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A comprehensive review of the evolving and cumulative nature of eco-innovation in the chemical industry

Fernando J. Díaz López [a, b, c, *], Carlos Montalvo [a]

[a] Netherlands Organisation for Applied Scientific Research TNO, Delft, Netherlands
[b] Faculty of Industrial Engineering, Stellenbosch University, Matieland, South Africa
[c] Universidad Autónoma Metropolitana, Colaborador externo del Cuerpo Académico "Gestión del Conocimiento y Política de Ciencia, Tecnología e Innovación", Cuajimalpa, Mexico

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ABSTRACT

Different bodies of literature have attempted to explain what factors and events drive industries throughout processes of environmental change. The latter is a gradual, historical process of evolution from lower to higher degrees of development. Based on concepts derived from evolutionary economics, greening technological progress and resource-based view of the firm, this article informs the sustainability transitions literature by providing an account of the evolution in the chemical industry's striving for the design, use and production of environmentally sound chemical processes and products based upon eco-innovation. A conceptual model was elaborated depicting five stages of environmental change in the chemical industry in the period 1901–2030. The authors empirically tested this model by conducting a longitudinal computer-aided content analysis of 255 documents addressing different environmental and innovation aspects in this industry in the same period of time. The results of this article advance our modern understanding of the different stages of evolution of the chemical industry in terms of environmental change. Consistent with the conceptual model hitherto presented, the findings of this article highlight a number cumulative of factors that enabled the evolution of the chemical industry throughout time supporting eco-innovation, highlighting the intertwined nature of regulation, innovation, and technological change. It is plausible that the future development of this industry might be shaped by the policy-driven paradigms of sustainability and resource efficiency.

1. Introduction

This article provides a comprehensive account of the evolution of the chemical industry towards environmentally sound chemical processes and products, while aiming to remain competitive in a context of globalised value chains and new forms of innovation.

It is well known that all modern technologies are unavoidably accompanied by side effects – negative externalities (Rosenberg, 1976). Historical and empirical evidence has repetitively shown that manufacturing and service activities of many companies have contributed to environmental degradation and pollution in many ways and with different levels of intensity (Utting, 2000; Thomas and Graedel, 2003). Moreover, it is widely accepted that controlling pollution does not necessarily avoid environmental degradation. The reason of this is that, in the long term, pollution control fails simply because once potentially polluting agents are generated these can travel from one physical medium to another (see: Montalvo, 2002). Hence, every existing industrial process has a 'potential to pollute', which can be estimated and diminished but so far cannot be fully avoided (Graedel and Howard-Greenville, 2005).

It is extremely difficult to accept among academic circles that achieving higher environmental performance in firms and industry is costly, of low priority and detrimental to industrial competitiveness (c.f. Walley and Whitehead, 1994). For quite some time a vast amount of evidence has been assembled on the positive relation between environmental and economic performance (c.f. Florida, 1996; Hart and Ahuja, 1996). Moreover, a number of approaches and tools for environmentally conscious manufacturing are available (e.g. 3M and UNEP, 1982; Ilgin and Gupta, 2010; OECD, 2011). Many top executives claim that corporate sustainability is

* Corresponding author. Netherlands Organisation for Applied Scientific Research TNO, Expertise Centre for Strategy and Policy, PO Box 49, Delft, Netherlands. Tel.: +31 8888668307.
E-mail addresses: fernando.diazlopez@tno.nl (F.J. Díaz López), carlos.montalvo@tno.nl (C. Montalvo).

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driven by a combination of public pressures, regulation and securing a competitive position in the markets (Mckinsey and Company, 2011). Some authors claim that sustainability has become a proxy for quality management, reduction of energy and resource consumption, and higher efficiency and reliability (Porter and Kramer, 2011).

Eco-innovations are broadly defined as innovations that contribute to sustainable development (Rennings, 2000, p. 322).[1] At the industry level, the development and use of eco-innovations constitute a mechanism for achieving sustainability and resource efficiency goals. This is because environmentally friendly and socially responsible innovation fosters technological, institutional and organisational changes to the knowledge base of existing production systems (Coenen and Díaz López, 2010). A major sustainability transition (in industries) requires new forms of eco-innovation. This is because incremental improvements to the environmental efficiency of technologies and production systems may not be sufficient for achieving the radical changes required by sustainable development (van den Bergh et al., 2011).

Clearly, achieving more radical forms of eco-innovation is a complex issue due to a number of conflicting issues and dilemmas (Ekins, 2010; Kemp, 2010). Notwithstanding, a central point to consider in this article is the evolution of the chemical industry in relation to environmental change. Scholars argue that companies and industry in general have undergone a gradual transformation process along several environmental behaviour paradigms, evolving from a lower to a higher degree of environmentalism (c.f. Hart, 1995; Hoffman, 1999; King, 2000; Lee and Rhee, 2005). In this sense the origins of environmental innovation in the chemical industry have a relatively long history that can be tracked back to the end of the nineteen century (c.f. Clow and Clow, 1958; Warner, 1982; Heaton, 1994).

The authors of this paper argue that there are several historical and industry-specific factors that have enabled *environmental change*.[2] Path dependent co-evolving processes of learning and accumulation of capabilities, competences and resources help firms interacting within the broader context of their production and consumption system, so that eco-innovation and its associated business models can emerge and evolve in a given industry. In addition to institutional and cultural change (Hoffman, 1999), innovation is contingent to organisational and socio-technical change along specific trajectories and paradigms (Kemp and Soete, 1992; Freeman, 1994).

It is the aim of this paper to provide an account of the evolution of eco-innovation in the chemical industry and to illustrate the cumulative path of the chemical industry towards achieving sustainable development. For this reason the authors focus on a twofold research question: (a) what factors have contributed to environmental change in the chemical industry? (b) What factors have motivated the evolution of eco-innovation in the chemical industry?

The content of this article is structured as follows: Based on a comprehensive literature review Section 2 collects a number of key concepts that enable the creation of a framework concerning the evolutionary and cumulative nature of eco-innovation in the chemical sector. Section 3 presents an overview of environmental change in the chemical industry followed by the conceptual model in Section 4. Section 5 briefly introduces the method of literature content analysis used in the analysis of documents for the empirical validation of the conceptual model guiding this article. Section 6 presents the main results of the literature analysis whereas Section 7 presents the analysis and discussion. The last section provides the main conclusions, limitations and avenues of future research of this work.

2. Useful approaches to understand eco-innovation in relation to a transition to sustainability

Providing an account of eco-innovation in industries requires adopting a systemic approach to innovation (Coenen and Díaz López, 2010), where the unit of analysis are firms embedded within socio-technical systems for production, consumption and distribution (Berkhout, 2005; Tidd, 2006). One of such approaches is found in the emerging academic of area of sustainability transitions (Geels, 2004; Hekkert et al., 2007).[3]

Sustainability transitions have been defined as long term, multi-dimensional and radical transformations processes leading to shifts in socio-technical systems to more sustainable modes of production and consumption (Markard et al., 2012).[4] According to this body of literature, socio-technical systems consist of network of actors (firms, individuals, etc.), institutions (norms, regulations, etc.), material artefacts and knowledge (Geels, 2004; Markard et al., 2012). The transformational power of sustainability transitions is evident because they induce large scale transformations in a number of dimensions, including: user practices, institutions, technologies, economics, political, etc. (Jacobsson and Bergek, 2011; Markard et al., 2012). Focussing mostly on socio-technical systems of energy supply, water supply, urban environment and transport, studies in this novel field of research aim at explaining how different green technologies compete against each other at the regime level, leading to the creation of new products, services, business models, and organisations (Markard et al., 2012). (Reinstaller, 2008).

The field of sustainability transitions, while addressing some key concepts to understand the cumulative nature of technical change and factors for socio-technical transformations, have not yet sufficiently enquired into the historical events and particular factors which have motivated the process of evolution of eco-innovation in manufacturing sectors, in particular in the chemical industry.[5] Markard et al. (2012) recognised eco-innovation as one of many related strands of research on 'green issues' informing sustainability transition studies, but these authors did not elaborate

[1] One of the most accepted definitions of eco-innovation was provided by Kemp and Pearson (2008), within the context of the MEI project. These authors defined eco-innovation as: "*the production application or exploitation of a good, service, production process, organisational structure, or management or business method that is novel to the firm or user and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the negative impacts of resources use (including energy use) compared to relevant alternatives*." Please refer to Kemp (2010) and Ekins (2010) for an overview of eco-innovation research in terms of definitions, measurement, useful theories and policy implications.

[2] The term *environmental change* has been used as a proxy to environmental performance and corporate environmentalism in a number of studies (e.g. Hoffman, 1999; King and Lenox, 2000. As it will be shown in the present article, *environmental change* is accompanied by institutional, technological, social and economic change, the authors of this paper consider 'environmental change' as an indication of the degree of evolution of eco-innovation in the chemical industry.

[3] Coenen and Díaz López (2010) present an extensive overview of commonalities, differences and complementarities of two highly influential approaches in sustainability transitions: Technological Innovation Systems and Socio-technical Systems (including transition management and strategic niche management).

[4] Refer to Markard et al. (2012) for an overview of the main characteristics, theoretical positioning, empirical methods and research needs of the novel field of sustainability transitions.

[5] A notable exception is the study of eco-innovation diffusion provided by Reinstaller (2008). Using a quantitative method of logistic substitution analysis based on Fisher and Pry (1971), this author studied the technology diffusion of chlorine free pulp bleaching technologies in the Nordic countries and the U.S.A. Albeit not focussing on the chemical industry this study is one of the few exceptions of empirical studies in manufacturing sectors informing sustainability transitions literature.

further on their relationships, complementarities or differences. With the purpose of building the most suitable theoretical approach needed in the present article, the following paragraphs present concepts and propositions from evolutionary economics (Dosi, 1982), greening technological progress (Kemp, 1994; Kemp and Soete, 1992), and the resource based-view of the firm applied to the environment (Hart, 1995).

