A Study on Common Topics in Industrial Ecology and Operations Management publication

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Abstract

The exhaustion of the current paradigm of organizing operation in open chains, or cradle to grave sequence, suggesting that only interventions that adopt the whole operation-consumption system perspective, or the cradle to cradle sequence, are effective to face the challenges of today´s major environmental issues. Considering this broader perspective, this paper aims to identify complementarities and interface approaches for the Operations Management and Industrial Ecology on topics related to sustainability. For that, a bibliometric analysis was done for the topics *production*, *supply chains* and *sustainability* with satisfactory results.

Keywords: Industrial Ecology, sustainability, supply chain

Introduction

The initial steps for Industrial Ecology (IE) to become a field of scientific research were taken recently. The first publications related with the concepts of (IE) were elaborated in the 1960's, among which is the pioneering work of Robert Ayres (1969) based on the analogy between the metabolism of food in living creatures and in industrial production processes. For Ayres, as in food chains, industrial productions activities transform raw material into useful products for consumption with energy use, resulting in flows of energy/matter that can be calculated taking into account their initial and final inventory. Moreover, Ayres pointed out that while the biogeochemical metabolisms are circular and optimize the final balance of matter and energy, industrial processes are linear and more inefficient according to the Law of Physics.

In this sense, the economic activities of mankind depend on the availability of the Earth natural resources to be a source of both energy and raw materials and to receive the final destination of waste and pollution. However, for the authors of Ecological Economics (EE), if the growing rate of the global population is the same and the current industrial paradigm keeps unchanged, there will be natural resource consumption, waste generation and pollutions above Earth´s absorption biocapacity. Thus the analogy between biological and economic systems, which is the analytical basis of IE, directly involves one of the central issues of EE: the interdependence between the equilibrium conditions of natural environment and anthropogenic impacts of productive activities.

In order to separate the fields of IE and EE that can overlap because of this common object of study, this paper recovers the original theoretical contribution, for both subjects, in the next two sections. Then, in a section regarding the discussions on the theoretical basis of IE, a framework was elaborated with a systemic approach related to IE´s interdisciplinary topics. After that, taking into account that *production, supply chain* and *sustainability* are exemples of this kind of topic, there is a section assessing the interdisciplinary nature of IE through a bibliometric analysis of articles published in the most important journals of the IE and Production and Operations Management subject. Finally, in the last two sections the possibilities of rising new interfaces between IE and Operations Management are discussed and evaluated conclusively.

Industrial Ecology: history and theoretical contributions

From the seminal text by Ayres to the present, a significant amount of research and analysis was conducted based on the idea of considering the operation of productive activities in the same way as the food chains cycles or, more broadly, ecosystems work.

Table 1: Main IE initial publication

Author(s)	Publication	Theme
Tibbs, H. (1992)	*Industrial Ecology: an Environmental Agenda for Industry*	IE as a management approach
Frosch,R.A.& Gallopoulos, N.E (1989)	*Strategies for Manufacturing*	Industrial symbiosis and ecosystems
Ayres, R.U & Kneese, A.V (1969)	*Production, Consumption, and Externalities*	Industrial metabolism
Watanabe, C. (1972)	*Industrial Ecology: Introduction of ecology into industrial policy*	IE and industrial policies
Gertler, N. (1995)	*Industrial Ecosystems: Developing Sustainable Industrial Structures*	IE and industrial clusters
Lowe, E.A. (1997)	*Creating byproduct resource exchange: Srategies for eco-industrial parks*	Eco-industrial parks
Cohen-Rosenthal (2000)	*A Walk on the Human side of Industrial Ecology*	Organizational strategies
Billen et al (1983)	*L´ecosysteme Belgique essai d'ecologie industrielle*	Macroeconomic analysis based on IE

Some of these works are devoted exclusively to the development of a retrospective of the major theoretical contributions on the discussion themes proposed by IE (Ehrenfeld, 2004; Ayres, 2002; Erkman, 1997). Table 1 shows the result of a survey of these related works, highlighting the main contribution of the authors.

