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Bringing Inter-Regional Linkages Back In: Industrial Symbiosis, International Trade and the Emergence of the Synthetic Dyes Industry in the late 19th Century.

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Abstract:

Many sustainable development theorists and environmental activists often take two basic assumptions for granted. The first is that local production is generally preferable to long-distance trade. The second is that renewable sources of energy or materials are preferable to non-renewable sources. These assumptions are, to a large extent, implicit in much of the industrial symbiosis and eco-industrial park literature. This paper takes a critical stance on these issues through a discussion of the contribution of the economist and geographer Erich Zimmermann (1933) on the nature and geographical extent of by-product linkages. Zimmermann's insights are further illustrated through a discussion of the development of synthetic dyes from coal gas residuals and their worldwide impact on some ecosystems and agricultural production centers in the late nineteenth and early twentieth century. The case is made that, while valuable, the industrial symbiosis perspective should not frame the discussion of regional sustainability in a way that downplays the environmentally beneficial role of inter-regional trade and the larger division of labor in which human actions are embedded.

Keywords:

Loop Closing, Industrial Symbiosis, Erich Zimmermann, Porter Hypothesis, Madder, Indigo, Synthetic Dyes.

1. Introduction

Many sustainable development theorists deem local production and exchange preferable to long-distance trade (Wallner et al., 1996; Parto, 2000). Renewable sources of energy or materials are also typically viewed by the same individuals as more desirable than non-renewable inputs. Both assumptions, however, are debatable on several counts. For example, the idea that the distance traveled by food items from their production sites to market is a valid measure of their environmental impact (the so-called ‘food miles’ perspective) has been deemed invalid by scholars who point out that New Zealand agricultural exports are cheaper than local alternatives on British supermarket shelves because of the greater overall efficiency - and therefore lesser environmental impact - of the New Zealand agribusiness system (Saunders et al., 2006). Assessing the potential impact of renewable energy sources if they were scaled up to become a significant component of modern energy systems, Ausubel (2007) argues that renewables are not green in light of their massive infrastructure requirements, limited power generation capacity and intermittent nature.

These ‘local’ and ‘renewable’ assumptions are very common in the industrial symbiosis and eco-industrial park literature. For example, discussions of Kalundborg’s recovery linkages are often framed around the notion of a ‘localized industrial ecosystem.’ But while many local exchanges of physical residuals and heat can be observed among the local coal-fired power plant (Asnæs), oil refinery (Statoil), plasterboard manufacturing plant (Gyproc), pharmaceutical plant (Novo Nordisk) and smaller concerns, several interregional and international linkages are rarely mentioned. At one point in time, however, almost a third of Gyproc’s supply of virgin gypsum was derived from the scrubber of a power plant located in Southern Germany, with a lesser quantity imported from Spain. Both the Statoil (sulfur) and Asnæs (fly ash and clinker) operations sold some of their by-products to the Kemira and the Aalborg Portland cement company whose plants are located on the Jutland peninsula. In the early 1990s, Asnæs’ fish farm exported most of its annual production of trout and turbot to the French market (Desrochers, 2001; 2002).ⁱ

Using historical evidence, this paper makes the case on behalf of the economic and environmental benefits of interregional by-product linkages. The essay is structured as follows.

The first section reviews the economic and geographical analysis of by-product development penned by the economist and geographer Erich Zimmermann (1933) more than seven decades ago. This is done in order to establish the fact that residual linkages have long been observed at various geographical scales and deemed beneficial in many respects. A more detailed case study of the displacement of natural dyes by coal-tar derived synthetic dyes in the late nineteenth and early twentieth century then illustrates in more detail Zimmermann's main points. Implications for industrial ecosystems boundaries are finally derived.

