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Comparing evolutionary dynamics across different national settings: the case of the synthetic dye industry, 1857–1914*

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Abstract. Current models of industry evolution suggest that development patterns should be the same across different levels of analysis. In comparing the evolution of the synthetic dye industry at the global level and in the five major producer countries before World War I (Britain, Germany, France, Switzerland and the United States), it is shown that patterns of industry evolution differed significantly across national contexts. Based on a quantitative and qualitative database of all firms and plants in the industry, the paper analyzes how German firms came to dominate the industry and identifies factors such as availabilities of crucial skills, economies of scale and scope, and positive feedback mechanisms between firms and national institutions that likely produced these national differences. The empirical analysis calls for formal models of evolution that incorporate differences in institutional environments.

Key words: Comparative industry evolution – Institutional analysis – Technological innovation – Longitudinal dataset of firms and plants

JEL classification: L10, O30

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1 Introduction

Empirical investigations of the evolution of industry have flourished over the last two decades. But with the exception of Carroll and Hannan's automobile study (1995) and to some degree Chesbrough's (1999) work on the hard drive industry, no one has examined in a systematic fashion whether evolutionary patterns are the same in different social contexts (see Carroll and Hannan, 2000, for a survey). The goal of this paper is to present some striking dissimilarities in patterns of evolution that appear when the level of analysis is not the global level, but rather individual countries. These variations in country patterns raise questions about current models of industrial evolution and call out for an explanation. Based on our detailed study of the synthetic dye industry from 1857 to 1914,[1] we propose a number of general factors that may be the driving forces behind these differences. To assess the generality of the causal processes identified in the present study, future research needs to test our conjectures in other industrial settings.

The synthetic dye industry is a promising setting for a number of reasons. First, dye production started in different countries at about the same time – Britain (1857), France (1858), Germany (1858), and Switzerland (1859) – enabling us to compare the simultaneous evolution of national firm populations. Second, the synthetic dye industry is often referred to as the first science-based industry because of two distinguishing characteristics. It represents one of the first instances in which scientific research led directly to a new commercial product, and the industry was the setting where industrial R&D labs were created for the first time in the 1870s. It took about a year for the discovery of the first synthetic or coal-tar dye to be translated into an industrial product, and scientists continued to develop new dyes in the decades that followed. This feature will allow scholars to compare the path of the synthetic dye industry with the evolution of contemporary high-tech industries and identify invariant patterns as well as the drivers of differences. Third, our data set of virtually all firms in the synthetic dye industry from 1857 to 1914 makes it possible to contribute to contemporary research in industrial organization and add a historical perspective to the present debate on competitiveness.[2]

Our research into the evolution of the early synthetic dye industry is novel in a number of ways. As we have collected data not only on firms in all dye-producing countries but also on their plants and the various types of products they made, we are able to provide new evidence about the process of industry evolution. Our data allow us to examine in more detail than previous studies the causal dynamics that lead firms to enter and exit an industry.

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[1] The present investigation stops in 1914 because the First World War triggered massive state intervention in all countries and dramatically altered the industry's dynamics all over the world.

[2] Our data set also includes makers of organic intermediate chemicals since we wanted to be able to investigate how many such producers integrated forward into dye making. Some observers have claimed that German firms came to dominate the dye industry because they were the only ones that made their own intermediates. We wanted to be in the position to test this claim in a systematic manner.

Second, we have conducted a study of the synthetic dye industry that involved both quantitative and qualitative methods. Our database of firms and plants contains numerical as well as relevant qualitative data. Because we pulled together information from a wide variety of sources - histories of the dye and chemical industries, histories of firms, trade directories of various kinds, reports on firms exhibiting at world exhibitions, trade association membership lists, and biographies of leading industrialists and chemists - our database is considerably richer than any hitherto amassed.[3]

Third, we constructed our database of firms and plants after we had already acquired a considerable understanding of the dynamics that marked the industry. One of us, Ernst Homburg, participated in a Dutch research team that in the 1980s investigated the synthetic dye industry before the First World War (Homburg, 1983; van den Belt et al., 1984; van den Belt and Rip 1987; Homburg, 1992; Hornix, 1992; van den Belt, 1992). Our knowledge of this industry allowed us to design the database with an eye toward potentially key micro-variables that influenced the development of the industry. For instance, we tracked products such as synthetic alizarin, which has been identified as an important innovation in the historiography of the synthetic dye industry. These data would make it possible to examine hypotheses advanced in the historiography of the industry in a more systematic fashion. A case in point is the idea that a new wave of entry occurred in the industry because of the development of synthetic alizarin. Furthermore, we realized that while some firms disappeared, their plants continued to operate because they were taken over by other firms. This led us to develop a separate plant database that tracked all plants and their key products. We exploit the plant level database in the present paper by examining, for example, whether the evolution of the industry is marked by a trend toward multi-plant firms.

To investigate similarities and differences in the patterns of industrial evolution across social settings, we first examine the global pattern of the industry's evolution from 1857 to 1914. Before the First World War, synthetic dyes were produced in Britain, Germany, France, the USA, and Switzerland (major producer nations), as well as in Russia, the Austrian Empire, the Netherlands, Belgium, Italy, and – very shortly before the war – in Rumania (one firm), Greece (one firm), and Canada (two firms). Next we compare the global pattern with that of Britain, Germany, and France. Because of the small number of firms in Switzerland and the U.S., we treat these two countries more briefly. We then attempt to identify some causes that may generate differences in industry evolution across social settings. Finally, we discuss some of the implications of our study for research on industrial evolution.

[3] We plan to make the database available over the Internet sometime in the future. Because we identify all our sources for a particular firm or plant record, researchers will be able go back to the original data.

2 Patterns of evolution at the global level

Number of producers (density)

William Henry Perkin, the inventor of the first synthetic dye, started production of aniline purple near London at the end of 1857 and remained the only producer for at least a few months. To commence dye production, Perkin also had to develop processes to make crucial chemical inputs, the so-called 'intermediates' (i.e. organic chemical compounds that are made from raw materials). While some of the organic intermediates were already made for other industrial purposes, Perkin could not buy all necessary intermediates in the market and had to make nitro-benzene, for example, in-house.

The year 1858 already saw a dramatic increase to 8 firms participating in the industry.[4] The number of firms continued to increase steeply in these early years. By 1864 a temporary maximum of 68 firms was reached. Over the next fifty years the global population grew much more slowly, reaching a peak of about 84 firms (see Fig. 1, upper graph).

If we restrict our analysis to the five leading countries, Britain, France, Germany, Switzerland, and the USA, the patterns look very similar, except for the period after 1900, when the number of firms drops for the 5-country aggregate but rises for the entire world. The number of firms in a given year is, of course, determined by the number of firm entries and exits since the previous year. Showing in more detail the global industry dynamics of the early years, Figure 2 plots the 3-year moving averages of the number of entries and exits in each year. The entry graph reveals that the largest amount of entry occurred very early in the industry around 1863.

The rapid entry of firms between 1858 and 1864 was propelled by a strong demand for aniline dyes, especially in the field of luxury textiles (silks) and highly priced fashionable designs. The number of synthetic dye producers rose so quickly that the intensifying competition soon led to falling prices for the new dyes. By 1864, the price of fuchsine (aniline red), for instance, had fallen to about ten percent of the 1860 levels (Morris and Travis, 1992, p. 65). A number of firms could not cope with the swift decline in prices that resulted from production overcapacity and were forced to exit. The number of exits at the global level peaked in 1864 with 9 exits (see the firm exit graph in Fig. 2).[5]

The period from 1864 to 1869 was marked by a process of consolidation. Many companies now produced more than a few dyes and offered a full "rainbow" of dyes to customers. This proliferation of synthetic dyes led to a decline in sales of such natural dyes as archil and cochenille-carmine.[6] But competition

[4] All graphs in figures report three-year moving averages.

[5] Meyer-Thurow studied contemporary reports of chambers of commerce in Germany and found that local officials became quite aware of a crisis in the dye industry in the years 1863-4. Manufacturers complained about falling prices and typically blamed overcapacities for the difficulties in selling product (personal communication to one of the authors).

