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The Evolving and Cumulative Nature of Sustainable Innovation in an energy intensive Industry

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Sustainable innovation, eco-innovation, chemical industry, greening technological progress, evolution and accumulation

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TNO Working Paper Series

The evolving and cumulative nature of sustainable innovation in an energy intensive industry

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Abstract:

Different bodies of literature have attempted to explain what factors and events drive industries and firms towards more advanced levels of environmental performance. This is a gradual, historical process of evolution from lower to higher degrees of development. Based on notions derived from green evolutionary economics literature this article provides an account of the evolution in the chemical industry striving for environmentally sound chemical processes and products via sustainable innovation. We conducted a content analysis on 255 documents addressing different environmental and innovation aspects of the evolution of the chemical industry. Our findings highlight the fact that greening chemical processes is about change in existing products, processes, organisations and systems aiming at higher environmental performance, whereas sustainable innovation is an incremental, continuous and cumulative process focusing on emerging technologies, new markets and a continuous evolution and accumulation of firm-specific resources, capabilities and competences contingent to the strategy adopted by firms. Equally, we found that new forms of innovation are embedded into the larger production and consumption system and achieving sustainability implies breaking up with old, non-environmentally friendly technological paradigms.

JEL codes: O31, O32, N7, Q48

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1 Introduction

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

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; Parto and Herbert-Copley 2007). 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 (Montalvo 2002). Hence, every single existing industrial process has a ‘potential to pollute’ – which can be estimated and diminished but cannot necessarily be fully avoided (Graedel and Howard-Greenville 2005).

It is extremely difficult to accept among academic circles that achieving higher environmental performance is costly, of low priority and detrimental to firm’s competitiveness (c.f. Walley and Whitehead 1994). For quite some time now there is vast evidence on the positive relation between environmental and economic performance (Florida 1996; Hart and Ahuja 1996; Russo and Fouts 1997; Sharma and Vredenburg 1998). And a number of approaches and tools for environmentally conscious manufacturing are available (3M and UNEP 1982; GEMI 1993; Ilgin and Gupta 2010; OECD 2011). Nowadays top executives claim that corporate sustainability is driven by a combination of public pressures, regulation and securing a competitive position in markets (Mckinsey & 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).

Clearly, achieving sustainable innovation is a complex issue due to a number of conflicting issues and dilemmas (Kemp 2008). Notwithstanding, a central point to consider in this article is the evolution of firms towards higher environmental performance. Scholars argue that firms (and industry in general) have undergone a gradual process of environmental transformation (Hart 1995; Hoffman 1999; King 2000), from a lower to a higher degree of environmental performance. Such is the case of the chemical industry (Hoffman 1999). This is an energy and material intensive industry where the origins of the process of ‘greening’ can be long tracked in history (Warner 1982; Heaton 1994; Mol 1995; Homburg 1998; Wilmot 1998).

We argue that there are a number of historical and firm-specific factors that enable sustainable innovation in firms. In addition to institutional and cultural change (Hoffman 1999), sustainable innovation in firms is contingent to organisational and technological change along specific trajectories and paradigms (Kemp and Soete

1992; Freeman 1994). 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 the (technological) paradigm of sustainable innovation and its associated business models can emerge.

Against this background this article aims to show the evolution of the chemical industry regarding technical and organisational changes in their manufacturing process to improve environmental performance, while remaining competitive via sustainable innovation. In this article we focus in a twofold research question: What factors have contributed to greening chemicals manufacturing for a higher environmental performance? What events have motivated sustainable innovation in the chemical industry?

The content of this article is distributed as follows. Section 2 provides a brief explanation of the rationale for the study of the chemical industry. Section 3 defines a number of concepts guiding this work. Section 4 is a literature review on sustainable innovation in the chemical industry. This section is subdivided into two main topics. First we present a brief literature review on greening technological progress, resource-based view of the firm (applied to the environment), sustainable (systems) innovation and proactive environmental management. This is followed by a sub-section on literature on sustainable innovation and the process of greening of the chemical industry. Section 5 contains a description of content analysis as the method guiding the empirical part of this article. Section 6 continues with the main results of our analysis. The content of this section is divided into the five main categories of evolution of sustainable innovation in the chemical industry: early challenges for sustainable innovation, early responses for sustainable innovation, responsible and strategic management for sustainable innovation, design for sustainable innovation, and an era of strategic sustainable innovation. The last section provides main findings and conclusions of this work.

2 The importance of studying the chemical industry

The chemical industry is the ideal candidate for providing an account of the evolution of sustainable innovation in an economic sector. Some of the main arguments supporting this suggestion are briefly introduced below.

From an innovation perspective the study of the chemical industry is justified for at least three reasons: its high-tech history, dynamics, and the fact that it is related to a large number of industries and products (Arora, Landau et al. 1998), This is a mature and cyclic industry with well defined technological trajectories and innovation dynamics (Achilladelis, Schwarzkopf et al. 1990; Landau 1998; Gent 2002). Its position in the value chain makes it a very heterogeneous industry. This industry has developed products and technologies for many different markets. In this sense, its effects on recipient sectors can be easily tracked, compared and studied (Achilladelis, Schwarzkopf et al. 1990). Equally important is the availability of scientific, technological and business data that enables comparability of this industry with other sectors, industries and countries (Achilladelis, Schwarzkopf et al. 1990).

From an economic perspective, the size, value and structure of this industry makes it a very appealing candidate of any academic enquiry. In terms of size, a recent estimate of the global value of the chemical industry was $2,9 trillions of revenue in the year 2009, being basic chemicals the most lucrative sub-sector with 41% of this value (Data Monitor 2010). Its market structure also facilitates its analysis, as each branch in the chemical industry is traditionally composed of no more than six to twelve large firms, and a number of smaller firms (Cesaroni, Gambardella et al. 2007). For example the top firms in the world (in terms of revenue) in 2009 were BASF (GER), Dow Chemical (USA), Koch (USA) and Bayer (GER) (Data Monitor 2010). Finally, it is impossible not to mention the growing importance of (renewable) chemicals in the conformation of a global bio-based economy (OECD 2009; Vennestrøm, Osmundsen et al. 2011). It has been estimated that the global market of chemicals will be worth 4,3 trillion dollars in the year 2014 (Data Monitor 2010), and a large share of this demand will be met from renewable chemicals (Thomson and Youngman 2010).

From a sustainability perspective, the study of the chemical industry is justified simply because this is one of the most representative cases of positive environmental evolution and change (Hoffman 1999). In addition, its early interaction with public pressure and scrutiny, environmental accidents and regulation have driven this industry towards an advanced level of corporate self-regulation (García-Johnson 2000), exemplified by Responsible Care® (Tapper 1997) . This industry is also considered a best practice case of inter-industry organisation and one of the most influential stakeholders in environmental policy making processes (Grant 2007).

3 Some basic definitions

Before advancing any further it is convenient to provide basic definitions in relation to what we understand by chemical industry and sustainable innovation. In addition, we also present additional concepts extensively used throughout this work.

In order to define the chemical industry it is important to clarify its boundaries. There are a number of classifications of the world Chemical Industry. The OECD considers four main divisions: basic chemicals (e.g. black carbon, benzene, and chlorine), speciality chemicals (e.g. adhesives, rubbers, and catalysers), life sciences (e.g. pharmaceuticals, agrochemicals, biotechnologies) and consumer products (e.g. soaps, detergents, bleaches, fragrances) (OECD 2000). Market research companies often divide it into six (similar) categories: base, consumer, pharmaceutical, specialty and fine chemicals and agricultural chemicals (Data Monitor 2010). Due to the explorative and narrative focus of this article we adopt a general definition of the world chemical industry, with no specific regional or national focus. In terms of a sector focus, we excluded pharmaceuticals and consumer products. It is widely acknowledged that the former sector presents different innovation and environmental dynamics compared to the rest of the chemical industry, so it is often studied (and classified) as a separate industry (see Achilladelis and Antonakis 2001; Blum-Kusterer and Hussain 2001; Schoter 2007).