2. By-Product Development and Geographical Constraints: The Contribution of Erich Zimmermann

One of the best concise discussions of by-product development ever written can be found in the German-born American economist Erich Zimmermann's (1888-1961)ⁱⁱ chapter "Resources from test tubes, waste heaps, and junk piles" in the first edition (1933) of his massive *World Resources and Industries*.ⁱⁱⁱ Although this author's work is usually associated with the German Historical School and the American Institutionalists,^{iv} his *magnum opus* was heavily influenced by the work of economic geographers and addresses geographical considerations in much detail.^v

Zimmermann's chapter begins with a discussion of the "movement away" from "the limitations of nature" that resulted from the activities of both synthetic organic chemists (hereafter "synthetic chemists") and the reclamation industries. As he put it: "Formerly nature was the only reservoir from which man drew the raw materials of production; today, a growing number of industries can choose between virgin, or primary, source of supplies, and secondary sources of supplies, salvaged from the waste heap and the junk pile, or artificial substitutes, especially synthetic products" (p.762). In his opinion, synthetic chemists "by investing natural products with new utilities, rendere[d] possible the fuller use of natural substances" and promoted "the economy of natural resources." Salvage activities, such as lead or steel recovery, similarly enhanced "the value of nature's contribution" by reducing "the drain on her stores" (p.763).

Because, in his opinion, "a comprehensive survey of waste elimination would fill volumes (p.769)," Zimmermann limited himself to the description of a few outstanding examples, such as cottonseed, bagasse (a by-product of sugar production from sugar cane), scrap steel and (mostly) packing house

wastes. From these and other cases he inferred a few general patterns, such as the facts that “the boundary lines between waste products and by-products are vague [and in] our modern dynamic economy the transfer from one category to the other is an almost daily occurrence” (p.768) and that one of “the major functions of modern science [is] to lower the cost of waste elimination; for reduction in such cost may render profitable, and therefore economically justified, practices of waste elimination which otherwise might be technically feasible but unwarranted for economic reasons” (p.767).

Zimmerman also anticipated the so-called “Porter hypothesis”^{vi} when he identified “legal action” as a “third factor” leading to a fuller utilization of energies and substances (after scientific advances and economies of scale triggered by increased competition). “Not all business is free to strive from the maximization of profit without social interference,” he wrote, and “waste elimination may be enforced by law even if it does not pay in the economic sense.” It sometimes happened, however, “that a corporation compelled by legal action to eliminate a waste at great expense, and unable to pass the cost on to the consuming public, may succeed, with the aid of scientific research, in converting the waste products into paying by-products – perhaps, even into a product of major importance” (p.768).

More importantly for the purpose of this essay, Zimmermann drew some geographical implications from his observations. After observing that the profitability of reclamation activities depended on the collection and distribution costs and on the market price of any recovered substance, he added that “since transportation is an important cost item, all economies in that field, as well as increased population density which tends to lessen the distances to be covered, are apt to lower the cost of making secondary materials available and to strengthen the competitive position of junk” (p.774). Zimmermann, however, did not limit his comments to local exchanges:

This supplementation of the natural supply of raw materials by supplies drawn from the test tube, the waste heap, and the junk pile is of far-reaching importance for modern industrial civilization. By depriving some of competitive advantage long taken for granted and creating opportunities for others which were hardly suspected even yesterday, it affects the location of industries. It tends to intensify the competitive struggle; it puts important industries on a broader and safer raw material basis. It tends to make production more economical, lowering costs and, as a rule, prices. Above all, it

calls for a reappraisal of the resource basis on which modern industry rests and of the alignment of present and potential industrial producers (p.763).

Zimmermann (1933, p.763) similarly speculated that by-product development would in time help equalize the distribution of economic activities on the globe. “As long as production rested wholly on a natural basis,” he wrote, “the accidents of mineralization and of climatic conditions exercised a stronger influence over economic developments on this planet than holds true today.” Scientific advances involving “synthetic chemistry, by-product utilization, waste elimination, and the recovery of secondary materials” (idem), however, had begun “to whittle down the discrepancies between advantages and promises.” In time, he argued, this process may “bring about a more equal distribution of industrial opportunities among nations” (idem).

A brief discussion of the impact of the development of synthetic dyes from a residual of coal gas production from the middle of the nineteenth century to the First World War will now illustrate Zimmermann’s analysis and further document the environmentally beneficial impact of the processes he described.^{vii}

3. Case Study: Synthetic Dyestuffs, Agricultural Production and International Trade.

In the words of Findlay (1917, p.48): “From time immemorial, men, denied by nature the more varied and gorgeous colourings of the animals, have delighted in staining their bodies or dyeing their garments by means of the various colouring matters with which the animal and vegetable creation supplied them.” The first colorants for textiles, cosmetics, basket materials and pottery, were probably obtained from the application of non-organic pigments, such as gypsum, iron rust, ochre and crushed or burnt lime. As dyeing (i.e., the process of coloring materials whereby the dye molecule attaches to the fiber) developed, however, organic inputs became increasingly important.

