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Review

Theoretical contribution of industrial ecology to circular economy

Yovana M.B. Saavedra [a, b, *], Diego R. Iritani [a], Ana L.R. Pavan [c], Aldo R. Ometto [a, c]

[a] Department of Production Engineering, School of Engineering of São Carlos, University of São Paulo, Brazil
[b] Center of Natural Sciences, Federal University of São Carlos, Brazil
[c] Environmental Engineering Sciences, School of Engineering of São Carlos, University of São Paulo, Brazil

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ABSTRACT

Circular Economy (CE) currently represents a viable option for countries, governments, academia and society to transform the linear and semi-circular materials and energy flows into circular flows and obtain better sustainable benefits. In this sense, Industrial Ecology (IE) with its tools can assist in the transition to CE. Therefore, the main goal of this paper is to present the theoretical contribution of IE to CE. The methodology used was based on bibliometric analysis in the international context. With regard to the bibliometric analyses, we have identified that the evolution of CE would not be possible without the existence of IE concepts and tools, especially with tools such as Industrial Symbiosis (IS) and Eco-Industrial Parks (EIPs). Furthermore, three levels of IE contribution to CE were identified, such as: conceptual, technical and policy aspects. Finally, new CE based researches from an IE perspective with bibliometric analysis and with co-citation networks are possible, including, solid waste management and policies.

Contents

1. Introduction

Industrial Ecology (IE) is a study aimed at understanding the circulation of materials and energy flows; therefore, IE must first understand how the industrial ecosystem works, how it is regulated and its interactions with the biosphere in order to determine how the industrial ecosystem can be restructured to resemble how natural ecosystems function (Erkman, 1997).

The IE was first announced at the end of the 1980s (Erkman, 1997). The seminal article by Frosch and Gallopoulos was published in 1989, a time when it became increasingly clear that traditional and reactive approaches, such as "end-of-pipe", were insufficient to treat industrial waste during product manufacturing processes (Frosch and Gallopoulos, 1989).

The IE is therefore a broad, holistic framework aimed at guiding the transformation of the industrial system to a sustainable basis (Lowe and Evans, 1995). The concept of Industrial Metabolism, launched by Robert U. Ayres in 1988, is a key concept in IE, which is focused on improving knowledge and understanding the societal uses of natural resources and their total impacts on the environment (Anderberg, 1998).

* Corresponding author. Department of Production Engineering, School of Engineering of São Carlos, University of São Paulo, Brazil.
E-mail address: ybarrera11@yahoo.es (Y.M.B. Saavedra).

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List of abbreviations

CAPES	Coordination for the Improvement of Higher Education Personnel
CE	Circular Economy
CNPq	National Council for Scientific and Technological Development
IE	Industrial Ecology
IS	Industrial Symbiosis
EIPs	Eco-Industrial Parks
PSS	Product Service System
TEDA	Tiajin Economic-Technological Development Area
USA	United States of America
WoS	Web of Science

In addition to this concept, the term Industrial Symbiosis (IS) is vital for the IE field. It originated from biology and the existing biological symbiotic relationships in nature, in which two or more unrelated species exchange materials, energy or information in a mutually beneficial manner (Chertow, 2000). According to Hardy and Graedel (2002), the basis of IS is the biological analogy that exists in natural ecosystems: nutrients are cycled and energy is cascaded between the actors of the systems in a mutually beneficial manner. Therefore, the principle of IS is to create physical links between independent companies by exchanging energy, materials, water and by-products (Chertow, 2000). According to Prosman et al. (2017) IS is a key strategy to closing material flows.

Despite the advances in the field of sustainable development and the increasing progress of IE, the evolution of the global economy has been dominated by a linear model of production, in which consumer goods are manufactured from raw materials, sold, used and then discarded as waste.

In this sense, Circular Economy (CE) has been attracting increasing attention in recent years, aimed at maintaining products, components and materials at their highest level of utility and value. Therefore, it is in a continuous positive cycle of development that natural capital is conserved and enhanced, minimizing systemic risk by managing finite stocks and renewable flows. The CE concept is grounded in the study of real world and nonlinear systems, in order to facilitate effective flows of materials, energy, labor and information (Ellen MacArthur Foundation, 2015). Moreau et al. (2017) adds that CE promotes circular flows to reduce environmental impacts, while maximizing resource efficiency.

The CE has become more popular among companies and policy makers; however, there are still issues that need to be explored and discussed, even the core basis regarding concepts, elements and tools and their relationship with IE, a field that has been extensively studied (Moreau et al., 2017).

