

## RESEARCH ARTICLE

# A critical review of symbiosis approaches in the context of Industry 4.0<sup>☆</sup>

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## Abstract

The implementation of symbiosis approaches is recognized as an effective industrial strategy towards the optimization of resource exploitation and the improvement of collaboration in the context of Industry 4.0. An industrial system can be considered as a complex environment in which material, energy, machine, and human resources should cooperate towards the improvement of efficiency and the creation of value. According to this vision, the paper presents a detailed literature review about the existing symbiosis approaches: (i) industrial symbiosis models, which mainly aim at the sharing of resources among different companies, and (ii) human symbiosis, which focuses on how to effectively strengthen the synergy among humans and machines. Strengths, weaknesses and correlations among the most common symbiosis approaches are analysed and classified. Finally, the existing symbiosis models are related with the pillars of the Industry 4.0 paradigm, in order to understand what should be the future directions of research in the context of collaborative manufacturing.

**Keywords:** industrial symbiosis; human symbiosis; Industry 4.0; collaborative manufacturing

## 1. Introduction

The ever-increasing trend of industrial automation will lead to a completely automated and interconnected industrial production. As a consequence, the concept of Industry 4.0 is acquiring importance in the industrial sector (Stock & Seliger, 2016). The convergence of information–communication and industrial automation technologies is strongly contributing to the creation of completely novel technology architectures and new connections between physical and digital systems (Martin, Marcos, Aguayo, & Lama 2017). The Industry 4.0 paradigm will be a step towards the creation of a more sustainable industrial value. This step represents an essential contribution to all the three sustainability dimensions: environmental, social, and economic (Crvalho, Chaim, Cazarini, & Gerolamo 2018).

However, in this context, digital enterprises need not only to be interconnected but also the practical implementation of collaborative engineering approaches is required, in order to efficiently put in practice collaborative actions among various stakeholders and resources. In a period where the focus of the scientific community is mainly pointed on the efficient use and exploitation of big amounts of data, computing power and connectivity of equipment, open data or Internet of Things, the novel idea of this paper is to focus on how to optimize the use and stimulate the collaboration among internal and external resources: material resources, energy resources, and human resources. Thus, the main research question of the present paper is: how is it possible to optimize the use of material, energy, and human resources according to the Industry 4.0 paradigm, and

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respect the constraints of sustainability pillars? The implementation of symbiosis approaches seems to be the best answer. In particular, two main categories of symbiosis can be found in literature: industrial symbiosis and human-machine symbiosis.

Industrial symbiosis focuses on how to optimize material and energy resources. In particular, it aims to investigate the relationships between the industrial systems and the natural environment in which it operates (Chertow, 2010). The final objective is generally to find the best solution 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 (Chertow, Ashton, & Espinosa, 2008; Marconi, Favi, Germani, Mandolini, & Mengarelli 2017). The main means to practically realize the symbiosis between companies are the following:

- utility and infrastructure 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.

Human-machine symbiosis, instead, analyses the figure of the operator inside a smart factory. According to this approach, the human-machine synergy can be considered an interesting opportunity for the company to increase productivity (Horiguchi, Burns, Nakanishi, & Sawaragi 2013). The technologies and architectures developed in the context of Industry 4.0 add considerable complexity due to the introduction of autonomous and semi-automatic agents that communicate and interact with the application networks. In this environment, the collaboration needs to be extended to human workers, robots, and other intelligent entities and gives rise to a kind of holistic integration, along different levels of abstraction and coordination (Hadorn, Courant, & Hirsbrunner, 2015). By implementing human-machine symbiosis, human workers and artificial systems dynamically adapt and cooperate to achieve common goals (Romero, Bernus, Noran, Stahre, & Fast-Berglund 2016).