Defining sustainable innovation is not an easy task. In spite of the popularisation of the term to date there is no agreement on what it really entitles (Kemp 2008). Innovation refers to technologically novel or improved material goods, intangible services or ways of producing goods and services (Edquist 2005). But innovation does not occur in isolation, so that learning activities, knowledge sharing, and competence building are important elements in the innovation process (Villavicencio 2000). Sustainable is often associated to the mainstream term 'sustainable development' (WCED 1987).

The notions of pollution control and pollution prevention and waste minimisation are a basic constituent of any definition related to sustainable innovation. Pollution control basically refers to identify and tackle the largest point sources of pollution, , such as discharges to water and sewer (Crathorne, Rees et al. 1983). Pollution prevention and waste minimisation move one step forward. It aims at reducing or eliminating waste at the source by modifying production processes, promoting the use of non-toxic or less-toxic substances, implementing conservation techniques, and re-using materials (EPA 1996). These schemes involve modifications to chemical and/or physical operations in particular steps of the manufacturing systems (Thomas and Graedel 2003). Environmentally sound technologies, cleaner production technologies and methods and improvements to production support systems are acknowledged as a common form of innovation (Kuehr 2007; Foxon and Pearson 2008). This is because they foster technological, institutional and organisational changes to the knowledge base of existing production systems (Coenen and Díaz López 2010).

At the facility or plant level innovation for sustainability process is related to the optimisation of production processes in order to reach a higher environmental performance. The so-called 'best practices' are linked to cost-saving strategies and/or profit-maximisation opportunities (Christmann 2000). At the operational, manufacturing and distribution levels, sustainable innovation can be associated to the process of incorporating environmental and social issues as a strategic component in long-term strategies and plans (e.g. Hart 1997; Ledgerwood 1997). Change and novelty can also be of non-technological nature. Especially in firm-level areas related to design, organisational, management, and logistics areas of support systems (Anttonen 2010). Hence, we can understand sustainable innovation as a process for the adoption or development of technologies, know-how and organisational practices in order to use less material and energy, maximising renewable resources as inputs, avoiding generation of pollutants or harmful waste during product manufacture and use, producing recyclable or biodegradable products (Jenck, Agterberg et al. 2004), aiming to achieving an ideal sustainability situation of firms in relation to society and relevant stakeholders.

A number of technology-related concepts guiding this work are: technological paradigms, technological trajectories, evolution and accumulation, path dependency, and routines. We take these concepts from the field of evolutionary economics of technological change (see section 4). Routines are regular and predictable behavioural pattern of firms (Nelson and Winter 1982). Path dependency refers to norms and routines and past experiences being influential in current and future innovation efforts (Teece, Pisano et al. 1997). Evolution and accumulation are metaphors borrowed by social scientists from the natural sciences, in particular from biology. These concepts refer in broad terms to the emergence, diversification, addition and selection of novelties, where learning an the emergence of building blocks are the defining factors for change (Devezas 2005). 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, Metcalfe et al. 1986; Dosi 1988) or techno-economic paradigm (Freeman and Perez 1988). A technological paradigm is both a set of exemplars – basic artefacts which are to be developed and improved and a set of heuristics (Dosi 1988: 225).

A final set of firm-related concepts come from the field of the resource-based view of the firm and dynamic capabilities. Resources as firm-specific assets difficult to imitate, and difficult to be transferred due the transaction costs and tacitness of knowledge (Teece, Pisano et al. 1997). Competences are combinations of firm-specific resources that allow an organisation to achieve some purpose, and define a firm's fundamental business as a whole (Prahalad and Hamel 1990). Rigidities refer to the opposite. They make the firm entering into a lock-in or blockage situation that constrains its innovative capacity (Leonard-Barton 1992). The concept of absorptive capacity is critical to explain how firms integrate (or not) external knowledge and information, assimilate it, and apply it to their strategy (Cohen and Levinthal 1990).

The following section provides a summary of the literature selected for the study of sustainable innovation in the chemical industry.

4 Theoretical position

Literature analysing aspects related to sustainable innovation in firms and industries can be grouped into at least 10 different categories. A non comprehensive list would include: economics of innovation and technological change applied to the environment (Kemp and Soete 1992; Kemp 1994; Freeman 1996; Sartorius 2006), sustainable system innovation (including sustainability transitions) (Weterings, Kuijper et al. 1997; Foxon and Pearson 2008; Geels, Hekkert et al. 2008), resource based view of the firm applied to the environment (Hart 1995; Russo and Fouts 1997; Bansal and Roth 2000; Hart and Milstein 2003), institutional theory (Hoffman 1999), proactive environmental management (Roome 1994; Henriques and Sadorsky 1996; Sharma and Vredenburg 1998; Aragon-Correa and A. Rubio-Lopez 2007), business strategy (Porter and van der Linde 1995; Porter and Kramer 2011), ecological modernization (Mol 1995; Janicke and Jacob 2004), greening firms and industries (Davis 1991; Hart 1997; Graedel and Howard-Greenville 2005), corporate social responsibility (Carroll 1979; Dyllick and Hockerts 2002; Hockerts 2003), green entrepreneurship (Andrea 2000; Allen and Malin 2008), eco-innovation research (Fussler and James 1996; Jones, Harrison et al. 2001; Pujari 2006; Arundel and Kemp 2009; Diaz Lopez 2012), and ecological economics (Rennings 2000; Beise and Rennings 2005; Horbach 2005).

A vast number of empirical work is available in relation to greening and/or sustainability practices, products and technologies in the chemical industry Different studies have focused on local, regional, national, and global levels and have adopted a view on specific technologies, firms, industry or sector level (e.g. Christmann 2000; King and Lenox 2000; Eissen, Metzger et al. 2002; Jenck, Agterberg et al. 2004; Kirchhoff 2005; Kortman, Theodori et al. 2006; García-Serna, Pérez-Barrigón et al. 2007; Holladay, White et al. 2007; Arthur D Little 2009; Jones 2009; Bhavik R 2011; Vennestrøm, Osmundsen et al. 2011).

The study of sustainable innovation should be based on complementary levels of analysis, preferably at the level of technologies, production systems, industries and above all firms. For this reason the following section presents two summaries of literature, starting by one mainly based on evolutionary economics and technological change applied to the environment , and some elements from sustainable (systems) innovation resource-based view of the firm (applied to the environment), and proactive environmental management. This is followed by a specific section on literature on sustainable innovation and the process of greening of the chemical industry.

4.1 The evolving and cumulative nature of sustainable innovation

The field of evolutionary economic of technological change approach (Dosi 1982; Pérez 1983; Freeman 1984) is focused on firms and new technologies, its development, commercialisation and diffusion (Rosenberg, Landau et al. 1992). It provides a comprehensive framework for the understanding of processes of change determined by past routines that governs future actions (Nelson and Winter 1982), and how technologies become a source of wealth through an evolutionary, path dependent and incremental process (Dosi 1982), with clear differences of innovation activity across economic sectors (Pavitt 1984).

Grounded in the field above, literature on the greening of technological progress provides the basis for the understanding of innovation in complex (technological) systems. It also explains what social, economic and technical factors need to be transformed if we ought to achieve a major transition towards an optimal sustainability situation (Kemp and Soete 1992; Kemp 1994; Freeman 1996; Sartorius 2006). Kemp (1994) noted 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, radical innovations are produced and co-exist with old technological paradigms until gradually replacing them by new, emergent, environmentally friendlier alternatives (Kemp and Soete 1992). Montalvo (2002) argued that pollution prevention and cleaner technologies constituted a new technological paradigm for the industry in the early 2000s. Montalvo (2002: 24) suggested that the existing technological regime based on the 'product life cycle management' needs to be gradually replaced for a 'service life cycle management' more accordingly to the needs of sustainable development. Kemp (1994: 1034) identified a series of factors that need to be present in order that a change to a greener paradigm can be achieved: (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.