According to Nakajima (2000), IE can be helpful to transition towards a more CE, creating different alternatives of the materials and their wastes through reuse, repair, recycling and remanufacturing. That is, with these alternatives, it is possible to increase the recovery of components with their materials and in some cases extend their lifecycle. Additionally, the aforementioned author referred to other IE tools and how they can be used such as dematerialization, material substitution, pollution prevention, design for environment or Ecodesign and Ecoindustrial Parks (EIPs).

Considering the above paragraphs, this study investigates the following question: How is CE incorporated into the field of IE? The specific goal of this paper is: to analyze the theoretical contribution of Industrial Ecology to Circular Economy. The paper is structured as follows: Section 2 describes the methodology used. Section 3 discusses the results related to Bibliometric and section 4 concludes the effects of this study on the theoretical contribution of IE to CE and present the three levels of contribution of IE to EC.

2. Methodology

This section describes the research methodology used in this study. We used three main phases: 1. Systematic approach regarding CE and IE; 2. Bibliometric Analysis regarding CE and IE and 3. Discussion based in the phase 2 regarding CE, general concepts, its evolution and main contributions of IE to CE.

In the phase 1 we took a systematic approach to search the relevant literature regarding CE and IE and chose the ISI Web of Science (WoS) as the data source for the research, pointed out as the most important data source for bibliometric analysis in the sciences (Van Leeuwen, 2006).

The search included articles published until 2016, combining the terms “Circular Economy”, “Industrial Ecology”, “Industrial Symbiosis”, “Industrial Metabolism”, “Eco-Town”, “Eco-Industrial Park” and “Industrial Ecosystem” in article titles, abstracts and/or keywords. A total of 110 records matched the above-mentioned filtering criteria (see Appendix 1 with top ten references).

In the phase 2 and after summarizing the significant publications regarding CE and IE, the bibliometric analysis was performed. Bellis (2009) stated that bibliometrics is a set of methods to quantitatively analyze scientific and technological literature. Additionally, according to Broadus (1987), it describes the body of research by measuring items from physical units of publications, bibliographic citations and their proxies (Broadus, 1987). The analysis of bibliometric networks allows identifying patterns in the literature, clusters by research area and their relationships, as well as the most relevant publications (Carvalho et al., 2013).

The method of bibliometric analysis implemented in this research follows the methodology proposed by Borner et al. (2007), which comprises the development and analysis of bibliometric networks. To this end, the Sci^{2}Tool software (version 0.5 alpha) was used (Sci2team, 2009). Bibliometric networks were elaborated/constructed through data extraction in the WoS database. Then, the data were treated in the Sci^{2}Tool software resulting in the co-citation network, which shows the similarity between citations in a research area – it shows pairs of citations that were mentioned by articles found in the search (cutoff criteria used at least five relationships) (Culnan et al., 1990; Pilkington and Liston-heyes, 1999; Carvalho et al., 2013).

Two bibliometric indicators were used to analyze and discuss the networks: total node degree, which shows the number of relationships between the nodes – the higher the number of connections, the higher the influence of the node in the network – and node between centrality, which indicates the ability of the nodes to connect different clusters and research areas. Finally, the word co-occurrence network was structured, which creates a weighted network where each node is an abstract keyword and edges connect words to each other where the strength of an edge represents how often two words occur in the same body of text together (Borner et al., 2007; Wasserman and Faust, 1994).

Finally, in the phase 3 with the results of the phase 2 we show the results and main conclusions on CE and the main theoretical contributions of IE to CE.

3. Results and discussion

This item presents the results and discussion relative to the bibliometric analysis.

Firstly, the main conceptual background concerning CE and IE is summarized in the co-citation network (Fig. 1).

The central cluster highlighted in Fig. 1 defines the central references used by the Circular Economy literature. In other words, these 43 publications represent the contributions of IE to the development of CE literature. The summary with the top ten references are shown in Appendix 2.

The results show that most of the publications of the co-citation network are related to IE concepts and applications, especially regarding IS and EIPs (see Appendix 2). Chertow (2000, 2007) are the most influential publications in the IE literature according to the node degree and node between centrality indicators: they represent the most central publications, i.e., they have more relationships with other publications or clusters than any other; and, they are the most important cited papers in different groups because of their high values of node between centrality. These results can be justified because Chertow (2000) presents an extensive literature review on IS; and in Chertow (2007) several IS projects are analyzed. Additionally, both papers used the reviews of different IS projects to present the main benefits, barriers, IS and EIPs models, a main tool used in IS and for these reasons they are used as reference in other publications, justifying its high node degree value.