The objective of this paper is to propose a new literature review focused on the analysis of common and different features between industrial symbiosis models and human-machine symbiosis. Existing literature studies (Boons, Spekkink, & Mouzakitis, 2011; Ferreira, Doltsinis, & Lohse, 2014; Charalampous, Kostavelis & Gasteratos, 2017; Jiao & Boons, 2018) treated the two symbiosis typologies (i.e. industrial and human) as separate aspects. However, industrial systems can be considered complex environments in which different resources (i.e. material, energy, machine, and operators) are exploited towards the creation of value. An effective cooperation among resources should be guaranteed to improve both the internal efficiency of single companies, and the overall efficiency of production networks (Marconi, Marilungo, Papetti, & Germani 2017). Therefore, a comprehensive view is needed to investigate how collaboration and symbiosis among the different resources could take place and positively influence the performance of the entire industrial system. This justifies the need of a new literature review mainly focused on the integration of industrial and human symbiosis approaches, under the common umbrella of the Industry 4.0 paradigm.

After this Introduction section that contextualizes the study, the Research Methodology section describes the method applied

to select the papers from the scientific literature. The Industrial Symbiosis Models section presents a classification of industrial symbiosis models in three different categories (industrial symbiosis districts, eco-industrial parks, and platform for industrial symbiosis), together with their main strengths and weaknesses. The Human-Machine Symbiosis section presents an analysis of possible human-robot/machine synergies. The Discussion section reports a discussion on how the existing approaches can be effectively used in the context of Industry 4.0, together with the analysis of the industrial sectors involved. Finally, the Conclusions and Directions for Future Research section summarizes the obtained outcomes and gives indications about possible future developments on symbiosis topics.

## 2. Research Methodology

The review has been conducted by using the ScienceDirect, Scopus, and Research Gate databases as sources of scientific papers, as well as considering articles derived from the bibliography of the analysed papers. The review covers a time span of about 30 years, as shown in Fig. 1.

The search of the papers has been structured in four phases, using different sets of keywords. First, the keywords 'symbiosis' and 'Industry 4.0' have been used to identify relation between symbiosis and Industry 4.0. Second, multiple keywords have been used to analyse general information of industrial symbiosis: 'industrial symbiosis', 'resource efficiency', and 'industrial ecology'. Third, different keywords have been used to classify the three main industrial symbiosis models: 'industrial symbiosis districts', 'eco-industrial parks', and 'platform for industrial symbiosis'. Fourth, 'human-machine symbiosis' and 'human-robot symbiosis' have been used to investigate the field of symbiosis in terms of human-machine/robot collaboration.

The analysis allowed finding 1245 references, as shown in Fig. 1. As we can see from the graph, the human-machine symbiosis is a less thorough topic in the scientific literature that is growing in recent years.

The full set of references has been collected, analysed and categorized according to the following criteria:

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

Among all the papers found, 61 articles were selected, as they were considered more significant and more interesting for this review. Figure 2 reports the temporal distribution of references used in this study.

## 3. Industrial Symbiosis Models

Industrial symbiosis is a sustainable and ecologically integrated industrial model. The industrial symbiosis has been defined as the engine for the development of the circular economy in view of Industry 4.0. Sharing resources among different companies and integrating information along the value chain from supplier to consumer are considered pillars for the development of Industry 4.0 (Stock, Obenaus, Kunz, & Kohl 2018).

The final aim of industrial symbiosis models is to encourage exchanges and sharing between companies; thus, the traditional concept of waste disappears. In this way, material candidates to be exchanged are considered economic goods. This

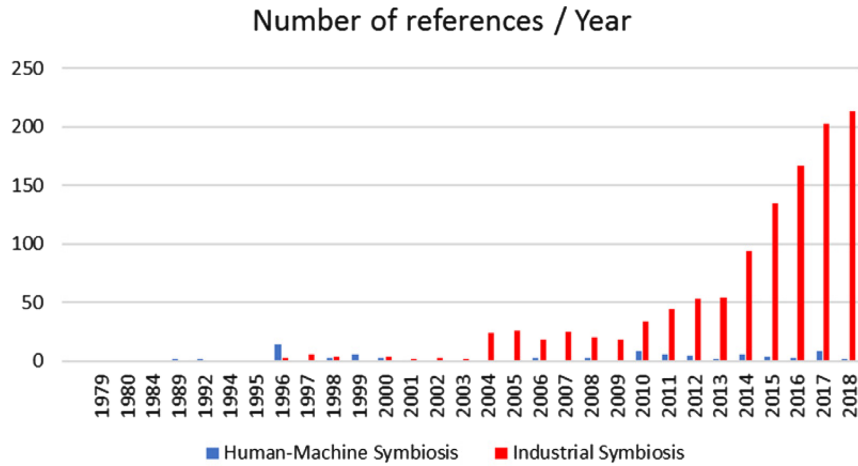


Figure 1: Temporal distribution of human-machine symbiosis and industrial symbiosis papers found in literature.

allows to create 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, using 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 a landfill (Chertow, 2007).