The area of evolutionary economic of technological change approach (e.g. Dosi, 1982; Pérez, 1983; Freeman, 1984) is focused on firms and new technologies, its development, commercialisation and diffusion (Rosenberg et al., 1992). Evolutionary economics provide a comprehensive framework for the understanding of processes of change determined by past routines that governs future actions, and how technologies become a source of wealth through an evolutionary, path dependent and incremental process, with clear differences of innovation activity across economic sectors. Important concepts from the field of evolutionary economics are technological paradigms, technological trajectories, evolution and accumulation, path dependency, and routines.[6] *Technological trajectories* are patterns of problem solving activities of selected techno-economic problems (Dosi, 1982). Clusters of the former constitute a technological paradigm (Dosi and Orsenigo, 1988), also known as technological regime (Georghiou et al., 1986; Dosi, 1988) or techno-economic paradigm (Freeman and Perez, 1988).[7]

Building on the above-mentioned concepts from evolutionary economics, literature on the greening of technological progress provided a good theoretical basis for the understanding of eco-innovation in complex socio-technical systems. Kemp and Soete (1992) and Freeman (1994) explained that social, economic and technical factors need to be transformed if an industry is to achieve a major transition towards sustainability. In particular, Kemp (1994) noted that the problem of changes in technological regimes is highly complex, since it involves changes in technology, production, organisation, consumption and living styles. So, in certain historical moments, innovations are produced and co-exist with old technological paradigms until gradually replacing them by newer, environmentally friendlier alternatives (Kemp and Soete, 1992). Kemp (1994: 1034) identified a series of conditions for a change to a greener paradigm: (1) radical innovations depend on new scientific knowledge, and in some cases, on advances in engineering and material technology; (2) technological needs need to be present that cannot be satisfied with the available technologies; (3) old trajectories that reach its limit or that further advances leading to increasing marginal costs; (4) the presence of new industries/diversified firms with different knowledge base offering alternative technologies or vested interests inhibiting the advance of different technologies; and, the propensity to take risks by entrepreneurs.

The company-based approaches of resource based view (RBV) of the firm (Wernerfelt, 1984; Barney, 1991) and dynamic capabilities (Teece et al., 1997) have recently received attention of sustainability transitions scholars (e.g. in Musiolik et al., 2012). This is because the RBV of the firm enhances our understanding how firms and industries can actually move across sustainability-driven paradigms (see Hart, 1995). Building also on evolutionary economics, Teece et al. (1997) explained why firms own capabilities distinctive and dynamic. Dynamic capabilities are a key aspect of the evolution of firms, and are defined as 'the firm's ability to integrate, build and reconfigure internal and external competences to address rapidly changing environment' (Teece et al., 1997). Clearly, this is a process of accumulation of capabilities contingent upon the existence of prior, related knowledge (Cohen and Levinthal, 1990). When applied to the study of environmental change (Hart, 1995; Hart and Milstein, 2003), the RBV of the firm approach suggests that firms manage to evolve towards a higher degree of environmentalism and develop/adopt eco-innovations because they are owners of uncommon specific resources and capabilities that are difficult to imitate (c.f. Diaz Lopez, 2009). Kleef and Roome (2007) suggested that a shift in capabilities and competences to eco-innovate require the active involvement of a diverse range of actors and networks in comparison to 'conventional' innovation. Hence, calling for using a systems view in future eco-innovation research.

The literature review presented in this section sheds light on a number of external and internal factors enabling eco-innovation and environmental change in companies. The interrelationship and relevance of determinants of eco-innovation varies depending on the industry analysed, sector innovation dynamics, etc. (Kemp, 2010). Following Montalvo (2008), factors enabling change can grouped into six generic categories, namely: (1) technological (e.g. technological capabilities, design capabilities, etc.), (2) organisational (e.g. management systems, etc.) (3) institutional (e.g. regulations, social norms, etc.), (4) economics (e.g. cost reduction, size of company, etc.), (5) markets (e.g. market share, future markets, etc.), and (6) society (e.g. community pressure, consumer choices).

A complementary review of environmental and techno-institutional change in the chemical industry is presented in the subsequent paragraphs.

3. Environmental change and techno-institutional evolution of the chemical industry

It is acknowledged that evolution and change has always been one of the distinctive features of the World chemical industry (Freeman, 1968; Smith, 1994). There are more than 200 years of recorded history of chemicals manufacturing built over generations of accumulated empirical and scientific knowledge (Clow and Clow, 1958; Arora and Gambardella, 2010). Historical and empirical evidence suggests that resource efficiency and the use of by-products and waste as a source of value creation has been known to chemical producers for over 100 years (c.f. Richardson, 1908; Lancaster, 2002).[8] Scholars have acknowledged that achieving environmental change is not the result of single events or efforts, but rather the result of a combination of driving forces and intra and inter-firm factors (Colby, 1991; Hoffman, 1999). In order to better understand the evolution of this industry it is important to explain the dynamics of this industry and the influence of disruptive economic, socio-cultural, and techno-institutional factors on eco-innovation and environmental change (c.f. Gent, 2002).

[6] Routines are regular and predictable behavioural patterns of firms (Nelson and Winter, 1982). Path dependency refers to the influence of norms and routines and past experiences on current and future innovation efforts (Teece et al., 1997). Evolution and accumulation are metaphors borrowed by social scientists from the natural sciences, in particular from biology (Penrose, 1952). These concepts refer to the emergence, diversification, addition and selection of novelties, where learning and the emergence of building blocks are the defining factors for change (Devezas, 2005).

[7] A technological paradigm is both a set of exemplars and basic artefacts (models), which are to be developed and improved; and a set of heuristics and procedures (patterns of solution), which provide direction for the exploitation of new technological opportunities (Dosi, 1982: 152, 1988: 225).

[8] For example, A. W. Hoffman (the first president of the Royal College of Chemistry in London) declared in 1848 that: "In an ideal chemical factory, there is, strictly speaking, no waste but only products. The better a real factory makes use of its waste, the closer it gets to its ideal, the bigger its profit" (Lancaster, 2002: 21).

Rothwell and Zegveld (1985) noted that the business cycle of the chemical industry has been characterised by stages of accelerated growth (expansion or revitalisation), prosperity (consolidation & stability), recession (slow-growth) and depression. Throughout time, the cyclic performance of this industry has been moderated by investment levels, profit margins, productivity, technological change, innovation and aggregated growth (Arora et al., 1998a,b). Different business cycles have been accentuated due to effects on demand and drastic changes in the world economy influenced by events such as the 1930s depression, the Second World war, the post-war reconstruction of Europe, and the period of accelerated growth in the 1960s (Achilladelis et al., 1990). The expansive wave following the oil shocks & major environmental accidents (1970s–1980s) was characterised by a process of restructuring, re-configuration and a new revitalisation of the industry (Hikino et al., 2007a,b).

Environmental change in this industry has been primarily enacted by the effect and co-evolution of institutional and socio-cultural factors. Hoffman (1999) studied the historical evolution of environmental change in the US chemical industry in the 1960–1993 period, primarily focussing on the examination of cultural and institutional systems affecting corporate environmentalism.[9] The seminal work of Hoffman demonstrated how disruptive events, such as chemical accidents, changes in public perceptions and new regulations motivated environmental institutional change in this industry.[10] According to this author a number of intra and inter-firm organisational factors also evolved as a response to changes in environmental institutions. Among others, Hoffman identified the following factors: the implementation of management systems, corporate codes of conduct, compliance with new regulations, etc. This author identified four distinctive stages of institutional change and evolution in the chemical industry.[11] The main findings of each stage according to Hoffman (1999) are as follows:

a. *Environmentalism as a challenge* (1960–1970): in this period companies denied environmental issues related to their operations, while (the US) government showed low regulatory enforcement. Organisational changes related to environmental practices were non-existent. Environmental awareness was only emerging (p. 360).
b. *Environmentalism as a regulative institution* (1971–1982): this period was characterised by enforcement of government standards. Industry resisted and confronted environmental authorities. The industry considered environmental authorities to be powerful and the process of compliance too costly (p. 361).
c. *Environmentalism as a normative institution* (1983–1988): This was an era of greater cooperation with environmental authorities and the beginning of social responsibility, but regulation remained a norm. The emerging environmental values and expectations of this period about the role of technology for solving environmental problems helped conforming to the emerging concepts of pollution prevention and waste minimisation (p. 363).
d. *The birth of environmentalism as a cognitive institution* (1989–1993): this stage represented the start of a new era of corporate environmental responsibility. By the end of 1993 the attention to environmental issues had reached an historical peak. Responsible Care® was seen as a major source of public relations and an important tool for proactive environmental management.[12] An upsurge in the adoption of organisational innovations, such as management systems, environmental reporting, hiring environmental specialist, etc. was identified (p. 363–364).

Although it was not the primary purpose of Hoffman's work, the analysis of this author also took into account technological change as a key factor for environmental change (see Hoffman, 1999, p. 370).[13] Hoffman did not explicitly focus his research attention to the evolution of technology *vis-à-vis* institutions. In spite of the scepticism of this author about the role of technology for solving environmental problems, the analysis of Hoffman unveiled a key message about the evolution of eco-innovation (p. 353): "*In the history of the chemical industry environmentalism, the belief that technological progress improved the quality of life but the required the acceptance of certain level of risk persisted as a cognitive institution, despite the gradual incorporation of associated environmental institutions.*" According to this author, throughout all four periods of analysis the role of technology development for solving environmental problems retained certain degree of importance in the view of industry, government and non-governmental organisations (NGOs).[14] As noted in the introductory section of this article, the not so evident focus on technologies of Hoffman's work is of particular relevance for our study because of the implicit relation between of technological change cycles and its effects on environmental change. In relation to this, innovation and industrial organisation studies of the chemical industry have shown that previous scientific and technical knowledge has been a pre-condition for technological change, new forms of eco-innovation and increased competitiveness (Freeman, 1968; Arora et al., 1998a,b; Arora and Gambardella, 2010).[15]

One of the main messages of the review above is that technological, institutional, organisational and socio-economic factors are

[9] A similar analysis was performed in the South Korean chemical industry by Lee and Rhee (2005). The categories tested by these authors were: ignorance era (prior to 1976), compliance era (1977–1990), and strategic compliance era (1991–2000).

[10] The notion of institutions used by Hoffman derives from institutional theory (Powell and Dimaggio, 1991). Hoffman understands institutions as (p. 351): "*… rules, norms, and beliefs that describe reality for the organization, explaining what is and what is not, what can be acted upon and what cannot.*"

[11] Each of these periods showed a very distinctive pattern of institutional change: challenge to existing institutions, regulative institutions, normative institutions, and cognitive institutions, with a clear indication of interconnection (accumulation) and evolution of institutional factors from one stage to another (p. 365).

[12] The main aim of Responsible Care® is the incorporation of environmental, health and process safety aspects into (corporate) management systems. Global guiding principles comprise the philosophy of the programme and include: efficient use of resources, recognition and response to community's demands regarding use of chemical products and operations, consideration of health, safety and environment aspects in production, communication of chemical risks, participation with governments in policy-creation processes, etc.

[13] Two categories related to innovation were analysed by Hoffman (p. 370): technological research and development (R&D), and predictions of technological development.