Other central publications focus on case studies that highlight motivations and barriers for the implementation of EIPs: Chertow and Lombardi (2005) explore the main environmental and economic benefits of IS in Puerto Rico; Heeres et al. (2004) compare the development of EIPs in the USA and Netherlands, showing how different approaches can lead to different results; Jacobsen (2006) analyzes some exchanges in Kalundborg Park from an economic and environmental perspective; Gibbs and Deutz (2007) present the main results in sixteen EIPs in the USA.

Zhu et al. (2007) mentioned the main strategies used by the Guitang Group in China to create and increase the network synergies of IS, internally and externally. The main motivation to create these synergies was to decrease emissions and the final disposal costs.

The article of Shi et al. (2010) is a publication with high node degree and node between centrality indexes which mentions CE. They present the results of the Tianjin Economic-Technological Development Area (TEDA), which was chosen as the national pilot industrial zone for demonstrating CE in China. Yuan et al. (2006) also mentioned this as a result of the inclusion of CE as a strategic issue for the Chinese Government. These are the most central publications that explicitly mentioned CE in the co-citation network. Geng et al. (2009a) also present case studies on the application of CE in China.

In the Japanese context, Van Berkel et al. (2009a) present an analysis of the industrial and urban symbiosis in the country between 1997 and 2006. Coincidentally, the Chinese and Japanese publications present a high node between centrality index, which can be understood by the wider scope of issues addressed, such as CE and Urban Symbiosis. It is justified that authors interested in this