[6] It took several decades before all natural dyes were replaced by synthetic equivalents. Natural dyes such as dyewoods were produced on a large scale until the 1880s and to a lesser extent well

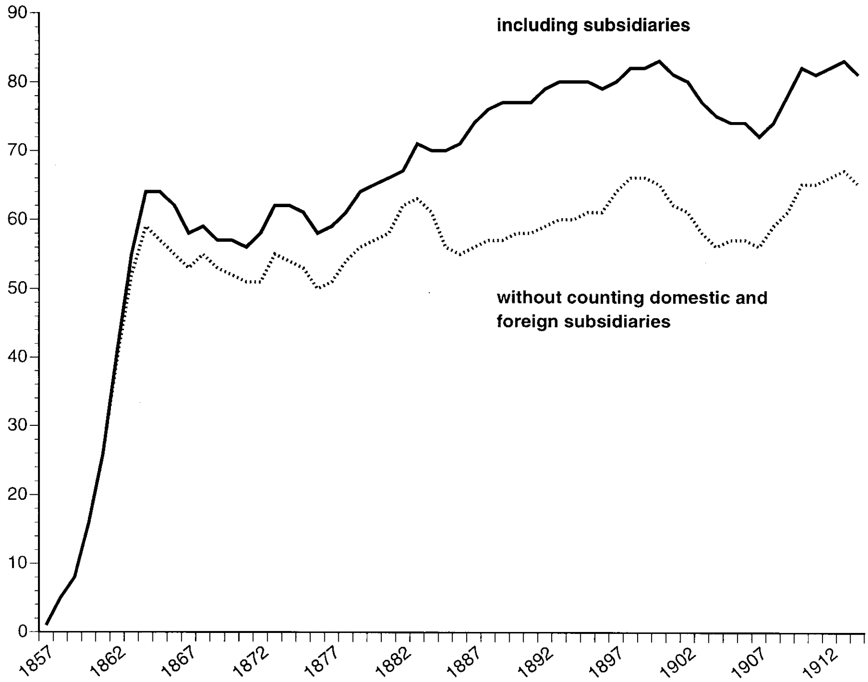

Fig. 1. Number of dye firms in the world, 1857–1914

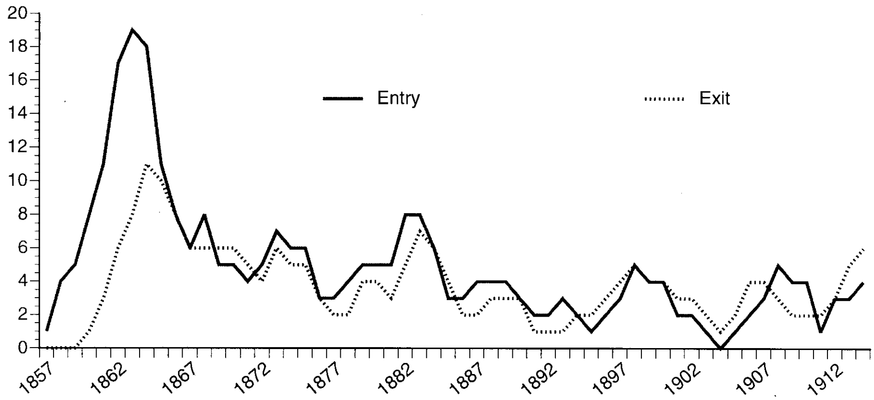

Fig. 2. Global firm entries and exits 1857–1914

from new synthetic dyes also took sales away from older synthetic dyes such as aniline purple.

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into the 20th century. The advent of the direct cotton (azo) dyes in the 1880s dealt a major blow to several of the natural dyes. It is safe to assume that a couple of thousand synthetic dyes appeared on the market between 1857 and 1914. Dyers and printers could choose from at least 900 different dyes when World War I broke out. Such a variety was never available before the advent of synthetic dyes.

In more general terms, two important developments characterized the market penetration of synthetic dyes after the creation of the first synthetic dye: (1) unremittingly falling prices and (2) the continual invention of new classes of synthetic dyes. Ever-lower dye prices soon made it possible for synthetic dyes to be used not only on luxury textiles but also on more common cottons and woolens. Falling prices were a key force driving the gradual replacement of natural dyes (of which there were about thirty different kinds) by cheaper synthetic equivalents. The invention of new classes of synthetic dyes was even more important in this substitution process. The early aniline dyes replaced only a few of the natural dyes. Later innovations led to the gradual replacement of the other natural dyes. Every single major breakthrough led to new waves of entry in the synthetic dye business.

The second entry wave, which occurred between 1871–1873, provides a good example of the consequences of such a major breakthrough. The development of synthetic alizarin in 1868 opened up a huge market that was formerly served by natural dye makers. Many firms sought to profit from this fast-growing market and entered the industry, leading to another significant jump in the number of firms in the industry. We found support for the proposition that firms entered the industry to take advantage of the alizarin market by comparing the product portfolios of all synthetic dye producers on January 1, 1868, with the product portfolios of new producers in their entry year for the period from 1868 to 1876. There were 52 producers of aniline dyes on January 1, 1868, 4% of which also made azo dyes, 19% made natural dyes, 17% fine chemicals, 8% inorganic basic chemicals, 13% organic basic chemicals, and 33% intermediates. None of these firms made alizarin (see Table 1). In 1869 a few existing companies (Hoechst, BASF and Perkin & Sons) started to make alizarin. But soon new companies were founded that started as specialized alizarin producers. In 1870, 2 of the 7 entrants (28.6%) made alizarin and 5 of the 7 entrants (71%) made aniline dyes. In 1871, 20% of 10 entrants made alizarin, in 1872 75% of the 4 entrants did, and from 1873 to 1876 between 33% and 66% of the new entrants were founded as alizarin producers (Table 1).[7]

The third entry wave, 1878–1885, was stimulated by the invention of a new class of azo dyes that were based on the so-called “coupling” reaction. This coupling reaction gave rise to seemingly endless possibilities for new dyes (van den Belt and Rip, 1987, pp. 148–149). By the First World War, the largest number of dyes sold in the market fell into the class of azo dyes.

The fourth entry wave, 1904–1913, probably was a result of the general economic uplift in the years just before the First World War, as well as the development of a new class of dyes (the so-called sulfur dyes), the growing specialization among the dye firms, and the emergence of dye firms in some smaller countries. Sulfur dyes were cheap and easy to make and therefore facilitated the entry of new firms into the synthetic dye industry (as, for example, in the cases of Th. Handschin & Co. and James Robinson & Co., Ltd.). Furthermore,

[7] At first glance the numbers in Table 1 seem somewhat different from those in Figures 1 and 2. But this is not so. Figures 1 and 2 present the 3-year moving averages of the data in Table 1.

Table 1. Alizarin producers among existing firms and entrants (1868–1876)

Year	Number of entrants	% Alizarin producers	Number of existing firms	% Alizarin producers
1868	1	0.0	52	0.0
1869	0	0.0	53	3.8
1870	7	28.6	48	8.3
1871	10	20.0	52	11.6
1872	4	75.0	54	14.8
1873	13	46.2	56	26.8
1874	3	33.3	57	33.3
1875	3	66.6	54	29.9
1876	6	50.0	55	29.1

some firms entered the industry to produce dyes for niche applications such as leather (as in the case of the Central Dyestuff & Chemical Co.). Finally, the industrialization of smaller countries together with protectionist national policies encouraged entrepreneurs to start dye plants that would serve the growing home market.

A comparison of the entry and exit graphs shows that the patterns for the two processes are remarkably similar. Very often spikes in exits followed spikes in entry with a one- or two-year delay. Large numbers of new entries invariably seem to lead to exits either because incumbent firms experienced more competition and were more likely to fail or because the new entrants did not have the strength to survive in the industry and were quickly forced out again. Starting around 1897 the number of exits in many years was larger than the number of entries. We also analyzed the entry and exit data excluding dye firms that were subsidiaries of another dye firm and hence could be interpreted as not constituting a *de novo* entrant. With these slightly reduced samples we nevertheless obtained very similar patterns.

General trends

One of the striking patterns at the global level (as well as at the leading 5-country aggregate) is that no visible shakeout – a dramatic reduction in the number of firms – occurred in the period before 1914 (Fig. 1). Shakeouts have been found in many studies of U.S. industries (Gort and Klepper, 1982; Klepper and Graddy, 1990; Klepper, 1997). Carroll and Hannan (1995) also report shakeouts in the automobile industries of Britain, Germany, France as well as the United States.

Another remarkable pattern is the extent to which production became concentrated in Germany. For the first 8 years, until the middle of the 1860s, British and French firms were clearly market leaders. But in the second half of the 1860s German firms caught up and surpassed their British and French rivals. Around 1870, German firms were responsible for 50% of world production. By 1900, Germany's worldwide share climbed as high as 75% where it remained with relatively minor fluctuations until the First World War. If one also counts German-owned plants in foreign countries, German market share reached as high as 90% (Thissen, 1922).