3.1 Organic Dyes^{viii}

From ancient times up to the middle of the nineteenth century, all dyes (or dyestuffs) were made from a variety of natural sources, ranging from plants (whether from roots, berries, flower heads, or leaves), minerals and trees (especially barks) to lichens, insects, mollusks, and guano. For example, red dyes were derived from plants such as madder, beetroot, cranberry, safflower, and

orchil; and from insects such as cochineal (from Central America and, for a time, southern British North American colonies) and Kermes (from Southern Europe and the Middle East). Yellows were extracted from Persian berries, weld, dyers broom and saffron. Interestingly, despite its seemingly natural abundance, greens could only be obtained by double-dyeing with yellow (fustic or annatto) and blue (indigo) (Hardie and Pratt, 1966). While dyers had historically settled down on the large-scale use of a dozen main inputs, plants were by far the most important. Among these, common madder and true indigo, while not the most valuable on a unitary basis, stood out in terms of volume produced.

Although the issue is complex, vegetable dyes were typically extracted by pounding or cutting up the coloring material, then by immersing it in water which was then heated long enough to transfer the coloring matter to the dye solution. The main problem was then to make these dyes “fast,” i.e., adhere strongly to cloth. While some dyes (so-called “substantive dyes”) required no additional chemicals to attach themselves to plant or animal fiber,^{ix} virtually all natural dyestuffs - the notable exception being indigo, a so-called “vat dye” soluble in alkaline liquids that bonded with fiber by oxidation - had to be saturated with an auxiliary chemical fixing agent (or mordant), such as a metallic salt like alum, to form an insoluble compound with the fiber. Cotton (and later rayon), being composed of cellulose, could be dyed by adsorption or reaction of a dye with the cellulose molecule or through the use of a mordant. Protein fibers that contain both acidic and basic groups, such as silk and wool, could be dyed directly by basic and acid dyes.

A brief geographical description of the past cultivation of the most important coloring plants and their eventual replacement by synthetic dyes derived from what had previously been a waste product will now illustrate more concretely the worldwide impacts of some forms of by-product development which ultimately relied on much industrial symbiosis.

Madder^x

The roots of what was historically the most important source of vegetable dyes, common madder (*Rubia tinctorum*), contain twenty-eight coloring matters, including red (alizarin), orange (rubiadin), purple (purpurin) and yellow (xanthine). Common madder had been cultivated on a large scale and in various locations since at least 2000 BC. By the middle of the nineteenth

century, the most important European production centers were the Dutch province of Zeeland and the French regions of Alsace and Provence, with those regions controlling perhaps as much as 90% of the world madder market (Chenciner, 2000, p.246).^{xi} Additional quantities were also being produced, although mostly for local consumption, in areas ranging from some Italian States (especially Lombardy and Naples), Russia (mostly in the Caucasus), Belgium (mostly in Flanders) and other European countries, to Turkey, India (where much of it was of the *Rubia cordifolia* and *Rubia sikkimensis* varieties), Ceylon (now Sri Lanka), Afghanistan, Egypt and the Americas. According to MacRae (1880), at its apex in the 1860s, roughly 50,000 tons of madder were consumed annually in Great Britain and a similar amount in producing countries.^{xii}

