informal conversations, and observations in field | 2012 | (Paquin and Howard-Grenville, 2012) |
| United Kingdom | England/ Scotland/ Wales | | | Geographic Information Systems software package | 2011 | (Jensen et al., 2011) |
| United Kingdom | Bristol | | Port-based industrial complexes | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| United Kingdom | Wissington | | Sugar factory, liquefaction facility, bio refinery and an animal feed production facility | Semi structured interviews | 2014 | (Short et al., 2014) |
| United Kingdom | | | Distributor of timber and building materials to trade | Face-to-face interviews with open-ended questions | 2015 | (Leigh and Li, 2015) |
| United Kingdom | | | Dairy, anaerobic digestion plant, consulting firm for food and agriculture, waste, water and energy management services company, and automotive and aerospace components industry | Semi-structured interviews | 2018 | (de Abreu and Ceglia, 2018) |
| Sweden | Landskrona | >20 | Chemicals, waste management, metals processing and recycling, various types of printing and printed packaging, motor vehicle components, agricultural seeds, transport and logistics companies and public organisations | Interviews | 2005 | (Mirata and Emtairah, 2005) |
| Sweden | Southern Sweden | | Sawmill, paper processing industries, paper mill, and energy service company | Interviews | 2007 | (Wolf et al., 2007) |
| Sweden | Sundsvall-Timrå | | Two sawmills, paper mill, pulp mill, two integrated pulp and paper mills and the municipalities of Sundsvall, Timrå, Härnösand and Bollstabruk | On-site observation and open-ended interviews | 2007 | (Wolf and Petersson, 2007) |
| | Mönsterås | | Chemical pulp mill, sawmill, pellet production facility and the municipality of Mönsterås | | | |

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| Sweden | Östergötland | | Forest industry, pulp mill, pellet production plant, slaughterhouse, biogas production facility, renewable energy companies, combined heat and power plant, and ethanol plant | Planned and unplanned IS activities analysis | 2011 | (Baas, 2011) |
| Sweden | Händelö | | Energy, recycling, forestry and biofuel production plants | Visits, interviews and material and energy flows | 2011 | (Martin and Eklund, 2011) |
| Sweden | Händelö | | Integrated ethanol and biogas plants, combined heat and power plant, forestry, municipality, and regional farmers | Direct inquiry to the companies, life cycle assessment, EPD 2008 method, energy allocation method and system expansion method | 2014 | (Martin et al., 2014) |
| Sweden | Händelö | 3 | Combined heat and power, ethanol and biogas plants | Life cycle assessment, EPD 2008 method, energy allocation method, system expansion method and the 50/50 method | 2015 | (Martin, 2015) |
| Sweden | Västra Götaland | 4 (mushroom) 7 (beer) | Mushroom and beer production | On-site visits and semi-structured interviews | 2018 | (Patricio et al., 2018) |
| Sweden | Stenungsund | | Chemical industry cluster: industrial and specialty gas products and services; paints and coatings; polyolefins, base chemicals and fertilizers production; chemical; and specialty chemicals products companies | Life cycle assessment and CML 2001 method. Cost-effectiveness analysis: Indicator: ratio between investment cost and reduced global warming potential | 2018 | (Røyne et al., 2018) |
| Sweden | Sotenäs | 10 | Fish/food industry, algae production, salmon farming, waste treatment and energy and plastic recycling | Interviews, consultation with key experts, life cycle assessment and socio-economic assessments | 2018 | (Martin and Harris, 2018) |
| Netherlands | Rotterdam | | Air supplier; organic chemical, inorganic chemical, aluminium-processing, cement, chemical and metal-working companies, and residential areas | Role of organizations in the cluster based on Sustainability capabilities | 2007 | (Baas and Boons, 2007) |
| Netherlands | Rotterdam | | Refinery, greenhouse companies, residential area, port, and shrimp farm | Analysis of the synergistic role of embeddedness and capabilities in industrial symbiosis | 2008 | (Baas and Huisingh, 2008) |
| Netherlands | Rotterdam | | Air supplier, organic chemical company, inorganic chemical company, aluminium-processing company, cement company, residential areas, greenhouse horticulture, port authority, and shrimp farm | Historical background and development analysis | 2010 | (Baas and Korevaar, 2010a) |
| Netherlands | Rotterdam | | Refineries, city, greenhouse companies, chemical company, truck cleaning company, and power plant | Planned and unplanned IS activities analysis | 2011 | (Baas, 2011) |
| Netherlands | Rotterdam | | Port and city | On-site visits, and individual or collective | 2014 | (Cerceau et |

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| | | | | interviews performed on site | | al., 2014) |
| Netherlands | Canal Zone of Zeeland | | Four greenhouses; alcohol factory; fertilizer, agricultural, waste processing, and chemical companies | Interviews and event sequence analysis | 2013 | (Spekkink, 2013) |
| Netherlands | Canal Zone of Zeeland | | Agricultural industry, process industry, greenhouses, regional port authority, and chemical company | Event sequence analysis | 2014 | (Boons et al., 2014) |
| Netherlands | Zeeland | | Agricultural and horticultural greenhouse complex and fertilizer plant | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| Netherlands | Sloe Area and Canal Zone | | Food industry, greenhouse horticulture zone, alcohol factory, fertilizer industry, and waste processing | Interviews and event sequence analysis | 2015 | (Spekkink, 2015) |
| Netherlands | South of the Netherlands | | Industrial company, greenhouse farming, local government (Local province/Local Municipality/Local Port Authority) and management company | Interviews with the operating and financial managers, brainstorming sessions with academic experts, comparative analysis, visual analysis and strategic design co-creation workshop | 2019 | (Baldassarre et al., 2019) |
| France | Mèze | | Sewage treatment plant, and marine micro-algae production | In-depth, semi-structured interviews, and on-site visits | 2007 | (Gibbs and Deutz, 2007) |
| France | Marseille-Fos | | Energy intensive companies and liquefied natural gas terminal | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| France | Bazancourt-Pomacle | | Sugar factory, starch and glucose processing plant, producer of molecules for cosmetic use, producer of plant-sourced succinic acid, bioethanol producer, and recovery and processing plant for $CO_2$ | Interviews | 2015 | (Schieb et al., 2015) |
| France | Dunkirk | 14 | Steel industry, power plant, central heat power plant, cement grinding centre, cement factory, cement subsidiary, steel slag treatment company, agricultural market, brick manufacturer, construction company, crude still mill production and dust recycling company | Interviews conducted with expert analysts and researchers, site visits and collaborations with local organizations. Geographical system dynamics method. Causal Loop Diagrams | 2019 | (Morales and Diemer, 2019) |
| France | | | Waste incinerator steam network symbiosis and local companies | Semi-structured interviews, site visits, and qualitative and quantitative model of the stakeholder value network approach | 2017 | (Hein et al., 2017) |
| Russia | Kola Peninsula | 9 | Mining industry | Stakeholder interviews, counterfactual method, eco-efficiency indicators based on input-output analyses, and material flow analysis | 2007 | (Salmi, 2007) |
| Finland | Kuusankoski | | Pulp and paper mill, three chemical plants (chlorine dioxide, hydrogen peroxide and calcium carbonate | Quantifiable indicators for each of the conditions of The Natural Step System | 2010 | (Pakarinen et al., 2010) |