According to the analysed literature, industrial symbiosis can be realized through the implementation of three principal models (Yazan, Romano, & Albino 2016): (i) development of industrial symbiosis districts, (ii) design of eco-industrial parks, and (iii) networks designing for industrial symbiosis. Following this classification, Fig. 3 reports the percentage distribution of the reviewed papers, while the most interesting research studies related to each model are described in the following paragraphs. More than 50% of studies are related to the implementation of industrial parks, followed by districts and platform for industrial symbiosis.

### 3.1. Industrial symbiosis districts

The development of industrial symbiosis districts is a 'bottom-up' approach. Relationships between companies are developed independently by following long-term programming. These relations are based on specific agreements between two interlocutors that decide 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 (Gibbs, 2003).

On one hand, Branson (2016) claims that a prerequisite for the development of industrial symbiosis districts is the geographic proximity between the involved organizations, especially a 'short mental distance' between managers. Valentine (2016), on the other hand, states that the four pillars that foster collaboration are essentially the following:

- a pragmatic environmental mentality;
- the existence of opportunities to explore possibilities;
- mutually beneficial initiatives;
- the presence of dominant needs that stimulate a proactive search for solutions.

### Annual distribution of selected reference

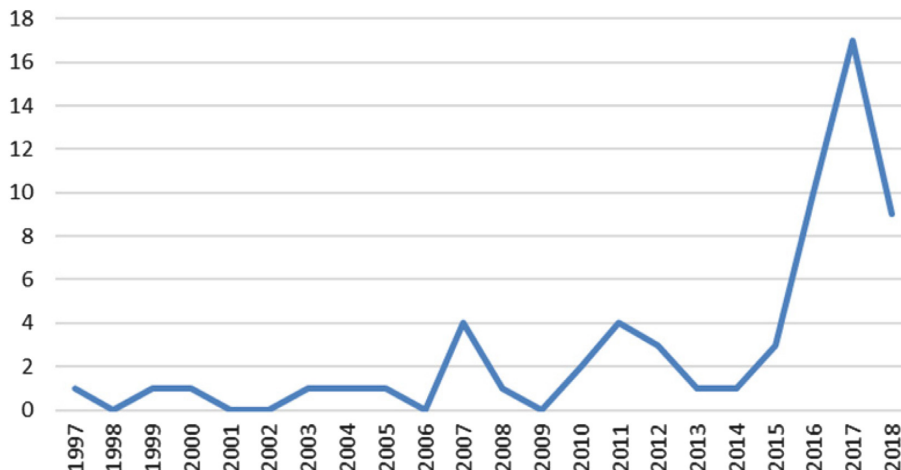


Figure 2: Temporal distribution of references used for the review.

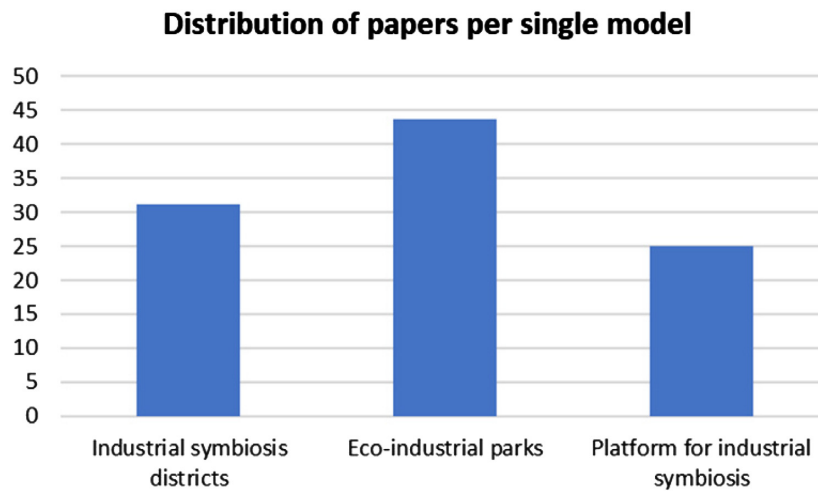


Figure 3: Percentage distribution of papers per single model.

