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A Critical Review of Industrial Symbiosis Models

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Abstract. The growing attention on sustainable development themes, in line with an increasing awareness of the exhaustibility of natural resources, has made the traditional linear economic model obsolete. Therefore, the concept of "Circular Economy" was developed to favour products and materials recovery and regeneration. To this end Industrial Symbiosis represents a promising approach to foster the transformation towards this type of economy, based on resource efficiency, sustainable manufacturing, materials, energy, water and/or by-products exchange and sharing between different companies. In this context, the aim of this paper is to present a classification and a critical discussion about existing industrial symbiosis models. According to the presented literature review, industrial symbiosis can be realized thorough the implementation of three different models: (i) industrial symbiosis districts that develop from a bottom-up approach and are based on resources sharing and materials exchanging, (ii) eco-industrial parks that develop from a top down approach and are determined by eco-sustainable infrastructures and systems, and (iii) networks for industrial symbiosis that evolve through cognitive/relational tools and are based on resources supply and demand intersection. The final objective of this study is to evaluate strengths and weaknesses of each model, to explore the applicability in real contexts, and to identify potential economic and environmental benefits (e.g. reduction of polluting emissions and landfilled wastes, economic savings due to reuse of scraps, energy sharing). The study concludes by identifying research gaps, reflecting on possible application of industrial symbiosis and proposing suggestions for future work.

Keywords. Industrial symbiosis, resource efficiency, industrial symbiosis districts, eco-industrial parks, collaborative platform

Introduction

In recent decades, the concept of sustainability has acquired growing importance and many methodologies have been developed to promote product and process sustainability within companies. In 1989 Frosh and Gallopoulos published the study entitled "Strategies for Manufacturing" in which the industrial ecosystem concept was firstly introduced. Authors stated that traditional industrial activity models should be turned into more integrated models, by changing the way in which companies pick up raw material, make products and generate waste to dispose of [1]. The industrial

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ecology concept, based on the interaction between different industrial systems and between industrial and ecological systems, was essentially born with this study. The idea of industrial ecology stems from its close similarity with ecological natural systems. Models derived from natural systems, by analogy, can be applied to the design of processes and forms of industrial organization [2].

In this context, industrial ecologists mainly aim to promote economic development and the simultaneous reduction of environmental impacts, through the maximization of efficiency in the exploitation of energy and material inputs. In accordance with the Circular Economy paradigm, each company participates in a productive system in which all inputs are transformed into output (total throughput), scraps and wastes are recovered (zero waste system) and emissions are null. The achievement of this result implies the need for new forms of cross-sectoral integration (industrial clusters) for the valorisation of wastes.

To this end Industrial Symbiosis represents a promising approach to foster the transformation towards this type of economy. Industrial symbiosis investigates the relationships between the industrial systems and their natural environment [3], and wants to address the question of how to involve separate industries in one collective approach aimed at obtaining competitive advantages deriving from the sharing of materials, energy, water and/or by-products [4]. The main means to practically realize the symbiosis between companies are:

- utilities and infrastructures sharing for an efficient use and management of resources such as steam, energy, water and waste;
- the joint provision of services to meet common needs related to businesses, safety, hygiene, transport and waste management;
- the exchange of materials, traditionally intended as wastes or by-products instead of commercial products or raw materials.

The literature analysis shows that some reviews on industrial symbiosis have already been carried out, in particular concerning classification of resources and utilities that can be shared. However, issues related to creation and design of industrial symbiosis networks have not been reviewed yet. Therefore, the aim of this paper is to propose a new literature review focused on the analysis of features, strengths and weaknesses of the different models of industrial symbiosis implementation.

After this Introduction that contextualizes the study, the Materials and Methods section describes the method applied to select the papers from the literature. Industrial Symbiosis section presents a classification of industrial symbiosis models (industrial symbiosis districts, eco-industrial parks, platform for industrial symbiosis). Finally, Discussion and Conclusions section presents a critical discussion of the reviewed studies, together with conclusions and proposals for future developments.