Sustainable (systems) innovation studies have attempted to explain how different technologies compete against each other in order to set a dominant paradigm, often referred to as the winning technology (Jacobsson and Bergek 2004; Hekkert, Harmsen et al. 2007). But providing an account of sustainable innovation in the (chemical) industry requires adopting a systemic approach to innovation (Coenen and Díaz López 2010), where the unit of analysis should be based on firms embedded into technological systems for production, consumption and distribution – and not only about single technologies (Berkhout 2005; Tidd 2006).

The fields of resource based view of the firm (Wernerfelt 1984; Barney 1991) and dynamic capabilities are the perfect complement to understand how firms can actually move from one technological paradigm to another (see Hart 1995). Firms manage to evolve towards a higher environmental performance and develop/ adopt sustainable innovations because they are owners of uncommon firm-specific resources and capabilities that are difficult to imitate (Kleef and Roome 2007). Again building on evolutionary economics, Teece, Pisano et al (1997) explain why firms own capabilities "distinctive" (Teece and Pisano 1994) and 'dynamic' (Helfat and Peteraf 2003) – inclusive for achieving higher environmental performance (Sharma and Vredenburg 1998). 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, Pisano et al. 1997). Clearly, this is a process of accumulation of capabilities contingent to the existence of prior related knowledge (Cohen and Levinthal 1990).

As noted in the introduction, there is a vast amount of empirical evidence in the chemical industry on how leading firms have managed to develop and accumulate sound capabilities, resources and competences for increasing its environmental performance and economic performance (e.g. Spinardi and Williams 2001; Eder 2003). In fact, studies from the field of proactive environmental management have used concepts related to the accumulation and use of resources and (dynamic) capabilities (Hart and Milstein 1999; Aragon-Correa and A. Rubio-Lopez 2007). But the different bodies of literature hitherto described have not sufficiently enquired what historical events have motivated the process of (environmental) evolution towards sustainable innovation in the chemical industry. Building on the notion of evolution and (technological) paradigm change, a review of sustainable innovation in the chemical industry is presented below.

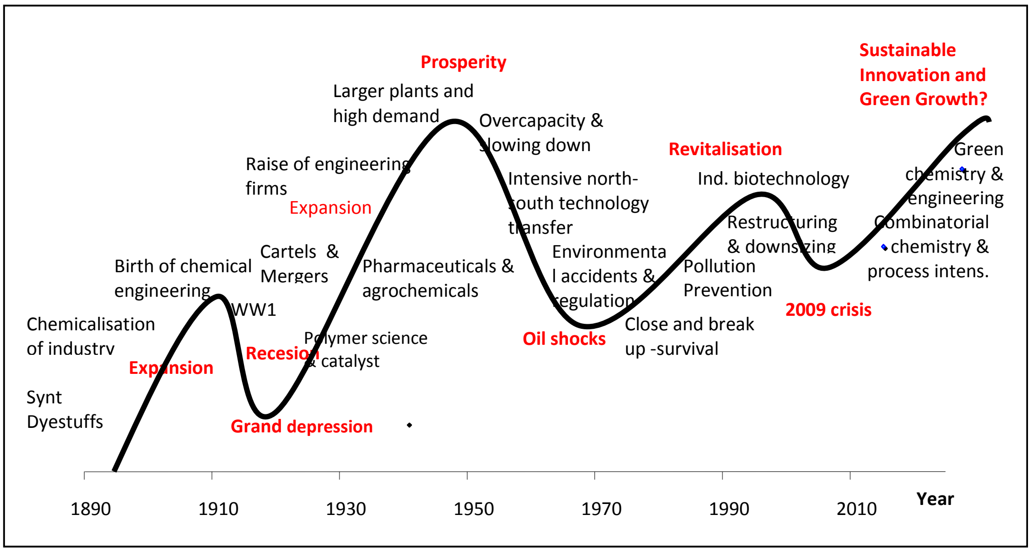
4.2 Evolution and change towards sustainable innovation in the chemical industry

The seminal work of Hoffman (1999) of the historical evolution of environmentalism in the US chemical industry showed how disruptive events, such as chemical accidents, public perception and regulations motivated an environmental institutional change of this industry. The empirical analysis of Hoffman primarily focused on the examination of cultural and institutional systems of chemical firms. This author identified four very distinctive stages of institutional change and evolution: environmentalism as a challenge (1960-1970), environmentalism as a regulative institution (1971-1982), environmentalism as a normative institution (1983-1988) and the birth of environmentalism as a cognitive institution (1988-1993).

Albeit it was not the purpose of Hoffman's work, his analysis also took into account technological change and innovation as a key factor for environmental change. The empirical analysis of this author used two categories related to innovation: technological research and development, and predictions of technological development (see Hoffman 1999, p. 370). The (not so evident) focus on technologies of Hoffman's work is of particular relevance for our study. We know that chemicals is an industry where the development and use of resource-beneficial, environmental technologies has always been a major concern (Richardson 1908; 3M and UNEP 1982 ; Lancaster 2002; Dewulf, Van Langenhove et al. 2010). This is an industry where expertise in environmental control originated vis-à-vis with technological developments for alkali production in the XIX century (Diaz Lopez and Montalvo 2012).

A schematic representation of major technological paradigms that have prevailed in the chemical industry is depicted in Figure 1. A brief description of highly relevant paradigm follows, with especial focus on 'green' trajectories.

Figure 1 Production cycles and dominant technological paradigms in the chemical industry



Source: Diaz Lopez and Montalvo (2012)

Innovation studies of the chemical industry have repetitively shown that previous scientific and technical knowledge is a pre-condition for technological change, new forms of innovation and increased competitiveness (Freeman 1968; Arora, Landau et al. 1998; Cesaroni, Gambardella et al. 2004; Arora and Gambardella 2010). The early work of Freeman (1989) and Rosenberg (1998) clearly showed that scientific knowledge (from Universities and R&D centres) in the technological paradigms of organic, bio-chemicals and polymer chemistry has been the cornerstone for successive product innovation in the chemical industry. The paradigm of polymer chemistry (1920s-1930s) has been referred as the one with the highest patent activity of all times (Freeman and Soete 1997). Polymer chemistry is a mature paradigm, but it is now co-evolving with renewable chemicals (e.g. bio-solvents), material sciences (e.g. green plastics), nano-materials (e.g. energy efficient composites), etc.

As previously noted, achieving higher environmental and economic performance is not the result of single events or efforts. 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) – or technological trajectories. A similar pattern to the one described above has been observed for the development of environmental technologies (Arduini and Cesaroni 2004). A clear example is posed by the biotechnology paradigm originally applied to health, microbial, food and plant genetics. It is now being applied to environment protection, eco-textiles, waste management, bioinformatics, aquaculture, etc.

It is commonly believed that the current paradigm of eco-efficiency dominates the industrial agenda (Schmidheiny 1992; Schmidheiny, Holliday et al. 2002). But as previously noted, pollution prevention, and cleaner production have been signposted as an advanced sign of corporate greening in the chemical industry (Spinardi and Williams 2001), where a technological shift from eco-efficiency and resource productivity towards cleaner production started over a decade ago (c.f. Keijzers 2002). The application of industrial biotechnology in a number of chemical routes, process automation, and micro and nano technologies are often equalled to the notion of sustainability in chemical manufacturing (Jenck, Agterberg et al. 2004; Clark 2007; Arthur D Little 2009).