Concentration processes also occurred within national industries after the 1860s. In all major countries output became increasingly held in the hands of a few firms. These firms were all relatively early entrants. Britain, Germany, and the USA illustrate this trend. In Germany the top three producers accounted for 55% of the 60 million marks domestic dye production in 1883. More specifically, BASF had a market share of 23.3%, Hoechst of 16.7% and Bayer of 15% (Meyer-Thurow 1982). In 1914, the top three producers accounted for 66% of domestic production. BASF, Bayer, and Hoechst were each responsible for about 22% of domestic production and, given Germany's world market share, for almost 20% of world production each.[8] At the start of the First World War, Levinstein and Read Holliday also possessed a dominant position among domestic producers in Great Britain with a share of about 30% each of British production.[9] At this time, in the U.S., Schoellkopf held a 50% share of domestic dye production, Heller & Merz had 21%, and the Bayer subsidiary, Hudson River Aniline, had 17% (Haynes, 1954, p. 313).

Important drivers behind these concentration tendencies were economies of scope and to a lesser extent economies of scale. The case of Bayer, a firm that became one of the three largest German dye producers, illustrates the process of exploiting scope and scale economies. Bayer achieved unit cost reductions through a variety of ways. Over the years it increased the size of production reactors by several orders of magnitude. In 1868 Bayer used autoclaves with a capacity of 30 liters; by 1905 it used 2000-liter autoclaves (Bayer, 1918, pp. 251-252). At the beginning of the azo dye era, Bayer reactors had at most a size of between 1000 and 2000 liters (Bayer, 1918, p. 182). By 1907 a reactor to make azo dye had a capacity of 20,000 liters (Bayer, 1918, p. 182).

These economies applied not only to production but to R&D as well. (See also Chandler, 1990, on the importance of scale and scope economies in other industries.) In the era where firms' R&D laboratories replaced university laboratories as the main source of new dyes, large-scale experimentation and testing of dyes reduced the cost of finding competitive new dyes. In 1906, Meyer-Thurow (1982) reports, 2,656 new chemical compounds were synthesized in Bayer's research laboratories. Sixty of those were tested on a larger scale after a first screening, and only 36 ever reached the market.[10] Synthesizing only a few new molecules and testing some of them for their usability on different fabrics was likely to yield

[8] The latter figure is calculated from data provided in Redlich (1914, p. 18) and Beer (1959, p. 138).

[9] It is very difficult to come by exact numbers on British market shares. We have estimated this figure from the information that Levinstein and Read Holliday were the two largest dye firms of comparable size (Reader, 1954, p. 263) and that after their merger the combined firm held about 75% of domestic production in 1918 (Richardson, 1962, p. 117).

[10] Hoechst, besides BASF, Bayer's biggest rival, developed a similar testing organization. In 1900 Hoechst tested 3,500 of its new colors or combination of old colors. Only 18 reached the market. A few years later 29 out of 8000 tested dyes were marketed (Beer, 1959, p. 89).

no new dye. It is important to keep in mind that competition was very fierce and large firms constantly introduced new dyes to follow changes in market trends. If a company employed only a single research chemist, for example, his efforts would be unlikely to yield a new dye. By contrast, if a firm employed a large team of chemists who would synthesize thousands of new compounds, the odds were much better that a firm would be able to come up with a competitive product before fashion trends changed. This is why hiring a large number of research chemists created the scale at which the unit cost of developing a new dye would go down significantly.

Economies of scope and scale also affected distribution and marketing. The case of Bayer again serves as a good illustration. In 1913 Bayer had 44 sales subsidiaries and 123 sales agents (Verg, 1988, p. 198). When Bayer stopped relying solely on sales agents but also on the company's own sales force to market product, the first unit of dyes sold was much more costly than the *n*-th unit. Similarly, in terms of translating dye labels and marketing campaigns into foreign languages, the first unit of dyes sold would be much more expensive than a later unit. But why was it so important for dye firms to do their own marketing rather than contracting that function out to independent firms that would sell the products of many firms? One important reason why all leading German dye firms developed their own marketing and distribution capabilities was that it provided their R&D departments with direct feedback from users. AGFA, for example, initially sold its products through an exclusive sales firm in Magdeburg, Töpfke & Leidloff. But in 1879 AGFA bought Töpfke & Leidloff and took sales, distribution, and marketing into its own hands. Similarly, in 1873 BASF bought two of its key sales firms, H. Siegle and R. Knosp, both of Stuttgart, and integrated these companies into its own operation. A general sales firm which distributed the dyes of many different companies simply did not possess any incentives to provide one particular dye maker with detailed feedback from users. Consistent with Teece's (1986) argument that stresses the need of co-specialized assets to profit from innovation, the large German dye firms felt compelled to internalize a large portion of their marketing and distribution functions. These in-house sales and marketing capabilities allowed a large dye maker to obtain reliable knowledge and feedback from users, making it easier to create competitive new dyes.

Moreover, as Chandler (1990) pointed out, a company could not afford to build large plants if it could not count on a steady flow of orders. Building large distribution networks hence was an effective tool for ensuring relatively steady demand for a firm's product. Investing large sums in R&D allowed firms to keep up with advances in dye technology and introduce dyes that were adapted to changes in market demand.

It is necessary to reemphasize that scope economies were relatively more important in dye making than scale economies. The marketing power of a firm like Bayer was based on its ability to construct and sell complete classes of similar dyes (that is, dyes that came in all possible shades, but had similar chemical properties such as acidity, solubility, etc.). These scope economies were crucial for winning customers because dyers wanted to be able to mix and combine different dyes to construct their own fashionable shades. German companies such as Bayer could only make these series of dyes because they produced a large number of chemical intermediates. A firm that made many intermediates and dyes could make an even larger number of dyes because a particular dye often served as an intermediate for other dyes. Making hundreds of dyes and intermediates gave rise to the possibility of making thousands of different dyes. As a result, the number of different dyes increased exponentially with the number of different intermediates available. The leading synthetic dye firms in Germany exploited these scope economies and developed elaborate production schedules for producing different intermediates and dyes in the same production facilities (see van den Belt et al. 1984, for details). Because smaller firms could not afford to make the large number of intermediates required to make all possible shades of a dye family, large firms such as Bayer possessed an important competitive advantage. To be sure, a market for the high volume dye intermediates such as aniline developed over time, but such a market did not emerge for most intermediates before 1914. This had a number of reasons. First, patents protected several key intermediates. Second, for an independent firm to begin the manufacture of a particular intermediate, it had to have the perception that the size of the market would be large enough to allow efficient production. Some firms such as Merk and Hahn produced intermediates on a very small scale to supply university laboratories and other experimental establishments. But a demand for large volumes of many dye intermediates did not exist, which would have enabled large-scale independent producers to enter the business at a profitable level. The large German dye firms recognized their advantage in producing intermediates efficiently and selectively sold some of their intermediates to other firms that were not perceived as a serious competitive threat. For all these reasons, smaller firms were forced to concentrate on niche markets, e.g. make only blue dyes for blue and white textiles; or make black dyes for shoe polish, and so on.

The synthetic dye industry before 1914 was also characterized by a trend toward multi-plant firms. While most of the firms remained one-plant firms, some firms came to have more plants as the industry developed. In 1864 firms with two or more plants were rare. In 1913 there were several (German) firms that operated more than four plants (in one instance even 9 plants) at home and abroad.[11] Table 2 presents the distribution of plants across firms. Our unit of analysis, which we call "firm-year," is a particular firm in a particular year. Calculations based on firm-years produce analyses that take the life-times of the firms into account. We have divided the entire period of our study (1857 to 1914) into two equally long periods to examine in more detail the distribution

[11] In 1864, 93 firms have 99 plants; 87 are one-plant firms and 6 are two-plant firms. In 1913, 130 firms have 156 plants; 114 are one-plant firms, 9 are two-plant firms, 5 are three-plant firms, 1 is a four-plant firm, and 1 is a 5-plant firm. If foreign subsidiaries are counted not as separate firms, the trend toward multi-plant is even more striking. 1864: 86 firms have 99 plants, on average 1.15; 73 are one-plant firms and 13 are two-plant firms. 1913: 101 firms have 166 plants, on average 1.64: 77 are one-plant firms, 10 are two-plant firms, 7 are three-plant firms, 2 are four-plant firms, 2 are 5-plant firms, 2 are six-plant firms, and 1 is an eight-plant firm.

of plants across firms. Altogether there are 6102 firm-year observations in our database – 2522 observations until 1886 and 3580 observations after 1886. The vast majority of firms (87%) are single-plant firms in both periods. In the later period, there are fewer 2-plant firms (8.3% versus 10.8%) and more 3-plant, 4-plant, and 5-plant firms (4.8% versus 2.3%) (see Table 2 for details). If we count foreign-owned plants as plants of the mother company, the trend toward multi-plant firms is even more striking. In the later period, there are fewer single- and two-plant firms (87.3% vs. 95.5%), but more firms that operate more than three plants (12.6% vs. 4.5%).