[14] This relative importance was estimated by Hoffman using the number of occurrences of articles in trade journals written by the industry, government or NGOs with titles about the technological concerns related to both regulatory compliance and pollution control. The results were as follows. For the industry, 66% of occurrences in the period 1962–1970, 43% in the period 1971–1982, 27% in the period 1983–1989, and 14% in the period 1989–1993. For the government: 6%, 8%, 7& and 5% in the same periods. For NGOs: 0%, 0% 38% and 56% in the same periods.

[15] For example, the work of Freeman (1968, 1989) presents a historical-based discussion of the changing conditions that affected innovation from the 1930s to the 1990 period. Freeman and Soete (1997, first edition from 1974) present a summary the main factors for process and product innovation of the chemical and oil industries for the 1870–1970 period. Chandler (1990) uses an industrial organisation and historical perspectives (with special focus on firms and sectors) to provide a review of the USA, British and German chemical industry in terms of organisational capabilities, investment, strategies and management of large firms and its innovation success stories for the first half of the 20th century. Achilladelis et al. (1990) presents a comprehensive study about mechanisms and dynamics of innovation in the world chemical industry for the 1930 to 1982 period. Finally, Chapman (1991) presents a discussion of the cyclic performance of the world petrochemical industry and its implications for growth, location, business strategies, investment, technological change and productivity.

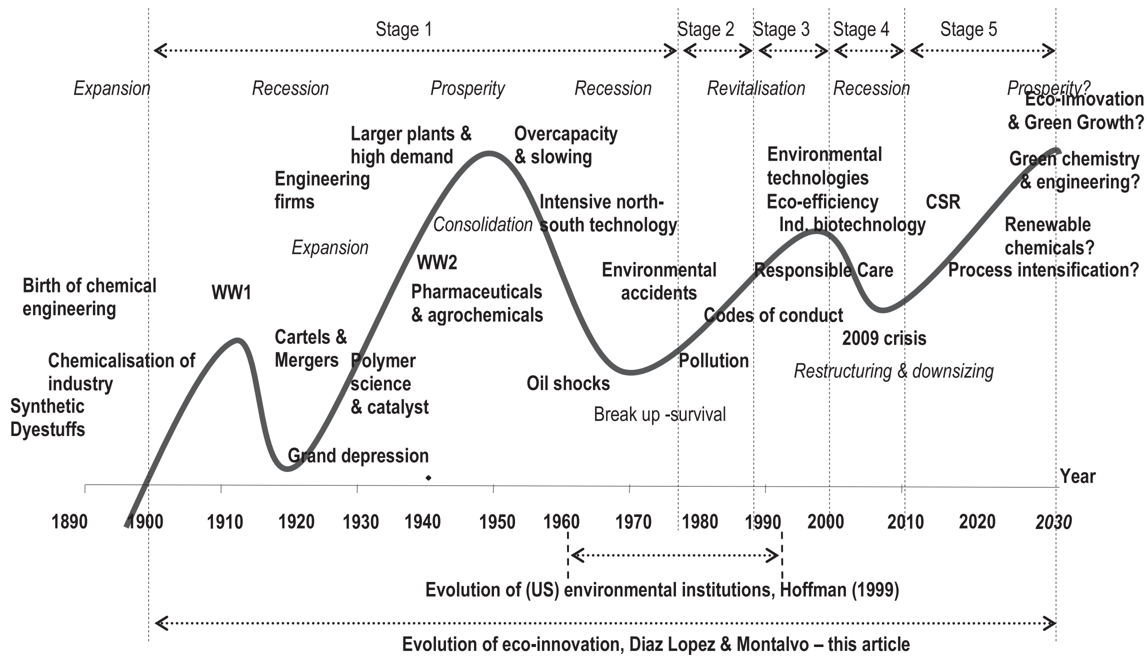

Fig. 1. Conceptual model of the evolution of eco-innovation in the world's chemical industry from 1890 to 2030.
Source: modified from Diaz Lopez and Montalvo (2012), after Freeman (1989), Chapman (1991), Smith (1994), Arora et al. (1998a,b), Gent (2002), Cesaroni et al. (2004) and Diaz Lopez (2009).

propelling forces of environmental change and eco-innovation in the chemical industry. Another message is that the intertwined nature of these factors can foster competition and co-evolution of technological paradigms within and across industries.

The following section presents the conceptual model used in this paper.

4. Conceptual model for the study of evolution and change of eco-innovation in the chemical industry

Summarising the literature review above it is possible to provide a conceptual representation of major historical events and technological paradigms that have framed the evolution of the World chemical industry in the period 1901 to 2011. In doing it so, it is also possible to hypothesise about possible factors and events contributing to environmental, institutional and technological change. Given that, in the long run, the future evolution of this industry is uncertain, it also possible to speculate about the possibility of radical eco-innovation becoming a major force for future accelerated, green growth and prosperity to the year 2030 (Fig. 1).

The main characteristics of the five stages of the evolution of this industry depicted in Fig. 1 are described below.

4.1. Stage 1 (1901–1979)

The first stage of evolution of the industry depicted in Fig. 1 can be best described as focussing on emergence and rapid expansion of knowledge and technologies. The historical works of Chandler (1990), Arora et al. (1998a,b), Spitz (2003) and Hikino et al. (2007a,b) describe a stage focused on building global production capacity and major product diversification. Following a wave of organic chemical products (e.g. pigments) (Landau, 1998), in the 1920s–1930s polymer chemistry emerged as a dominant paradigm with the highest patent activity of all times (Freeman and Soete, 1997). Freeman (1989) and Rosenberg (1998) showed that scientific knowledge from Universities and R&D centres in the technological paradigms of organic, biochemical and polymer chemistry were the cornerstones for successive product innovations. The establishment of chemical engineering as an educational and scientific discipline and the introduction of the concept of unit operations (manufacturing method) were critical for building knowhow, industry-University collaboration capabilities and critical manufacturing competences (Rosenberg, 1998).[16] In terms of use of resources, the focus on material use in this stage was mainly in relation to ensuring availability, applications and costs (c.f. Clow and Clow, 1958).

4.2. Stage 2 (1980–1989)

The second stage of evolution of the chemical industry depicted in Fig. 1 could be characterised with compliance with regulations, the more cooperation with environmental authorities, emergence of social responsibility, and the emergence of pollution control and waste minimisation as technical methods for the solution of environmental problems (Hoffman, 1999).[17] According to the literature, the cost of pollution control and prevention and the loss of confidence in the industry (due to a number of accidents) were some of the underlying reasons for the sudden increase of attention to community and government relations in this stage (King and Lenox, 2000). These factors which fostered the emergence of declaration of principles and corporate codes of conduct (Jenkins, 2002) and were conducive to better relationships with regulators (Zotter, 2004).

[16] George E. Davies is considered to be the father of chemical engineering because he published the first 'Handbook of Chemical Engineering' in 1901. But Mr Davies is less known for his environmental credentials. He was one of the most successful and feared British alkali inspectors in the late 1800s and one of the revisers of the UK Alkali Act of 1881. The first formal programmes in chemical engineering are attributed to the Massachusetts Institute of Technology, which graduated its first bachelors in chemical engineering as early as 1891, opened a formal department on the subject in 1920 and awarded their first doctorate degrees in 1924.

[17] There is anecdotal evidence of the industry's expertise in environmental control originating vis-à-vis with technological developments for alkali production in the nineteen century. For a review see Diaz Lopez and Montalvo (2012).

4.3. Stage 3 (1990–1999)

The third stage of evolution of the chemical industry showed in Fig. 1 presents an era of increased attention to corporate responsibility. This stage witnessed the adoption of management practices and tools in order to ensure en eco-efficient chemical production, such as Responsible Care®. This stage has been characterised by methods for the reduction or avoidance of negative impacts on human health and the environment commenced to be tackled through good housekeeping, eco-efficiency, good engineering practices and the introduction of pollution control devices combined with end of pipe and process-integrated environmental technologies (c.f. Eder, 2003; Graedel and Howard-Greenville, 2005).[18] An important observation from the literature is that cost reduction would continue to be a major factor for competitiveness, as this would ensure higher production efficiency. In terms of use of resources, eco-efficiency emerged as ab approach to ecological and economic value creation and a key driver for cleaner production and innovation (DeSimone et al., 2000).

4.4. Stage 4 (2000–2011)

The fourth stage of the evolution of the chemical industry in Fig. 1 can be attributed to an increased focus on innovation for the environment. This stage corresponds to the emergence of industrial biotechnology, resource efficiency, industrial ecology and sustainable manufacturing paradigms. The applications of industrial biotechnology to a number of chemical-processing routes, process automation, and micro/nano-technologies have been equated to 'sustainability in chemical manufacturing' (e.g. in Jenck et al., 2004; Clark, 2007).[19] At the level of manufacturing operations, the implementation of environmental technologies and sustainable manufacturing methods based on a life-cycle approach[20] (c.f. Arduini and Cesaroni, 2004; Braungart et al., 2007). In terms of use of resources, energy, water, raw material supply and waste management, treatment, and disposal costs have been identified as important factors for eco-innovation (c.f. Keijzers, 2002; Diaz Lopez and Montalvo, 2012). Industrial ecology approaches (e.g. zero emissions and by-product synergies) emerged as methods for an improved efficiency of material use (see Baas, 2007 for a review).[21]

4.5. Stage 5 (the future until 2030)

The fifth stage of evolution of the chemical industry in Fig. 1 speculates about the possibility of (radical) eco-innovation becoming the main driver factors for a new era of green growth and prosperity. For years, several attempts to envision and predict the future of "sustainable chemical manufacturing" have been performed (e.g. in Eissen et al., 2002; Jenck et al., 2004). The paradigms of climate mitigation technologies (e.g. energy recovery), renewable chemicals (e.g. bio-solvents), material sciences (e.g. green plastics), nano-materials (e.g. energy efficient composites), etc., have been signposted with potential to contribute to an upsurge of this industry (c.f. Thomson and Youngman, 2010; Vennestrøm et al., 2011). Scholars believe that future radical eco-innovation could be based on molecular-level modifications of traditional chemicals to inherently greener and safer chemical routes (c.f. Anastas and Breen, 1997; García-Serna et al., 2007).[22] The following emerging areas in sustainable chemicals manufacturing have also created some expectations for the future of this industry (Diaz Lopez and Montalvo, 2012): process intensification (Stankiewicz, 2003), multi-scale plants (Rauch, 2003), combinatorial chemistry (Jung, 1999), and process automation (Groover, 2003). New business models for the 'servitisation' of manufacturing companies (Tan et al., 2010), such as the provision of chemical services (Anttonen, 2010) and the emergence of sustainability requirements (e.g. environmental profit and loss accounting) across the value chain has also been mentioned as areas of increased importance (Sarkis et al., 2011). Finally, the renewal of the chemical engineering discipline has been identified to be of prime importance to help to support the necessary paradigm changes toward sustainable chemicals manufacturing (Hall and Howe, 2010).[23]

Summing up, the description of the conceptual model guiding this work identifies a number of co-evolving paradigms in the chemical in the industry: pollution control/prevention, environmental technologies, industrial biotechnology, resource efficiency, eco-innovation and sustainable manufacturing, and sustainable design/green chemistry and engineering of renewable chemicals. One of the implicit messages in the conceptual model hitherto described is the challenge to predict a dominant radical paradigm for eco-innovation in chemicals.