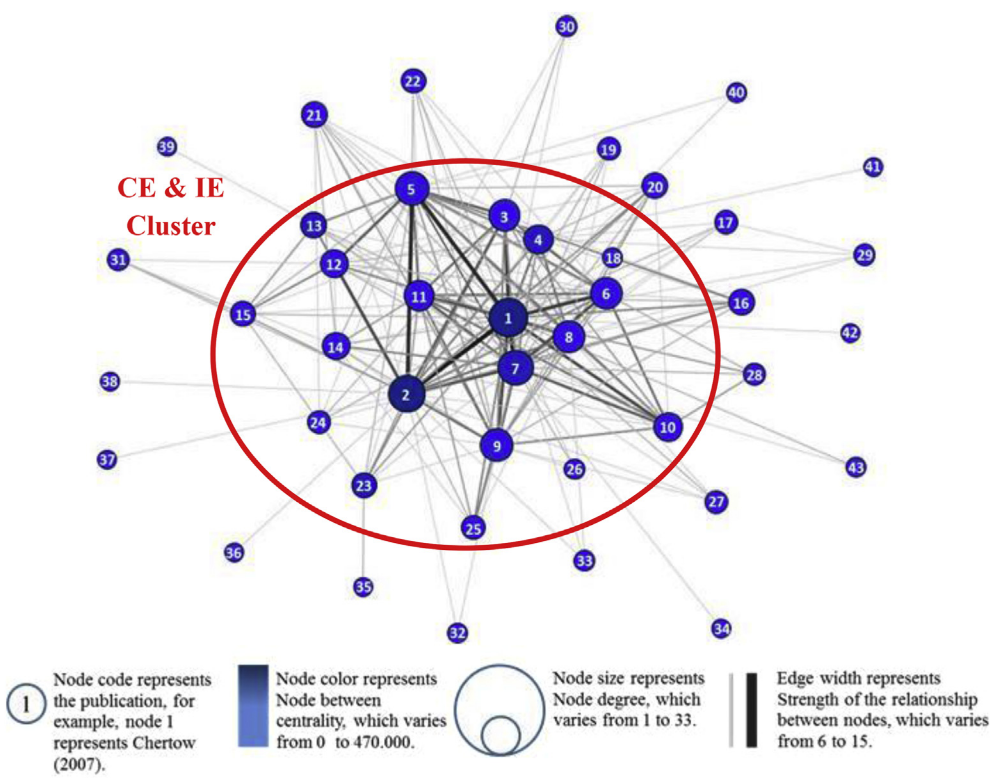

Fig. 1. Co-citation network for CE and IE literature (cutoff criteria = at least five relationships). Note: the node size indicates total node degree; the node color indicates node between centrality; edge width indicates the strength of relationships between nodes; and the node code indicates the publication, as described below. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[1] Chertow (2007); [2] Chertow (2000); [3] Chertow and Lombardi (2005); [4] Heeres et al. (2004); [5] Jacobsen (2006); [6] Zhu et al. (2007); [7] Shi et al. (2010); [8] Gibbs and Deutz (2007); [9] Mirata (2004); [10] Van Beers et al. (2007); [11] Park et al. (2008); [12] Yuan et al. (2006); [13] Geng et al. (2009a); [14] Zhang et al. (2010); [15] Geng and Doberstein (2008); [16] Mirata and Emtairah (2005); [17] Chiu and Geng (2004); [18] Zhu and Cote (2004); [19] Sterr and Ott (2004); [20] Ashton (2008); [21] Costa et al. (2010); [22] Mattila et al. (2010); [23] Van Berkel et al. (2009a); [24] Van Berkel et al. (2009b); [25] Boons et al. (2011); [26] Chertow and Ehrenfeld (2012); [27] Costa and Ferrão (2010); [28] Ehrenfeld and Gertler (1997); [29] Roberts (2004); [30] Hashimoto et al. (2010); [31] Geng et al. (2009b); [32] Geng et al. (2008); [33] Baas and Boons (2004); [34] Fang et al. (2007); [35] Geng et al. (2010); [36] Geng et al. (2007); [37] Lombardi and Laybourn (2012); [38] Geng and Côté (2003); [39] Li et al. (2010); [40] Ashton (2009); [41] Lambert and Boons (2002); [42] Frosch and Gallopoulos (1989); [43] Gibbs and Deutz (2005).

topic use these articles for important information regarding the urban symbiosis and urban environments.

Furthermore, level of nodes with high betweenness centrality indicates some trends regarding CE studies that are supported by IE concepts: inclusion of urban symbiosis in the scope of CE research which is carried out by solid waste management studies in areas with geographic proximity and focused on maximizing the integration of IS through previously discarded municipal, commercial and industrial waste materials, as addressed in the studies of Sterr and Ott (2004) and Costa et al. (2010) (Van Berkel et al., 2009a).

Regarding the word co-occurrence network, Fig. 2 shows the relationship in the words, and Table 1 shows the twenty principal words, with relationships and their edge weight.

The main results of the word-occurrence network indicate that Industrial Ecology, Circular Economy, Economic and Development are the most cited words in articles. It is noted that Eco-Park, resource, sustainability and China are frequently cited. This is an expected result given that the keywords are used in the exploratory literature review, and also due to their relevance in the areas of Industrial Ecology and Circular Economy.

In terms of the frequency regarding the relationship between keywords (see Table 1), Environmental and Economic show a high relationships with Industrial Ecology and Circular Economy. It represents this dimension as fundamental to address the pillar of sustainability, however the word social is lacking, which represent the third dimension of sustainability. Finally, resource presents a good number of relationships with industrial ecology and circular economy.

The results of the bibliometric analysis show that most articles relating to CE and IE were published focusing on Chinese cases. China began to show greater interest to develop CE in the country for different reasons, such as environmental challenges related to rapid industrialization and urbanization, pollution and resource scarcity (McDowall et al., 2017). Other drivers are given by Su et al. (2013), such as biodiversity loss and deforestation, issues that are strictly related to climate change which in turn lead to production and environmental standards and regulations in international trade (green barriers).

In this sense, the reforms in governance ideology undertaken by

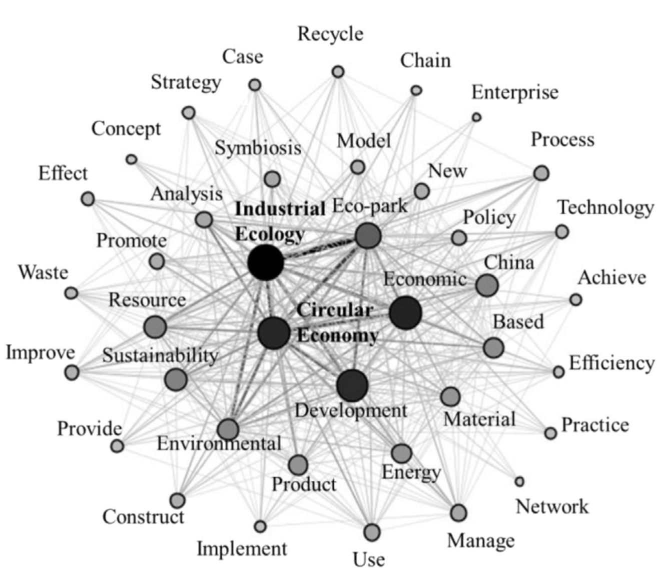

Fig. 2. Word co-occurrence network for CE and IE literature. Note: Nodes are sized and colored by the number of times the word is used, and edges are sized and colored based on the number of publications in which they co-occur. Some words have been truncated.