Identifying the next major paradigm for the chemical industry is a topic of open debate (right hand side of Figure 1). Resource efficiency is now shaping a new technological paradigm of sustainable innovation in the whole manufacturing and services industry (Machiba 2010). Resource scarcity is considered one of the biggest threats to the production system. Energy, water, raw material supply and waste management/ treatment/ disposal costs are important variables for sustainable enterprise and manufacturing (Keijzers 2002; Diaz Lopez and Montalvo 2012). At the level of manufacturing operations, the paradigm of eco-effectiveness through sustainable manufacturing practices and the introduction of eco-innovations is emerging (Diaz Lopez 2012). Another possible paradigm for the chemical industry could be related to radical modifications at the molecular level, or sustainable design of bio/renewable chemicals.

A new cluster of technological trajectories for sustainable innovation could be based on the modification of traditional chemical routes in combination with alternative methods using green chemistry and engineering, biocatalyst, combinatorial chemistry, process intensification and automation, multi-purpose plants, and bio-synthesis (García-Serna, Pérez-Barrigón et al. 2007; Manley, Anastas et al. 2008; Nikolau, Perera et al. 2008; Lang-Koetz, Pastewski et al. 2010; Vaklieva-Bancheva and Kirilova 2010; Vennestrøm, Osmundsen et al. 2011). One of the reasons supporting the perception outlined above is the economic relevance and future prospects of renewable chemicals. Overall, the largest market potential of industrial biotechnology applications is found in the production of fine chemicals for the pharma and agro industry, bio-polymers and bio-fuels (Festel 2010).

One of the overall messages of the literature review is that major sustainability transformations in firms and industry may require new forms of business models and sustainable innovation – as greening technologies may not be sufficient for achieving the radical change demanded by sustainable development. An account of the evolution of sustainable innovation in the chemical industry may shed light on the cumulative path and further needs of this industry towards achieving a real sustainability situation.

5 Methods and data

The objective of the empirical part of this article was to identify major trends and tools for sustainable innovation in the chemical industry over the period 1908 to the present date (November 2011). We used content analysis as the main qualitative method for an exploratory examination of secondary sources of information on sustainable innovation in the chemical industry. One of the main advantages of choosing a methodology for performing a systematic review of texts is related to rigour and transparency (Dixon-Woods, Bonas et al. 2006). We used the NVivo® software for performing a computer-aided analysis using the functions of 'word frequency count' for the examination of 255 pre-selected documents in the period of study. The latter provided an account of major trends and tools for sustainable innovation in this industry, in the form of frequency of keywords and figures summarising such results – best known as 'tag clouds'.

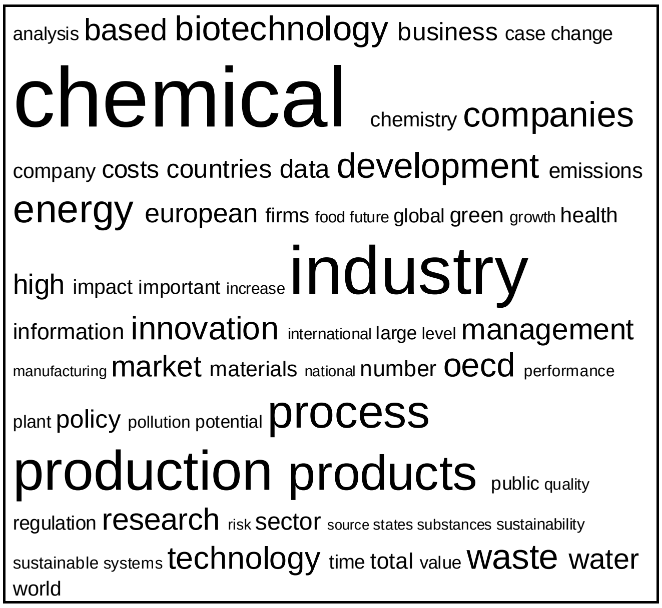
Method. Content analysis is a qualitative analytical technique (applied to text) for making inferences by objectively and systematically identifying specified characteristics of messages (Stone, Dunphy et al. 1966, p. 5). Duriau, Reger et al. (2007) noted it is possible to set up a longitudinal research design and to use different sources of data. Content analysis allows a fair amount of flexibility, producing results both at the level of basic statistics of deeper interpretation of meanings. Typically it includes a range of strategies, relying heavily on electronic bibliographic databases. The steps of surveying, indexing and coding systems of controlled keywords are used to categorise and store documents to be further analysed (Dixon-Woods, Bonas et al. 2006). A sound implementation of this method entails the specification of category criteria for reliability and validity checks that fosters the creation of a replicable dataset (Duriau, Reger et al. 2007, p. 7). Therefore, the formulation of categories to allocate content is one of the key features of this method, as they provide the connection between the researcher's theoretical concern and empirical work, being such groupings of sufficient operational specificity to be applied validly and reliably (Woodrum 1984).

Surveying and data collection approach. In this part we followed a threefold step for surveying, narrowing down (searching and collecting) and selecting relevant electronic documents (mostly in PDF format). We carefully selected a number of academic articles, practitioner papers and recent future-oriented reports commissioned reports commissioned by Governments. As a first step, we consulted the main databases for scientific and practitioners articles dating back to early 1900s (See Annex 1 for databases consulted). We also used specialised web search engines for identifying relevant reports. The next step consisted in a semi-automated selection of articles using key words and a manual inspection of the corresponding list of references. Finally, we classified documents in groups (per main keyword) and created a dataset of all potential documents. As noted by Hoffman(1999), a degree of specialised knowledge in the topic (innovation, environmental sustainability, the chemical industry) was required in order to avoid the inclusion of non-relevant material. Please refer to Annex 1 for description of the Coding Scheme used.

Sample. A total of 300 electronic documents were identified as candidates for our analysis. After non-relevant, non-compliant and duplicates documents were excluded the sample comprised of 255 documents. Please refer to Annex 1 for further details on the composition of the sample.

Exploratory content analysis. Before performing the content analysis we ran a cluster analysis and a frequency analysis of all documents included in the sample with the aim to validate if the key words used to identify relevant materials were in fact important words with high frequency. Our results highlighted that most of the words originally included in the criteria were well fitted for the purposes of the study (see Figure 2 below). In this figure we can observe that all pre-defined keywords had a relatively high frequency mark (statistics not reported here).

Figure 2 Tag-cloud of word frequency in the sample in the period 1908-2011 (N=255)



Using the NVivo® software our content analysis formally consisted on the stages of coding, formulation of categories, analysis of content and interpretation of results. Please refer to Annex 1 for a description of the method and practical considerations. The results of the empirical analysis are presented in the following section. Normal text

6 Sustainable innovation in the chemical industry: empirical results

As previously noted the main purpose of the empirical analysis was to identify general trends of sustainable innovation per categories (pre-defined periods of time). The provision of an account of general trends of sustainable innovation is graphically represented by a “tag cloud” of the most relevant words for each corresponding period of analysis (see e.g. Figure 2).

The identification and description of trends and specific tools using frequency counts aimed providing and identifying factors of causality, accumulation and patterns of evolution. This was performed using frequency count of keywords in comparison with the trends and tools previously identified by Hoffman (1999), Garcia-Serna et al. (2007) and Díaz Lopez (2012). The accompanying explanatory text contains data from the frequency count of specific words in each period of analysis. Due its length (often reaching more than 65,000 words), is that we do not include the frequency tables. Please note that word frequencies are expressed in bracketed numbers. For example the frequency for the word ‘regulation’ during the period 1980-1989 was 870. This is expressed in the explanatory text as: technology (870). Also note that we refrain from including obvious words such as ‘chemical’ and ‘industry’.

The following paragraphs contain our empirical results for each stage of evolution of sustainable innovation in this industry.

Early challenges for sustainable innovation (1908-1979) the seminal work of Hoffman clearly showed that social and regulatory pressures have often been a response from a number of disruptive events which have shaped the process of corporate environmentalism in this industry. This author found that the period between 1962 to 1970 (environmentalism as a challenge) was in complete denial of environmental awareness and low regulatory enforcement (Hoffman 1999).