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 favourable environment for symbiotic synergies creation (Taddeo, Simboli, Morgante, & Erkman 2017).

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 (Valentine, 2016). The collaborations started in the 1970s 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 a significant reduction in the volume of generated wastes and virgin raw material consumption (Domenecha & Davies, 2011).

Notarnicola, Tassielli, & Renzulli (2016) highlighted how the industrial symbiosis could be an opportunity to overcome economic crisis in the Taranto industrial district, Italy. Through 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 status of symbiosis and proposes new feasible symbiotic interactions.

Wang et al. (2017a) wanted to encourage companies in 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, they 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.

Through the analysis of previous case studies related to industrial symbiosis in three Italian 'Cluster Industrial', Taddeo et al. (2017) classified technical and non-technical aspects that can influence the potential development of industrial symbiosis: (i) geographical and technical requirements of the site, (ii) homo-

geneity/heterogeneity of industries, (iii) active participation of the stakeholders, and (iv) the regulatory system. At the end, they analyse how the key factors can act (both positively and negatively) in industrial symbiosis development (a previous state, current state, and future state).

Another opportunity for industrial symbiosis is seized in the study by Mauthoor (2017), who aimed to encourage opportunities for industrial symbiosis among main polluting industries in 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.

### 3.2. 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 centres, 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' (Alexander, Barton, Petrie, & Romagnoli 2000). 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 to companies' individual work (Boix, Montastruc, Pantel, & Domenech 2015).

An eco-industrial park must be configured through the choice of the number of connections between the individual actors. However, decisions on several connections and quantification of energy and materials to be exchanged are usually guided by design objectives, as well as economic and environmental indicators. This consequently leads to one of eco-industrial park issues identified in literature: dominance of the global optimum over the local optimum. According to Kuznetsova, Zio, & Farel (2016), eco-industrial park design process requires a stronger

'balancing' of industrial companies' desires with global eco-industrial park design goals.

The main countries that have positively adhered to eco-industrial park development are the United States of America (Chertow and Lombardi, 2005), Australia (Beers, Corder, Bossilkov, & Berkel 2007), Canada (Venta & Nisbet, 1997), Finland (Korhonen & Wihersaari, 1999), Korea (Behera, Kim, Lee, Suh, & Park 2012), and China (Zhu, Lowe, Wei, & Barnes 2007). In particular, many preliminary studies concerning the implementation of possible eco-industrial parks in China can be found in literature. Sun et al. (2017), for example, realized a flow analysis with the aim to highlight the ecological benefits originating from the implementation of industrial symbiosis in a typical industrial city in China. Dong et al. (2016) focused on a case of industrial and urban symbiosis in Guiyang city. Donga et al. (2017) promoted urban industrial symbiosis in a typical industrial city named Liuzhou (southern China), through hybrid evaluation model that integrates life-cycle assessment and input-output (IO) analysis. Similarly, all those studies wanted to show eco-benefits that could be obtained from eco-industrial parks' development in China. Process synergies, waste reuse, and utilities sharing (energy, water, etc.) 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 park operations in Italy. According to Taddeo, Simboli, & Morgante (2012), 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, cannot 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 (Li & Xiao, 2017).

### 3.3. Platform for industrial symbiosis

As said before, industrial symbiosis involves separate companies and organizations to promote innovative strategies for a more sustainable use of resources. In cases of the development of industrial symbiosis platforms, geographical proximity is not necessary. The networks for industrial symbiosis are cognitive/relational tools that aim to favour meeting opportunities between interlocutors of different companies and their relative supply and demand for resources (Laybourn & Lombardi, 2012).