1. Material and Methods

The review has been conducted by using the ScienceDirect, Scopus and ReaseachGate databases as sources of scientific papers, as well as considering articles found in the bibliography of the analyzed papers. The review covers a time span of about 30 years, as shown in Figure 1. The search of the papers kas been structured in two phases, using different sets of keywords. Firstly, multiple keywords have been used to identify general information of industrial symbiosis: “industrial symbiosis”, “resource efficiency” and “industrial ecology”. Secondly, different keywords have been used to analyze the three main industrial symbiosis models: “industrial symbiosis districts”, “eco-industrial parks” and “platform for industrial symbiosis”.

The analysis allowed founding 42 references (in particular 30 journal papers and 12 conference papers). The references have been collected, analyzed and categorized according to those informations:

- general information: title, authors, years;
- paper typology: proposal of theoretical methods, practical approaches, review paper, case study.specific information: objective, main findings, conclusions, limitations of the study;

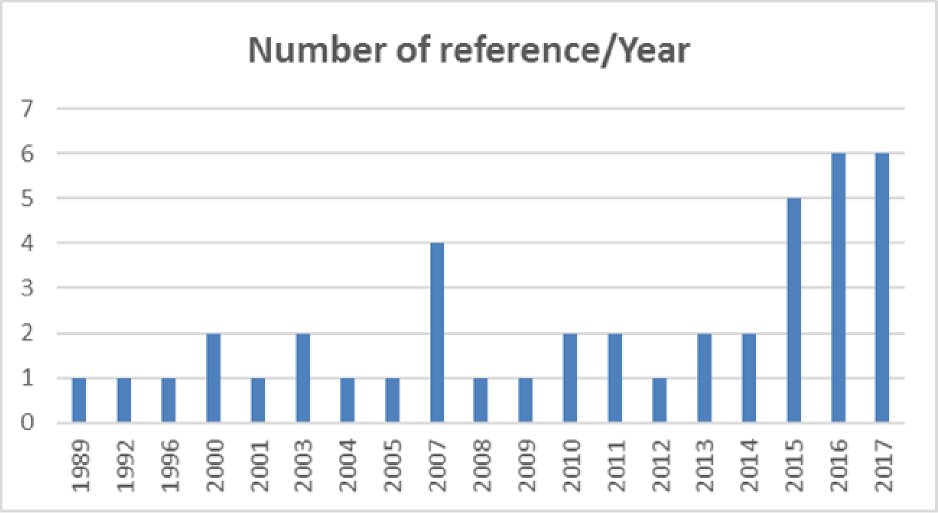

Figure 1. Temporal distribution of references analysed.

Successively, a further criterion has been used to classify the industrial symbiosis models in three different typlologies, as shown in Figure 2:

- industrial symbiosis districts;
- eco-industrial parks;
- platform for industrial symbiosis.

2. Industrial Symbiosis models

Industrial symbiosis is a sustainable and ecologically integrated industrial model. The final aim is to encourage exchanges and sharings between companies, thus the traditional concept of waste disappears and materials candidate to be exchanged are considered economic goods. This creates important advantages for the business system and for the community, both in economic and environmental terms. From the economic point of view, the reuse of products can potentially lead to the reduction of production costs, through the use of low cost second-life resources and/or the selling of production wastes. From the environmental point of view, instead, benefits are linked to the reduction of resources consumption (water, coal, oil, gypsum, fertilizers, etc.), emissions in water and atmosphere, production of wastes and the consequent disposal in landfill [5].