5. Methods and data

As an exploratory study, the objective of the literature analysis was to identify major factors influencing environmental change and eco-innovation in the chemical industry over a period of 110 years (1901–2011). This paper used (computer-aided) content analysis as analytical method for a longitudinal and systematic examination of secondary sources of information (Stone et al., 1966; Woodrum, 1984; Bringer et al., 2006). Further details of the method employed in the present article can be found in Diaz Lopez and Montalvo (2014).[24]

[18] The term eco-efficiency is often equalled in the literature to that of 'best practices' which is a common engineering tool in this industry for achieving higher process efficiency. Best practices encompass concepts and strategies for dematerialisation, increased resource productivity, reduced toxicity, increased recyclability (down-cycling) and extended product lifespan of chemical products and safer design of unit operations in production systems.

[19] Originally applied to health, microbial dimensions, food and plant genetics, biotechnology is now being applied to environmental protection, eco-textiles, waste management, bioinformatics, aquaculture, etc.

[20] Life-cycle analysis tools are used for evaluating the environmental sustainability of existing and new chemical products and processes. These are often performed at R&D labs of corporate headquarters and are product and technology specific.

[21] For example, waste-to-energy and co-generation technologies to produce both electricity and steam have been available for a number of years and represent a cost-effective solution for energy provision (especially in highly exothermic chemical processes).

[22] These approaches are also known with the generic term of *sustainable design of bio/renewable chemicals*. The list includes: the Natural Step, bio-mimicry, cradle to cradle, zero waste, resilience engineering, inherently safer design, ecological design, green chemistry and self-assembly. For example, three main areas of green chemistry are often referred as to holding great transformation potential: (1) the use of alternative synthetic pathways, (2) the use of alternative reaction conditions and (3) the design of safer chemicals that are less toxic than current alternatives or inherently safer with regards to accident potential. See García-Serna et al. (2007) for a review.

[23] A highly influential book that reviewed the evolution of this evolving discipline is Perry's Chemical Engineering Handbook, first published in 1934. Since the fifth edition (1973) this book includes aspects about product recovery and waste management. Since the seventh edition (1999) it includes sections on waste management, process safety management and energy management. Newer topics such as climate change, green chemistry, etc. have not been included in the 8th edition of this book, published in the year 2008.

[24] The method used by the authors was elaborated based on the method adopted in the seminal work of Hoffman (1999), further replicated by Lee and Rhee (2005) in a Journal of Cleaner Production paper analysing the evolution of corporate environmentalism in Korea. Diaz Lopez and Montalvo (2014) include a full description of the method of content analysis, coding scheme, and the full list of documents used in the analysis. The latter is also available directly from the authors upon request.

Software NVivo9® was used to analyse selected documents during the methodological the stages of data collection, coding, formulation of categories, analysis of content and interpretation of results. In total 255 documents were selected, categorised and further analysed following the conceptual method presented in Section 3 (Fig. 1). Documents were distributed according to their publication date as follows: (Stage 1) 1901 to 1979, 16 papers; (Stage 2) 1980 to 1989, 12 papers; (Stage 3) 1990–1999, 62 papers; (Stage 4) 2000 to 2011; 127 papers; and (Stage 5) the future until 2030, 38 reports (published in the period.

The results of the analysis are presented (Section 6) as weighted ratios of the frequency count in relation to the number of documents. Histograms and tag clouds were used to graphically present the findings of this study. Histograms show the weighted ratio of the frequency count of factors (key words) in relation to the number of documents. These frequency graphs only included the top 25 factors affecting eco-innovation in each of the five periods of analysis, albeit the results of the literature analysis included up to 100 factors.[25] Tag clouds are a recognised visual method to improve reader's understanding of data sets (Gwizdka, 2009). These are used to show tag importance by font size, weight and/or colour, and are displayed in alphabetical order (Hearst and Rosner, 2008).[26] The generic categories of determinants of eco-innovations (institutional, technological, market, economic, social and organisational) were used to provide further guidance in the description of results about factors being identified by the literature study.

The analysis of results (Section 7) involved the categorisation and selection of top factors in each stage of evolution of the chemical industry (Fig. 1). However, the type of document included in Stage 5 (38 government-funded reports) was considered non-comparable to those in stages 1–4 (217 scientific papers). For this reason, the former category was excluded from the presentation of the analysis and it was used for comparison purposes only. The five tables of weighted frequency counts (one per period) were collected and ordered from higher to lower counts. The top-ten factors of each stage were identified and the average weighted-frequency count was estimated, resulting in 26 factors across the entire analytical stages. A clustered graph was subsequently elaborated (Fig. 2). The top-ten factors of each period were used to elaborate a summary table ordered by words (rows) and stages (columns) (Table 1). Factors with above-average values were re-ordered into the six different categories of determinants of eco-innovation (see above).[27]

The following section presents the results and discussion of our literature-analysis.

[25] Please note that the weighted frequency of words is expressed in each column's histogram. For example the frequency for the word 'sustainable' during the period 2000–2011 was 3019 words divided by 127 documents equals 22.9.

[26] NVivo9® uses a linear mapping from frequency count to font size in order to display words in tag clouds. The most frequently occurring word is given a font size of 60 points whereas the 100th most frequently occurring word gets a font size of 10 points. The font size of words in between is calculated using a linear mapping between frequency and font size. Please note that the figures provided in this article have been re-sized to fit the scale of the paper.

[27] This summary table originally included 27 missing values corresponding to 10 factors outside the top-ten lists (e.g. the word 'strategy' was a top-100 factor in stages 1 and 2). Hence missing values were located from the raw data (of frequency counts), converted into a weighted-frequency value and manually inserted in the corresponding cell. Diaz Lopez and Montalvo (2014) includes these summary tables of top-100 factors for each analytical period. However, all of these values resulted to be below-average, therefore these are not included in Table 1. Summary tables are also available directly from the authors upon request.

6. Evolution of eco-innovation in the chemical industry: results from a literature study

6.1. *Early challenges for chemical products and technologies (1901–1979)*

The defining factors in this stage faithfully represent the focus on technological development for chemicals manufacturing. Consistently with our conceptual model, the results of the first stage of evolution of the chemical industry depict an era of technical and scientific capacity building for chemical production. Identified factors in this stage were: 'process', 'products, 'plants', 'technologies', 'science', 'operations', 'costs', 'materials', 'design', 'University', 'research', 'training', 'investments', 'prices', etc. (see Fig. 2).

Albeit the authors of this paper did not identify high weighted-frequency counts of words associated to major environmental events in Stage 1, the authors of this paper found some occurrences of the words 'resources' (energy and water), environmental problems (e.g. acid rain), and valuable 'by-products' (soda and bleaching), and some mentions.

6.2. *Early response to environmental and health challenges (1980–1989)*

The defining element of the second stage of the evolution of the chemical industry can be characterised by regulation-driven innovation due to rising environmental and social concerns (pollution and health). In this stage, a clearly observable result can be associated to a reactive behaviour of the chemical industry to compliance with health and safety regulations.

The results of the literature analysis shows that 'regulations', followed by 'innovations' were the most frequent words in this stage (see Fig. 3). These factors were followed in importance by a combination of technological and social determinants. On the one hand we identified factors such as 'products', 'technology', 'development', 'process', and 'standards'. On the other hand there were high-frequency counts of words 'exposure', 'cancer', 'pollution', 'toxic' and 'health''. Economic factors such as 'costs' and 'markets' also appeared with high weighted-frequency counts. It is also important to note the increased importance that water had in this period of time.

6.3. *Responsible management for environmental change (1990–1999)*

While keeping an emphasis on regulation, the results of this stage refer to an increased attention to environmental responsibility, strategy, management and business concepts, and to the development of environmental technologies.

In Fig. 4 it is observable high occurrences of words related to corporate responsibility (public, responsible care, reporting), regulations, and government. The authors of this paper also noticed an upsurge of frequency count organisational terms, such as 'management', 'organisational', 'change', 'corporate, and above all 'strategy'. Technological factors continued having a high-frequency count (products, processes, production, patents, technology, research & development and innovation). 'Patents', 'costs' and 'markets' were also important. Albeit our analysis only found a low count of the term (eco-) efficiency, the word 'best practice' was found in the top 100 factors revealed by the content analysis.

6.4. *Technology development for eco-innovation (2000–2011)*

The fourth stage of the evolution of the chemical industry can be best characterised with an increased attention to environmental

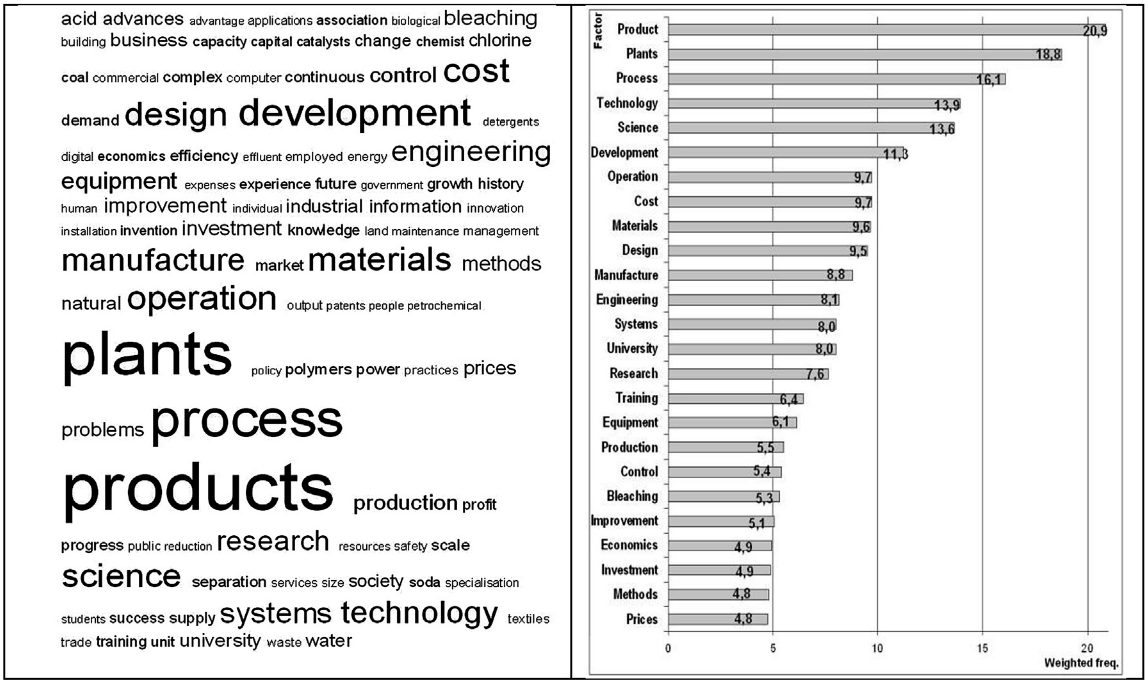

Fig. 2. Tag-cloud (top 100) and weighted frequency histogram (top 25) of factors influencing eco-innovation in the chemical industry. Scientific papers published in the period 1908–1979 (n = 16).