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| | | | plants), a power plant, a water purification plant, two sewage plants and a landfill | Conditions for the analysis of sustainability | | |
| Finland | Kymenlaakso | | Pulp and paper mill, chlorine dioxide, calcium carbonate, and hydrogen peroxide plants, power plant, local electricity, municipal sewage treatment plant, and landfill | Process, hybrid and input-output life cycle assessment approaches, and LCIA-RECIPE method | 2010 | (Mattila et al., 2010) |
| Finland | Kymenlaakso | | Pulp and paper mill, three chemical plants (chlorine dioxide, hydrogen peroxide and calcium carbonate plants), a power plant, a water purification plant, two sewage plants, a landfill, and a regional energy supplier | On-site survey; life-cycle inventory methodology of life-cycle assessment | 2011 | (Sokka et al., 2011b) |
| Finland | Kouvola | | Pulp and paper mill; calcium carbonate, hydrogen peroxide, chlorine dioxide, municipal wastewater treatment, and power plants | Life cycle assessment | 2011 | (Sokka et al., 2011a) |
| Finland | Kouvola | 9 | Pulp and paper mill, three chemical plants, power plant, energy distributor, water purification plant, wastewater treatment plant, and a landfill | Semi-structured interviews | 2011 | (Lehtoranta et al., 2011) |
| Portugal | Chamusca | | Integrated recovery, treatment and elimination centre for hazardous wastes, municipal waste management, non-hazardous industrial waste landfill, wastewater treatment facilities, plastics recycler, dismantlers of end of life vehicles, biomass processers, fertilizer producers, metal reclamation projects, container refurbishment, aluminium slag processor, battery recycler, paper pulp producer, and local farms | Unstructured interviews, on-site visits, and middle-out approach | 2010 | (Costa and Ferrão, 2010) |
| Portugal | Lisbon | 44 | Manufacturer of pulp, repair and maintenance of ships and boats, construction of railways and underground railways, wholesale of waste and scrap, manufacturer of doors and windows of metal, manufacturer of other fabricated metal products, shaping and processing of flat glass, production of electricity, logging, manufacturer of cement, manufacturer of household and sanitary goods and of toilet requisites, aluminium production; manufacturer of plastic plates, sheets, tubes and profiles; manufacturer of basic iron and steel and of ferro-alloys, and manufacture of flat glass | Material Flow Analysis | 2015 | (Patrício et al., 2015) |

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| Portugal | | | Pulp and Paper Industry | Unstructured interviews with members and interviews with two experts from a paper industry association. Eco-efficiency, reuse and industrial symbiosis indicators. Comparative analysis method. Comparative index. Radar chart graph | 2019 | (Ferreira et al., 2019) |
| Austria | Styria | | Paper producing industries, pressboard plant, scrap material dealer, wastewater treatment plant, mining company, wastepaper dealer, textile plants, chemical plant, saw mill, iron scrap dealer, construction materials plants, power plants, region of Voitsberg, stone and ceramic industries, cement plants, region of Graz, iron manufacturing industry, used tire dealers, plastics plant, colour industry, and fuel producer | Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| Italy | Taranto | | Cement factory, steelworks factory, power plants, refinery, construction material producing companies, distilleries, and wine companies | Questionnaires | 2014 | (Notarnicola et al., 2014) |
| Italy | Taranto | >15 | Steelworks, refinery, cement, food sector, construction and construction materials production industries, agricultural firms and power stations | Collection and analysis of data and questionnaires surveys | 2016 | (Notarnicola et al., 2016) |
| Italy | Industrial area of Venice, Veneto region | | Chemical industry | Surveys data | 2015 | (Mannino et al., 2015) |
| Italy | Prato, Tuscany | | Textile industry | Data collected directly from managers and telephone interviews | 2015 | (Daddi et al., 2015) |
| | Ponterosso, Friuli-Venezia Giulia | | Chemicals, food, glass, machinery and components production companies | | | |
| | Ancona, Marche | | Maritime activities such as shipbuilding, mechanical repairs, electrical systems, nautical decor, food supplies, logistics, shipping agencies and seafood processing | | | |
| Italy | Abruzzo | | Chemical/automotive/agri-food | On-site survey and questionnaires | 2017 | (Taddeo et al., 2017) |
| Italy | S.Croce sull'Arno, | | Tannery industry | Life cycle assessment | 2017 | (Daddi et al., 2017) |