Table 2. Distribution of plants across different firms in two periods

Number of plants per firm	Number of firm-years (% between brackets)			
	Domestic plants only		Foreign and domestic plants	
	1857–1886	1887–1914	1857–1886	1887–1914
1	2194	3114	1958	2192
	(87.0)	(87.0)	(83.1)	(75.9)
2	271	297	291	329
	(10.8)	(8.3)	(12.4)	(11.4)
3–4	57	153	97	281
	(2.3)	(4.3)	(4.1)	(9.7)
5–6	0	16	10	55
	(0.0)	(0.5)	(0.4)	(1.9)
7–9	0	0	0	30
	(0.0)	(0.0)	(0.0)	(1.0)
Total	2522	3580	2356	2887

3 Country patterns

Present formulations of evolutionary theory make no predictions that patterns of industry evolution at smaller social units such as countries would be different from patterns at the global level. A plot of the number of firms for individual countries (Fig. 3) reveals, however, striking dissimilarities at the country level from the pattern we saw earlier at the global level.[12]

Industry shakeout in France

France, just as in the case of the global industry, displays a steep rise in the number of firms from 1858 to 1862. The rise would be even steeper if we were

[12] We should note at this point that the national industries are, of course, not fully isolated from one another but linked through trading and sometimes through common ownership. Carroll and Hannan (2000) argue that national industries are also linked by helping to legitimize a new business model at the global level. As a first approximation, it is useful to treat national industries as independent units. We will later acknowledge that know-how and products flow across borders.

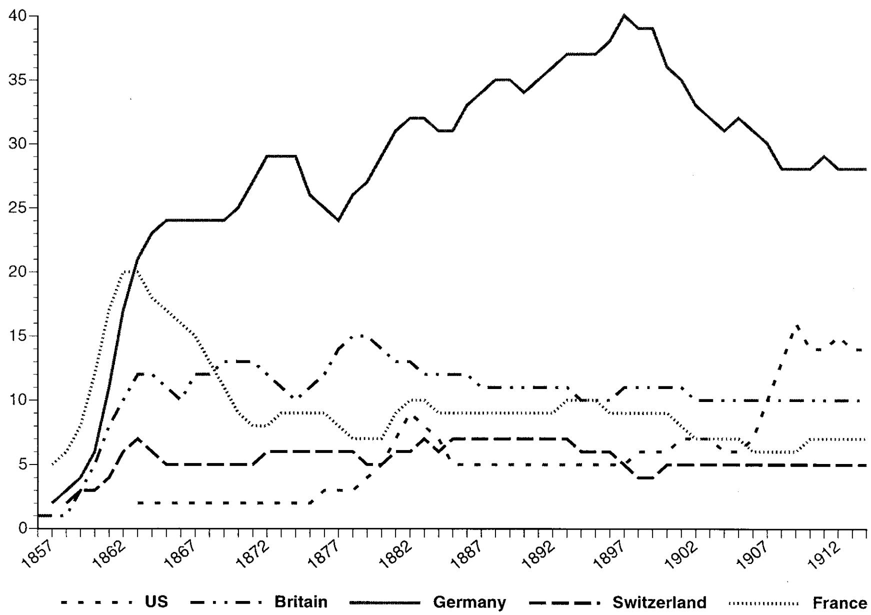

Fig. 3. Number of dye firms by country, 1857–1914

to count also the number of intermediate chemical makers, which were numerous in France. Between 1862 and 1870 a constant steep decline occurred in the French synthetic dye industry from 21 to 7 firms (40 firms to 15 including intermediate makers). Between 1870 and 1914 the number of firms in the French dye industry stayed at a remarkably constant low level.[13] France is a clear example of an industry shakeout that appears to characterize many industries. The automobile industry is perhaps the most prominent case of a severe industry shakeout documented in the literature (Carroll and Hannan, 1995; Klepper and Simmons, 1997). Carroll and Hannan report that between 1920 and 1930 the American automobile industry and between 1924 and 1934 the German, British and French automobiles industries all experienced a severe shakeout. In the case of the French dye industry, however, the shakeout came much more quickly than in the automobile industry. Carroll and Hannan (1995, p. 195) place the start of the French automobile industry in 1885, with the shakeout happening about 40 years later. In the French dye industry the shakeout occurred within about a decade after the start of the synthetic dye industry in 1858. Carroll and Hannan (2000) speculate that in high-tech industries shake-outs come more quickly. Synthetic dyes undoubtedly were a high-tech industry in the 19*th* century, partly confirming the Carroll-Hannan hypothesis. But the fact that a clear shake-out only occurred in the French dye industry and not the other countries suggests

[13] The graph does not show a decline of the number of firms in the wake of the Franco-Prussian war. The loss of the few Alsatian firms was compensated by the formation of new French firms.

that being a high-tech industry is not sufficient to cause a quick shake-out. Social context matters too, as we describe in more detail below.

Relatively small fluctuations in Britain

The British pattern in the early years of the synthetic dye industry resembles more the S-shaped curve that has been found in studies of diffusion of innovations, diseases, or fashions. The entry slope for Britain is not as steep as that of France. Britain, with a peak of 16 firms, never reached the industry participation level of France. The period of rapid growth took place from 1859 to 1863. Britain also experienced a decline of synthetic dye firms from 1864 to 1866, but the decline was not nearly as dramatic as in the case of France, where one can truly speak of a shakeout. Existing historiography emphasizes that Britain was the leading country in the early synthetic dye industry, with France closely following and Germany far behind (Beer, 1959; Travis, 1993). Our data show, however, that France was not trailing at all. These findings call for a reevaluation of the early period in the synthetic dye industry (see Fig. 3). Growth in France was earlier and quicker, and more firms participated in the French industry in the very early years. Figure 4, which plots the fraction of the global firm population that resided in each of the five major countries in a given year, makes this point forcefully. Already in 1858 the French share in the global firm population surpassed the British share, and until 1870 the number of synthetic dye firms in Britain was lower than in France. The British industry reached the lowest (relative) level in the number of firms in 1864. From 1864 to 1914 the number of industry participants remained fairly constant in Britain. The British industry stabilized earlier than the French, but it is striking how the levels of industry participation became similar in the two countries from the 1870s onward, with Britain having a slightly larger number of firms than France.

Germany: Long rise in the number of firms

Germany also displays a steep rise in the number of firms between 1858 and 1863. The number increased from 2 firms in 1858 to about 22 in 1863. Existing historiography does not discuss this early entry of a large number of firms in Germany, in part because these early German entrants did not possess the visibility of the leading British and French firms during this period. The timing of the German rise is about the same as in France, but Germany began at a lower level in 1858. The striking difference between Germany, on the one hand, and Britain and France, on the other, is that the number of firms in Germany continued to increase after 1863. The lasting growth in the number of German firms is the reason the dramatic shakeout that occurred in France does not show up at the global level. After a short consolidation phase (1873-76), the growth continued from 1877 to 1897. In this period the number of firms increased as a step function, alternating between periods of rapid growth and stabilization,

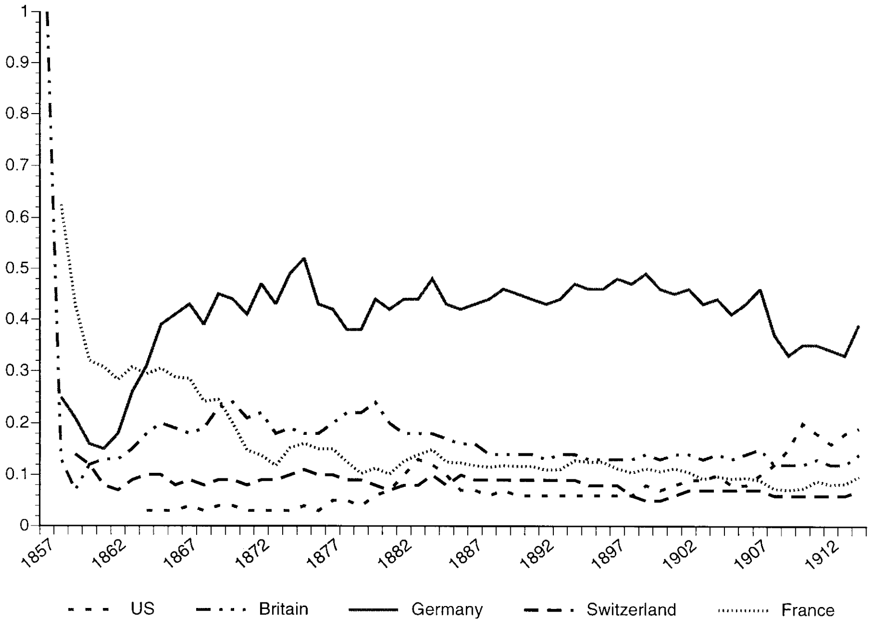

Fig. 4. Country shares of global firm population

rising from 24 firms in 1877 to 43 firms in 1897. This pattern is very different from both France and Britain where such growth phases did not take place. A substantial decline in the number of firms occurred in Germany much later than in France. Between 1897 and 1907 there was a consolidation in the German dye industry, and participation fell to the 1870s level of about 25 firms.