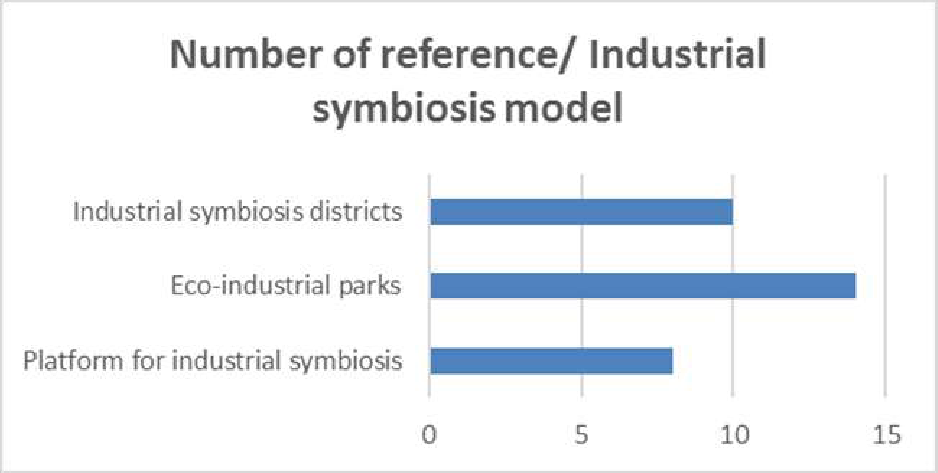

Figure 2. Number of references analysed for each industrial symbiosis model.

According to the analyzed literature, Industrial symbiosis can be realized through the implementation of three principal models [6]:(i) development of industrial symbiosis districts, (ii) design of eco-industrial parks, and (iii) networks designing for industrial symbiosis. The following paragraphs present the most interesting research studies related to each model.

2.1. Industrial symbiosis districts

The development of industrial symbiosis districts is a "bottom-up" approach. Relationships between companies are developed independently from long-term programming. These relations are based on specific agreements between two interlocutors that agree to carry out exchanges of materials, energy flows or even services. Different studies demonstrate that the regional economy and the economic geography should be the starting point for the development of industrial symbiosis[7].

Branson claims that prerequisites for the development of industrial symbiosis districts are the geographic proximity between the involved organizations, but especially a “short mental distance” between managers [8]. Valentine, on the other hand, states that the four pillars who foster collaboration are essentially: i) a pragmatic environmental mentality, ii) the existence of opportunities to explore possibilities; iii) mutually beneficial initiatives; and iv) the presence of dominant needs that stimulate a proactive search for solutions [9]. However, the variety of territory 's companies can be considered a starting point for the development of waste exchange networks. For this reason local industrial agglomerations can be considered a favorable environment for symbiotic synergies creation [10].

The most influential example of industrial symbiosis district is the eco-industrial system at Kalundborg.This example, cited in many literature studies, constitutes the archetypal system of the industrial symbiosis [9]. The collaborations started in the 70s and resulted in a complex network of material and energy exchanges. The number of subjects involved and projects realized have grown over the years. The involved actors belong to different sectors of activity, such as power plants, chemical companies, plasterboard producers, a land reclamation company, a refinery, the municipality of Kalundborg, acting as a supplier of materials and energy flows and utilities, a fishing factory, and some materials recycling companies that act as recipients for several material flows. All the involved actors have brought numerous advantages in terms of significant reduction in the volume of generated waste and virgin raw material consumption [11].

Notarnicola et al. highlighted how the industrial symbiosis could be an opportunity to overcome economic crisis in Taranto district, Italy. Trough the implementation of an industrial symbiosis district, this geographical area could be more competitive and environmentally sustainable. After a classification of all the companies present in the district the study presents the current status of symbiosis and proposes new feasible symbiotic interactions [12].

Wang et al. wanted to encourage companies of the Chinese industrial area to engage in waste trade. The aim of their study was to identify reusable wastes as a means towards sustainable industrial development. However, in this research, Wang et al. seek to overcome limits of communication between managers of different companies through the identification of an organizational committee that collectively provides the information, knowledge, skills and abilities required to help the district development [13].