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| | Tuscany | | | | | |
| Spain | Galicia | | Port-based industrial complexes | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| Spain | | | Pulp and Paper Industry | Unstructured interviews with members and interviews with two experts from a paper industry association. Eco-efficiency, reuse and industrial symbiosis indicators. Comparative analysis method. Comparative index. Radar chart graph | 2019 | (Ferreira et al., 2019) |
| Belgium | Antwerp | | Petrochemical industries, chemical industries, and city | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| Belgium | Brussels | | Port-based industrial complexes | | | |
| Belgium | Koekhoven | | Biogas cogeneration firm, manure-drying farmers, farmers, greenhouses, energy firm consultant, cattle farmers, jatropha cogeneration, power grid, retail, unpack organic wastes, and garden centre | Open questions and semi-structured interviews, observations in project meetings, field visits and dual-perspective framework application | 2016 | (Verguts et al., 2016) |
| Germany | | | Cement industry | Simplified life cycle assessment model, $CO_2$ emissions from different production systems and products | 2015 | (Ammenberg et al., 2015) |
| Latvia | | | Brewery industries, agricultural farms, bakeries (cookie production), and biogas production | Stakeholder interviews. Integrated method for evaluation of the quality of industrial synergies: overall evaluation score for exchange quality through three evaluation categories (environmental quality, economic quality, and geographic proximity) | 2015 | (Rosa and Beloborodko, 2015) |
| | | | Wood-processing industries: plywood production, manufacture of furniture, sawmilling and wood procession, wood product transfer harbour, composite wood board production, energy recovery, pellet production, and a farm | | | |
| Denmark/ United Kingdom/ Portugal/ Switzerland | | | | Interviews and quantitative and qualitative descriptors | 2010 | (Costa et al., 2010) |
| **North America** | | | | | | |
| United States of America | Guayama, Puerto Rico | | Coal-fired power plant, public wastewater treatment plant, petrochemical refinery, and waste stabilization | Interviews | 2005 | (Chertow and Lombardi, 2005) |
| United States of | Guayama, Puerto Rico | | Refinery, cogeneration plant, pharmaceutical firms, industrial landfills, road construction, and | Field research at industrial sites, in-person interviews, detailed questionnaires, empirical | 2008 | (Chertow et al., 2008) |

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| America | | | wastewater treatment facility | observation, and material flow analyses | | |
| United States of America | Barceloneta, Puerto Rico | | Pharmaceutical firms, hay farm, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms | Field research at industrial sites, in-person interviews, detailed questionnaires, empirical observation, and material flow analyses | 2008 | (Chertow et al., 2008) |
| United States of America | Barceloneta, Puerto Rico | 15 | Pharmaceutical manufacturing facilities, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms | Interviews, social network analysis | 2008 | (Ashton, 2008) |
| United States of America | Barceloneta, Puerto Rico | | Pharmaceutical firms, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms | In-person and telephone interviews, congruence method, and integrated framework based on economic geography, industrial ecology, and complex systems theory | 2009 | (Ashton, 2009) |
| United States of America | Barceloneta, Puerto Rico | | Pharmaceutical manufacturing facilities, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms | Open-ended interviews and in-person semi-structured interviews | 2011 | (Ashton, 2011) |
| United States of America | Pennsylvania | | | Evaluation of the difference in environmental impacts (primary energy and emissions) between reuse and production of the substituted material using the life cycle inventory databases of GREET and Ecoinvent | 2009 | (Eckelman and Chertow, 2009) |
| United States of America | Honolulu | 11 (8 analysed) | Coal-fired power plant, oil refinery, city water recycling plant, concrete production company, quarry, construction and demolition waste landfill, city water agency and recycling company | Interviews. Quantification of environmental benefits (changes in consumption of natural resources, and emissions to air and water), and economic benefits (revenue streams from by-products, disposal costs avoided, reductions in raw material and transportation costs) | 2010 | (Chertow and Miyata, 2010) |
| United States of America | Honolulu | 11 | Biosolids beneficiation company, local golf course, wastewater treatment plant, oil refineries, power plant, oil and tire recovery company, municipal water authority, cogeneration plant, cement company, and private construction and demolition waste landfill | Life cycle assessment | 2013 | (Eckelman and Chertow, 2013) |
| United States of America | Kansas City | 9 | Synthetic resins and plastics materials producer, long steel producer, greeting cards and gift products company, motorcycle manufacturer, solid waste treatment, electric utility company, construction | Material flow network and mixed integer programming model | 2011 | (Cimren et al., 2011) |

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| | | | materials company, organic recycling facility, and provider of by-product co-processing services | | | |
| United States of America | Choctaw | | Tire crushing, tire pyrolysis, carbon black processing, ink cartridge production and recovery, plastics, plastic products, wastewater treatment, and crushed steel recovery plants; hard rubber tire manufacturers, and greenhouse | Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| United States of America | New York/New Jersey | | Port-based industrial complexes | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| United States of America | Long Beach | | Ports and marinas | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| United States of America | North Dakota | | 1st generation bioethanol and combined heat and power plants | Interviews, surveys, and direct observations. Stochastic mixed integer linear programming model, Sampling average approximation. Bioethanol production, economic, GHG emission, irrigation land usage, water usage, and energy efficiency analysis | 2015 | (Gonela et al., 2015) |
| United States of America | Upper Valley | 2 | Solid waste resource management company and manufacturer | Interviews | 2017 | (Krones, 2017) |
| United States of America | Chicago | | Real estate developer, education, research and development, agriculture/farming, consulting, compost collection, beverage producers and food producers | Measurements of material and energy flows on-site and off-site, interviews, routine observations, questionnaires, and material flow analysis | 2018 | (Chance et al., 2018) |
| Canada | Sarnia-Lambton | | Fertilizer company, greenhouse operator, gas specialist company, power plant, medium-sized fine-particle manufacturer, oil refinery, chemical company, integrated energy company, and cattle farmers | Interviews | 2009 | (Bansal and Mcknight, 2009) |
| Mexico | Altamira-Tampico | 15 | Petrochemical industry | Open and face-to-face interviews, and on-site visits | 2019 | (Morales et al., 2019) |
| **Asia** | | | | | | |
| South Korea | Ulsan | | Automobile, oil-refinery, shipbuilding, petrochemical, chemical, non-ferrous metal smelting, and cement companies, and metropolitan city | Analysis of the development of IS | 2006 | (Won et al., 2006) |