The results of our content analysis support Hoffman’s findings. We did not obtain substantial evidence on the existence of major environmental concerns in the 1908 to 1979 period. We did encounter an indication of some environmental issues seen as a challenge, and some early drivers of technological and institutional change for sustainable innovation (see Figure 3).

Figure 3 Tag-cloud of major trends influencing sustainable innovation in the chemical industry 1908-1979 (n=16)

These historical works of Chandler (1990), Arora, Landau et al (1998), Spitz (2003) and (more recently) Hikino, Zamagni et al.(2007) showed that this was a period of building global production capacities and a major product diversification in this industry. It is no surprise that the early stages of industry evolution of chemicals manufacturing was mainly concerned to installing new plants (300), scientific developments (197), process (170) and product (123) diversification, discovery of new materials (150), new technologies (114) and equipment (93), basic research and development (104), large (122) scale investments (65) for expanding installed capacity (51), and new designs (93), cost reduction (86), and searching new business opportunities (67).

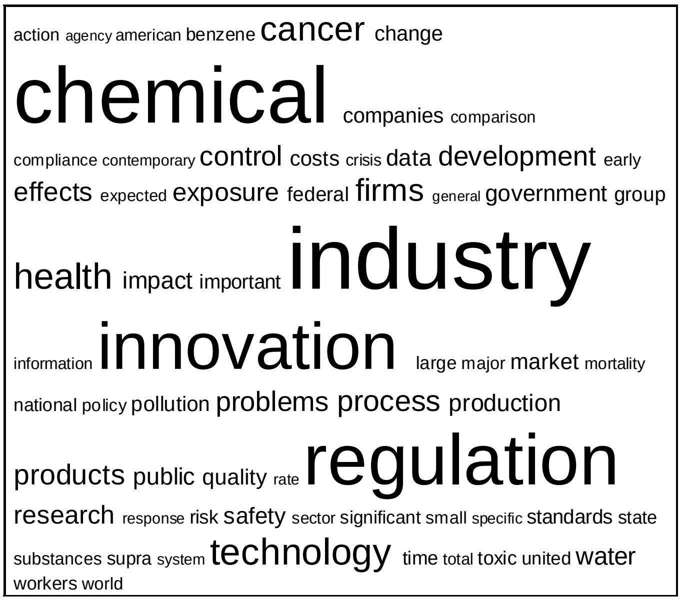
A number early concepts related to sustainable innovation started appearing at this stage: material (114), energy (36) and water (4) use, efficiency (33), acid rain (62), and specific chemical agents with well known environmental issues (chorine, 57), or by-product recovery potential (bleaching, 58) (refer to Diaz Lopez and Montalvo 2012 for an explanation of the latter point). In fact, historical evidence suggest 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 (see Richardson 1908). As an example of this Lancaster (2002: 21) quoted the first president of the Royal College of Chemistry declared in 1848 that: “In and idea 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”.

Finally, two extremely important, yet less known set of concepts related to sustainable innovation in this industry were also highlighted by our empirical analysis: the creation of science (138) and engineering (53) capabilities. The general knowledge about these words is that both are directly associated to the process of accumulation of technological capabilities for innovation in new chemicals products and processes (Landau 1998). However, the chemical engineering discipline and a number of scientific discoveries are also directly responsible for building environmental capabilities in this industry (c.f. Diaz Lopez 2012). More importantly, this discipline has been signalled of prime importance to help fostering a paradigm change in sustainable chemicals manufacturing (Hall and Howe 2010). But at this point in time our analysis suggests that the basis for a paradigm of sustainable innovation were at an initial stage.

Early response to sustainable innovation (1980-1989) the seminal work of Hoffman (1999) clearly showed that social and regulatory pressures have often been a response from a number of disruptive events which have shaped the process of corporate environmentalism in this industry. The combination of these factors has traditionally been acknowledged as one of the main driving forces for a reactive behaviour of firms in the chemical industry (Hoffman 1999; OECD 2000); and hence conditioning factors for innovation and sustainability. The empirical results of Hoffman for the stage between 1983 and 1988 (environmentalist as a regulative institution) were mainly related to an era of social responsibility, compliance with regulations and cooperation with environmental authorities. Hoffman suggested that the dominant values and expectations of the period drove the industry to conform to the emerging notions of pollution prevention and waste minimisation (p. 363), an important first step towards sustainable innovation.

Our results are aligned to supporting Hoffman's findings. Regulation (870) and innovation (538) are the two most frequently cited words in all articles between the years 1980 to 1989. These words are followed by technology (463), health (288), cancer (260), control (200), water (199), and safety (197). Product (214), process (213) and research and development (199), are also important words to be highlighted, as these are concepts deeply related to technological trajectories of innovation and change. It is important to note the emerging role that words associated to competitiveness (quality, costs, market) had in this period of time.

Figure 4 Tag-cloud of major trends influencing sustainable innovation in the chemical industry 1980-1989 (n=12)



In Figure 4 it is clearly observable that words associated to compliance (103) with health and safety public policies were also related to pollution effects (cancer, mortality, etc), causes (substances, exposure, risk, toxic, benzene, etc) and stakeholders involved (government, workers, public, groups, etc). It is widely acknowledged that the reduction or avoidance of negative impacts on human health and the environment in this industry has been traditionally tackled trough good housekeeping, good engineering practices and the introduction of pollution control devices and low and non-pollution technology. But as noted in the introduction of this article, pollution control and the use of conventional environmental control technology simply fail to constitute a real solution to environmental problems.

In spite of the limitation highlighted above, our results point out to an intermediate stage of (technological) capacity building for sustainable innovation in the period 1980-89. The defining element of this stage seems to be the technological paradigm of pollution control and prevention induced by regulation. But beyond the notions of pollution control and the use of environmental technologies it is difficult to establish a list of specific sustainable innovation tools available for the chemical industry during this stage. Another observation is that cost reduction was a dominant paradigm for increased efficiency, whereas compliance has always been seen as a mechanism for ensuring good relationships with regulators (see Mueller 1974; Walley and Whitehead 1994; Zotter 2004). All in all, these factors may have constituted early building blocks for an eventual shift towards a responsible management paradigm for sustainable innovation.

Responsible and strategic management for sustainable innovation (1990-1999) In spite of only being to provide an account of the environmental evolution of the (US) chemical industry until 1993, Hoffman (1999) identified the start of a new era of environmental responsibility (environment as a cognitive institution). This view is supported by a number of authors and a number of empirical evidence has been provided (see section 4). Hoffman found that by the end of 1993 the attention to environmental issues had reached an historical peak, in particular in relation to management.

Our content analysis found that strategy (1217), business (1172), and management (1012) dominated the word frequency in articles of the period 1990 to 1999. If we extrapolate the findings of Hoffman until the end of this decade, our finding of an increased role for management is compliant with earlier claims. But our findings go beyond this by highlighting the role that strategy development and business planning (234) and models (285) may have for sustainable innovation.

Figure 5 Tag-cloud of major trends influencing sustainable innovation in the chemical industry 1990-1999 (n=62)

Indeed Hoffman identified an upsurge in the adoption of organisational innovations, such as management systems, environmental reporting, hiring environmental specialist, etc. In addition, the cost of pollution control and prevention, the lost of confidence in the industry (due to a number of accidents), and the need to be seen as a good ‘citizen’, among other factors, are some of the underlying reasons for the sudden increase of community relations and the emergence of corporate self regulation programmes, such as Responsible Care® (Jenkins 2002). A programme associated to corporate stewardship leading to higher management capacities for greener manufacturing (García-Johnson 2000; Jenkins 2002; Acutt, Medina-Ross et al. 2004; Evangelinos, Nikolaou et al. 2010). Our findings are fully aligned to previous evidence from a number of authors. On the one hand our results also found that concepts related to public concerns (473), responsible care (401), policy (392), regulations (386), government (385), and were an important part of our sample. On the other hand our findings also seem to support Hoffman’s observations on the upsurge of organisational innovation, as management (1012), organisational (794), change (572), corporate (539), and reporting (344) were also highly mentioned in the sample.