Most of the platforms identified in literature, as the Core Resource for Industrial Symbiosis Practitioners, the Bourse des résidus industries du Québec, and the RecycleMatch, work through an IO match of diversified resources deriving from industrial entities. The idea is to try to improve these networks by adding elements to support an analysis of economic profitability, considering potential negotiations (Raabe et al. 2017). The concept of IO correspondence generally aims to allocate process outputs (waste) to inputs (raw material) of another process. This essential phase must be supported by a detailed analysis of materials flows, processes and information, and data exchanged (Grant, Seager, Massard, & Nies 2010). Consequently, a crucial aspect for the development of industrial symbiosis platforms and for the matching process is the data collection and classification

(Halstenberg, Lindow, & Stark 2017). For this reason, Song, Yeo, Kohls, & Herrmann (2017) discussed methods to apply a big data approach to obtain all the necessary information for discovering potential industrial symbiosis opportunities.

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 proposal of an industrial symbiosis initiative, developed on a national scale. Over the years, it has recruited almost 13 000 companies and is equipped with 12 regional working 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 (Jensena, Basson, Hellawell, Bailey, & Leach 2011).

Another example has been developed in the context of a research project co-funded by the European Commission and coordinated by the University of Athens. E-Symbiosis platform aims to support communication between small- and medium-sized enterprises in the European Union. E-Symbiosis is a web-based tool that allows companies to identify interesting connections and to directly communicate with partners (Cecelja et al., 2011).

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 small- and medium-sized enterprises to identify symbiosis opportunities in their region (Cutaia et al., 2015).

### 3.4. Strengths and weaknesses of industrial symbiosis models

The analysed models for industrial symbiosis have different implementation methodologies. However, in all the models, the main aim is 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. In addition, the transition towards circular economy is fostered (Saavedra, Iritani, Pavan, & Ometto 2018). Table 1 shows the main strengths and weaknesses of the three analysed 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 (Gibbs, 2003). 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 (Mirata, 2004). 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 the implementation of industrial symbiosis models 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 and adapting them to new input materials (i.e. recovered wastes or scraps).

The analysis of the literature shows that some of these problems are common to all the industrial symbiosis models, while

**Table 1:** Strengths and weaknesses of industrial symbiosis models.

Model	Strengths	Weaknesses
Industrial symbiosis districts	<ul style="list-style-type: none"> <li>• utilities sharing</li> <li>• easy transport of waste</li> </ul>	<ul style="list-style-type: none"> <li>• communication between managers</li> <li>• synergies depend on territory multidimensionality</li> </ul>
Eco-industrial parks	<ul style="list-style-type: none"> <li>• easy trust relationships between partners</li> <li>• connections between companies are identified by third parties</li> <li>• energy efficient buildings</li> <li>• easier production processes design based on waste of other companies</li> </ul>	<ul style="list-style-type: none"> <li>• dependence on geographic position</li> <li>• more attention to global than to individual advantages</li> <li>• authorization issues</li> <li>• economic investments</li> </ul>
Platform for industrial symbiosis	<ul style="list-style-type: none"> <li>• possibility to develop the connection independently from the geographical position of the involved industries</li> <li>• easier to know about any waste exchanges</li> </ul>	<ul style="list-style-type: none"> <li>• resistance to data sharing</li> <li>• difficulty in transferring resources</li> <li>• difficulty in utilities sharing</li> <li>• relationship difficulties between managers</li> </ul>

other ones are specific for each model. Thus, the choice of a model strictly depends on the context of application, and in some cases, weaknesses of a model represent strengths for another one.

#### 4. Human–Machine Symbiosis

With the fourth industrial revolution, Industry 4.0, it is necessary to deepen the concepts of symbiosis. The vision of industrial symbiosis, seen only as a sharing of resources, is now obsolete. It is necessary to contextualize the companies in a historical context related to the evolution of research on human factors. Resources alone are not enough; man is at the centre of the company's growth. Thus, the concept of human–machine symbiosis is developing. Hadorn, Courant, & Hirsbrunner (2016), in their work, highlighted how the 'conversation' between humans and machines leads to beneficial results for both business and employees. The collaboration between human beings and IT systems will generally reduce costs (less waste), favour the work of human beings working with a system (less stress), and at the same time increase the efficiency of human–machine collaboration.

In the same way, Ansari, Khobreh, Seidenberg, and Sihh (2018) described how to consider different levels of interaction and conversation, preserving human integrity, in human–machine symbiosis. Jones et al. (2018) emphasized that the distinction between humans and machines is no longer necessary. They must not be thought of as separate components that interact through interface. Through the human–machine symbiosis, they can work on the same task and in the same temporal and physical spaces, as a collaborative team.