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| South Korea | Ulsan | | Chemical, petroleum, and petrochemical company; industrial waste treatment and disposal company; chemical companies; tank terminal business; copper smelter and refinery; non-ferrous metal smelting company; paper mill company; wastewater treatment facilities; specialty chemicals and life science products company; integrated water management enterprise; and Ulsan Metropolitan City | On-site surveys | 2008 | (Park et al., 2008) |
| South Korea | Ulsan | 41 | Industrial and municipal waste incinerator, sewage treatment, paper mill, non-ferrous metals, chemical, petrochemical, steel, metal, non-metal, metal recovery, aluminium manufacturer, transport and oil spill restoration companies | Field survey | 2012 | (Behera et al., 2012) |
| South Korea | Ulsan | 21 | Industrial and municipal waste incinerator facilities, municipal wastewater treatment plant, paper mill, petrochemical, zinc waste processing, paint manufacturing, zinc manufacturing and chemical companies | Eco-efficiency indicators: one economic indicator and three environmental indicators (raw material consumption, energy consumption, and $CO_2$ emission) and eco-efficiency evaluation | 2014 | (Park and Behera, 2014) |
| South Korea | Ulsan | | Waste-to-energy incinerator and chemical plants | Economic and indirect benefits analysis | 2014 | (Park and Park, 2014) |
| South Korea | Ulsan | | Port-based industrial complexes | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| South Korea | Ulsan | | Chemical, chemical manufacturer, steel, petrochemical, aluminium manufacturer, aluminium, metal, metal recovery, non-ferrous metals, automobile, non-metal, transport, paper mill, utility supplier, waste treatment, municipal waste incinerator, food waste treatment, wastewater treatment, municipal waste landfill, industrial waste incinerator, and sewage treatment facilities, and oil spill restoration company | Eco-production strategy analysis and assessment of economic, social and environmental benefits | 2015 | (Park and Behera, 2015) |
| South Korea | Ulsan | 2 | Zinc smelter and paper mill company | Method for the assessment of total and allocated greenhouse gas emissions from IS exchanges based on the GHG protocol and life cycle assessment. LCA allocation methods: cut-off, avoidance impact, and 50/50 | 2018 | (Kim et al., 2018b) |
| South Korea | Yeosu | 27 | Refineries, power plants, and petro-chemical companies | Interviews, questionnaires, and waste heat utilization network model | 2010 | (Chae et al., 2010) |

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| South Korea | Banwol-Sihwa | | Textiles dyeing and printing firms, cogeneration plant, residential areas, and cement manufacturing industry | Fieldwork, and semi-structured interviews | 2018 | (Yoon and Nadvi, 2018) |
| South Korea | | 596 | | Network analysis (NetMiner 4.0). Economic benefits (cost savings and revenues, and total economic surplus) and environmental benefits (reduction of energy consumption, and reduction in the generation of waste, wastewater, and emissions) analysis | 2019 | (Park et al., 2019) |
| China | Guigang | | Sugar refinery, alcohol plant, pulp and paper mills, cement plant, compound fertilizer plant, and alkali recovery plant | Interviews | 2007 | (Zhu et al., 2007) |
| China | Guigang | | Sugar-making industry, alcohol-processing plant, compound-fertilizer plant, cement mill, and paper making system | Eco-industrial development analysis | 2007 | (Fang et al., 2007) |
| China | Guigang | | Sugar, pulp, paper, alcohol, power, fertilizer, and calcium carbonate plants; cement mill, and alkali recovery facility | Analysis of the different technological evolution trend and the diversified dynamics of the selected environment | 2011 | (Guo and Hu, 2011) |
| China | Guigang | | Sugar refinery, sugarcane planting system; and alcohol, pulp and paper, compound fertilizer, power, wastewater treatment, alkali recovery, cement, and light calcium plants | Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| China | Guigang | | Sugar processing and refinery, pulp, paper manufacturing, alcohol, cement mill, fertilizer, caustic soda, calcium carbonate, alkali, wastewater treatment, and water recycling facilities; combined heat and power, local and regional farmers, and road material manufacturers | Social network analysis, material flow analysis, and comparative analysis | 2017 | (Shi and Chertow, 2017) |
| China | Guigang | | Sugar plant, brewery, fertilizer plant, thermal power plant, pulp mill, paper mill, and cement factory | Robustness analysis under random failure and intentional disturbance, and optimization of eco-industrial symbiosis network. Node failure rate, indicator for structural robustness (natural connectivity), and indicator for performance robustness (network efficiency) | 2018 | (Q. Wang et al., 2018a) |
| China | Guigang | | Sugar plant, brewery, chemical fertilizer plant, thermal power plant, pulp mill, paper mill, and | Assessment of the vulnerability of eco-industrial symbiosis network based on the | 2018 | (Q. Wang et al., 2018b) |

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| | | | cement factory | automatic control theory | | |
| China | Wudi County, Shandong province | | Cement and marine chemical industries | Eco-industrial development analysis | 2007 | (Fang et al., 2007) |
| China | Wudi County, Shandong province | 8 | Ammonium phosphate, cement, sodium hydroxide, salt, sulfuric acid, ammonia, bromine, and electric power plants | Environmental and economic benefits analysis | 2010 | (Wang et al., 2010) |
| China | Wudi County, Shandong province | | Salt field; chlor-alkali, ammonium phosphate, sulphate, cement and power plants | Analysis of the different technological evolution trend and the diversified dynamics of the selected environment | 2011 | (Guo and Hu, 2011) |
| China | Wudi County, Shandong province | | Ammonium phosphate, sulfuric acid, cement, thermal power, chlorine, aquaculture, bromine, salty gypsum production, and chlor-alkali plants; raw salt production, potassium magnesium salt production, and living area | Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| China | Wudi County, Shandong province | 8 | Ammonium phosphate, sulfuric acid, cement, ammonia, thermal power, bromine, salty gypsum production; and potassium and magnesium salt production plants | Ecological network analysis | 2015 | (Zhang et al., 2015b) |
| China | Wudi County, Shandong province | 21 | Thermal power plant, culture of special species, crude salt plant, salt field, aquaculture, sea water desalination, potassium magnesium plant, water enrichment plant, bromide plant, chlor-alkali plant, petrochemical plant, hydrochloric acid plant, titanium dioxide plant, salt gypsum plant, alumina plant, chemical fertilizer plant, ammonium phosphate plant, sulphuric acid plant, cement plant, synthetic ammonia plant, and urea plant | Social network analysis. Densities. Centrality indicators: degree and relative degree centrality, betweenness and relative betweenness centrality, and closeness and relative closeness centrality. Centralization measures: degree, betweenness, and closeness centralization. Small-world and scale-free effects: average clustering coefficient, average path length, and power law distribution of degree. Stability analysis: network fragmentation degree. Comparative analysis | 2019 | (Zhang and Chai, 2019) |
| China | Guiyang | | Aluminium and phosphorus chemical industries | Eco-industrial development analysis | 2007 | (Fang et al., 2007) |
| China | Guiyang | | Iron/steel, aluminium, phosphorous chemical, coal, and cement industries; power plant, urban areas, and agriculture sector (greenhouses) | Hybrid model integrating an input-output approach and process-based inventory analysis. Carbon emissions from a production and consumption perspectives. Indirect/direct ratio and production/consumption ratio indexes. Carbon footprint intensity and | 2017 | (Fang et al., 2017) |