Small players: Switzerland and U.S.

Whereas synthetic dye production started in Switzerland at about the same time (1859) it did in Germany and France, the first producer in the U.S. appeared only in 1864. Just as Britain, Germany and France, Switzerland experienced a steep growth from 1858–1862 when the number of firms increased from 0 to 8. Parallel to the situation in France, a first decline set from 1862 to 1866 in which the number of firms fell from 8 to 4. Between 1867 and 1873 the number of firms increased again from 4 to 7. This is different from France where the number of firms did not increase in the late 1860s and early 1870s, but was similar to the German pattern of growth in the number of firms. From 1871 until the First World War the number of firms was roughly the same in France and Switzerland, but there was one important difference: on average the Swiss firms were larger than their French counterparts. With a 7% share in world dye production in 1913, the Swiss dye industry had, to be sure, only one tenth of the size of their German counter parts, but it was larger than the dye industry of countries with a far greater population or textile industry, such as Great Britain (6.5% of world dye production), France (5.4%) and the United States (3.3%) (Thissen, 1922, p. 18).[14] If we eliminate from our analysis all domestic or foreign subsidiary firms, it becomes even more apparent that the Swiss dye industry surpassed the French one. Figure 5 graphs the number of firms by country without counting subsidiaries and shows that by 1884 there were more domestically owned firms in Switzerland than in France. German companies had bought up many of the French plants.

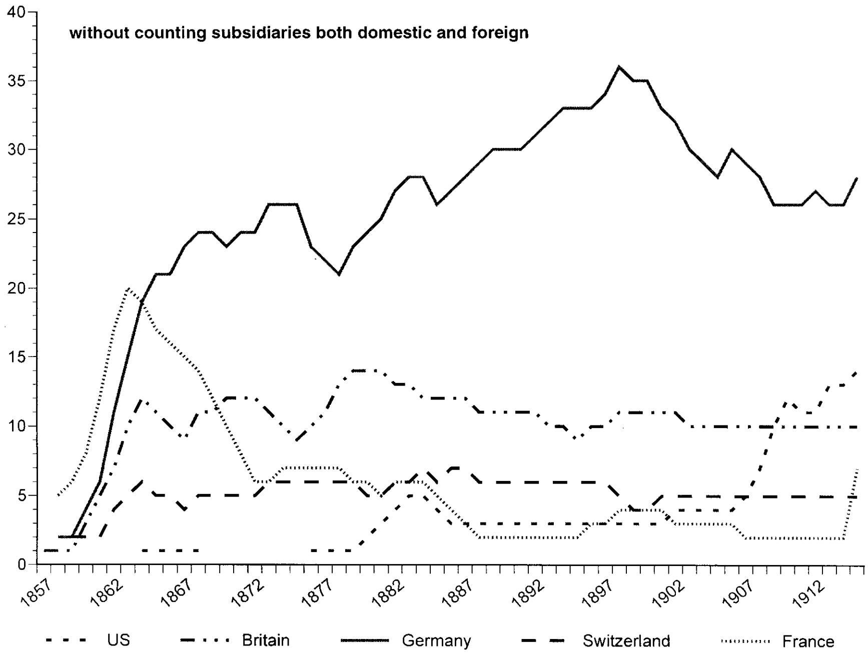

Fig. 5. Number of dye firms by country, 1857–1914

The United States is different from the four other countries in that it did not experience an initial steep take-off (Fig. 3). From 1864 to 1875 only two firms participated in the industry (1868 being an exception with 3 firms). A steep growth occurred in the U.S. from 1878 to 1882 when the number of firms increased from 3 to 10 firms. What happened at this time in the U.S. is in striking contrast to France and Britain, but parallel to the growth in Germany. Between 1883 and 1884 the number of firms decreased rapidly by 50% from 10 to 5 firms. For the next 20 years the number of firms hovered around 5 firms. Unlike in the four other countries, the number of firms in the U.S. industry grew from 5 in 1897 to 12 in 1914. This increase sharply contrasts with the consolidation of the German industry after 1897.

[14] Comparing the number of firms in two countries does not necessarily tell us about their relative market share. One country with fewer firms could have more output than a second country with more firms. However, in comparing longitudinal trends in an industry where firms compete with one another across borders, it can give us a hint about the relative performance of national industries.

Comparing the distribution of plants across firms in the five different countries

Earlier, at the global level, we saw that the frequency of multi-plant firms increased over time (see Table 2). Before examining whether this pattern holds true in the five major countries as well, it is useful to look at the distribution of multi-plant firms for each country over the entire period. Table 3 reveals that only German and French firms ever had more than two domestic plants. And only German firms ever operated at home more than three plants at the same time. The temporal dynamics at the country level are also noteworthy. The trend of an increasing frequency of multi-plant firms that we saw at the global level is not true for every single country. Again comparing the period before 1887 with the period 1887-1914, the number of multi-plant firms declines in Britain and France.[15] German firms were clearly driving the global pattern. The frequency of 3-plant firms increases from 4.4 % to 6.9%, 4-plant firms from 0.6% to 2.9% and 5-plant firms from 0% to 1.0%.

Table 3. Number of dye plants per firm across the different countries

Numbers of plants/ firm	Number of firm-years (% in parentheses)									
	Britain		France		Germany		Switzerland		U.S.	
	Home	All	Home	All	Home	All	Home	All	Home	All
1	834	747	966	683	2082	1813	352	272	492	325
	(83.1)	(79.3)	(93.4)	(87.6)	(80.2)	(72.5)	(96.7)	(78.6)	(97.8)	(96.7)
2	169	173	62	75	295	308	12	30	11	11
	(16.8)	(18.4)	(6.0)	(9.6)	(11.4)	(12.3)	(3.3)	(8.7)	(2.2)	(3.3)
3–4	0	22	6	18	204	291	0	40	0	0
	(0.0)	(2.3)	(0.6)	(2.3)	(7.5)	(11.6)	(0.0)	(11.6)	(0.0)	(0.0)
5–6	0	0	0	4	16	57	0	4	0	0
	(0.0)	(0.0)	(0.0)	(0.5)	(0.6)	(2.3)	(0.0)	(1.2)	(0.0)	(0.0)
7–9	0	0	0	0	0	30	0	0	0	0
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(1.2)	(0.0)	(0.0)	(0.0)	(0.0)
Total	1003	942	1034	780	2597	2499	364	346	503	336

Explanation of the table: “Home” refers to domestic plants of a firm; “All” refers to the sum of (1) the domestic plants that are not owned by a foreign firm and (2) the plants owned by domestic firms in other countries.

When the analysis also includes plants that firms owned in foreign countries, the patterns are even more striking. If a German firm owned a plant in the U.S., for example, the plant would not be counted in this analysis among the U.S. plants but among the German. The maximum number of plants controlled by a particular firm then jumps from 5 to 9 for Germany, from 2 to 6 for Switzerland, from 3 to 6 for France, and from 2 to 3 for Britain. In the case of the U.S. the maximum remains at 2. The trend toward multi-plant firms appears not to be true for Britain, and only partially true for France (the percentage of 2-plant firms

[15] More detailed figures on the distribution of plants across firms for the different national industries can be obtained from the first author upon request.

increases from 3.8% to 9.5% but the percentage of three-plant firms falls from 0.9% to 0%). The most significant drivers behind the trend are still Germany and Switzerland. In Germany the frequency of 3-plant firms increased from 3.2% before 1887 to 11.0% in the years 1887–1914. The numbers for 4-, 5-, 6-, 7-, 8- and 9-plant firms also increased after 1887. In Switzerland, the frequency of 3-plant firms increases from 0% to 13.8%, and numbers for 4-, 5- and 6-plant firms increased as well.

4 Forces causing differences in evolutionary patterns

Until now we have offered descriptions but we have not provided any explanation for the observed differences in patterns. Our next task is to excavate the forces that most likely were responsible for the specific country patterns. Let us briefly bring back into focus some of the striking patterns and then identify plausible causes. We need to explain

1) why rapid entry occurred early in the industry in Germany, Britain, France, and Switzerland, but not the U.S.?
2) why, in the very early years, more firms entered in France than in any other country?
3) why, in the very early years, more firms entered in Germany than in Britain (18 versus 10)?
4) why German industry participation continued to increase after the consolidation phases in the mid 1860s while British and French industry participation stayed rather steady at a much lower level?
5) why a dramatic shakeout occurred only in France?
6) why France never recovered from the shakeout while the U.S. and Switzerland saw their numbers of firms increase from the late 1870s onward?
7) why the number of firms decreased in Germany after 1897, but much less so in France and Britain?
8) why U.S. industry participation increased in the years just before the First World War?
9) and why Germany came to dominate the industry with 75% market share in 1914?