Aspects such as autonomy, responsiveness, adaptability, collaboration, and man–machine symbiosis are increasingly important within an intelligent factory (Weber, Konigsberger, Kassner, & Mitschanga 2017). According to Jarrahi (2018), the synergy among artificial intelligence and men would be a winning

strategy for companies. This relationship allows to compensate the limits of one part with the strengths of the other one. Comprehensive investigations on these synergies and subsequent implementations highlighted the advantages that can be gained from a digitalized production (Bokrantz, Skoogh, Berlin, & Stahre 2017).

Wang et al. (2017b) propose a new structure for collaborative human–robot assembly system. The symbiotic human–robot collaboration (HRC) system is tested in three industrial scenarios: food packaging, assembly of aeronautical components, and assembly of electric motors. Peruzzini, Pellicciari, & Gadaleta (2018) present a work focused on the design of human-centred manufacturing workstations. A case study is presented in collaboration with a world's leading manufacturer of steel pipes and related services. The study focuses on optimizing the workstation and human–machine collaboration. Peruzzini, Grandi, & Pellicciari (2018) develop virtual prototypes to make workers interact with the digital factory to simulate human–machine interaction. The study analyses the design of industrial systems focused on humans. The research approach is tested on a case study in collaboration with a global producer of agricultural and industrial vehicles.

Differently from industrial symbiosis, human–machine symbiosis is a recent concept, born in the last years together with the Industry 4.0 paradigm. For this reason, currently only preliminary study can be found in literature, while a systematic classification of models or significant applications does not exist. However, Table 2 reports a brief list of strengths and weaknesses of human–machine symbiosis, derived from the present literature review.

#### 5. Discussion

Technological advances have driven the increase in industrial productivity since the dawn of the first industrial revolution. The rise of new digital industrial technologies is driving, once again, the transformation of the factory into the 4.0 industry. In this

**Table 2:** Strengths and weaknesses of human–machine symbiosis.

Model	Strengths	Weaknesses
Human–machine symbiosis	<ul style="list-style-type: none"> <li>• considers ergonomics aspects</li> <li>• favours productivity increase</li> <li>• reduces costs (less waste)</li> </ul>	<ul style="list-style-type: none"> <li>• resistance of operator to change</li> <li>• economic investments in new technologies</li> <li>• redesign of production processes</li> </ul>

Table 3: Classification of industrial sectors involved in symbiosis activities.

Paper	Symbiosys typology	Industrial sectors involved in symbiosis					
		Agriculture	Automotive	Chemical	Other manufacturing industries (metal, plastic, food, mining, electrical equipment, etc.)	Municipalities	Utilities
(Korhonen & Wihersaari, 1999)	Industrial symbiosis			X		X	X
(Alexander et al., 2000)	Industrial symbiosis			X			X
(Chertow & Lombardi, 2005)	Industrial symbiosis			X	X	X	X
(Chertow, 2007)	Industrial symbiosis			X	X		X
(Beers et al., 2007)	Industrial symbiosis			X	X		X
(Zhu et al., 2007)	Industrial symbiosis			X	X		X
(Domenecha & Davies, 2011)	Industrial symbiosis		X	X	X	X	X
(Jensena et al., 2011)	Industrial symbiosis	X	X	X	X		X
(Ceceija et al., 2011)	Industrial symbiosis	X	X	X	X		X
(Behera et al., 2012)	Industrial symbiosis	X	X	X	X		X
(Taddeo, Simboli, & Morgante 2012)	Industrial symbiosis	X	X	X	X		X
(Cutaita et al., 2015)	Industrial symbiosis	X		X	X		X
(Yazan et al., 2016)	Industrial symbiosis	X		X	X		X
(Valentine, 2016)	Industrial symbiosis	X		X	X	X	X
(Notarnicola, Tasselli, & Renzulli 2016)	Industrial symbiosis	X		X	X		X
(Kuznetsova, Zio, & Farel 2016)	Industrial symbiosis	X		X	X		X
(Dong et al., 2016)	Industrial symbiosis			X	X		X
(Stock & Seliger, 2016)	Human-machine symbiosis			X	X		X
(Taddeo et al., 2017)	Industrial symbiosis	X	X	X	X		X
(Wang et al., 2017a)	Industrial symbiosis			X	X		X
(Mauthoor, 2017)	Industrial symbiosis			X	X		X
(Sun et al., 2017)	Industrial symbiosis			X	X	X	X
(Dong et al., 2017)	Industrial symbiosis	X		X	X	X	X
(Wang et al., 2017b)	Human-machine symbiosis		X	X	X	X	X
(Li & Xiao, 2017)	Industrial symbiosis			X	X		X
(Peruzzini, Pellicciari, et al. 2018)	Human-machine symbiosis		X				
(Peruzzini, Grandi, et al. 2018)	Human-machine symbiosis		X				