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| | | | | carbon footprint per person | | |
| China | Nanning, Guangxi | | Sugar industry | On-site survey | 2008 | (Yang and Feng, 2008) |
| China | Nanning, Guangxi | | Sugar industry | Material flow analysis | 2008 | (Jianhua and Zhaohua, 2008) |
| China | Dafeng | 5 | Barley field, feedstuff plant, livestock husbandry plant, beer company, and fish ponds | Environmental and economic benefits analysis | 2010 | (Wang et al., 2010) |
| China | Guangdong | 13 | Coagulation, aluminium processing, metal smelting, synthetic fibres, plastics, activated charcoals, plastic additives, environmental protection instruments, wood planking, adhesive, ceramic, steam, and sound-proof material plants | | | |
| China | Tianjin | | Public utilities and environmental infrastructures (sewage, water, and wastewater treatment plants; cogeneration, desalination, steam and hot water supply, and thermal power plants); electronics industry; food and beverage industries, pig farms, farms, coal briquette factory; biotechnology and pharmaceutical industries, eco-landscaping development company, public works company; automobile and machinery industries, battery products manufacturer, paper mill, and cement mill | Field trips and interviews | 2010 | (Shi et al., 2010) |
| China | Tianjin | | Metal mill and power factories | Survey questionnaires | 2011 | (Qi and Wang, 2011) |
| China | Tianjin | | Water treatment plant, industrial, commercial and residential users, wastewater treatment plant, construction companies, cogeneration plant, new water source company, desalination plant, resource recovery company, cast iron company, auto die makers, automatic transmission company, aluminium smelting, resource management company, stemless steel pipe maker, steel scrap contractors, refineries, chemical companies, lead recycling company, cement mill, rubber company, batteries company, and various lead acid battery users | Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| China | Tianjin | | Wastewater treatment plant, cogeneration power | Data collection in the field, semi-structured | 2014 | (Yu et al., |

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| | | | plant, and companies involved with packaging waste, scrap iron, and waste oil | interviews, and process analysis | | 2014b) |
| China | Tianjin | | Port-based industrial complexes | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| China | Tianjin | | Wastewater recycling and cogeneration and waste recycling | On-site field research, technique for order of preference by similarity to ideal solution method (based on seven indicators divided into two subgroups) used as multicriteria decision analysis, and process analysis approach | 2015 | (Yu et al., 2015) |
| China | Tianjin Binhai | | Power plant, desalination station, salt-making, chemical plant, and building materials producer | Transition course analysis | 2011 | (Li, 2011) |
| China | Tianjin Binhai | | | Participant observation and semi-structured interviews | 2017 | (Q. Wang et al., 2017) |
| China | Suzhou | | Wastewater treatment plant, sludge drying company, and power plant | Field study, face-to-face interviews, questionnaire-based surveys, and energy-related greenhouse gas emissions using IPCC guidelines method | 2012 | (L. Liu et al., 2012) |
| China | Suzhou | | Companies of the main production chain of printed circuit boards, and waste treatment facilities and disposal services | Questionnaire surveys, interviews with stakeholders, and field surveys. Substance flow analysis and resource productivity indicator | 2015 | (Wen and Meng, 2015) |
| China | Weifang | 2 | Salt field plant and soda plant | Open ended and face to face interviews, and investigation on site | 2012 | (C. Liu et al., 2012) |
| China | Weifang | 11 | Soda, bromine, salt field, silica, saleratus, calcium chloride, bromide, potassium sulfate, cement, thermal power plants and residential zone | Investigation on-site, survey questionnaires, open-ended interviews and three-level approach | 2015 | (Liu et al., 2015) |
| China | Weifang | | Salt field plant, soda plant, thermal power plant, bromine plant, calcium chloride plant, potassium sulfate plant, saleratus plant, petrochemical company, chlor-alkali colophony plant, and wastewater treatment facility | Field research and open-ended interviews with the managers, technicians and the government staff. System dynamics method. Causal loop diagram, stock–flow diagrams and numerical simulation. Method of scenario analysis | 2018 | (Cui et al., 2018) |
| China | Liuzhou | 3 | Iron and steel, fertilizer, and cement and construction industries; and communities | Hybrid physical input and monetary output model, co-benefit indicators: $CO_2$ emissions reduction per unit of waste reduction, $SO_2$ and $NO_x$ reduction per unit of waste reduction and economic revenue; $CO_2$ | 2013 | (Dong et al., 2013a) |