Let us take them in turn. Given the space limitations of an article, we can support many of our arguments only with a short discussion. For a more detailed treatment of many points, see Murmann (1998, 2000).

Pattern 1: The United States did not experience rapid entry into the industry because the market for synthetic dyes in the U.S. was much smaller than in Europe in the early years. Initially, synthetic dyes were very expensive and only applied to luxury textiles such as silk. Because colorists traveled from one dyer to the next, a network of leading silk dyeing firms had developed across Europe. The biographies of the leading colorists reveal that this network extended from Britain to Russia (and everywhere in between) in the 1860s, but not to the U.S. The U.S. was simply not included in this important network through which the early aniline dye knowledge was transmitted (Homburg, 1983). Second, and less significantly,[16] the U.S. did not possess a large number of people who had the skills to start production of organic intermediate chemicals or synthetic dyes. Without organic intermediates, dye production was not possible unless entrepreneurs imported intermediates from Europe.

Pattern 2: France most likely experienced the largest amount of entry in the early years because of the very three factors that were absent in the U.S. Most importantly, as home of the largest market for luxury textiles, the highest demand for the initially very expensive synthetic dyes occurred in France. Many entrepreneurs decided to enter the market when they saw how large the demand for Perkin's aniline purple was in France (Homburg, 1983). The perceived size of the French market acted as an inducement for potential entrepreneurs. Secondly, before 1857, an infrastructure of organic intermediate producers existed in France who supplied producers of perfumes and semi-synthetic dyes sold on the luxury market (Chateau, 1868).[17] These intermediate producers had experience that they could use to integrate forward into synthetic dye production or, alternatively, to produce and sell dye intermediates to newly formed synthetic dye companies. Thirdly, besides a developed market for intermediates, France possessed two important centers of chemistry, one in Paris and one in Lyon. Pelouze's laboratory in Paris trained students who subsequently founded many of the synthetic dye firms around the city (Travis, 1993, pp. 149-150, pp. 71–72, p. 79).

Pattern 3: Why was the entry rate in the early years higher in Germany than in Britain even though Germany's textile industry was about 23 times smaller than that of Britain? The most important reason seems to lie in the patent system. In Britain dyes were protected by patents, whereas in Germany no such protection existed because the customs union (*Zollverein*) eliminated any effective patent protection.[18] This meant that anyone who wished to enter the synthetic dye business in Germany could do so. But in Great Britain entry into the dye business was severely restricted because, starting with Perkin's aniline purple, many of the synthetic dyes were under patent protection.

Pattern 4: Why did German industry participation continue to increase after the mid 1860s, contrary to the developments in France and Britain? Again the patent legislation seems to have made all the difference. Because patent protection was not available in Germany until unification and the creation of an

[16] Skills in organic chemistry were much less important in this early phase. We came to this conclusion in part by studying the question of why a synthetic dye industry did not emerge in the Netherlands in the 1860s. There was some of knowledge of organic chemistry in the Netherlands, but virtually no silk dyeing or other production activity for the luxury textile market. The Dutch textile firms were isolated from the leading textile producers abroad and hence did not learn about the new dyes as quickly.

[17] A semi-synthetic dye such as *murexide* involved in its manufacture and application both the traditional natural dye extraction techniques as well as synthetic chemical procedures. See Homburg (1983) for details.

[18] A special article (an 1842 addition) in the *Zollverein* (customs union) agreement did allow the member states to grant patents in their territories, but forbade members to prevent producers in other member states from selling the product in all member states (Penrose, 1951, p. 14; Heggen, 1975).

all-German patent system (1877), German entrepreneurs could continue to enter the industry after the consolidation phase in the mid 1860s by imitating the products of existing producers both at home and abroad. A second reason why industry participation probably resumed its growth in Germany relates to the entrepreneurial risk set. Several German states invested considerably in the creation of chemical laboratories for the training of students. During the 1860s Prussia built large and luxurious chemical laboratories in Bonn and Berlin, and Saxony erected a laboratory of similar standing at Leipzig (Bentley, 1972; Homburg, 1993, pp. 11–12). Germany, unlike France and Britain, continued to produce an ever larger number of qualified chemists who could venture into the synthetic dye industry. Furthermore, the large German synthetic dye firms constituted an important knowledge and experience pool. Several of the smaller German firms were founded by chemists who had previously gained experience working for one of the larger firms.[19] In the British and French dye industries, which beginning in 1862 were populated by fewer firms (see Fig. 3), opportunities for such spillovers were more limited. In Germany there were more entries, but also more exits in the dye industry. Because German firms in the early period of the dye industry were not protected by patents as was the case in Britain and France, in Germany a Darwinian type of process weeded out many firms and only allowed the strongest firms to survive.

Why did the number of German firms not go down in the mid-1860s when competition became very fierce? The market for synthetic dyes continued to expand because step by step natural dyes were replaced by synthetic counterparts. Moreover, the German economy as a whole was growing much faster than the economies of France and Britain. It is very likely that the number of German firms rose until around 1890 because technological advances in synthetic dyes opened up new market segments. When this was no longer the case in the mid-1890s, the number of firms dropped in Germany.

Pattern 5: Why did a dramatic shakeout occur only in France? France had an effective patent law on the books. The shakeout in France most likely was a direct result of one company, La Fuchsine, receiving a sweeping patent grant in late 1863 after a protracted legal battle with rival producers. By court order, La Fuchsine obtained a patent for aniline red that served as a precursor to numerous other synthetic dyes and thereby was able to use the French police to shut down many rival producers (van den Belt, 1992). In effect, the French patent ruling was responsible for the shakeout that occurred in France. At least seven firms

[19] Examples are: Dr. E. Ullrich was chemist at Bayer, 1865-1867. Thereafter he was involved in the founding of several small firms: *Frische (& Ullrich)* in 1867; *Ullrich & Grothe* around 1874, and an alizarin factory in Austria. Dr. P. Greiff was a chemist of *J.W. Weiler* in the 1860s. He then founded *Chemische Fabrik von Dr. P. Greiff.* Dr. E. ter Meer was chemist at BASF, and founded *Dr. E. ter Meer & Co.* in 1878. Dr. Marx and Dr. Mueller both were chemists at the *ter Meer* company. They founded *Marx and Mueller* in 1887. Dr. F. Raschig was a BASF-chemist before founding his own company, *Dr. F. Raschig*. Dr. Walther Wolff was chemist at AGFA before he founded *Dr. Walther Wolff*.

(Feer, Durand, Dollfus, Guinon/Monnet, Gerber-Keller, and Poirrier[20]) closed down production and set up shops across the border in Switzerland (which had no patent law). Other French firms had to focus on minor dyes. In Britain, by contrast, Thomas Holliday through litigation was able to invalidate the important arsenic acid process patent for aniline red held by the firm Simpson, Maule and Nicholson, and as a result firms could enter freely into this important dye market by 1865 (Travis 1993, pp. 104–137).

Pattern 6: But why did the French industry not recover after new dyes were invented that did not fall under the La Fuchsine patent? It seems that three dynamics conspired to make it very difficult for the French industry to reclaim its leadership position. German companies had become very strong by the late 1860s and exported their product to France.[21] This meant that new entrants into the French dye industry would have to convince customers that their product was either cheaper or better than what German and existing French firms had to offer. Second, German firms started to patent new dye innovations in France, buy up French plants, and produce the patented dye in France in small quantities while exporting large quantities from their German plants. By concentrating production in their home factories, German firms captured economies of scale and scope. A third factor was that the most influential teacher in the field of industrial organic chemistry in France, Th.-J. Pelouze, died in 1867. His private laboratory had been a breeding ground for dozens of young industrial chemists, several of whom went into the dye industry. When Pelouze died there was no one to continue his successful teaching laboratory, and therefore the production of highly qualified organic chemists who could start new dye ventures virtually ended for many years (Leprieur, 1979). As a result, the risk set of potential entrepreneurs decreased dramatically in France. At this particular time, the structural differences in the French and German university systems made the supply of entrepreneurs in France much less robust than in Germany. The centralized French academic system, which had one major chemical research center in Paris and one more in Lyon, was much more vulnerable to a temporary dramatic loss in quality and output than the decentralized German system. If one German center declined for some time, there were still about 7 major centers of organic chemistry research and teaching left.[22]

Why did the number of Swiss and U.S. firms increase at the same time? The superior performance of the Swiss dye industry appears to have been mainly due to two factors: the aforementioned absence of a patent law, and the presence

[20] Poirier did not close down its entire firm in France but transferred its fuchsine dye production to Switzerland.