The first texts using the term industrial ecology, with a different meaning according to the current definition, are related with the characteristics of the environment in which business plants are located in and also in manifestos of entrepreneurs organization lobbying against the creation of the *US Environmental Protection Agency*. Afterwards, the use of the term industrial ecology, in its scientific meaning based on the analogy between ecosystem and production systems, is recorded in the work by geologist Preston Cloud presented at the *Annual Meeting of the German Geologists*, 1977. In this sense, it is interesting to observe the interdisciplinary character of the initials works related to IE in the fact that there were contributions from physicists, biologists, geologists, engineers and economists in groups of research-oriented analysis and studies of industrial structures of their respective countries (Erkman, 1997). The first of these groups was created in Japan in the early 70´s, with the aim of proposing industrial policies to reduce the Japanese economy dependence in relation to raw material shortages (Watanabe, 1972). In turn, in Belgium, also in the 1970´s, some researchers who participated in the socialist government used the concept of IE to propose an economic view based on material flow rather than the traditional monetary flow (Billen et al, 1983).

These studies and national experiences in using the IE concept in industrial policies do not have a relevant impact on business and academic communities, which made clear the scepticism about the explanatory and analytical power of this new paradigm of productive activities working based on the science of ecosystems (Erkman, 1997). However, there were huge environmental disasters during the 1980's and also the dissemination of indicators that showed a strong climate change. Then an intense debate occurred in international forums, culminating with the *Brundtland Report* and widely known definition of what is sustainable development. In this context, an article published in *Scientific American* (Frosch and Gallopoulos, 1989) rekindled the interest in the analytical power of IE so that a large amount of new studies both in academic and business communities followed (Ehrenfeld, 2004).

Together with the Frosch and Gallopoulos´ article, to be detached is the role played by the *US National Academy of Engineering* (NAE) for conducting a large number of conferences and programmes associated with the IE principles. Braden Allenby (1992), presented the first doctoral dissertation on IE after spending a year fellowship in one of these programmes, t*he NAE Technology and Environment Program*. In 1995, Allenby published the first IE textbook together with Thomas Graedel who, in 1997, became the first IE professor at *Yale University* in USA. With financial and institutional support, n the same year, the NAE contributed to the creation of the *Journal of Industrial Ecology* which can be considered acknowledgement of IE as research field by the academic community. Likewise, by present the ideas of Frosch´s article in a language and rethoric appropriated to businessmen, Tibbs (1992) also showed that IE can open broad horizons for a systemic approach of environmental management practices.

With the possibilities of new researches again opened and also with the support of both the academic and the business community, a huge number of specific issues have been discussed based on the IE theoretical framework, among which are the industrial symbiosis (Gertler, 1995) and eco-industrial parks (Lowe, 1997). Other topics researched for decades began to be interpreted according to the IE framework, such as the availability and use of resources (Malebaum, 1978), resource productivity (Shimidt-Bleek, 1993) , transmaterialization (Wadell and Labs, 1988), descarbonization (Ausubel, 1996), functionality and service economy (Sthael and Reday Malvey,) and organizational strategies (Ed Cohen-Rosenthal, 2002).

Ecological Economics and its missing link

Just as IE, EE emerges in the academic world throughout the 1980´s. It is a regular discipline in the field of economics that came with the mission to recover a historic debt of the economic thought related to the role of natural resources in its theoretical construction. Unlike Malthus, Smith and Mill and other classical economists who have shown the importance of considering the natural aspects in the development of economic theories (Perrings, 2008), especially those related to the growth of production and consumption, almost all members of the economic mainstream in the 19^{th} and 20^{th} century considered the hypothesis that long term shortage of natural resources does not constitute a barrier to productive activities because technological developments would always be able to promote alternative sources for these resources. Contrary to this economic view of the dominant schools of economic thought, EE authors took up the classical tradition and brought issues to the center of the debate such as the interdependence of economic systems and ecological constraints to the growth of production and consumption due to the Earth´s biocapacity and the ineffectiveness in the use of natural resources.

Taking into account the interdependence between ecological and economic systems, the EE states the need of compensatory measures for the harmful environmental impacts of productive activities and consumption, among which are climate change, declining biodiversity and depletion of natural resources, especially water. Another stream of EE researches goes further and says that the growth of consumption derived from population increase which takes the Earth´s carrying capacity at an unsustainable level and, therefore it must be seek both income redistribution of income and a reduction of the consumption patterns of countries with higher incomes. For the third stream of EE the economic system is a physical frame that combines energy and material and so it is subject to the action of natural laws, especially the Second Entropy Law according to which the energy balance of the universe is negative in terms of ability to generate work. Therefore, through dissipative processes, economic and ecological systems evolve and stay away from both energy efficiency and total balance. Such systems depend on the influx of energy and material from the environment and also use the Earth for the final disposal of waste derived from production processes and consumption.