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| | | | | emissions calculated on the basis of energy consumption and inventory method | | |
| China | Liuzhou | | Iron and steel, cement and construction, ammonia and fertilizer industries, and community | Surveys data | 2013 | (Dong et al., 2013b) |
| China | Liuzhou | 3 | Iron and steel, fertilizer, and cement and construction industries; and urban community | Material flow analysis, $CO_2$ emission reduction from the avoided resource or waste | 2014 | (L. Dong et al., 2014) |
| China | Jinan | | Iron and steel, aluminium, ammonia, chromium chemical, and cement and construction industries; and community | Company-level questionnaire surveys and interviews with stakeholders | 2013 | (Dong et al., 2013b) |
| China | Jinan | 6 | Iron and steel, aluminium, ammonia, chromium chemical, carbonate production and cement and construction industries; and urban community | Company-level questionnaire surveys, interviews with stakeholders; material flow analysis, $CO_2$ emission reduction from the avoided resource or waste | 2014 | (L. Dong et al., 2014) |
| China | Changsha Huangxing | | Camellia oil refinery, nucleic acid extraction, IC manufacturing; and food, cellulose enzyme, tea-leaf, aloe deep-processing, cosmetics, camellia oil, citrus, beverage, beer, antiviral medicine, tea cake processing, orange peel deep-processing, medicine, daily-use chemical, fertilizer, food additives, agricultural production, IC packing, purifying agent, plastics manufacturing, household appliances, air conditioner, metal recovery, wastewater treatment, rice husk, environmental protection equipment, green paint, green building materials, intelligent metals, green adhesives, plastics, ceramics, building bricks, equipment parts, and building materials plants | Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| China | Shihezi | | Achnatherum cultivation, paper-making, livestock breeding, wastewater treatment, and animal products processing systems; and eco-tourism industry | | | |
| China | Wujing | | Coking, chemical, titanium white, carbon products, hydrogen peroxide, and Chlor-alkali plants | | | |
| China | Liaocheng | | Chlor-alkali plant, alumina plant, lime factory, calcium carbide factory, electrolytic aluminium plant, aluminium processing factory, electric power plant, medium-density fibreboard plant, PVC plant, system of supply heating, and carbon plant | Field investigations. Energy-saving indexes (IS energy-saving index, contribution rate of energy saved through IS, fractional energy savings, and cut rate of energy consumption per gross industrial output value) and | 2014 | (Li et al., 2015) |

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| | | | | financial indexes (IS input–output ratio, static investment payback period of IS, net present value, and internal rate of return of IS) | | |
| China | Liaocheng | 16 | Sewage treatment, polyvinyl chloride, alumina, electrolytic aluminium, aluminium processing, and steel plants; cogeneration system; red mud recycling system; soda ash, lime, calcium carbide, carbon, density board, brick, fertilizer and building materials factories | Data from laboratory determination, questionnaire surveys and field investigation. Substance flow analysis. Carbon accounting methods: based on IPCC 2006 and the Greenhouse Gas Emission Accounting Methods and Reporting Guidelines (Trial) | 2015 | (F. Yu et al., 2015a) |
| China | Liaocheng | | Sewage treatment plant, polyvinyl chloride plant, soda ash factory, lime factory, calcium carbide factory, carbon factory, cogeneration system, alumina plant, electrolytic aluminium plant, aluminium processing plant, density board factory, brick factory, fertilizer factory, red mud recycling system, steel plant and building materials factory | Life cycle assessment | 2015 | (F. Yu et al., 2015b) |
| China | Liaocheng | 27 | Cogeneration system, coal mine, board fireproofing, gypsum board, extracting iron, dealkalize, rock wool, composite board, extracting bauxite, brime; ore, alumina, electrolytic aluminium, aluminium deep processing, salt, calcium carbide, PVC, chlor-alkali, PVC deep processing, lime, fluoride salt, carbon, brick, desulfurization, red mud recycling, fertilizer, and eco-cement plants | On-site investigations, company-level questionnaires, interviews with experts and stakeholders; network analysis method, social network analysis program, and node importance indexes of the industrial symbiosis network (degree, betweenness, closeness, and eigenvector centralities) | 2017 | (Han et al., 2017) |
| China | Shenyang | | Cogeneration power plants; construction materials, chemical and pharmaceutical, manufacturing and electric, and metallurgy and casting enterprises | Interviews, informal meetings, emergy analysis method, industrial symbiosis emergy indicators (absolute emergy savings, relative emergy savings from different resources, and emdollar values of total emergy savings) | 2014 | (Geng et al., 2014) |
| China | Shenyang | | Power plant, chemical company, pharmaceutical group, construction material group, heavy industries, metal casting plant, steel manufacturing and metal casting | Key informant interviews, informal meetings, emergy analysis method and logarithmic mean divisia index method | 2018 | (Dong et al., 2018) |
| China | Ningbo | | Metallurgical company, and plastic and steel producers | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| China | Rizhao | 94 | Grain oil, food and beverage, machinery, pulp and paper, textile and garment, wine refining and | Questionnaire surveys and interviews | 2015 | (F. Yu et al., 2015c) |

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| | | | biochemical industries | | | |
| China | Jiangsu | 86 | Textile industry, chemical industry, electronic industry, thermal power plant, inorganic chemical company, photovoltaic production, nitrogen fertilizer production, citric acid production, organic compounds production, cement, concrete, and other building materials production, and machinery components production companies | Synthetic data acquisition method, surveys and interviews. Geographical information systems. Interconnected network model based on complex network theory. Degree centrality, edge betweenness metric, disruptions, cascade effect of failure and resilience. Response curve and the area under the curve score | 2015 | (Li and Shi, 2015) |
| China | Dalian | | Wastewater recycling, and solid waste recycling | On-site field research, technique for order of preference by similarity to ideal solution method (based on seven indicators divided into two subgroups) used as multicriteria decision analysis, and process analysis approach | 2015 | (Yu et al., 2015) |
| China | Dalian | | Petro-chemical, equipment manufacturing, IT industry, aviation metallurgy, ocean shipping industry, and bio-medicine | Field survey; emergy analysis; impact, population, affluence, technology formula, and index decomposition analysis | 2016 | (Zhe et al., 2016) |
| China | Dalian | 7 | Ammonia, soda, ammonium nitrate, cogeneration power, cement, wastewater treatment and a fertilizer plants | Life cycle assessment | 2017 | (Zhang et al., 2017) |
| China | Jiayuguan | 26 | Iron and steel industry | Backward approach, substance flow analysis and substitution analysis method | 2016 | (Wu et al., 2016a) |
| China | Midong | 18 | Chemical, cement, building material, iron and steel, concrete, copper, rubber and paper mill companies, thermal power plant and coal mines | Stakeholder interviews, questionnaire survey and material flow analysis. Evaluation of benefits of IS: resource consumption reduction, waste emission reduction, cost saving of raw material, cost saving of waste disposal and waste sales income | 2016 | (Guo et al., 2016) |
| China | Shanghai Caohejing | 10 | Electronics and information industry | Site investigations | 2016 | (Huang et al., 2016) |
| China | Gansu | 12 | Iron and steel industry | Bow-tie and risk index methods | 2017 | (Wu et al., 2017b) |
| China | Hefei | | Cogeneration power plant, manufacturing home appliances, electronic equipment, automobiles and parts, fast-moving consumer goods, electronic information, new materials and bio-pharmaceuticals industries | On-site survey, interviews, and emergy analysis | 2017 | (Fan et al., 2017) |