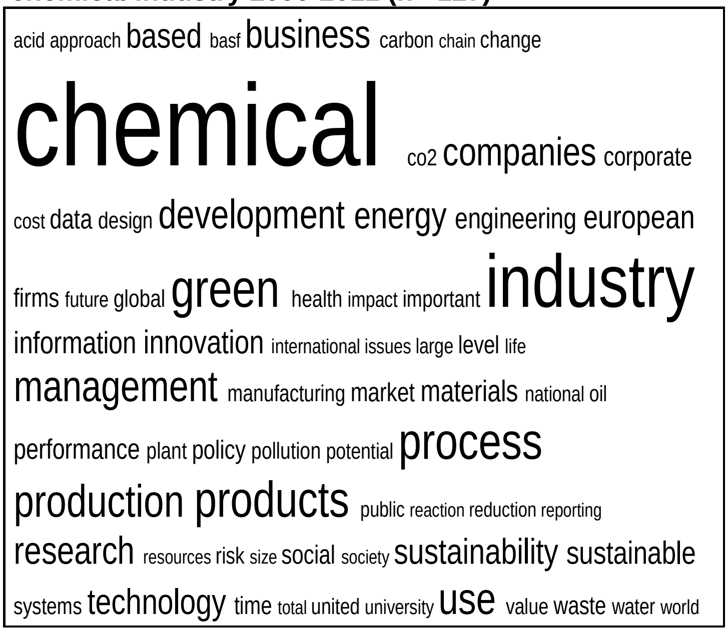
Corresponding to a continuous technical evolution in chemicals, products (1504), processes (816), production (574), patents (783), technology (639), research & development (566) and innovation (540) were concepts with high frequency counts in our sample. But costs (792), markets (648), waste (631), green (627), sustainable development (599), pollution (514), and performance (426) factors followed in importance. The previous may be depicting a well balanced scenario where technological, competitiveness, economic and environmental factors were (nearly) equally important.

The notion of eco-efficiency is seen by many authors as a source of both ecological and economical value (DeSimone, Popoff et al. 2000). This concept has been recognised in the present decade as a key driver for cleaner production and innovation (Coenen and Díaz López 2010). Eder (2003: 347) explained that: "Eco-efficiency in the form of raw material and energy efficiency as well as waste minimisation through a sophisticated system of coupled production has always been key competitiveness -determining factors particularly of bulk chemical production […]". In spite of its popularity, our analysis only found a really small word frequency of the terms efficiency (148) and eco-efficiency (12) in the period 1990-1999. Perhaps the reason why we did not find support to earlier claims on the relevance to eco-innovation is due to the fact that associated 'best practices' are a normal engineering practice in this industry. Best practices encompass concepts and strategies for dematerialization, increased resource productivity, reduced toxicity, increased recyclability (down cycling) and extended product lifespan of chemical products and production systems (Braungart, McDonough et al. 2007).

Design for sustainable innovation (2000-2011) Garcia-Serna et al. (2007) provides an overview of design-based approaches to greening chemicals, including: the Natural Step, bio mimicry, cradle to cradle, zero waste, resilience engineering, inherently safer design, ecological design, green chemistry and self-assembly.

Our content analysis found that during the period between the years 2000 and 2011 concepts related to sustainable development (2972) and green (2599) climbed up the latter of importance in the sample of documents of practitioners and academic articles. Our findings did not identify the relevance of a number of concepts suggested by Garcia-Serna et al (2007) – except for those related to sustainable design and zero waste.

Figure 6 Tag-cloud of major trends influencing sustainable innovation in the chemical industry 2000-2011 (n= 127)



Correspondingly with the technological evolution in chemicals, products (4173), processes (4020), production (2109), technology (3402), innovation (1820), research & development (1734), engineering (1181), patents (818), and standards

(618), were concepts with high frequency counts in our sample. Environmental and resource-variables such as materials (1916), energy (1694), carbon (1570), waste (1129), pollution (1075), water (827) have also keep a high frequency count. Non-technological trajectories such as management (2780), change (1315), organisational (1309), and corporate (1100) followed. Social (1720), regulation (1395), policy (1349), public (736) and community (530) factors followed. Economic factors such as costs (1304), markets (1289), performance (1114) and efficiency (653) were at the bottom of the frequency count. Newer trajectories such as innovation in services (957), design (846), value chain (748), life cycle (524) and climate (228) appeared in the count with growing importance.

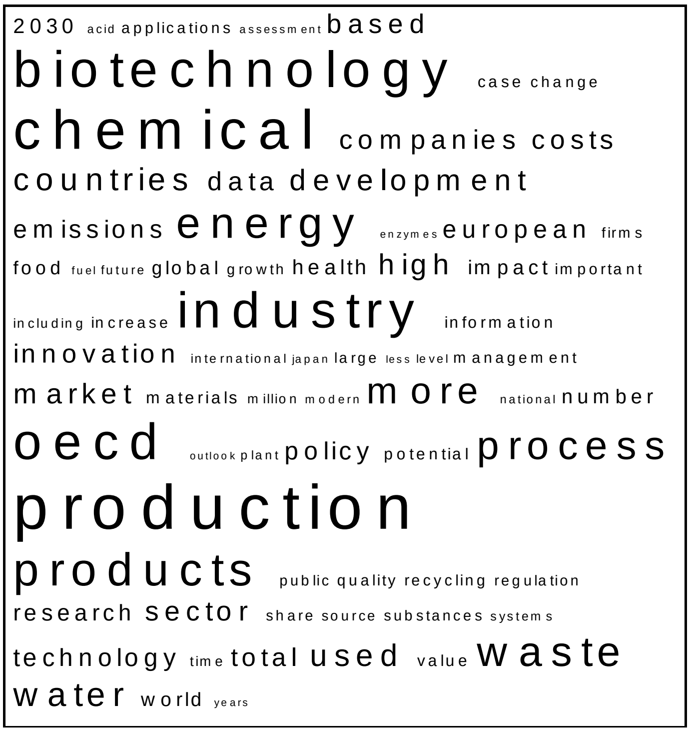
An interesting finding is related to the higher count of climate and resource-related factors, which seem to be driving the sustainability agenda of the sector (and the industry more generally). This is no surprise, as innovation represents a solution to the climate and ecological crises (OECD 2011). The chemical industry has always had the challenge to become inherently safer and more energy efficient (Arora and Gambardella 2010). An underlying reason is found in the fact that this is an industry with the constant pressure to demonstrate its efforts to reduce its overall environmental footprint. A more preventive approach and constantly complying with regulations has always been part of the profile of this industry (OECD 2000). We seem to have reached a stage of evolution of technological trajectories where sustainability is more integrated into the technological, management and design areas.

From all the newer factors unveiled by our empirical analysis it is interesting to note the growing importance than design-based approaches for sustainable innovation. Technological trajectories such as life cycle and system redesign seem to have gained strategic importance in this industry. Opposed to simply design new products in relation to cost, functional properties and manufacturability, eco-design-based approaches incorporate environmental criteria since the design stage. For example, there are three main areas of green chemistry: (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 (Diaz Lopez and Montalvo 2012). Similarly, the concept of cradle-to-cradle has gained popularity in recent years, albeit its development is a couple decades old (McDonough and Braungart 2002; Storey 2002). 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. These approaches are implemented to know which material and chemical functionalities will be delivered keeping the lowest environmental impact as possible (Jenck, Agterberg et al. 2004).

A new era of strategic sustainable innovation ahead (2011-2030) For years several attempts to envision and predict the future of “sustainable” chemical manufacturing have been performed (e.g. Weterings, Kuijper et al. 1997; Eissen, Metzger et al. 2002; Jenck, Agterberg et al. 2004; Kircher 2010). Díaz Lopez (2012) provides an overview of the following emerging areas in chemicals manufacturing, where a number of them have environmental sustainability applications: process intensification, multi-scale process units, combinatorial chemistry, and process automation.