Table 1
Categorisation of top factors for eco-innovation in the chemical industry. Period 1901–2030 (only above-average factors displayed).

Category	Factor	Stage 1 1901–1979	Stage 2 1980–1989	Stage 3 1990–1999	Stage 4 2000–2011	Stage 5 future?
Technological	Innovation		55.8	17.6	16.9	61.8
	Development	11.3	29.1	19.1	27.0	94.3
	Technology	13.9	49.4	22.5	27.0	75.5
	Process	16.1	24.4	19.9	34.6	126.6
	Product	20.9	49.9	35.3	60.2	362.3
	Science	13.6				
	Operations	9.7				
	Design	9.5				
	Plants	18.8				
	Materials	9.6				
Institutional	Regulation		95.3	17.6		
	Exposure		33.5			
	Energy					70.3
	Waste					75.9
	Sustainable				23.8	
Organisational	Management			21.8	21.5	
	Strategy			22.8		
	Change		22.9			
Markets	Market			15.5		
	Biotechnology					95.7
	Business			20.5	15.7	
Economics	Cost	9.7	20.6			
	Reduction				21.6	
Society	Cancer		23.7			
	Health		23.0			
	Average value	**6.4**	**20.6**	**12.3**	**15.6**	**62.2**

technologies and sustainability as factors of environmental change.[28]

The results of the literature analysis revealed that during the period between the years 2000 and 2011 concepts related to sustainability and greening increased in importance in the sample of documents. Technological factors for chemical, production continued having high-frequency counts (products, processes, research & development, innovation, manufacturing, and engineering). Organisational factors such as business, strategies, models, management, change, and information followed in terms of frequency count. Albeit not in the top 25 factors, social factors were of high importance (public and community). Economic factors such as 'markets', 'costs', and 'performance' were also present in the frequency count.

[28] As noted earlier in this paper the work of Hoffman only provided insights on environmental evolution and change until the decade of 1990s. Any comparison of the factors unveiled by our literature analysis would need to be based on case study and anecdotal evidence.

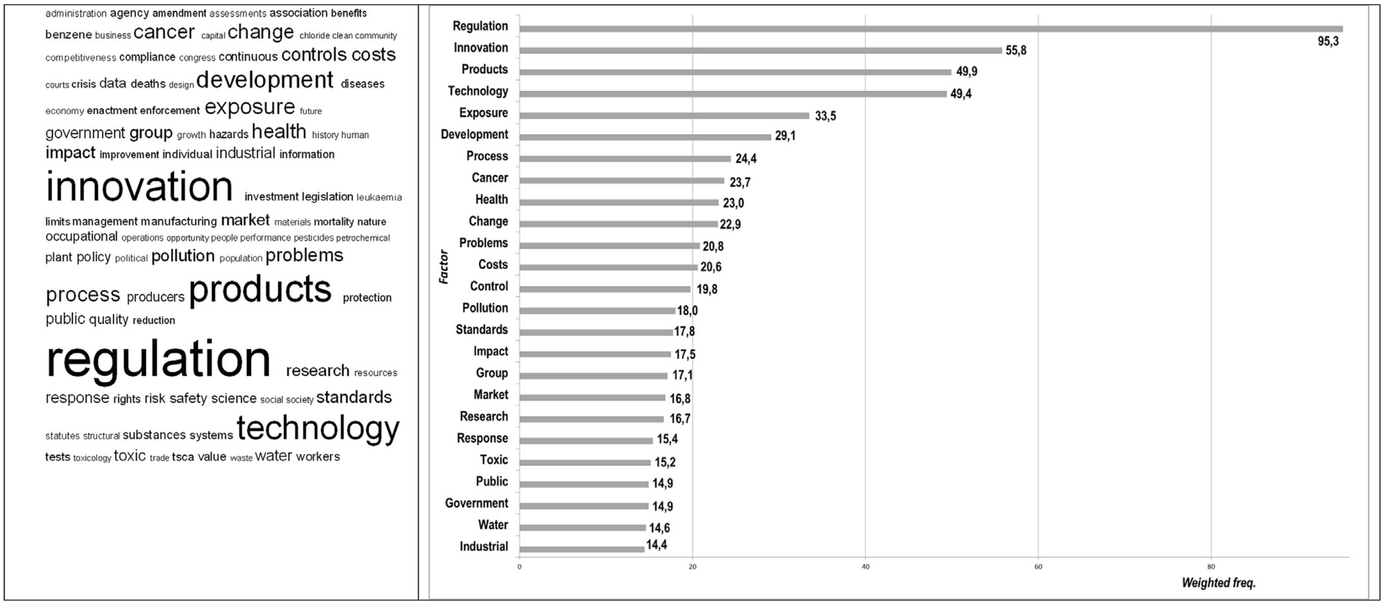

Fig. 3. Tag-cloud (top 100) and weighted frequency histogram (top 25) of factors influencing eco-innovation in the chemical industry. Scientific papers published in the period 1980–1989 (n = 12).

Fig. 4. Tag-cloud (top 100) and weighted frequency histogram (top 25) of factors influencing eco-innovation in the chemical industry. Scientific papers published in the period 1990–1999 (n = 62).

From the factors suggested by our conceptual model, it is interesting to note the growing importance of design-based approaches for eco-innovation (30th factor). Our results identified words such as ‘life cycle’ and ‘supply chain’ with high count during this stage. One of the most important results was related to the high count of the word “resources” (materials, energy, waste, and water) and the fact that the term “climate change” only appeared in the top 400th factors of this period. Finally, no words related to radical change could be identified as part of the top-factors in this stage.

6.5. An era of eco-innovation ahead? (2011–2030)

The results presented in this analytical stage are based on publicly-funded, future-oriented reports speculating about the future of sustainable manufacturing in the chemical industry –

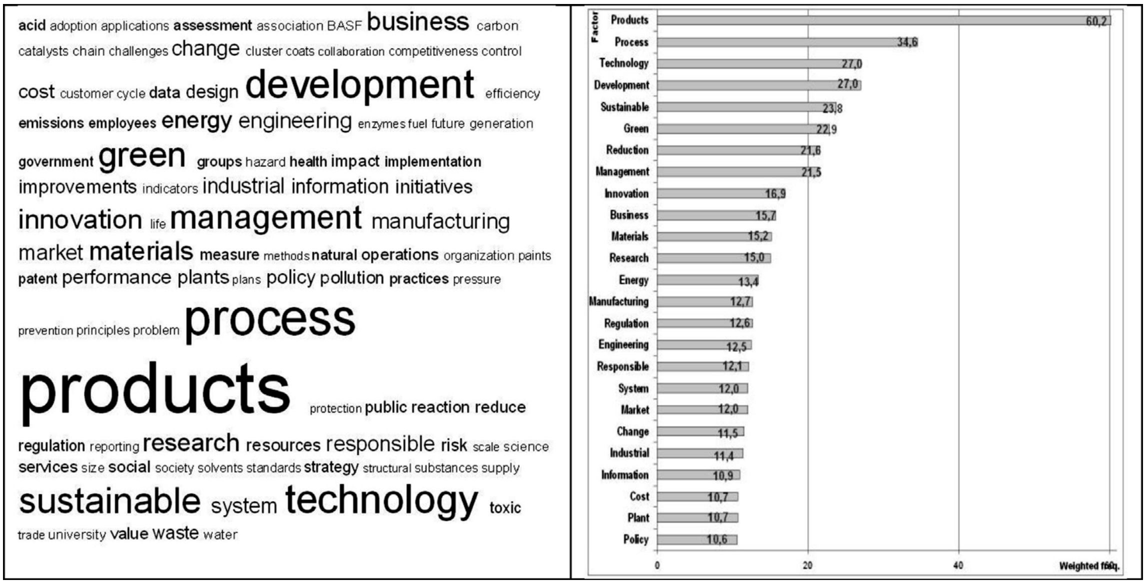

Fig. 5. Tag-cloud (top 100) and weighted frequency histogram (top 25) of factors influencing eco-innovation in the chemical industry. Scientific papers published in the period 2000–2011 (n = 127).

with a time horizon to the year 2030. Therefore, the results of the content analysis are considered as speculative.[29] Notwithstanding, this future-oriented stage could well be characterised by eco-innovation enabled by applications of industrial biotechnology and renewable chemical processes and higher attention to carbon footprint and resource efficiency measures (see Fig. 6).

The results of the content analysis suggest an increased count of technology-related factors. Products, processes, technology, innovation, applications, and research & development were concepts with high frequency counts in the sample of documents analysed. Environmental and resource-variables were also important, with water, energy, emissions, and waste having a high frequency count. Our findings support earlier observations of many authors that material and energy are major concerns, both in terms of availability of resources and effects on prices/costs. It is interesting that economic factors such as costs, markets, efficiency, and performance are very likely to remain important in the future due to their high frequency count. The emergence of alternative business models and the provision of environmental services are important factors in the future of eco-innovation in chemicals (top 100 factors). Organisational factors (e.g. change, management, organisational, strategy) and social factors (e.g. community) resulted into a lower frequency count in comparison to technological factors.

7. Analysis of results

Albeit of explorative nature, the empirical validation aimed at identifying the most salient aspects of evolution used to promote socio-technical, institutional, and environmental change in the chemical industry. The relative importance of factors was measured in terms of occurrence number of words (weighted measure of the frequency count divided by the number of papers included in each analytical category). The authors of this paper found that, throughout time, top factors appear to have an increasing importance for eco-innovation in the chemical industry. The top 25 factors are summarised in the figure below, being regulation the word with the highest weighted frequency count (Fig. 7).

The following table includes the top ten factors of each category, identified by having a weighted frequency counts above the average value of each period.[30] From Table 1 it is observable that each top factor was at least 1 time above average in the corresponding stage, being an indication of a dominant factor in at least one analytical stage.