Through the analysis of previous case studies related to industrial symbiosis in three Italian “Cluster Industrial”, Taddeo et al. classified technical and non-technical aspects that can influence potential development of industrial symbiosis: geographical and technical requirements of the site, homogeneity / heterogeneity of industries, active participation of the stakeholders, regulatory system. At the end they analyze how the key factors can act (positively or negatively) in Industrial symbiosis development (previous state, current state and future state) [14].

Another opportunity for industrial symbiosis is seized in the study by Mauthoor, who aimed to encourage opportunities for industrial symbiosis among main polluting industries of the Republic of Mauritius (a group of islands located in the South-West of the Indian Ocean). By-product exchanges should alleviate the waste load on the only landfill in Mauritius, which is reaching saturation [15].

2.2. Design of Eco-Industrial Parks

Eco-Industrial Parks are designed and managed on the basis of ecology and industrial symbiosis principles.A park is always initially programmed and consists of a number of Industrial Symbiosis instances that allow exchanges of energy / materials between industrial companies. Eco-Industrial Park development, unlike the Industrial Symbiosis district, can be planned through a top-down approach. Generally it is managed by institutions of local administrations, research centers or universities. A commonly adopted definition is "an industrial system of planned materials and energy exchanges that seeks to minimize the use of energy and raw materials, the generation of waste and build up sustainable economic, ecological and social relations" [16][17]. A fundamental prerequisite for the effective implementation of eco-industrial parks is to demonstrate that economic and environmental gains obtained by working synergistically are superior than in case of companies individual work [18].

An eco-industrial park must be configured through the choice of the number of connections between the individual actors. However, decisions on number of connections and quantification of energy and materials to be exchanged are usually guided by design objectives and economic and environmental indicators. This consequently leads to one of eco-indutriale park issues identified in literature: dominance of the global optimum over the local optimum. According to Kuznetsova et al. eco-indutrial park design process requires a stronger "balancing" of industrial companies desires with global Eco industrial park design goals [19].

The main countries that have positively adhered to Eco-industrial park development are United States of America [20], Australia [21], Canada [22], Finland [23], Korea [24] and China [25]. In particular, many preliminary studies concerning the implementation of possible Eco Industrial parks in China can be found in literature. Sun et al., for example, realized a flow analysis with the aim to highlight the ecological benefits originated from the implementation of industrial symbiosis in a typical industrial city in China [26]. Dong et al. focused on a case of industrial and urban symbiosis in Guiyang city [27]. Donga et al. promoted urban industrial symbiosis in a typical industrial city named Liuzhou (southern China), through hybrid evaluation model that integrates life-cycle assessment (LCA) and input-output (IO) analysis [28]. Similarly, both studies wanted to show eco-benefits that could be obtained from eco-industrial parks development in China. Process synergies, waste reuse and utilities (energy, water, etc.) sharing would lead to significant resources savings and carbon dioxide emissions reduction, as well as to economic savings for the involved companies.

In spite of the tendency to develop forms of agglomeration of companies, there are still no relevant examples of eco-industrial parks operations in Italy. According to Taddeo et al. [29], the main problems that limited the development of eco-industrial parks are the following ones:

- the high complexity of solutions included in the eco-industrial park model;
- a cultural gap of companies and premises community compared to the new eco-industrial development;
- regulatory limits (in Italy, companies, unless authorized, can not directly manage or use scraps generated by other companies, since these flows are classified as wastes);
- the economic crisis, which has considerably limited the possibilities for new investments by companies [30].

2.3. Platform for industrial symbiosis

As said before, industrial symbiosis involves separate companies and organizations to promote innovative strategies for a more sustainable resources use. In cases of the development of industrial symbiosis platforms, geographical proximity is not necessary. The networks for industrial symbiosis are cognitive/relational tools which aim to favour meeting opportunities between interlocutors of different companies and their relative supply and demand for resources [31].