fourth transformation, machines, sensors, resources and IT systems will be connected not only with the individual company but along the entire value chain. Through the implementation of the pillars of Industry 4.0, a greater speed, flexibility and efficiency of the processes are expected to produce goods of superior quality at reduced costs. This will, therefore, favour an increase in productivity and subsequently a further industrial growth.

In this context, the different analysed symbioses appear as primary drivers to promote Industry 4.0's development. The correct management of resources (both natural and human) becomes fundamental in an industry of this type. In fact, the industrial symbiosis and the man-machine symbiosis represent the different forms of collaborative manufacturing.

On one side, the optimization on the use of natural resources, with the consequent reduction of the waste generated, is essential in today's society in which, to be competitive, it is necessary to respect the planet in which we live. The principles of environmental sustainability cannot be considered as optional (Recchioni, Mandorli, Germani, Faraldi, & Polverini 2007). So, if managers will be able to overcome the barriers related to communication and collaboration (see Table 1), by sharing information and resources, a step towards integration between companies in the same territory can be done. On the other side, a high technological context, such as the Industry 4.0 environment, will lead operators to perform new and different functions from the past, more demanding from a cognitive point of view, to dialogue with machines and complex systems, as well as to cooperate with them. Only effectively managing these aspects, related to man-machine symbiosis, the maximum productivity of the factory and quality of the final products can be guaranteed. Therefore, the two different forms of symbiosis are in line with the 'Horizontal and vertical system integration', according to the Industry 4.0 pillars, and should be jointly considered to pursue productivity, efficiency and sustainability.

However, analysing in more details the reviewed papers, it can be derived that the 50% of them present experiments or case studies in real industrial environments. The classification of sectors that favour the development of symbiosis activities (Table 3) revealed that currently the industrial and human-machine symbioses are applied in different contexts. It emerged that most of the companies involved in industrial symbiosis activities deal with utilities and chemical products. On the contrary, human-machine symbiosis is mainly applied in automotive or manufacturing industries. This situation certainly highlights the need for further research activities that foster the alignment among the two symbiosis approaches. In terms of Industry 4.0 and technological development, all the forms of symbiosis must be analysed as an overall optimization of resource management (natural and human).

## 6. Conclusions and Directions for Future Research

This paper presents a critical review of symbiosis approaches in the context of Industry 4.0. In particular, a classification of strengths and weaknesses of each model has been done. Then, common ground and differences among industrial and human-machine symbiosis approaches have been discussed to understand how future research activities should be focused.

First, future work might be focused on the development of the 'fourth' industrial symbiosis model that mixes strengths of

all three existing models, trying to eliminate, or at least mitigate the collaboration barriers listed above. In the meantime, the themes of human-robot symbiosis need to be further explored. For instance, studies on the cognitive stress deriving from this type of collaboration could be carried out. Innovative models or algorithms could be developed, aiming at reducing the physical and cognitive stress deriving from this type of interaction. It will therefore be possible to design innovative work stations with high physical-cognitive comfort. All these directions of research are essential to achieve a radical improvement in the quality of work in terms of operator satisfaction and, consequently, productivity.

Considering industrial systems as complex environments composed of different resources, the final step should be the integration of the two different symbiosis models, to jointly consider material resources and human capital. This new collaborative manufacturing model will foster a real transition towards Industry 4.0, allowing to obtain economic savings and reduction of negative environmental impacts, as well as improvement of social wellbeing for human operators and collectivity, coherently with the three pillars of sustainability.

## Conflict of interest statement

Declarations of interest: none.

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