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| China | Qijiang | 17 | Coal production and production of aluminous products for different uses | Participant observation, interviews, questionnaire-based survey and simulation analysis on the cascading failure mode | 2017 | (Li et al., 2017) |
| China | Qijiang | | Aluminium and copper industry | In-depth interviews, and field trips | 2017 | (Li Sun et al., 2017) |
| China | Wu'an | | Cement, iron and steel, thermal power, new building material, iron ore mining, lime, chemical, and sewage treatment plants | On-site investigations, material flow analysis method, $CO_2$ emission inventory analysis, gross benefit and dynamic investment payback period analysis | 2017 | (Cao et al., 2017) |
| China | Yulin/ Ordos/ Jining | | Coal industry | Field research, directed weighted cascading failure model based on the coupled map lattice, five network performance indicators, simulation and comparative analysis | 2017 | (D. Wang et al., 2017) |
| China | Ordos | | Coal and coal-derived chemical industry | Lotka-Volterra population ecology model, simulation on the MATLABR2012a and interpolation fitting method | 2018 | (D. Wang et al., 2018) |
| China | Gujiao | 38 | Coal mining, coal processing, wastewater treatment, power generation, construction materials and coal-based chemicals | Social network analysis | 2018 | (Song et al., 2018) |
| China | Bohai Bay | | Thermoelectric power plant; food service, biopharmaceutical, electronics and communications, auto manufacturing, chemical, and new energy source industries; farming food factory, green company, organic fertilizer site, electroplating wastewater conduction plant, tailing company, steel casting, non-ferrous metals, aluminium alloy, chemical, and waste heat centre | Field surveys, key informant interviews, and informal meetings | 2018 | (Liu et al., 2018a) |
| China | Northwestern China | | Coking industry | Interviews with experts and officials. Measurements and data obtained on site. Exergy analysis: exergy and energy efficiencies, environmental impact factor, exergetic sustainability index, exergy conservation supply curve, and energy consumption. Life cycle greenhouse gas emissions assessment. Water footprint analyses | 2018 | (Wu et al., 2018) |
| China | Daqing | | Natural gas processing industry, petroleum and petrochemical equipment manufacturing industry, | Questionnaire survey and field visit. Grey correlation analysis method. Eco-efficiency | 2019 | (Wang et al., 2019) |

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| | | | photovoltaic power generation industry, smart greenhouse industry, bulk logistics industry, and building materials industry | evaluation index. Economic performance, environmental benefit, material reduction cycle, and network structure indicators | | |
| China | | | Integrated Steel Mills | Expert interviews and substitution analysis method | 2015 | (Yu et al., 2015) |
| China | | | Iron and steel industry and thermal power plants | Exergy balance, total exergy losses, physical exergy of the material, chemical exergy of material, and total exergy. Energy efficiency and exergy efficiency. Total $CO_2$ emissions and equivalent $CO_2$ emission potentials associated with exergy losses, and due to inefficiency. Proposed indicators for measure and compare the overall performance of an industrial network: economic indicators and production capacity-related indicators | 2016 | (Wu et al., 2016b) |
| China | | | Lead and zinc concentration plant, waste acid and water treatment station of copper company, tailing impoundment, side air blowing reducing workshop, cement plant, sintering plant and fuming and fusion system | Field investigation, asymmetric distribution coefficient, environmental risk index, integral fracture risk index, stock redundancy, scale redundancy, functional redundancy, stability analysis method and probability method | 2017 | (Wu et al., 2017a) |
| Japan | Kawasaki | | Stainless steel mill, integrated steel works, cement firm, chemical firm, paper mill, home appliances dismantling, fluorescent light tubes recycling, concrete formwork plant, recycling plant, commercial and industrial waste collectors, municipal waste collector, and municipal waste water treatment plant | Follow-up visits, and material flow analysis | 2009 | (Van Berkel et al., 2009a) |
| Japan | Kawasaki | | Cement, stainless steel, steel, concrete formwork, ammonia, paper recycling, and scrap home appliances recycling companies | Questionnaire survey, material flow analysis, and life cycle $CO_2$ analysis method | 2010 | (Hashimoto et al., 2010) |
| Japan | Kawasaki | | Iron and steel; cement, chemical, concrete framework, and paper mill industries; commercial, industrial and municipal waste collectors; home appliances plant; home appliance recycling and municipal waste water treatment facilities, and community | Site visit, questionnaire surveys and intensive interviews. Material flows analysis; proposed indicators: "environmental gains" based on a material flow analysis and "economic gains" based on the analysis of the material exchange | 2013 | (Dong et al., 2013b) |
| Japan | Kawasaki | | Iron and steel, cement, chemical and paper and pulp industries; automobile dismantling company, home appliance recycling company and PET rebirth | On-site survey, interviews; lifecycle carbon footprint evaluated by the hybrid life cycle assessment model; calculation of carbon | 2014 | (H. Dong et al., 2014) |