Table 1
Relationship between the most cited keywords in abstract – word co-occurrence network.

Word co-occurrence	Edge weight
Industrial Ecology - Eco-Park	196
Circular Economy - Eco-Park	147
Industrial Ecology - Circular Economy	140
Economic - Circular Economy	125
Economic - Industrial Ecology	113
Develop - Circular Economy	113
Industrial Ecology - Environmental	112
Industrial Ecology - Development	108
Circular Economy - Environmental	100
Development - Eco-Park	94
Economic - Eco-Park	89
Eco-Park - Environmental	87
Circular Economy - Analysis	81
Economic - Development	69
Industrial Ecology - Resource	69
Circular Economy - Resource	68
Industrial Ecology - Analysis	67
Circular Economy - Sustainability	67
China - Circular Economy	66
Economic - Environmental	64

the Chinese government have led to great efforts in the pursuit of a better use of resources (McDowall et al., 2017), and a sustainable economic structure (Su et al., 2013). From the 1990s to 2002, the country showed a period marked by a conceptual introduction regarding CE (Yong, 2007). According to (McDowall et al., 2017) the CE concept in China is based on cleaner production, IE, ecology transformation thinking, as well as some initiatives in other countries such as Europe, Japan and United States. Since 2002, the Chinese government decided to adopt the new development strategy to promote the CE, achieving a significant dissemination of the CE concept (McDowall et al., 2017). In 2004, the meeting of the Central Economic Affairs decided to promote CE as a long-term strategic task for Chinese economic development, and one year later the Chinese government established CE into the 11th Five-year Planning Outline for National Economic and Social Development, known as the 11th Five-year Plan (Yong, 2007). In the same year, the Program for Experimental Units of Circular Economy was published, which involves key industrial sectors, parks and enterprises, within key areas, provinces and cities. Since then, the development of the CE concept has increased, followed by the implementation methods, tools and indicators, consolidating the country as a pioneer in CE practices as a large-scale development strategy (Heshmati, 2015).

China's Circular Economy Promotion Law came into force in 2009. The CE law is mainly focused on municipal and industrial wastes, wastewater and resources, ecodesign, regulations on some of final disposal goods and green consumption; and it is based on the principle of Reduce, Reuse and Recycle, with priority to reduce. Furthermore, it emphasizes the integration of CE principles into land-use planning and, designation of specific areas (provinces, cities or zones) to implant and finance industrial parks as pilot initiatives on CE (McDowall et al., 2017). The 12th five-year plan (2011–2015) emphasizes the economic and social development and also recommends the continuous implementation of the CE. The result obtained in the pilot zones are used to guide future decision-making policy development (Su et al., 2013). The impact generated by the CE results in China, both nationally and internationally, has boosted several studies aimed at explaining the fundamental concepts involved as well as evaluations on the practical implementation of CE in China.

In parallel, the European Union action plan for the CE is also worth mentioning within this context. It is a broad action plan, developed to ensure favorable conditions for innovation and the involvement of all stakeholders towards CE. The proposed actions support the CE in each step of the value chain, with a well-established life cycle perspective: "from production to consumption, repair and remanufacturing, waste management, and secondary raw materials that are fed back into the economy" (European Commission, 2015).

For the production phase, the action plan involves both product design and production processes, encouraging IS and innovative industrial processes. One example of the proposed action relies on the Ecodesign directive and work plan (European Commission, 2015). Furthermore, this phase involves the cleaner manufacturing, Research and Development (R&D) funding and knowledge centers (McDowall et al., 2017).

The European Union action plan recognizes the importance of the consumption stage. Among the goals, we can mention more reliable green claims, enhanced integration of CE in Green Public Procurement, testing a methodology to measure environmental performance and examining how ecolabels can contribute to CE (European Commission , 2015). Additionally, new forms of consumption are stimulated, such as sharing or collaborative economy based on accessing and recovering products to utilize idle capacity and new forms of the business model such as Product Service Systems (PSS). According to Tukker and Tischner (2006), PSS is a combination of tangible product and intangible services designed and combined so that jointly they are capable of satisfying final customer needs. Finally, PSS is considered to be the most effective instrument for society to transition towards CE, ensuring resources can be used more efficiently (Tukker, 2015).

Regarding the market for secondary raw materials, it is a set of activities related to the development of quality standards for secondary raw materials and further development of the EU Raw Materials Information System (European Commission, 2015). Another initiative in the European Union action plan is related to introducing product labelling for extended product durability, the use of pricing instruments, consumer protection rules and innovative consumption (McDowall et al., 2017).