Thus, while EE analyzes the joint evolution of both economic and environmental systems to prescribe future scenarios that allow for social actors to anticipate crises and conduct counter-cyclical measures (Daly and Farley, 2004), IE adopts biological cycles as a reference model to show the way productive activities and consumption must be managed taking into account the equilibrium of ecological systems. Therefore, IE clearly assumes the vality of the assumptions outlined by EE in relation to the environmental impacts of the economic system and proposes a systemic approach that integrates production processes and consumption taking considering the perspective of reducing the use of natural resources and minimization of waste generation.

The theoretical basis of IE

The discussions about IE, related to its rigorously defined theoretical framework, started since the first publication in which the authors pointed out the evident birth of a new research field. Referring to events that occurred in the 1990´s , Ehrenfeld (2004) argues that IE has evolved into a field involving its four keys aspects: the existence of a set of common concepts to researchers in related subjects, the training manuals and tools for practical application of these concepts, the organization of an institutional structure responsible for maintaining the quality and conceptual coherence and the existence of a community of social actors who make systematic use of these three aspects above. Taking an epistemological point of view, IE can be considered both a positive science, as Physics, or a prescriptive one as Theology is to extent it seeks to explain not only how the economic and ecological systems interact but also how their structures and internal organizations must work to remain balanced.

In relation to its basics concepts, IE assumes that there is an analogy between food metabolism, observed in natural ecosystems, and the economic system represented by the stages of industrial processing and consumption, for the fact that in both systems the living creatures transform natural resources into useful products. However, while in the ecological systems the material and energy flow are optimized, in the human activities of production and consumption there are imbalances derived from non-closing cycles, resulting in the depletion of natural resources and in the accumulation of a substantial amount of waste. In this sense, IE can be defined primarly as the study of material and energy flows and the steps of their transformation into products, byproducts and waste along the production and consumption chains. This primary definition plus the systemic view of ecology associated with the complexity of organizing communites constitute the conceptual definition of IE in its broad sense. Therefore, IE also seeks to identify and propose sustainable model of relationship between producers and between then and the natural ecosystems (Cohen-Rosenthal, 2003).

Based on this conceptual definition of IE, Graedel and Lifset (2002) highlight the following areas of discussion: biological analogy, use of systems perspective, the role of technological change, the role of companies, dematerialization and eco-efficiency and forward-looking research and practice. In turn, these areas of discussion are formed by the following topics:

- **Biological analogy**: the ability of self-organization and resilience of ecosystems and of the economic system; hypothesis of symbiotic relationship between business and closure of the production and consumption chains;
- **Use of systems perspective**: the perspective of life cycle analysis of flow of materials and energy, modelling and use of systemic analysis of flow and multi and interdisciplinary research;
- **The role of technological change**: ecodesign, reverse logistics, reuse, recycling and remanufacturing;
- **The role of companies**: proactive and cooperative behaviour, organizational strategies and sustainable development, pole of technological innovations;
- **Dematerialization and eco-efficiency**: the intensity of material use, descabonization and pollution control, and
- **Forward-looking research and practice**: uncertainty, precaution and prevention principle.

Moreover, each of these topics can be grouped into a framework according with the following levels of the EI operation shown in figure 1: firm, inter-firms and regional global. Thus, the elements of IE that are dependent on individual initiatives, such as ecodesign and remanufacturing, can be identified and differentiated along with those that are related to joint actions of firms associated with a economic sector or geographic area, such as the elaboration of eco-industrial parks. At the same time and in line with these individual and collective initiatives, there are comprehensive social actions focused on reducing the impacts of economic activities on the Earth´s biocapacity, as those related to dematerialization and decarbonization.