In accordance to our conceptual model, stage 1 is characterised by technology development, knowledge creation, building production capacity and cost reduction. Stage 2 is primarily health & environmental-regulation driven whereas Stage 3 appears to be focussing on strategic management, access to market and business survival. Stage 4 saw the emergence of sustainable development and for stage 5 it is possible to speculate that the chemical industry might witness a new upsurge of eco-innovation along the path of resource efficiency (e.g. energy and waste). Yet, the future dominant technological paradigm of eco-innovation for a sustainable chemical industry remains uncertain (e.g. industrial biotechnology).

One of the main observations derived of our literature analysis is the intertwined nature between policy (regulation), technology (technological capabilities, product and process development), and innovation. Such intertwinement was explicit in the literature review offered in section 2. The technological factors 'development', 'technology', processes and 'product' appeared as above-average across the whole period of study. The word 'innovation' appeared as top 10 factor in all but the Stage 1. In terms of policy-related factors and in correspondence to the literature (section 3), regulation was a top factor in stage 2 and stage 3. Closely related to regulations, society factors were also important for the stage 2 of environmental compliance and better relations with the community

[29] For example, a careful interpretation is needed due to the length of the reports compared with the scientific papers, which may be a factor for such a large (and substantially high) weighted-frequency counts.

[30] Clearly, selecting those factors with greater importance constituted a challenging task, also in relation to allocating each factor to a category of enablers of eco-innovation introduced in chapter 2. Qualitative methods such as factor analysis allow the integration of categories based on patterns of responses, often obtained from survey data. See Diaz Lopez and Montalvo (2014) for additional details of complementary methods to qualitative data mining of literature.

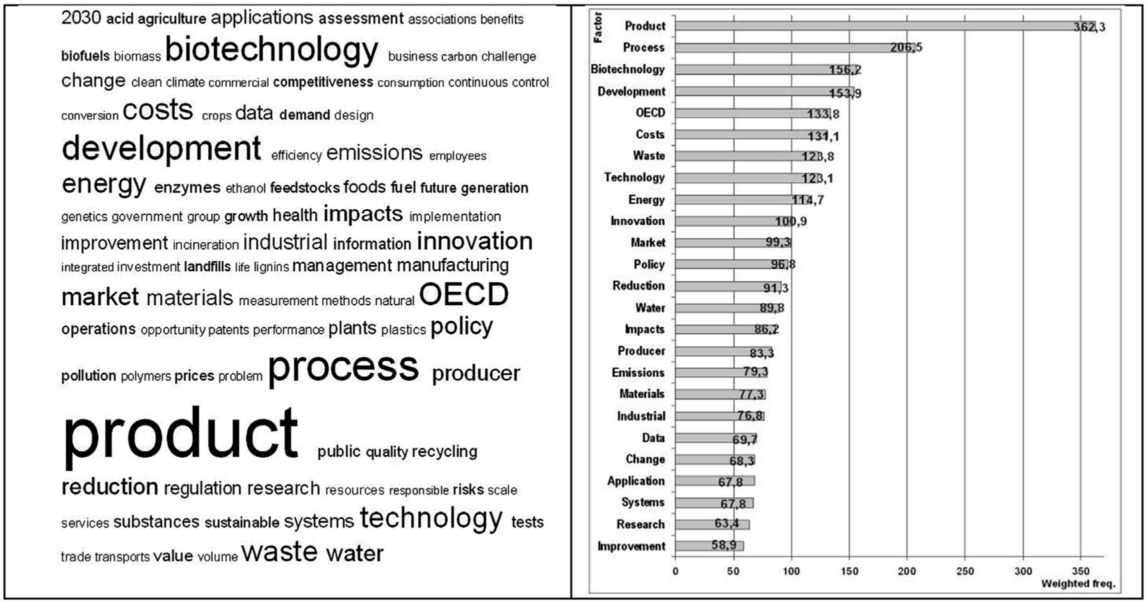

Fig. 6. Tag-cloud (top 100) and weighted frequency histogram (top 25) of factors influencing the future of eco-innovation in the chemical industry. Future-oriented reports published in the period 1999–2011 (n = 38).

and government. A related finding, yet speculative, is the role of policy for the future development of the industry. The above-average occurrences of sustainability and resource-related policy factors (waste and energy) in stage 4 and stage 5, respectively, may be an indication of the expected role of policy in a transition to sustainability. Summarising the main points discussed in the above, all of these observations and results are aligned to the findings of the seminal work of Hoffman (1999). It seems that all of the identified factors offer the possibility to contribute to eco-innovation in the chemical industry, but we can only speculate they could become major sources of growth and prosperity to the year 2030.

An interesting finding was in relation to the systemic nature of eco-innovation. Albeit not reported in Table 1, the word *system* was a recurrent factor in all stages of evolution of the chemical industry (indicated as top-100 factor in each tag cloud in Figs. 2–6). To this regard, in the theoretical part of this paper, the authors suggested that system thinking is needed for a better understanding of the evolution of eco-innovation in the chemical industry.[31] Aligned to the claims of transition scholars (e.g. van den Bergh et al., 2011), radical eco-innovations require a major process of creative destruction and breaking away from unsustainable paradigms of production and consumption. Notwithstanding, our literature analysis failed to provide evidence on factors directly associated to radical change at the systemic level.

The following section presents the main conclusions and further research needs derived from the present study.

8. Conclusions and further research needs

This article was designed to contribute to a better understanding of the evolution of eco-innovation in the chemical industry. This work had a two-fold, inter-related, objective: (a) to identify factors contributing to environmental change in the chemical industry? And (b) to identify factors motivating the evolution of eco-innovation in the chemical industry? Our main conclusions, limitations of the selected approach and avenues of future research are presented in the following paragraphs.

First, it is important to establish that eco-innovation continues to be an elusive concept. We adopted a general definition aligned to the economic and environmental benefits of innovation, which conditioned the literature analysis and its interpretation. An important challenge for academics and practitioners remains in order to accept a more definitive concept and to ensure its operationalisation. Focussing on innovation within the chemicals production system is an approach that facilitated the development of the present work. Narrowing down the unit of analysis to firms may have provided a more precise identification of elements and of the underlying causes. The vast number of case studies and empirical evidence of greening and sustainability practices, products and technologies in the chemical industry should be used for this purpose. The conceptual categories formulated in Fig. 1 and factors identified by our literature study could be used as pinpoints for the elaboration of the taxonomic categories and of proxy indicators of eco-innovation in the chemical industry.

In regard to our research questions, our study advances the modern scholarly understanding on what factors appear to have shaped environmental evolution of the chemical industry (Fig. 1). Therefore, one of the main contributions of this article advances the seminal work of Hoffman (1999) by characterising the co-evolution of socio-technical and institutional factors contributing to a transition to sustainability in the chemical industry. Overall, the results of our literature study suggest that the chemical industry is co-evolving along emerging technological trajectories with well-defined factors for eco-innovation at the systemic level, such as regulation, innovation, strategy, etc. Yet, we are unable to confirm the consolidation of any radical eco-innovation paradigm towards green growth.[32] What we can suggest is that the need for

[31] Clearly, a careful interpretation of this finding is needed. It could well be that given the heterogeneous theoretical positions of the literature analysed the word 'system' may refer to different analytical or empirical constructs, such as production system, innovation system, etc.

[32] For example, the authors of this paper are unable to confirm whether emerging technological paradigms such as multi-purpose plants, process intensification, etc. may have a significant contribution to the future development of this industry.

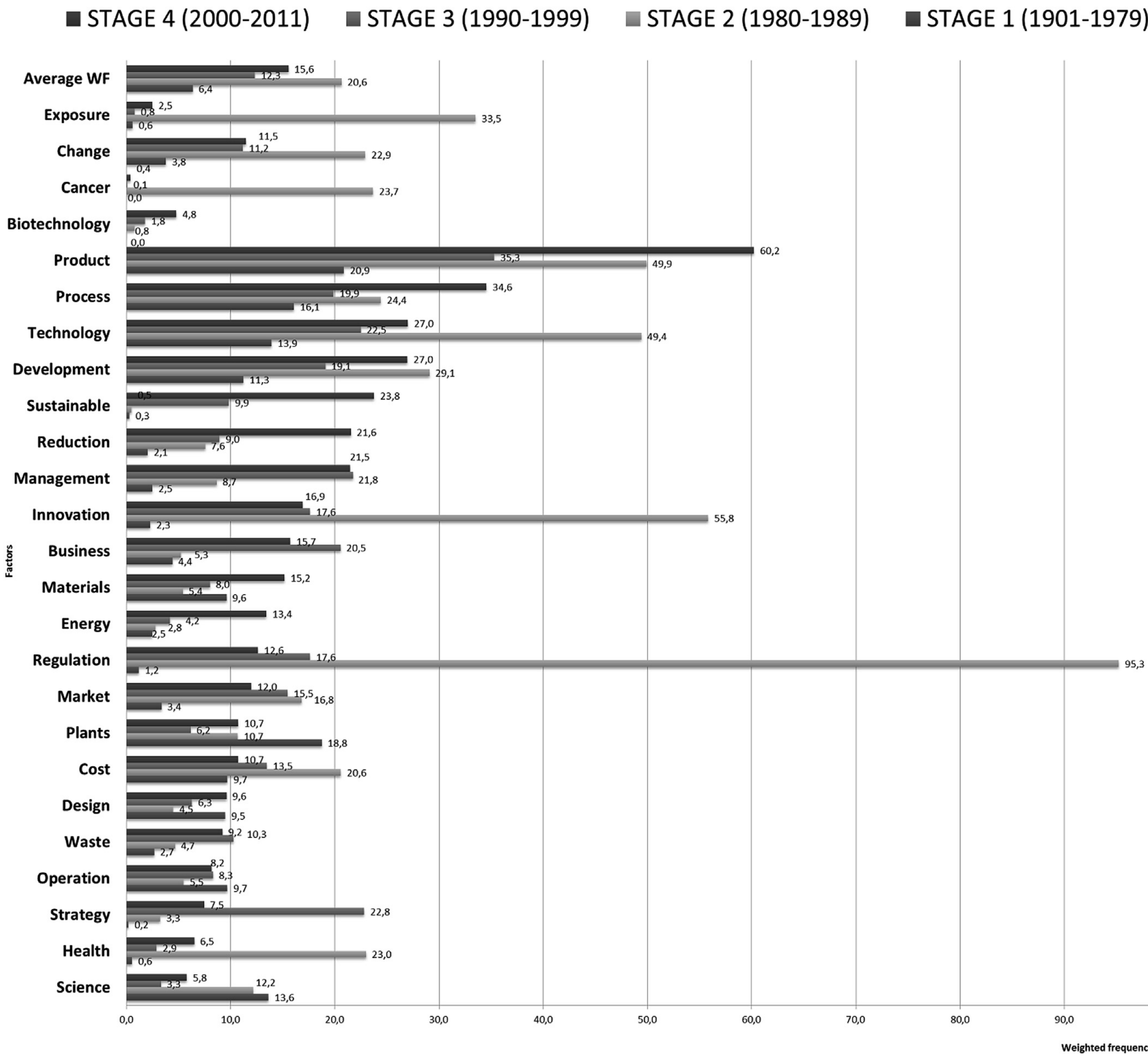

Fig. 7. Overview of top factors for eco-innovation in the chemical industry (period 1901–2011).

sustainable use of resources and sustainable development may continue influencing the future evolution of this industrial sector in coming years. Perhaps all of this competition in technological paradigms is slowly shaping a new disruptive event that will eventually contribute to promote a major sustainability transformation. An underlying reason is the fact that this is an industry with the constant pressure to demonstrate its efforts to reduce its overall environmental footprint and the risk of operations. Notwithstanding, more evidence is needed in order to fully understand the future of eco-innovation in the chemical industry.