Finally, much attention has been directed to waste management in the EU action plan, not only in a revised legislative proposal on waste, but also with regard to identifying, disseminating good practices in waste collection systems (European Commission, 2015). In addition, there is a focus on extended producer responsibility rules and direct funding support, selecting five priority areas: plastics, food waste, critical raw material demolition/construction waste and biomass and bioproducts and standards for secondary materials (McDowall et al., 2017).

Another CE initiative is headed by the Ellen MacArthur Foundation, which has the mission is to accelerate the transition towards a CE, working with business, government and academia in order to build a framework for an economy that is restorative and regenerative by design (Ellen MacArthur Foundation, 2014).

In the business context, the Ellen MacArthur Foundation has a cross-industry project, called Project Mainstream, which addresses a collaborative action plan for industry leaders to scale up CE from pilot projects to sectoral and market scales. There is also the CE 100 program, which is a pre-competitive innovation program established to enable business organizations to develop new opportunities and projects through collaborative projects and acceleration workshop. Another initiative is a New Circular Design Guide developed by the Ellen MacArthur Foundation and IDEO to help change-makers and designers get started with circular innovation. Finally, the Foundation has the New Plastic Economy project, which is a project to apply the principles of CE in order to re-think and redesign the plastics system (Ellen MacArthur Foundation, 2016).

The Ellen MacArthur Foundation has programs across government and academia, such as: Circular Cities Network, which offers a knowledge exchange platform for pioneering cities which are introducing CE into their urban operations; development of a CE toolkit for policymakers; the Disruptive Innovation Festival, which is an online open access event for the exploration of economic changes; partnerships with universities and researchers that are working on CE; and also a capacity building program based on courses (Ellen MacArthur Foundation, 2016).

4. Concluding remarks

The specific goal of this paper was analyze the theoretical contribution of Industrial Ecology to Circular Economy.

From this perspective, the bibliometric analysis was fundamental and provided a detailed examination that ranges from Industrial Ecology to Circular Economy in the context of theoretical contribution.

Our analysis regarding the contribution of IE to CE through the bibliometric analysis enabled to identify important studies related to IE literature over the last fifteen years, focusing on IS concepts (including Urban Symbiosis) and on the implementation of EIPs. Based on the results from the bibliometric analysis, we have identified the main publications that detail the three levels of contribution of IE to CE:

1. Conceptual contribution

It concerns contribution related to synergy networks, such as material energy and water flows, in order to implement CE from the application of symbiosis in industrial and/or urban environments. According to Gregson et al. (2015), the integration of IS in CE involves the exchange of by-products and wastes in planned complexes of co-located manufacturing plants, which increases the intensity of localized resource use, adding value from the same initial inputs.

2. Technical contribution

It concerns the use of IE tools to fully or completely support CE. In this case, the tools most used to support the CE, such as MFA, Ecodesign and Cleaner Production, are related to the application of IS and implementation of EIPs. In most cases, when applying these tools, different energy and material flows and common infrastructures and services are shared.

The study conducted by Li (2011) on EIPs illustrates the feasibility and rationality of this approach for the implementation of CE, providing more scientific information to enhance their performance and basis for decision making. It can be stated that the implementation of EIPs is an important practice at an intermediate (meso) level of CE as it enables clusters of firms to cooperatively manage material flows and by-products (Heshmati, 2015). Furthermore, CE can be implemented through methods and strategies such as Cleaner Production and Ecodesign.

Cleaner Production is relevant to reduce emissions, wastes and risks for humans and the environment, however, when the goal is to obtain and maintain the IS it could happen some tradeoff since Cleaner Production can substantially reduce or modify the generation of waste and the symbiotic exchanges (Shi et al., 2010). In addition, the application of CP practices focus mainly on manufacturing process efficiency, while IS and CE are related to system thinking and its effectiveness (Ellen Macarthur Foundation, 2014).

Ecodesign, on the other hand, is an effective strategy to advance the eco-efficiency of enterprises and can be a useful eco-innovation practice for CE since it integrates cost, performance, quality and

Table 2
Contribution of IE to CE.