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| | | | | emission reduction by symbiosis types: material carbon footprint method, input-output analysis method and detailed emission coefficient of blast furnace slag cement and Portland cement | | |
| Japan | Kawasaki | | Port-based industrial complexes | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| Japan | Kawasaki | 5 | Iron and steel, cement and paper industries; recycling and incineration facilities and urban sectors | Intensive interviews, questionnaire surveys; material flow analysis, carbon footprint and emergy methods | 2017 | (Ohnishi et al., 2017) |
| Japan | 23 cities | | Eco-town | Survey questionnaires, influencing factors (project scale, recycling boundary, and type of waste) and performance indicators (virgin material savings and operating rate) | 2012 | (Chen et al., 2012) |
| Japan | Kitakyushu | | Car disassembly factory, home appliance recycling factory, PCB treatment facilities, composite core facility; and plastic bottle recycling, waste office equipment, construction waste treatment, fluorescent lamps, empty cans, reused computer, recreational machine, waste wood and plastics, cooking oil, styrofoam, ink cartridges, scrap car, and organic solvent and waste plastics plants | Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods | 2013 | (Zhang et al., 2013) |
| Japan | Osaka | | Gas company, petrochemical plant, refinery, municipalities and ports | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| India | Nanjangud | 13 | Distilleries, sugar refinery, instant coffee and milk beverage powder manufacturer, and local farmers | Field data collection, interviews, material flow analysis, and network analysis | 2009 | (Bain et al., 2009) |
| India | Nanjangud | >14 | Garment, electrical insulation, and plywood manufacturers; oil extraction, granite polishing, food processing, and CO2 bottling facilities; paper mills, sugar cane refinery and distillery, distillery, alcohol bottling facility, textile mill and aromatic chemical processor | Structured interviews with managers and Material flow analysis | 2010 | (Bain et al., 2010) |
| India | Nanjangud | 12 | Garment manufacturer, oil extraction facility, food processing facility, electrical insulation manufacturer, plywood manufacturer, paper mill, aromatic chemical processor, textile mill, granite facilities, sugar cane refinery and distillery, distillery, alcohol bottling facility, and $CO_2$ bottling | Field surveys, structured interviews, material flow analysis, social network analysis, statistical network correlation analyses, and quantitative and qualitative measures for different dimensions of social embeddedness | 2012 | (Ashton and Bain, 2012) |

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| India | Tamil Nadu | | Sugar industry, sugarcane farms, paper manufacturing company, spirit manufacturing, waste paper recycling factory, cement manufacturing industry and wastewater treatment plant | Multi-objective mixed integer linear programming model and sensitivity analysis | 2019 | (Vimal et al., 2019) |
| Bangladesh | Sitakunda-Bhatiary | | Ship-breaking industry, and processing and recovery of scrap metal (reconditioned engineering products and remanufactured furniture) | Interviews | 2011 | (Gregson et al., 2011) |
| Thailand | Map Ta Phut | | Port-based industrial complexes | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| Singapore | Jurong Island | | Chemical plants, multi-utility service provider, storage and terminaling service providers, electricity pool, co-generation plant, refinery, gasification plant, and air separation plant | Online maps, workshop and survey | 2019 | (Yin and Lee, 2019) |
| Singapore | Ulu Pandan, and Clementi | | Wastewater treatment plant, co-digestion plant, reclamation plant, and domestic and commercial buildings | | | |
| Singapore | Tuas, Tuas South, and Senoko | | Municipalities, waste-to-energy plants, and metal recovery facility | | | |
| Singapore | | | Hotels, food and beverage establishments, and micro-refineries | | | |
| Singapore | | | Recycling companies, food processing factories, dryer, co-generation plant, parks and gardens, shipyards, treatment plant, concrete plant, construction industries, steel mill, processing plant, combined heat and power plant, plants, conservatories, water treatment, wastewater treatment plant and wafer fabrication plants | | | |
| **Oceania** | | | | | | |
| Australia | Kwinana | 35 | Alumina refinery, fused alumina and zircon producer, worm farm, cement manufacturing, industrial chemical and fertilizer producer, industrial gas producer, coal-fired power station, titanium mineral processing company, turf farm, construction company, cement mill, Blokpave producer, zirconia powder producer, water supply | Interviews | 2007 | (Van Beers et al., 2007) |

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| | | | and treatment company, coal mine, insulation plant, chlor alkali plant, cement and lime producer, fertilizer producer, mineral processing plant, inorganic chemical producer, pig iron plant, nickel mine, composting facility, oil refinery, synthetic rutile plant, titanium dioxide producer, nickel refinery, gas fired power station, co-generation plant, distributor and producer of LPG | | | |
| Australia | Kwinana | | Alumina refinery, fused alumina and zircon producer, worm farm, cement manufacturing, industrial chemical and fertilizer producer, industrial gas producer, coal-fired power station, titanium mineral processing company, turf farm, construction company, cement mill, Blokpave producer, zirconia powder producer, water supply and treatment company, coal mine, insulation plant, chlor alkali plant, cement and lime producer, fertilizer producer, mineral processing plant, inorganic chemical producer, pig iron plant, nickel mine, composting facility, oil refinery, synthetic rutile plant, titanium dioxide producer, nickel refinery, gas fired power station, co-generation plant, distributor and producer of LPG | Integrated research programme and framework to facilitate IS | 2007 | (Harris, 2007) |
| Australia | Kwinana | | Chemical plant, alumina refinery, oil refinery, manufacturer and supplier of chemicals and fertilisers, and industrial and medical gases producer | Key-informant interview and informal interviews | 2013 | (MacLachlan, 2013) |
| Australia | Gladstone | 7 | Cement and lime producer, aluminium smelter, alumina refinery, coal fired power station, waste transfer facility, local sewage treatment plant, used tires collection facility, and spent solvents collection facility | Interviews | 2007 | (Van Beers et al., 2007) |
| Australia | Gladstone | >8 | Alumina refineries, aluminium smelter, cement plant, ammonium nitrate and sodium cyanide producer, power station, sewage treatment plant and agricultural companies | Field survey | 2014 | (Golev et al., 2014) |
| Australia | Gladstone | | Alumina refineries, aluminium smelter, chemical company, coal power station, and cement producer | Interviews, and qualitative tool for analysis of IS barriers – IS maturity grid | 2015 | (Golev et al., 2015) |

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| **North Africa** | | | | | | |
| Morocco | Jorf Lasfar | | Port-based industrial complexes | On-site visits, and individual or collective interviews performed on site | 2014 | (Cerceau et al., 2014) |
| Algeria | Bejaïa | | Food processing industry, and local producers of soap, paint and mastic | | | |
| **South America** | | | | | | |
| Brazil | South-East | | Industrial construction, contractors, cement manufacturer, abrasive grains manufacturer, ceramic manufacturer, and wood processing company | Direct observations; indicators of quantitative data analysis (recycling rate, diversion rate, and rate of waste recovered through Industrial Symbiosis), and SWOT analysis | 2017 | (Freitas and Magrini, 2017) |

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## Author declaration

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3. Intellectual Property

☒We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.