Salient limitations of the approach used in this paper. Perhaps the most evident limitation is that the authors do not directly observe the chemical industry. Based on secondary sources of information, the account presented in this study is a systematic identification and description of factors affecting the environmental change of this industrial sector, which could be associated to eco-innovation. A more rigorous quantitative enquiry is needed in order to identify the causality and degree of association among explanatory factors and independent variables (e.g., environmental performance, eco-innovation, etc.). Another limitation is that publications are unavoidably biased by trends and fashions. New topics, such as sustainability management in the chemical industry, renewable chemicals, etc., need time to get visible in scientific publications (see Fig. 1). This is due to the publication process itself, but also due to the time difference epistemic communities need to identify those topics, write publications, and to legitimise their hypothesis, propositions and findings. Another factor contributing to the bias of the selected approach is due to the degree of secrecy around the chemical industry. It is possible that important industry R&D may not be published in academic journals – but it could only be identified from industry journals, expert enquiries and patents, for example.

Now the authors propose some avenues of future research. Understanding how industry operates, how firms accumulate know-how and experience, and the ways by which manage their assets for improving their efficiency and performance is a prerequisite for designing strategies and policies for promoting implementation of eco-innovation. Therefore, an important avenue of future research relates to policy intervention. We urgently need a deeper institutional analysis of the evolution of eco-innovation in relation to the broader sustainable innovation paradigm in this industry, beyond Hoffman's and our own contributions. A major shortcoming of this paper is that the authors have not properly addressed problems of un-sustainability and rebound effects of the chemical industry. An additional topic not addressed in this article is the cross-sector nature of chemical operations and its implications for major sustainability transitions in relation to other industries. This was unavoidable given the data and analytical method employed. These topics clearly require further analysis and provide an interesting avenue for future research.

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References

3M and UNEP, 1982. Low or Non-pollution Technology through Pollution Prevention. 3M Company for the United Nations Environment Programme, Office of Industry and the Environment, Paris, p. 35.

Achilladelis, B., Schwarzkopf, A., Cines, M., 1990. The dynamics of technological innovation: the case of the chemical industry. Res. Policy 19 (1), 1–34.

Anastas, P.T., Breen, J.J., 1997. Design for the environment and green chemistry: the heart and soul of industrial ecology. J. Clean. Prod. 5 (1–2), 97–102.

Anttonen, M., 2010. Greening from the front to the back door? A typology of chemical and resource management services. Bus. Strategy Environ. 19 (3), 199–215.

Arduini, R., Cesaroni, F., 2004. Development and diffusion of environmental technologies. In: Cesaroni, F., Gambardella, A., Garcia-Fontes, W. (Eds.), The Role of the European Chemical Industry? R&D, Innovation and Competitiveness in the European Chemical Industry. Kluwer Academic, Boston, London, pp. 205–230.

Arora, A., Gambardella, A., 2010. Implications for Energy Innovation from the Chemical Industry. In: NBER Working Paper Series. National Bureau of Economic Research, Cambridge, p. 20.

Arora, A., Landau, R., Rosenberg, N., 1998a. Chemicals and Long-term Economic Growth. Insights from the Chemical Industry. John Wiley and Sons, Inc, New York, Chichester, Weinheim, Brisbane, Singapore, Toronto.

Arora, A., Landau, R., Rosenberg, N., 1998b. Introduction. In: Arora, A., Landau, R., Rosenberg, N. (Eds.), Chemicals and Long-term Economic Growth. Insights from the Chemical Industry. John Wiley and Sons, Inc, New York, Chichester, Weinheim, Brisbane, Singapore, Toronto.

Baas, L., 2007. To make zero emissions technologies and strategies become a reality, the lessons learned of cleaner production dissemination have to be known. J. Clean. Prod. 15 (13–14), 1205–1216.

Barney, J., 1991. Firm resources and sustained competitive advantage. J. Manag. 17 (1), 99–120.

Berkhout, F., 2005. Technological regimes, environmental performance and innovation systems: tracing the links. In: Weber, M., Hemmelskamp, J. (Eds.), Towards Environmental Innovation Systems. Springer, Heidelberg, pp. 57–80.

Braungart, M., McDonough, W., Bollinger, A., 2007. Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design. J. Clean. Prod. 15 (13–14), 1337–1348.

Bringer, J.D., Johnston, L.H., Brackenridge, C.H., 2006. Using computer-assisted qualitative data analysis software to develop a grounded theory project. Field Methods 18 (3), 245–266.

Cesaroni, F., Gambardella, A., Garcia-Fontes, W., Mariani, M., 2004. The chemical sectoral system: firms, markets, institutions and the process of knowledge creation and diffusion. In: Malerba, F. (Ed.), Sectoral Systems of Innovation. Concepts, Issues and Analysis of Six Major Sectors in Europe. Cambridge University Press, Cambridge, p. 507.

Chandler, A., 1990. Scale and Scope: the Dynamics of Industrial Capitalism. The Belknap Press of the Harvard University Press, Cambridge (Mass); London.

Chapman, K., 1991. The International Petrochemical Industry: Evolution and Location. Blackwell Publishing, Oxford, UK (Cambridge, USA).

Clark, J.H., 2007. Green chemistry for the second generation biorefinery—sustainable chemical manufacturing based on biomass. J. Chem. Technol. Biotechnol. 82 (7), 603–609.

Clow, A., Clow, N., 1958. The chemical industry: interaction with the industrial revolution. A history of technology. In: Singer, C., Holmyard, E., Hall, A., Williams, T. (Eds.), IV. The Industrial Revolution c. 1750 to c. 1850. Oxford University Press, Oxford, pp. 230–257.

Coenen, L., Díaz López, F.J., 2010. Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. J. Clean. Prod. 18 (12), 1149–1160.

Cohen, W., Levinthal, D., 1990. Absorptive capacity: a new perspective on learning and innovation. Adm. Sci. Q. 35 (1).

Colby, M.E., 1991. Environmental management in development: the evolution of paradigms. Ecol. Econ. 3 (3), 193–213.

DeSimone, L., Popoff, F., WBCSD, 2000. Eco-efficiency. The Business Link to Sustainable Development. The MIT Press, Cambridge, London.

Devezas, T., 2005. Evolutionary theory of technological change: state-of-the-art and new approaches. Technol. Forecast. Soc. Change 72, 1137–1152.

Diaz Lopez, F.J., 2009. Environment, Technological Change an Innovation. PhD in Human Geography Unpublished PhD thesis. University of East Anglia.

Diaz Lopez, F.J., Montalvo, C., 2012. The greening of the chemical industry: past, present and challenges ahead. In: Sanghi, R., Singh, V. (Eds.), Green Chemistry for Environmental Remediation. John Wiley & Sons-Scrivener Publishing LLC, Salem, pp. 35–78.

Diaz Lopez, F.J., Montalvo, C., 2014. Qualitative Data Mining: the Case of Sustainable Innovation Long Waves in the Chemical Industry (1901-2011). In: TNO Working Paper Series. Netherlands Organisation for Applied Scientific Research TNO, Delft, p. 27.

Dosi, G., 1982. Technological paradigms and technological trajectories. Res. Policy 11, 147–162.

Dosi, G., 1988. The nature of the innovative process. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, R., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter Publishers, London, pp. 219–238.

Dosi, G., Orsenigo, L., 1988. Coordination and transformation: an overview if structures, behaviours and change in evolutionary environments. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, R., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter Publishers, London, pp. 13–37.

Eder, P., 2003. Expert inquiry on innovation options for cleaner production in the chemical industry. J. Clean. Prod. 11 (4), 347–364.

Eissen, M., Metzger, J.O., Schmidt, E., Schneidewind, U., 2002. 10 years after Rio—concepts on the contribution of chemistry to a sustainable development. Angew. Chem. Int. Ed. 41 (3), 414–436.

Ekins, P., 2010. Eco-innovation for environmental sustainability: concepts, progress and policies. Int. Econ. Econ. Policy 7 (2), 267–290.

Fisher, J.C., Pry, R.H., 1971. A simple substitution model of technological change. Technol. Forecast. Soc. Change 3, 75–88.

Florida, R., 1996. Lean and green: the move to environmentally conscious manufacturing. Calif. Manag. Rev. 39 (1), 80–105.

Freeman, C., 1968. Chemical process plant: innovation and the world market. Natl. Inst. Econ. Rev. 45 (1), 29–51.

Freeman, C., 1984. Prometheus unbound. Futures 16 (5), 494–507.

Freeman, C., 1989. Technical innovation in the world chemical Industry and changes of techno-economic paradigm. In: Lustrum Conference. University of Limburg, Maastricht, p. 32. MERIT, Maastricht Economic Research Institute on Innovation and Technology.

Freeman, C., 1994. The greening of technology: introduction. Futures 26 (10), 1019–1022.

Freeman, C., Perez, C., 1988. Structural crises of adjustment, business cycles and investment behaviour. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, R., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter Publishers, London, pp. 38–66.

Freeman, C., Soete, L., 1997. The Economics of Industrial Innovation. Pinter, London.

García-Serna, J., Pérez-Barrigón, L., Cocero, M.J., 2007. New trends for design towards sustainability in chemical engineering: green engineering. Chem. Eng. J. 133 (1–3), 7–30.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Res. Policy 33 (6–7), 897–920.

Gent, C., 2002. Changes in the chemical industry: the perspective of a catalyst supplier. Chem. Commun. 24, 2926–2928.