Contribution of IE	CE Principles based on Ellen McArthur Foundation
- Study the material and energy flows and their application. - Introduce the principles of the biological ecosystem in the industrial ecosystem - Transform the linear and semi-circular flows to circular or close flows. - Eliminate the dependence on the finite stocks and reuse the waste generated into the system. - Provide material flow analysis in a complex system.	Preserve and enhance natural capital by controlling finite stocks and balancing renewable resources flows.
- Use IS and EIPs. - Use waste as by-products. - Use strategies such as: reuse, recycling, repair and remanufacturing. - Extended the life cycle of products. - Do more with less (dematerialization) - Develop more services than products (PSS). - Use the Design for Environment or Ecodesign. - Implement Cleaner Production in the companies.	Optimize resource yields by circulating products, components and materials in use at the highest utility at all time in both technical and biological cycles.
- Use the indicators to monitor the system effectiveness. - Research aimed at developing new ways for CE transition. - Implement national and international economic development policies.	Foster system effectiveness by revealing and designing out negative externalities.

environmental attributes of a product by integrating environmental aspects into the product engineering design process (Fiksel, 1996). As stated by Haas et al. (2015), if a product is designed favoring recycling combined with economic incentives, there is a high potential to close material loops. Those authors applied a systemic and socio-metabolic approach to assess the current level of circularity of an economy and found that, even with considerably higher end-of-life recycling rates in the EU, the overall degree of circularity is low and decisive Ecodesign is required to advance toward a CE (Haas et al., 2015).

3. Political and standard contribution

It concerns the application of IE to support the development of policies, laws and standards in order to implement CE in local, regional and global environments. In order to achieve this systematic transition towards a CE at a macro level, the collaboration of the business community, policy makers and institutions is fundamental. Some policy instruments can be applied in this broader context of CE, such as regulatory instruments (including laws and directives), research and educational instruments, technology transfer and informational instruments (e.g. ecolabelling).

Table 2 presents the main contributions of IE to CE based on the information identified in the bibliometric analysis and the three principles of CE, as cited by the (Ellen MacArthur Foundation, 2016). It shows the different IE tools that can be applied in the second CE principle.

However, it was possible to identify a possible tradeoff between IE tools and its application, such as IS and Cleaner Production as cited by Shi et al. (2010) in a research focused on the Tianjin Economic-Technological Development Area case study in China. These kind of tradeoff should be further explored in future researches.

Moreover, according to some findings in the literature, CE is sometimes considered as a broader discipline than IE because of the inclusion of economic and policy issues, but most of the clusters found in the bibliometric analysis focus on the technical issues of IE, followed by the conceptual and policy issues of IE. In other words, there is a lack of conceptual background on economic issues which can be explored in future studies.

Finally, this research enabled to observe that CE evolution over time would not be possible without the existence of IE concepts and tools.

This study has some limitations. Regarding the bibliometric analysis, we highlight that the research separated the initial sample, implying a smaller view of the areas that compose the CE literature.

This paper highlights directions for future research in CE from an IE perspective. Based on the co-citation network, future clusters may include solid waste management and policies, which means that CE will address integrated solid waste management as a prominent approach to encourage collaboration between companies, industrial parks and local communities, thereby strengthening industrial and urban symbiosis.

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Appendix 1. Top ten References (Exploratory Literature Review)

#	Authors	Title	Journal	Year	Research Areas (according Web of Science)
1	Pan, SY; Du, MA; Huang, IT; Liu, IH; Chang, EE; Chiang, PC	Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review	J. Clean Prod.	2015	Engineering; Environmental Sciences & Ecology
2	Liu, Z; Geng, Y; Wang, H; Sun, L; Ma, ZX; Tian, X; Yu, XM	Energy-based comparative analysis of energy intensity in different industrial systems	Environ. Sci. Pollut. Res.	2015	Environmental Sciences & Ecology
3	Li, H; Dong, L; Ren, JZ	Industrial symbiosis as a countermeasure for resource dependent city: a case study of Guiyang, China	J. Clean Prod.	2015	Engineering; Environmental Sciences & Ecology
4	Haas, W; Krausmann, F; Wiedenhofer, D; Heinz, M	How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005	J. Ind. Ecol.	2015	Engineering; Environmental Sciences & Ecology

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(*continued*)