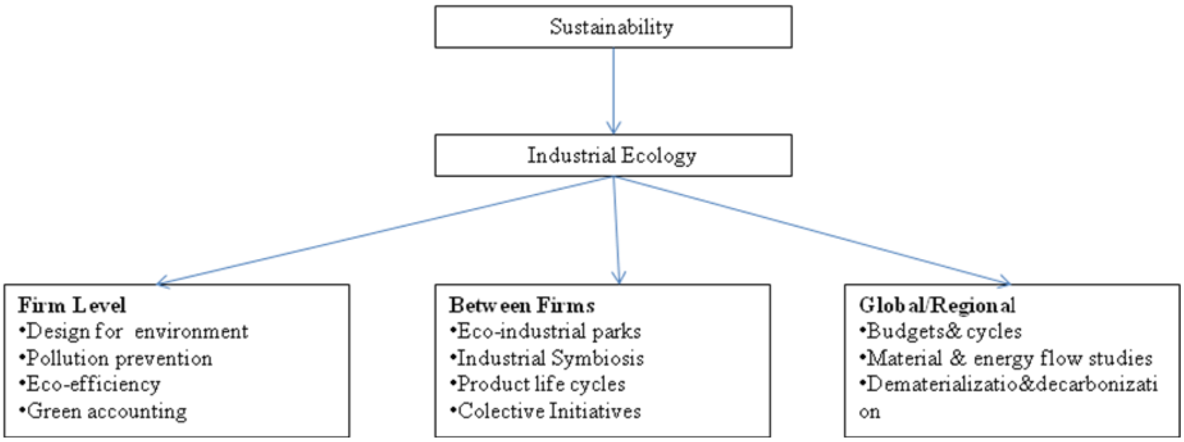

Figure 1: Framework in flux format, adapted from Graedel & Lifset, 2002.

In the next section this framework is applied on a set of academic texts in order to assess if the highlighted topics are in fact related to each other. In this sense, it is used proxies for selected topics, as the following: *production; supply chain and sustainability* are considered at firm, between firms and global/regional level respectively.

Research methodology and bibliometric analysis

Thirty eight journals were obtained from a sample of 52 articles selected according to the topics *production*, *supply chain* and *sustainability*. Using ISI Web of Science Database, every article that contained those topics in its title, keywords or abstract was identified and downloaded. The 52 articles included in the dataset cover 40 subjects areas arranged as the following: Environmental Sciences (22); Environmental Engineering (17); Biotechnology and Applied Microbiology (5), Energy and Fuels (5); Management (5); Operations Research and Management Science (5); Chemical Engineering (4); Manufacturing Engineering (4) and the remainder (each one equal or lower than 3). Despite the fact that the database in focus includes some articles in more than one subject area, this article distribution show interface possibilities between Environmental Science and Operations Management considering the topics adopted.

Regarding to the authors of the selected articles, the most frequently cited were: Gregory *et alli* (45 citations), Linton *et alli* (43 citations), Sim *et alli* (19 citations) and Lu LYY *et alli* (13 citations). As can be seen from these data, there were only four lead authors whose works were cited more than 13 times and interestingly these four lead authors have published in somewhat different journals – *Philosophical Transactions of the Royal Society Biological Sciences, Journal of Operations Management, International Journal of Life Cycle Assessment* and *International Journal of Product Research*. The Table 2 shows that only 2 of these authors have their articles published in the six most important journals.

Table 2: Ranking of journals, by articles

Ranking	Source Title	Record Count
1	*Journal of Cleaner Production*	6
2	*Journal of Industrial Ecology*	5
3	*International Journal of Life Cycle Assessment*	3
4	*Biomass and Bioenergy*	2
5	*International Journal of Operations and Production Management*	2
6	*International Journal of Production Research*	2
-	*"Others"*, with only one record	32

Elaborated by using the site ISI Web of Knowledge.

Considering the citation frequency and the journal in which the article was published, the results analysis was done in order to choose an article that best matches “times cited” and the most important journal in terms of the amount of their publication. By this condition, the article elected was *Sustainable Supply Chains*: an Introduction, written by Linton *et alli* (2007) in the *Journal of Operation Management*. The Figure 2 shows the forward generation of this article according to research field in which its components are classified. It means that the inquiry field of the elected article is Management and the fields of those articles which cite the article in focus are listed in the Figure 2.

Research fields per article in this forward (fwd) generation: Management is at the center and then, anticlockwise, are Operations Research & Management (9), Management (19), Ethics (1), Environment I (1), Environment II (6), Engineering (3), Computer Science (2) and Bussiness (1).