The results of our analysis of future oriented reports clearly support the idea that a promising area of sustainable innovation is related to the application of industrial biotechnology (5111) to chemical processes, energy use (4335), waste reduction (4188) and water (3340) as major sustainability (1370) and resource efficiency (1218) drivers – with a time horizon to the year 2030 (2130) (see Figure 7).

Figure 7 Tag-cloud of major trends influencing the future of sustainable innovation in the chemical industry. Reports in the period 1999-2011 (n=38)



The results of our content analysis of future oriented reports suggest a similar pattern than the precedent section in technology-related concepts, which will be important for sustainable innovation. Products (6880), processes (7729), technology (4637), innovation (3660), research & development (2290), patents (983), engineering (604), and standards (636), were concepts with high frequency counts in our sample. Environmental and resource-variables are still highly important, with water (3349), materials (2834), pollution (1050), climate (949) and carbon emissions (902) keeping a high frequency count (albeit in a different order). Regulation (2884) and policy (3672) are concept with increased frequency, possibly associated to resource/climate issues. The main difference with the precedent section is in relation to economic concepts such as costs (4853), markets (2867), efficiency (895), and performance (812) which might remain of strategic importance in the future. Non-technological concepts are now lower in frequency, with change (1549), management (1572), organisational (838), strategy (863), and corporate (278) with a considerable less frequency count. Public (1438), social (863), and community (170) notions followed in frequency count. Newer concepts such as innovation in services (1080), life cycle (860), design (599) and value chain (382), present slight variations in the frequency count compared to articles in the same period.

As highlighted by our findings, and in full support to earlier claims posed by many authors, resource efficiency is a major concern –both in terms of availability of resources and effects on prices/costs. Industrial ecology approaches, such as those related to zero emissions and by-product synergies could emerge as promising alternatives to aid with the issue of material use in a number of existing chemical production systems (see Young and Hurtado 1999; Baas 2007 for a review). 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).

The results of our content analysis (of reports) did not provide sound evidence that emerging trajectories outlined by Diaz Lopez (2012) are shaping a future technological paradigm of sustainable innovation. The following emerging areas had low frequency values: process intensification (15) (Stankiewicz 2003), multi-scale plants (5) (Rauch 2003), combinatorial chemistry (16) (Jung 1999), and process automation (24) (Groover 2003). The lack of supporting evidence to the latter area comes as a surprise. Automation, basically composed by a programme of instructions and a control system that executes the former, has a long tradition in the chemical industry. For example, chemical sensors operating at high temperatures are in use since 1975; whereas new developments in ICT have boosted automation as a source of large eco-efficiency potential in chemical and bio-chemical processes. With the evidence at hand it is not yet clear to what extent these relatively new and emerging trajectories can be truly considered as part of a new technological paradigm.

The emergence of alternative business models (961), increased attention to life cycle (860) and the provision of environmental services (1080) may be a promising area for the future of sustainable innovation in chemicals. The traditional business model in the chemical industry is related to sales per volume. This is being challenged by the manufacturing and sales of higher added value products (specialities). Usually both commodities and specialities are supplied in combination with some basic services, such as invoicing, delivering, product information and material safety data sheets (Mont, Singhal et al. 2006). But a new business model has been created: the provision of chemical services. These represent a restructuring of the traditional relationship between the chemicals supplier and user towards ‘a shift in focus, from selling/using chemical products, to selling/using combinations of chemical products and services, that together create a win-win situation for both customer and supplier (Kortman, Theodori et al. 2006; Anttonen 2010). Trajectories associated to green value chain are also gaining importance due to increasing consumer and societal awareness about environmental and social issues (Sarkis, Zhu et al. 2011). In the present decade great expectations have been created around the economic value of the eco-industry, where a large number of services under new business models which are inherently relevant to the chemical industry (Bartolomeo, dal Maso et al. 2003; Sinclair-Desgagné 2008). All of these new technological trajectories offer an interesting potential for sustainable innovation in the chemical industry.

7 Conclusion: greening or sustainability in the chemical industry?

This article aimed at contributing to a better understanding of the evolution of sustainable innovation in the chemical industry. This work had a twofold objective, from a historical perspective, to provide an account of what technological and organisational factors have contributed to the process to achieving higher environmental performance, and to provide a deeper understanding of the evolutionary and cumulative process of sustainable innovation in this industry. Our main findings, conclusions and avenues of future research are indicated below.

In regard to our first research question, one of the main empirical contributions of this article is complementing the seminal work of Hoffman (1999), and advanced our understanding on what cumulative factors are shaping the environmental evolution of the chemical industry.

Based on the evidence presented it is clear that the chemical industry has moved forward regarding environmental performance. While identifying the most salient aspects of evolution used to improve its overall environmental performance, we also found a number of regulatory, social, competitiveness, profitability, market, technological, cultural and institutional factors shaping current state of environmental performance in chemicals manufacturing. But our evidence suggests that it is only in the last 20 years that all of these variables started to be purposively integrated as part of a strategic component of firms.

Understanding how firms operate, how they accumulate knowhow and experience, and how these manage their assets for improving its efficiency and performance is a pre-requisite for designing strategies and policies for sustainable innovation. One of the main lessons derived of our work is precisely the intertwined condition between capabilities and strategy since the stage starting in the 1990s. None of the current strategies, business models and tools for sustainable innovation in chemicals could have come into existence without all previous knowledge and development of capabilities, resources and competences to innovate accumulated over time, since the early 1900s.

Regarding our second research question, important messages can be highlighted in relation to sustainable innovation. It is clear that this is an elusive concept that needs to be properly understood. Narrowing down the unit of analysis allows the identification of a number of elements and underlying causes. Focusing on innovation in firms within a production system is an approach that facilitated the development of the present work.

Albeit not reported in the empirical section, the word system is a key finding obtained from the analysis of all stages of evolution of the chemical industry in the world. In the theoretical part we suggested that system thinking is needed for a better understanding of the evolution of sustainable innovation in the chemical industry. It seems that a new trajectory of sustainable innovation and associated business models has emerged. But these new business models are still embedded into well defined paradigms of technical change within the existing production and consumption system. Sustainable innovations require a major process of creative destruction breaking away from unsustainable paradigms of production and consumption.

If we think of long term sustainability, the stage of evolution of sustainable innovation in this industry may still be at a very early stage of development. In contrast to a number of future-oriented studies that claim that sustainable innovation chemicals is seeing the emergence of a large number of technological paradigms (e.g. multi-purpose plants, process intensification, etc), our study cannot fully support such claims. The results of our content analysis suggest that the chemical industry is co-evolving along emerging technological trajectories. Yet, we cannot talk about the consolidation of the sustainable innovation paradigm. What we can suggest that the need for sustainable use of resources and the overall climate change issue (represented by carbon emissions) might be openly conditioning the future evolution of this industry. Perhaps all of this is shaping a new disruptive event that will contribute to promote a major sustainability transformation. More evidence is needed in order to fully understand the future of sustainable innovation in chemicals.

We can conclude that greening chemical processes is about change in existing products, processes, organisations and systems aiming at higher environmental performance, whereas sustainable innovation is an incremental, continuous and cumulative process. The latter implies a creative destruction process in firms, where the focus is on emerging technologies, new markets and a continuous evolution and accumulation of firm-specific resources, capabilities and competences. Discontinuity, trial and error, and overcoming pre-existing blocking technological trajectories also constitute determining factors of success for achieving a higher environmental performance in the chemical industry – and industry more generally.