Most of the platforms identified in literature, as the Core Resource for Industrial Symbiosis Practitioners (CRISP), the Bourse des résidus industriels du Québec (BRIQ) and the RecycleMatch, work through an input-output match of diversified resources deriving from industrial entities. Low et al. tried to improve these networks by adding elements to support an economic viability analysis, carried out by considering potential trades [32]. The concept of input-output correspondence generally aims to allocate process outputs (waste) to inputs (raw material) of another process. This process must be supported by a detailed analysis of materials flows, processes and information, and data exchanged [33]. As a consequence, a crucial aspect for industrial symbiosis platform development and for the matching process is the data collection and classification [34]. For this reason, Song et al. discussed methods to apply a big data approach in order to obtain necessary data for discovery potential industrial symbiosis opportunities [35].

The most emblematic example of industrial symbiosis platform, existing since 2005 in Great Britain, is the National Industrial Symbiosis Program (NISP). NISP network is the first symbiosis initiative industrial proposal on a national scale. Over the years it has recruited almost 13,000 companies and is equipped with 12 regional work groups that cover the entire UK territory. NISP is implemented through a network of members who can identify technological and commercial opportunities to exchange resources, materials, energy, water, logistics and expertise [36]. Another example has been developed in the context of a research project co-funded by European Commission and coordinated by University of Athens. E-Symbiosis platform aims to support communication between small and medium-sized enterprises (SMEs) in the European Union. E-Symbiosis is a web-based tool that allows companies, to identify interesting connections and to directly communicate with partners [37]. Also, the Italian agency for new technologies, energy and sustainable economic development (ENEA) has implemented an industrial symbiosis platform. The main objective of this project was to provide a methodology for the implementation of regional-scale industrial symbiosis as a support for SMEs to identify symbiosis opportunities in their region [38].

3. Discussion and Conclusions

The analyzed models for Industrial Symbiosis have different implementation methodologies. However, in all the models, the main aim is more or less the same: to identify production processes that can use as input the outputs coming from other processes/industries. This essentially favours products and materials recovery and regeneration and fosters the transition to circular economy [39].

Table 1 shows the main strengths and weaknesses of the three analyzed industrial symbiosis models.

Concerning barriers to practical implementation of industrial symbiosis models, trust and cooperation between different companies are key factors that heavily influence network and interchange activities [40]. In particular, it is necessary to reduce “mental distance” between companies. The coordination of a specific authority can provide a guide for companies towards an environmental improvement [41]. All these aspects, can be classified as "communication related barriers". This category also includes all issues related to information and data sharing.

Two other barrier classes for industrial symbiosis models implementation have been identified through this study. The first class concerns "companies geographical position related barriers", which include problems related to utilities sharing and ease of products transportation. The second class, instead, mainly regards "barriers related to readiness to change", which include issues related to propensity to change processes in order to adapt them to new input materials (i.e. recovered wastes or scraps).

Table 1. Strengths and weaknesses of industrial symbiosis models.

MODEL	STRENGTHS	WEAKNESSES
Industrial Symbiosis Districts	• utilities sharing • easy transport of waste • easy trust relationships between partners	• communication between managers • synergies depend on territory multidimensionality • dependence on geographic position
Eco-Industrial Parks	• connections between companies are identified by third parties • energy-efficient buildings • easier production processes design based on waste of other companies	• more attention to global than to individual advantages • authorization issues • economic investments
Platform for Industrial Symbiosis	• possibility to develop the connection independently from the geographical position of the involved industries • easier to know about any waste exchanges	• resistance to data sharing • difficulty in transferring resources • difficulty in utilities sharing • relationship difficulties between managers

Analysis of the literature shows that some of these problems are transverse to all the industrial symbiosis models, while other ones are specific for each model. Thus, the choice of a model strictly depends from the context of application, and in some cases, weaknesses of a model represent strengths for another one.

However, in general, all the identified models are difficult to put in practice. In fact, with the exception of specific cases, literature only contains preliminary and not fully operational case studies. Therefore, future studies might be focused on the development of a "fourth" model that mixes strengths of all three existing models, trying to eliminate, or at least mitigate the barriers listed above, in order to favor a real transition toward industrial symbiosis and circular economy [42].

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