[21] German companies had become very competitive because only the strongest ones survived the intense competition among the German producers in the early years of the dye industry. Germany had a larger pool on which selection could operate because the manufacture of fuchsine (= aniline red) was a precursor in the production of many other dyes that were derived from fuchsine [for details see Hornix (1992) and Hornix in van den Belt et al. (1984)]. In the mid-1860s, there were many fuchsine producers in Germany, in Britain a few, and in France only one, La Fuchsine.

[22] Altogether there were about 30 university and technical university departments in organic chemistry in Germany at the time.

of the Eidgenössiche Technische Hochschule (ETH), which then was a leading research center in organic and industrial chemistry. The absence of a patent law had been a major cause in the birth of the Swiss dye industry - when several French dye makers settled in Switzerland in order to evade the La Fuchsine dye monopoly in France – and remained important since it enabled the Swiss to copy the inventions made by their foreign competitors. (The U.S. case is discussed in pattern 8.)

Pattern 7: Why did the number of firms decrease substantially in Germany after 1897, but much less so in France and Britain? Until the early 1890s new classes of synthetic dyes were being discovered that gave firms an opportunity to move into less competitive niches. This was no longer the case by the mid-1890s. The large firms had all created R&D laboratories and offered a full portfolio of dyes to customers. Moreover, by this time nearly all natural dyes gradually had been replaced by synthetic ones. The process of substitution - which had given the synthetic industry an additional growth impetus during the first decades of its existence - came to an end. Unable to avoid fierce competition, some firms decided to exit the industry or engage in mergers,[23] initiating a consolidation of the German industry. This increased level of competition manifested itself also in the formation of large cartels.[24] Unlike the case in Britain, German law made it possible to enforce cartel agreements in a court of law just as any other regular business contract. The first attempt to form a cartel took place in 1877 among alizarin producers, and cartel agreements for particular classes of dyes subsequently proliferated. Between 1904 and 1907, the largest manufacturers formed two cartels (Dreibund [Union of Three] and Dreiverband [Association of Three]) which reduced competition within the two cartels, but at the same time threatened the existence of all the companies that stayed outside these two powerful cartels.[25] Probably the chief reason why the number of firms did not fall even further in France and Britain is that the dominant German producers found it in their interest to keep a few French or British firms in business. If all French and British producers had ceased to exist, their respective national governments would have been more responsive to calls demanding the protection of the national industry and, as a consequence, German producers likely would have suffered. Russia, for example, increased the protection of its dye industry and this forced German firms to create local plants.

Pattern 8: Why did the U.S. industry participation increase in the years just before WW I? The American textile market in 1913 was larger than that of France (approximately 3.5 times), Germany (2.5 times) and Switzerland (20

[23] Notable examples of such mergers are (1) Chemische Fabrik Griesheim AG which merged with Chemische Fabrik Elektron and with Chemikalienwerk Mainthal, and (2) Marx & Müller, which merged with Farbwerk Griesheim, to form the Chemikalienwerk Griesheim.

[24] See Beer (1959, pp. 115–133) for details on how the increased competition led to the formation of cartels.

[25] The "Dreibund" (Union of Three), formed in 1904, was made up of Bayer, BASF as well as AGFA and the "Dreiverband" (Association of Three), formed in 1905–1907, was made up of Hoechst, Cassella and Kalle.

times).[26] British, German and Swiss producers had always supplied the bulk of dyes to American dyers and printers. Especially after the textile lobby was able to persuade the U.S. Congress in 1883 to lower the tariffs on synthetic dyes by removing the 50 cents per pound specific duty (in addition to an ad valorem duty), half of the existing U.S. firms failed. This led to an even greater dependence on foreign producers. Just as in the case of Britain, the powerful textile industry of the United States was able to prevent, with one exception in 1897, the enactment of higher tariffs (Haynes, 1954, p. 311).[27] What, then, caused an increase in the number of firms just before the First World War?

It is well known in the historiography of the American dye industry that before 1914 some German and Swiss firms opened subsidiaries in the U.S. where they produced small quantities of dyes while shipping most of the dyes to the U.S. from Europe. To rule out the possibility that the increase in the number of firms was solely due to newly-established German and Swiss subsidiaries in the U.S., we analyzed the industry structures in the 5 countries omitting from the sample those firms that were owned by another dye firm (see Fig. 5 for the results of this analysis). In the case of the U.S. this means, for example, that all subsidiaries of foreign firms would not count as part of the U.S. dye industry. Based on this definition of a domestic industry, no firm operated in the American dye industry in the years from 1869 to 1875, and after 1875 there was always at least one British, German and Swiss firm that ran a subsidiary in the U.S. But even under this restricted definition of the U.S. dye industry, a sharp increase in the number of firms shows up starting in 1908. American-owned firms are clearly behind this entry wave. The number of firms jumps from 5 in 1906 to 12 in 1909.

The most likely factor responsible for the increase in the number of U.S. firms is that the technology for some organic intermediates had gradually diffused to the U.S. Although most dye intermediates were still imported at this time from Germany, the availability of some dye intermediates in the U.S. allowed entrepreneurs to enter the industry in niche markets where they would not be as easily attacked by the large German and Swiss dye firms. The most concerted effort to break the German hold upon key coal-tar intermediates was the Benzol Products company, which was organized in 1910 by the suppliers of key raw-materials – General Chemical, acids; Semet-Solvay, benzol and alkalis; and Barrett, which provided the plant. When the new company began to sell its products, German producers started a price-war, absorbing a recently enacted 10% tariff on aniline oil and lowering prices to undercut the new entrant (Welsh, 1944, pp. 65–66; Haynes, 1954, pp. 316–317). The Benzol company in the beginning sold aniline for $0.115 per pound and later could only charge $0.02 per pound. While the dramatic reduction in price was bad for the company itself – it rarely made a profit before the First World War – it is likely that local entrepreneurs took advantage of much lower intermediate prices and entered the synthetic dye industry.

[26] The British textile market was still twice as large as that of the U.S.

[27] Hesse (1915) provides a very detailed account of the battle for dye tariffs from the 1860s until 1914. See also Steen (1995) for data on how the tariff levels changed from 1864 to 1914.

Pattern 9: Why did Germany come to dominate the industry with 75% market share in 1914? With respect to understanding the sources of economic success, the increasing German dominance of the global synthetic dye industry between 1870 and 1914 stands out as the most remarkable pattern. What allowed the German industry to increase its market share from about 50% in 1870 to 75% in 1900? The absence of entry barriers in the form of patent protection created enormous competition among German firms from the very beginning of the industry. Those German firms that had survived the fierce competition of the early years tended to have better business skills than the British and French firms that were sheltered behind their patent protection. In the late 1860s, a number of the German firms (e.g. BASF, Bayer, and Hoechst) developed distribution networks in the major foreign markets, a strategy that was not pursued to the same extent by French and British firms. This gave German firms a bridgehead from which they could increase their activities in foreign markets. When in 1877 the electrical industry and the Association of German Engineers (VDI) were able to convince the German parliament to enact a patent law, lobbying efforts of the dye industry were successful in obtaining a special clause for chemicals, pharmaceuticals, and food products that allowed only process – not product – patents in these industries. This forced German companies to find all possible process routes to make a particular dye and, as a result, stimulated the inventiveness of German dye firms. In addition, the passage of the all-German patent law provided German firms with the incentives to undertake R&D because they could now obtain a 15-year monopoly for patented dye making processes. After 1877, a number of German dye firms hired chemists to focus on creating new dyes and production processes. The R&D laboratory as a routine function of the corporation was invented in the German dye industry (Homburg, 1992) and gave those firms that pioneered this new organizational form a large advantage, not only at home but also abroad, where German dye firms engaged in a strategy of "carpet patenting" to prevent foreign firms from entering the dye industry. German firms in 1891 engaged in another successful lobbying effort to make it impossible for Swiss firms to continue their practice of copying German patented dyes and shipping them into Germany.

To staff their growing R&D laboratories, German dye firms also successfully lobbied the state to provide more facilities and resources for the training of chemists. A dynamic was set into motion in which the economic success of German firms allowed them to engage in collective action as well as investing in the development of firm capabilities in production, R&D, distribution, and marketing. Unlike British firms, for instance, some German firms would translate their dyeing manuals and packing labels into foreign languages and provide dyers all over the world with technical assistance in the applications of synthetic dyes. German firms developed large enterprises with capabilities that any aspiring foreign firm would first have to replicate. Because leading German firms took every opportunity to expand their product portfolios and their ability to exploit scale and particularly scope economies, they developed a lock on the market that was difficult to break.