#	Authors	Title	Journal	Year	Research Areas (according Web of Science)
5	Iacondini, A; Mencherini, U; Passarini, F; Vassura, I; Fanelli, A; Cibotti, P	Feasibility of Industrial Symbiosis in Italy as an Opportunity for Economic Development: Critical Success Factor Analysis, Impact and Constrains of the Specific Italian Regulations	Waste Biomass Valorization	2015	Environmental Sciences & Ecology
6	Kopnina, H	Sustainability in environmental education: new strategic thinking	Environ. Dev. Sustain.	2015	Environmental Sciences & Ecology
7	Yu, B; Li, X; Shi, L; Qian, Y.	Quantifying CO2 emission reduction from industrial symbiosis in integrated steel mills in China	J. Clean Prod.	2015a	Engineering; Environmental Sciences & Ecology
8	Wang, H; Xu, XG; Zhu, GR	Landscape Changes and a Salt Production Sustainable Approach in the State of Salt Pan Area Decreasing on the Coast of Tianjin, China	Sustainability	2015	Environmental Sciences & Ecology
9	Yu, C; Dijkema, GPJ; de Jong, M	What Makes Eco-Transformation of Industrial Parks Take Off in China?	J. Ind. Ecol.	2015b	Engineering; Environmental Sciences & Ecology
10	Zhu, QH; Geng, Y; Sarkis, J; Lai, KH	Barriers to Promoting Eco-Industrial Parks Development in China: Perspectives from Senior Officials at National Industrial Parks	J. Ind. Ecol.	2015	Engineering; Environmental Sciences & Ecology

Appendix 2. Top ten references (Bibliometric Analysis Results)

ID	Reference	Node degree	Node between centrality	Summary
1	Chertow (2007)	33	451,42	The article examined 27 projects to provide a historical view regarding the motivations and means for pursuing industrial symbiosis (IS) and the importance of including the physical exchanges between energy, water, material and by-products among different clusters of firms for sustainable industrial development and design and to build eco-industrial parks (EIPs).
2	Chertow (2000)	29	469,99	The goal in this study is to present the review on industrial symbiosis (IS) and the efforts to develop Eco-industrial parks EIPs for the application of IS. Additionally, the paper presents five types of materials exchange and some tools.
3	Chertow and Lombardi (2005)	19	44,41	This paper shows the main results on the industrial symbiosis network in Guayama, Puerto Rico, and also explored the main environmental and economic benefits and regulatory perspectives for individual participants and the community.
4	Heeres et al. (2004)	15	183,23	The goal of this study was to compare the differences between six EIPs development projects, three located in the Netherlands and three in the US. The main results cited that the Netherlands project had more success than the US project. The main cause can be that the in US the EIPs are initiated by local and regional government and in general the companies have no interest in the project. On the other hand in Netherlands the EIPs are initiated by the companies that have financial support from the local and regional government.
5	Jacobsen (2006)	23	91,13	This paper presents the analyses in economic and environmental terms regarding some exchanges in Kalundborg park. The conclusion cited that de IS was viewed by the company as understanding the difference between individual economic and environmental performance and the collective approach to industrial sustainability.
6	Zhu et al. (2007)	19	59,13	This paper presented some internal and external strategies used in IS by the Guitang Group (GG) in China for more than four decades. Additionally, the GG invested to create its own collection with companies that can assist with the synergies, mainly with by-products. The internal IS operations include producers of white sugar, raw sugar, pulp, paper, alcohol, cement, and fertilizer. The external IS network includes the government, customer, suppliers and other sugar producers. This strategy helped to decrease emissions, disposal costs and improved the quality of sugar.
7	Shi et al. (2010)	26	229,70	This paper presents the results and the environmental benefits of the key symbiotic exchanges of the Tianjin Economic-Technological Development Area (TEDA). This park is one of the three EIPs in China. Moreover, some characteristics of EIP show progress in developing countries.
8	Gibbs and Deutz (2007)	20	50,60	This paper presents the main results based on interview surveys in 16 EIPs located in the USA and in Europe. The results showed there are few examples of the symbiotic exchanges, mainly waste and materials recycling, as these EIPs were in the early development phase. Finally, this paper cited the need to create more potential links within locality, helped by pro-active policies.
9	Mirata (2004)	21	85,26	This paper presents the revision of the factor that influences sustainable development in regional industrial symbiosis (IS) networks and discusses the roles of the coordination body and their main characteristics. For this, three programs in initial phase were analyzed and the national IS programme (NISP). The paper emphasizes that the UK and the public organs have the means to support the development of IS.
10	Van Beers et al. (2007)	14	11,22	This paper has an overview of the past and current situation in two main areas in Australia (Kwinana and Gladstone) in mineral processing and presents the assessment on the main barriers, drivers and trigger events on alternative synergies. The results cited that the two areas show maturity related to the existing synergies and show potential in three main areas: water, energy and inorganic by-product reuse. Additionally, to improve and support more initiatives, the Centre for Sustainable Resources Processing (CSRP) includes research for potential synergies, in order to provide support to this industry.

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