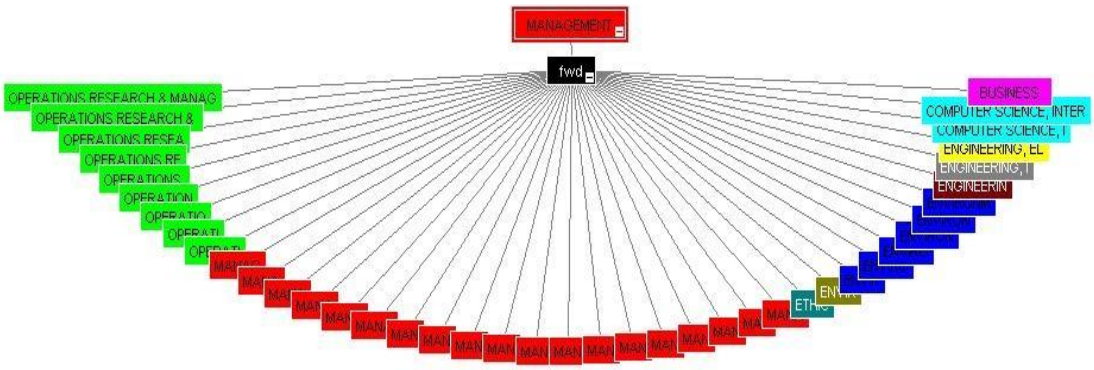

Figure 2: Forward generation diagram, by research field.

Firstly, it is important to note that this article was the second most cited of all, but it was chosen because the first one was strictly related to Biological Sciences. It was cited 42 times according to the subject areas showed in Figure 2. In this forward generation diagram can be seen the interdisciplinary aspect of the research fields that are related with the article in focus. It must be highlighted, in particular, the fact that in Management, Operations Research and Management and Environmental Sciences there are a great number of researchers interested in the elected article and so in the topics adopted. Moreover, the fact that some subject areas like Ethics, Business and Computer Science are in the list in focus suggests interesting new interfaces and also a kind of dialogue between them.

Results discussion

Some remarks can be done through an overview of the results achieved in this paper. By using a conceptual framework, it was possible to analyze a dataset of articles in terms of their relationship with different subject areas, particularly between Industrial Ecology and Operations Management. The 52 articles sorted in ISI Web of Science Database indicate a strong ability of this framework to highlight *sustainability, supply chain and production* as common topic between those areas. The indicator for this evidence is the properly titles of the main journals that cover those articles such as Cleaner Production, Industrial Ecology and Production Resource. Moreover, one of the most cited articles was published in the Journal of Operation Management, reinforcing the importance of those topics for Operation Management specific area.

Another good points are related to the interdisciplinary approaches that can be observed in two ways, first through the forward generation diagram where is shown that there are 10 areas using an article which subject area is just Operations Management, and second registering the fact that there are 38 journals in which the *topics production, supply chain and sustainability* can be published. Similarly some bad points must be highlighted, like the scarcity of articles and the fact that the first work, in the dataset in use, was done in 2003 despite of two decades of environmental issues discussion. Moreover, the results suggests that so many works of Industrial Ecology are spread along de 38 journals of 40 subjects areas and such diversity contributes for low degree of interaction and discussion.

Conclusion

The analysis of articles related to common topics between Industrial Ecology and Operations Management publication opens several toolboxes and spread very important insights in futures researches of both areas. Regarding to the state of the art of Industrial Ecology, there is a long road to be trailed, by integrating the contributions of other research fields to the conceptual framework elaborated and applied here or through the establishment of interfaces and interconnections to enlarge the systemic view in all Sciences, as proposed by the industrial ecologists.

The use of ISI Web of Knowledge in this paper showed that this tool is very helpful to discover the relationships research areas which are highly specialized, as it is the case of the academic works. For instance, research networks can be established among engineers, economists and environmental scientists based on the forward generation diagram present here, either to develop interdisciplinary projects on production, supply chain and sustainability or by developing a specific project with a broader approach.

This paper was prepared to go further ahead with citation/co-citation analysis and discover more networks by adopting a huge number of common topics between Industrial Ecology and Operations Management, such as ecodesign, remanufacturing and dematerialization. There are so many interfaces to be explored by doing in the academic community the same that Industrial Ecology suggests for whole society: the channels creation for a greater intensity of the resources use.

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