The most likely reasons why the number of firms did not decline at the global level in the decade before World War I despite German dominance was that smaller producer countries enacted protectionist policies to aid domestic producers, and some entrepreneurs spotted niches that were not served by the large producers. But this pattern should not distract from the overwhelming fact that German firms completely dominated the ever-growing market for synthetic dyes.

5 Classifying causal forces

The context-specific accounts and the causes presented above can be reclassified into more general categories that can potentially be applied to other industries. The case of the synthetic dye industry has shown that: 1) the same causal forces did not operate throughout the entire period from 1857–1914, and 2) what happened in one country was not entirely independent of other countries since local firms often experienced competition from foreign rivals. As a simple methodological rule we conclude from our dye industry study that in comparing industry evolution in different countries it is necessary to ascertain to what extent the different national industries are linked through trade and how key causal variables change over time. If the case of the dye industry generalizes to other industries, the following are promising candidates for key causal forces of industry evolution:

Legal environment

It appears that the legal environment can act as a barrier or facilitator of entry into the industry and hence influence industry dynamics in fundamental ways. In the synthetic dye industry, the differences in patent laws across countries shaped industry evolution by either encouraging or discouraging the formation of new firms. While patent laws seem to have the uniform effect of reducing entry, the competitive implications of patent laws depend on the industry's level of development. Patent laws can either help or hurt the competitive position of domestic firms, depending on the policies of other countries and the firms therein.[28] In order for patent laws to have a competitive effect, they obviously must vary across countries. Competition laws in countries can also have a direct effect on industry dynamics. The formation of cartels in the German dye industry was a mechanism to reduce competition between some of the large firms, especially after 1904.[29]

[28] For a review of different theories on the economic effects of patents, see Mazzoleni and Nelson (1998).

[29] At the end of 1925, the entire German dye industry was consolidated into one firm, I.G. Farbenindustrie (also known as IG Farben).

Availability of skills

When a new industry emerges, the number of entries in a particular social environment appears to be limited by the number of people in that environment who have the skills to carry on the business. Not every person in the five countries was in the "risk set" of starting a synthetic dye business. On average, entrepreneurs will seek out an industry where they believe they have a reasonable chance of succeeding. For example, knowledge of organic chemistry was an important skill that entrepreneurial ventures needed to possess. Because Germany had many more trained organic chemists than Britain, Germany possessed many more potential entrants than Britain once Perkin showed that synthetic dyes were commercially feasible. The availability of core skills is, in turn, partly a result of public policies taken toward education and the training of the workforce.

Existing industrial infrastructure

The availability of entrepreneurs appears also related to industrial activities that are undertaken in the country at a particular point in time. In terms of skills and knowledge that they require, some industries are closer to a new industry than others. If a country has many people engaged in an industry with similar skills, the pool of possible entrepreneurs for the novel industry is larger.

The existing industries not only form an "infrastructure," they also form a social structure in terms of who buys and sells to whom, who has more resources, and how actors in particular industries are connected to each other and to governmental organizations. In the battles between the domestic dye industry and domestic textile industry, the power equation in Britain and the U.S. was always heavily tilted toward the textile firms, and as a result textile firms typically obtained tariff regimes they favored. In Germany – where the textile industry was not nearly as large as in Britain or the U.S. when the synthetic dye industry appeared on the scene – the dye industry was able to achieve tariff regimes that were in its favor (Beer, 1959, pp. 109–110; Haber, 1958, pp. 216, 221–224).[30]

Economies of scale and scope

Because cost could be reduced by manufacturing a portfolio of dyes with the same production equipment and by scaling up plants, those firms which were able to scale up more quickly had an economic advantage over those firms operating at smaller scale and scope. In the synthetic dye industry scope economies appear to have been the key drivers that made firms such as Bayer, BASF and Hoechst

[30] Unlike other branches of the chemical industry which lobbied successfully to be protected against foreign competition, the dye industry had no interest in imposing tariffs on dye imports into Germany because of its dominant position in the world after 1875. Both in 1879 and in 1902 when the tariff law came up for revision, the German government decided that synthetic dyes would be admitted without tariffs just as the German dye industry demanded through its trade organization.

the global leaders. By producing a large number of chemical intermediates, these firms were able to offer a full portfolio of dyes that smaller firms could not deliver to their customers. Because they give larger firms a lower cost structure, economies of scale and scope can act as general forces that, over time, eliminate smaller competitors from the market.

Technological dynamics

Technological dynamics can have a direct impact on industrial dynamics. The invention of synthetic dyes destroyed the business of natural dye growers. When substitute products are created, existing producers who are not able to switch to a new technology are likely to be eliminated.[31] Technology can also change the minimum efficient scope and scale (the plant size at which production cost per unit is lower than at any other size). In the dye industriy, for example, production equipment was scaled up dramatically from 1857 to 1914. But technological innovations can also have the opposite effect of decreasing the minimum efficient scale. An example is the invention of minimills in the steel industry. As a general hypothesis, we propose that increases in the minimum efficient scope or scale reduce the number of firms, and decreases in the minimum efficient scope or scale increase the number of firms.

Positive feedback

Much of economic theory is based on the logic of negative feedback. If prices for a commodity increase substantially, new producers will enter the market and the additional quantities of goods on the market will bring prices down again. In a world of negative feedback, the development of advantages in market share, industrial infrastructure, or in legal environment will not make a difference over time. The incentives for other players to catch up will be large and with time lead to a competitive equalization of positions. In a world of positive feedback, however, small differences in conditions can translate into large differences in outcomes over time (Arthur, 1994). The monopoly of La Fuchsine that led to a shakeout in France appears to have given German firms a small advantage that they were able to translate into a complete domination of the French dye industry before the First World War. The central feedback mechanisms in this setting were profit levels and investments in new firm capabilities, and later lobbying efforts. Initially small differences in market share were translated into large differences in market share because successful firms could invest more than less successful rivals. A firm that made less money possessed fewer resources to invest in the next period and over time this led to a few firms (mainly German) with large

[31] Among the firms that switched from natural dyes to synthetic dyes early on were Jäger, Knosp, and Geigy and later Thomas Frères (madder producers). When synthetic alizarin killed the madder business, the largest Dutch madder producer, Salomonson, successfully switched to making phosphate fertilizers.

market shares. A key challenge in understanding industry evolution, then, is to determine whether and when positive feedback mechanisms are stronger than negative ones.

6 Implications for research on industry evolution

The primary objective of this paper was to demonstrate that patterns of evolution at the global level can differ from patterns at lower levels of aggregation. We showed this in the case of countries, but we have no reason to believe that this would not hold true as well for other levels of analysis, such as regions. Given that patterns of evolution also were different from one country to the next – in fact, none of the five countries examined displayed exactly the same pattern – we conclude that research on industry evolution needs to search for the underlying causes of this variation. Instead of trying to construct models that hold true for all times and places, we believe that useful models of industry evolution will incorporate important contextual features (see Tilly, 1984, for a forceful articulation of why social processes should be grounded in time and place).

In their recent mathematical model of industry evolution, Malerba, Nelson, Orsenigo, and Winter (1999) found it essential to build “stylized facts” of a particular industry (in their case the U.S. computer industry) into the model to make the exercise of modeling long-term industry dynamics a useful one. Malerba et al.’s specific research strategy was to achieve a more sophisticated understanding of key factors behind industry evolution by trying to generate a historical path of the computer industry. It is important to recognize that, if a number of scholars had not carried out a large amount of historical work in the past decades on the evolution of the computer industry, Malerba et al. would not have been able to construct their “history friendly” mathematical models. To create “history friendly” models not only for one industry in one country, but for several industries in several countries, researchers need to construct detailed empirical accounts of the evolution of different industries across a number of countries. To make significant progress, evolutionary economics needs longitudinal data sets that track firms participating in the industry, market shares, new products and so on. With the exception of Klepper (1982, 1990) and Agarwal and Gort (1996), such work has not been done by economists but by organizational ecologists such as Hannan and Freeman (1989) and Hannan and Carroll (1992) and management scholars such as Tushman and Anderson (1986) and Romanelli and Tushman (1994). To create robust theories of industry evolution, we believe that evolutionary economics needs many more longitudinal data sets of the kind that we are constructing for the global synthetic dye industry.

A close look at the synthetic dye industry reveals that, in addition to populations of firms, patent laws and patent practices evolved as well. The evolution of patent laws in the different countries was directly influenced by the lobbying activities of firms. Our research has convinced us that the interaction between firms and competitively relevant features of the social environment should be modeled as a coevolutionary process.[32] For the last 30 years, evolutionary biologists have devoted much attention to constructing coevolutionary models that achieve a more precise understanding of how species evolve [see Nitecki (1983) and Thompson (1994) for an overview]. It is time that research on industry evolution starts to examine coevolutionary processes as well.

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[32] See Mowery and Nelson (1999) for other industry studies that arrive at a similar conclusion.

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