Georghiou, L., Metcalfe, S., Gibbons, M., Ray, T., Evans, J., 1986. Post-innovation Performance: Technological Development and Competition. MacMillan, London.

Graedel, T., Howard-Greenville, J., 2005. Greening the Industrial Facility. Perspectives, Approaches and Tools. Springer, New York.

Groover, M., 2003. Automation, Production Systems and Computer Integrated Manufacturing. Prentice Hall, Upper Saddle River.

Gwizdka, J., 2009. What a difference a tag cloud makes: effects of tasks and cognitive abilities on search results interface use. Inf. Res. 14 (4).

Hall, G.M., Howe, J., 2010. Sustainability of the chemical manufacturing industry: towards a new paradigm? Educ. Chem. Eng. 5 (4), e100–e107.

Hart, S., 1995. A natural-resource-based view of the firm. Acad. Manag. Rev. 20 (4), 986–1014.

Hart, S., Ahuja, G., 1996. Does it pay to be green? An empirical examination of the relation between emission reduction and firm performance. Bus. Strategy Environ. 5 (1996), 30–37.

Hart, S., Milstein, M., 2003. Creating sustainable value. Acad. Manag. Exec. 17 (2), 56–69.

Hearst, M.A., Rosner, D., 2008. Tag clouds: data analysis tool or social signaller?. In: Proceeding HICSS '08 Proceedings of the Proceedings of the 41st Annual Hawaii International Conference on System Sciences. IEEE Computer Society, Hawaii.

Heaton, A. (Ed.), 1994. The Chemical Industry. Blackie Academic & Professional, Oxford.

Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., Smits, R., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Change 74 (4), 413–432.

Hikino, T., Zamagni, V., Galambos, L., 2007a. The Global Chemical Industry in the Age of the Petrochemical Revolution. Cambridge University Press, Cambridge.

Hikino, T., Zamagni, V., Galambos, L., 2007b. Introduction. In: Hikino, T., Zamagni, V., Galambos, L. (Eds.), The Global Chemical Industry in the Age of the Petrochemical Revolution. Cambridge University Press, Cambridge, pp. 1–20.

Hoffman, A.J., 1999. Institutional evolution and change: environmentalism and the U.S. chemical industry. Acad. Manag. J. 42 (4), 351–371.

Ilgin, M.A., Gupta, S.M., 2010. Environmentally conscious manufacturing and product recovery (ECMPRO): a review of the state of the art. J. Environ. Manag. 91 (3), 563–591.

Jacobsson, S., Bergek, A., 2011. Innovation system analyses and sustainability transitions: contributions and suggestions for research. Environ. Innov. Soc. Trans. 1 (1), 41–57.

Jenck, J., Agterberg, F., Droescher, M., 2004. Products and process for a sustainable chemical industry: a review of achievements and prospects. Green. Chem. 6, 544–556.

Jenkins, R., 2002. Environmental Regulation in the New Global Economy. Edward Elgar, Cheltenham, Northampton.

Jung, G., 1999. Combinatorial Chemistry. Synthesis, Analysis, Screening. Wiley-VCH, Weinheim.

Keijzers, G., 2002. The transition to the sustainable enterprise. J. Clean. Prod. 10 (4), 349–359.

Kemp, R., 1994. Technology and the transition to environmental sustainability: the problem of technological regime shifts. Futures 26 (10), 1023–1046.

Kemp, R., 2010. Las tecnologías sostenibles no existen. Ekonomiaz 3 (75), 22–39.

Kemp, R., Pearson, P., 2008. Final Report MEI Project About Measuring Eco-innovation. EU FP6 funded project 044513. UM-MERIT, ZEW, DTU, ICL, LEIA, Maastricht.

Kemp, R., Soete, L., 1992. The greening of technological progress: an evolutionary perspective. Futures 24 (5), 437–457.

King, A., 2000. Organizational response to environmental regulation: punctuated change or autogenesis? Bus. Strategy Environ. 9, 224–238.

King, A.A., Lenox, M.J., 2000. Industry self-regulation without sanctions: the chemical industry's responsible care program. Acad. Manag. J. 43 (4), 698–716.

Kleef, J.A.G., Roome, N.J., 2007. Developing capabilities and competence for sustainable business management as innovation: a research agenda. J. Clean. Prod. 15 (1), 38–51.

Lancaster, M., 2002. Green Chemistry: an Introductory Text. Royal Society of Chemistry, Cambridge.

Landau, R., 1998. The process of innovation in the chemical Industry. Chemicals and long-term economic growth. In: Arora, A., Landau, R., Rosenberg, N. (Eds.), Insights from the Chemical Industry. John Wiley and Sons, Inc, New York, Chichester, Weinheim, Brisbane, Singapore, Toronto, pp. 139–179.

Lee, S.-Y., Rhee, S.-K., 2005. From end-of-pipe technology towards pollution preventive approach: the evolution of corporate environmentalism in Korea. J. Clean. Prod. 13 (4), 387–395.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Policy 41 (6), 955–967.

Mckinsey, Company, 2011. McKinsey Global Survey Results: the Business of Sustainability. In: The McKinsey Quarterly. McKinsey & Company, San Francisco.

Montalvo, C., 2002. Environmental Policy and Technological Innovation. In: Why Do Firms Adopt or Reject New Technologies?. Edward Elgar, Cheltenham, Northampton.

Montalvo, C., 2008. General wisdom concerning the factors affecting the adoption of cleaner technologies: a survey 1990–2007. J. Clean. Prod. 16 (1, Suppl. 1), S7–S13.

Musiolik, J., Markard, J., Hekkert, M., 2012. Networks and network resources in technological innovation systems: towards a conceptual framework for system building. Technol. Forecast. Soc. Change 79 (6), 1032–1048.

Nelson, R., Winter, S., 1982. An Evolutionary Theory of Economic Change. Belknap Press, Cambridge, Mass.; London.

OECD, 2011. OECD Sustainable Manufacturing Toolkit. In: Seven Steps to Environmental Excellence. Organisation for Economic Cooperation and Development, Paris, p. 54.

Pérez, C., 1983. Structural change and the assimilation of new technologies in the economic and social system. Futures 15 (5), 357–375.

Penrose, E.T., 1952. Biological analogies in the theory of the firm. Am. Econ. Rev. 42, 804–819.

Porter, M., Kramer, M., 2011. Creating shared value. How to reinvent capitalism -and unleash the wave of innovation and growth. Harv. Bus. Rev. (January-February) 17.

Powell, W., Dimaggio, P., 1991. The New Institutionalism in Organizational Analysis. The University of Chicago Press, Chicago, London.

Rauch, J. (Ed.), 2003. Multiproduct Plants. Wiley-VCH, Weinheim.

Reinstaller, A., 2008. The technological transition to chlorine free pulp bleaching technologies: lessons for transition policies. J. Clean. Prod. 16 (1 Suppl. 1), 133–147.

Rennings, K., 2000. Redefining innovation – eco-innovation research and the contribution from ecological economics. Ecol. Econ. 32 (2), 319–332.

Richardson, C., 1908. A plea for the broader education of the chemical engineer. Sci. New Ser. 27 (281), 81–89.

Rosenberg, N., 1976. Technology and Environment: and Economic Exploration. In: Perspectives on Technology. Cambridge University Press, London, p. 353.

Rosenberg, N., 1998. Technological change in chemicals: the role of university- Industry relations. In: Arora, A., Landau, R., Rosenberg, N. (Eds.), Chemicals and Long-term Economic Growth. Insights from the Chemical Industry. John Wiley and Sons, Inc, New York, Chichester, Weinheim, Brisbane, Singapore, Toronto, pp. 193–230.

Rosenberg, N., Landau, R., Mowery, D., 1992. Technology and the Wealth of Nations. Stanford University Press, Stanford.

Rothwell, R., Zegveld, Q., 1985. Reindustrialization and Technology. Longman, Harlow.

Sarkis, J., Zhu, Q., Lai, K.-H., 2011. An organizational theoretic review of green supply chain management literature. Int. J. Prod. Econ. 130 (1), 1–15.

Smith, J., 1994. The end of the chemical century? Organizational capabilities and industry evolution. Bus. Econ. Hist. 23 (1), 152–161.

Spitz, P. (Ed.), 2003. The Chemical Industry at the Millennium: Maturity, Restructuring and Globalization. Chemical Heritage Foundation, Philadelphia, PA.

Stankiewicz, A., 2003. Reactive separations for process intensification: an industrial perspective. Chem. Eng. Process. 42 (3), 137–144.

Stone, P., Dunphy, D., Smith, M., Ogilvie, D., 1966. The General Inquirer: a Computer Approach to Content Analysis. MIT Press, Cambridge, Mass.

Tan, A.R., Matzen, D., McAloone, T.C., Evans, S., 2010. Strategies for designing and developing services for manufacturing firms. CIRP J. Manuf. Sci. Technol. 3 (2), 90–97.

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capabilities and strategic management. Strateg. Manag. J. 18 (7), 509–533.

Thomas, V., Graedel, T.E., 2003. Research issues in sustainable consumption: toward an analytical framework for materials and the environment. Environ. Sci. Technol. 37 (23), 5383–5388.

Thomson, A., Youngman, R., 2010. The Growing Importance of Renewable Chemicals. Executive Brief. Cleantech Group, London, p. 23.

Tidd, J., 2006. A Review of Innovation Models. University of Sussex, Brighton, p. 17.

Utting, P., 2000. Business Responsibility for Sustainable Development. UNRISD, Geneva, p. 62.

van den Bergh, J.C.J.M., Truffer, B., Kallis, G., 2011. Environmental innovation and societal transitions: introduction and overview. Environ. Innov. Soc. Trans. 1 (1), 1–23.

Vennestrøm, P.N.R., Osmundsen, C.M., Christensen, C.H., Taarning, E., 2011. Beyond petrochemicals: the renewable chemicals industry. Angew. Chem. Int. Ed. 50 (45), 10502–10509.

Walley, N., Whitehead, B., 1994. It's not easy being green. Harv. Bus. Rev. 72 (3), 46–51.

Warner, F., 1982. In: Sharp, D., West, T. (Eds.), Chemical Industry and the Environment. The Chemical Industry. Society of Chemical Industry, Ellis Horwood Limited, London, pp. 166–171.

Wernerfelt, B., 1984. A resource-based view of the firm. Strateg. Manag. J. 5 (2), 171–180.

Woodrum, E., 1984. "Mainstreaming" content analysis in social science: methodological advantages, obstacles, and solutions. Soc. Sci. Res. 13 (1984), 1–19.

Zotter, K.A., 2004. "End-of-pipe" versus "process-integrated" water conservation solutions: a comparison of planning, implementation and operating phases. J. Clean. Prod. 12 (7), 685–695.