Now it is turn to posit some avenues of future research. A major shortcoming of our work is that we have not properly addressed problems of un-sustainability and rebound effects of chemical products. An additional topic not addressed in this article is the cross-sector nature of chemical operations and its implications for major sustainability transformations in other industries. This was unavoidable given the data and analytical method employed, albeit it would be possible to provide a few reflections on these topics. Clearly, this “industry of industries” may have more chances of transformation when adopting emerging technological paradigms and using the most of their interdependencies with other related industries. The topics above clearly require further analysis and provide an interesting avenue for future research.

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Vitae

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Dr Carlos Montalvo works at the Netherlands Organisation for Applied Scientific Research TNO-Strategy and Policy as senior adviser on innovation policy. He holds a BSc. in Electro-mechanical Engineering and MPhil. in Industrial Economics. He completed a DPhil in Science and Technology Policy Studies at SPRU, University of Sussex (UK). His book on ‘Environmental Policy and Technological Innovation: why do firms adopt or reject new technologies’ is considered a seminal work in the field of eco-innovation and cleaner technologies. Dr Montalvo has 19 years of professional experience, with extensive practice as an engineer and in project and R&D management. His is an authority on technology innovation and management with wide experience in multidisciplinary and international research. Previous to joining TNO, Dr Montalvo held a number of engineering and management positions in industry and on international organisations. Dr. Montalvo current activities and research interest focus on: competitiveness, R&D and innovation; innovation and the environment, technology adoption and diffusion analyses, and in the application of behavioural and system dynamics models to explore the interaction between actors and barriers and drivers influencing innovation and change.

Annex 1. Coding Scheme: content analysis of 255 scientific articles, practitioner papers and reports in the period 1908-2011

Coding Scheme

Our coding scheme involved a sound definition of the boundaries of our population, defining criterion for inclusion, and ensuring the collection of adequate sample. Next, we proceeded to perform the content analysis (see below).

Boundary and criterion definition. The articles included in our content analysis had a technology focus at the system and sector level. We excluded articles from single subsectors (especially from pharmaceuticals and consumer products), countries, regions, or specific technologies. We ensured including academic and practitioner articles dealing with sustainable innovations (both technological and non technological) in the chemicals production system as a whole – and we refrained from including other sustainable innovations which involve chemical transformations in other sectors (e.g. chemical solar applications using hydrogen in the renewable energy industry). Rather than looking at specific technologies that improve the environmental performance of a single process for the manufacturing of chemicals, we aimed looking into examples illustrating the overall production system of any given group of chemical products. In simple words, we identified generic concepts or analytical constructs at a higher level of aggregation. An example of the former would be a non-mercuric catalytic method for the production of polyvinyl chloride e.g. Zhan, Lui et al. 2011 An example of the latter is the application of green engineering concepts to the manufacturing of plastics or other chemicals, e.g. Garcia-Serna et al (2007). We also assumed that no sub-sector level differences existed in terms of sustainable innovation dynamics. Albeit it may be true that factors for improving environmental performance and patterns of environmentally motivated innovations differ within different subsectors of the chemical industry. See Arduini & Cesaroni (2004). The type of document selected is a fundamental difference to the seminal work of Hoffman (1999), as we did not include company or industry reports or industry journals such as Chemical Week or Chemical Engineering. The reason for this is the bias interpretation of events and issues in this type of publications in order to meet its core audience (Hoffman, 1999). In spite of the fact that academic and practitioner articles may present a delay in time from the time they were written to the time they are published, we believe these constitute a valuable source of information for the purposes of our study, as they have been trough a process of scientific validity and reliability. An additional criterion for choosing scholarly articles is their degree of objectivity and availability, a condition that is often hampered in empirical research using company or industry documents. The underlying reason for including government-funded reports lies on the possibility to enquiry about strategic and future oriented sustainability-related aspects of chemicals manufacturing.

Data collection. The second step consisted in the collection of relevant material. The databases consulted included Science Direct, JStore, EBSCOhost, Wiley, Springer and Emerald databases. We also looked at specialised (and practitioner) Journals from the Royal Society of Chemistry and the American Chemical Society. We also used Google scholar® and Scirus® for identifying relevant industry, scientific or policy reports and open access journals. We did not include in our review journal articles reporting advances in basic chemical science and engineering, such as Frontiers of Chemical Science and Engineering, Chemical Engineering Science, etc. The level of technical detail of most articles in these second set of Journals in relation to aspects of sustainable innovation and greening chemical processes is very high. These journals provide research findings of on-going research about improving the environmental properties of specific materials or technologies, which are not necessarily mainstream or widely adopted in the industry. We also excluded articles that did not fit the criteria established in the surveying approach described above.

Data selection. The third step consisted in a semi-automated selection of articles using key words and a manual inspection of their corresponding list of references – so further references could be identified. We first used the advanced search mode of all journals databases in order to search articles using keywords, including: chemical industry, future, prospect, evolution, accumulation, innovation, safety, regulation, legislation, enforcement, pollution control, pollution prevention, waste prevention, stewardship, eco-efficiency, environmentally, cleaner production, sustainability, sustainable, and green (technology, innovation, engineering, design). We also included the words social and community, in order to try to identify literature talking about the social aspects of sustainable innovation. Using generic words such as ‘chemical’ or ‘chemicals’ produced a higher number of unrefined results that posed difficulties for the content analysis – hence we still required to manually identifying and excluding non-relevant articles. We cross-checked the content of each article with the basic criteria set up in our surveying approach. We also identified and excluded duplicates.

Sample adequacy. Our sample included 217 scholarly and practitioner articles from the Journal of Cleaner Production, Chemical Engineering Journal, Business Strategy and the Environment, Chemical Engineering and Technology, Chemical Technology and Biotechnology, Green Chemistry, etc. It also included 38 scientific reports commissioned by Governments analysing innovation, competiveness or sustainability aspects of this industry. Please note that the relatively small sample size gives this research an exploratory character, as content analysis research in the social sciences often includes thousands of observations. Therefore this data was considered an adequate sample size for exploratory purposes.

Content analysis

Our content analysis formally consisted on the stages of coding, formulation of categories, analysis of content and interpretation of results.

Coding. We relabelled the title of each electronic document. We chose a format YEAR-Type-Author_Title.extension for assigning a code to each document. Two general types of documents were considered: articles (P) and reports (R). An example of a code assigned to an article we have: 1999_P_Hoffman_Inst evolution and change chemical industry.pdf. By assigning such a label the dataset compiled in the NVivo® Software automatically assigned a ranked order to all articles defined by the year of publication.

Creation of categories. Hoffman (1999) noted that empirical research in the chemical industry using content analysis should have a clear theoretical basis as a point of reference. as this helps for any categorisation effort. For this purpose we used three main references from the literature, Hoffman (1999), Garcia-Serna et al. (2007) and Díaz Lopez (2012). First of all, we elaborated an important assumption: that the (environmental) evolution of the US chemical industry can be comparable to the evolution of the world chemical industry. Next, we ’Hoffman's environmental stages up to the year 1993 with a twofold purpose: (1) to compare the state of evolution of the global chemical industry in relation to sustainable innovation (See section 4). (2) For the creation of our own analytical categories (periods of time). Here, two assumptions were made. We also assumed the same behaviour prior 1979 (indifference to the environment) and that the period of

1988 to 1993 could be extended until the end of that decade. We then created the categories per decades: (1) prior to 1979, (2) 1980 to 1989), and (3) 1990-1999 and (4) from 2000 to date. Papers were classified and tested according to their year of publication. The name of the labels for each category was defined by the actual empirical findings of each group.

Data analysis. Using NVivo® we performed a frequency analysis for each of the 5 pre-defined categories. The categories and number of coded articles were: (1) 16 articles published between 1908 and 1979, (2) 12 articles published between 1980 and 1989, (3) 62 articles published between 1990 and 1999, (5) 127 articles published between 2000 and 2011. In addition, we performed a frequency analysis for all the 38 reports in the sample, published between the years 1998 and 2011. The list of articles and reports per category are available upon request.