Until the beginning of the nineteenth century, dyes were extracted from madder roots by drying, beating and pounding them to remove the rough parts, in the process yielding the cruder “umbro,” “munch” or “bunch” madder and the more expensive “crop” or “grade” madders, which were later matured in casks for two or three years. Despite what might now be considered its “organic” nature and “pre-industrial” mode of manufacturing, madder production and use often had significant environmental impacts. Reminiscing on advances made in previous decades, Playfair (1852, pp.173-174) observed: “The large quantities of spent [or used] madder constantly accumulating were found exceedingly inconvenient. It was not valuable enough for the manure-heap, and the rivers became polluted in carrying away the waste material.” Wrestling with the problem, some creative chemists eventually noticed that one-third of the coloring matter was thrown away in the process. In time, a simple treatment with a hot acid was devised and again rendered it available as a dye.^{xiii} Following this breakthrough, “waste heaps [were] now sources of wealth, and the dyer no longer [poisoned] the rivers with spent madder, but carefully [collected] it in order that the chemist may make it again fit for his use (idem.)” According to Simmonds (1854, p.483), the coloring matter recovered from spent matter gave a more scarlet red than unprepared madder, and a good chocolate and black, but were not so well fitted for dyeing purples, lilacs, and pinks.^{xiv}

Indigo^{xv}

Indigo dyes use dates from beyond 3000 BC and were produced from leguminous plants of the *Indigofera* genus consisting of almost 800 species. While dyeing matter had been extracted from

a few of these, the tropical and sub-tropical “true indigo” (*Indigofera tinctoria*), usually thought to have originated from India but long cultivated over much of the Sub-Indian continent, South-East Asia, the Middle East and Africa, was historically the most important and valuable species. Arab traders eventually introduced it to the Mediterranean region around the 11th century where, after centuries of political resistance, it eventually displaced woad (*Isatis tinctoria*) as the most commonly blue dye plant used in Europe. Indigo plantations, which were not only based on true indigo but also sometimes on local varieties that had been cultivated for centuries by native populations, were then created from the second half of the sixteenth century onwards in the Americas, in areas ranging from Southern and Central America and the West Indies to Louisiana and the Southern British North American colonies, with “Guatemalan” indigo (often produced outside the borders of modern day Guatemala) usually credited as being the most valuable.

Again, however, the manufacturing process associated with the transformation of a natural input into a dyestuff proved extremely damaging to the environment. For example, Beeson (1964, p.215) summarizes in the following terms a 1775 account of production practices observed in Florida:

The stench of the work vats, where the indigo plants were putrefied, was so offensive and deleterious, that the “work” was usually located at least one-quarter of a mile away from human dwellings. The odor from the rotting weeds drew flies and other insects by the thousands, greatly increasing the chances of the spread of diseases. Animals and poultry on an indigo plantation likewise suffered, and it was all but impossible to keep livestock on, or near, the indigo manufacturing site. Nevertheless, the manufacture of indigo was a most profitable venture anywhere.

In following decades, a combination of factors ranging from high export duties and increased international competition to more lucrative alternatives enticed New World producers to switch to other crops, such as sugar, cotton and coffee. By the late eighteenth century Indian regions (originally Bengal and later Bihar) had emerged, at first under the leadership of the British East India Company (which itself followed earlier initiatives by other European traders and entrepreneurs) and later of more independent British capitalists, planters and traders, as the dominant indigo producer, controlling at one point nine-tenths of the world trade in this commodity with the rest of the production (sometimes of different indigo species) being grown mostly in Java, the Philippines, Central America, Venezuela, Brazil and China. At its highest

point in 1896, the export of indigo dye from India was 9,366 tons, valued at £3 566 700 (approximately £ 250 000 000 today using the retail price index).

3.2 The Development of Synthetic Dyes^{xvi}

The raw material upon which the numerous synthetic dyestuffs that hit world markets in the late nineteenth century were to be fashioned was an abundant and cheap waste product of coal gas manufacture.^{xvii} Coal tar was often referred to in the early stages of the industry as the “abomination and nuisance of the gas works” (Anonymous, 1881, p.86). As Playfair (182, p.566) put it: “[Gas tar was] once the most inconvenient of waste materials. It could not be thrown away into rivers, for it polluted them foully. It could not be buried in the earth because it destroyed vegetation all around. In fact nothing could be done with it except to burn or to mix it with coal as fuel.” By the turn of the twentieth century, however, coal tar had become “the flower of the chemical industries” (Green, 1902), as its derivatives were used as basic inputs in countless products. Its particular usefulness as a basis for the production of dyes and so many other products was derived from its formation from numerous natural organisms and its resulting wide range of chemical constituents.^{xviii}

While it is beyond the scope of this paper to recount in detail the historical development of synthetic dyes, the most significant moments can be outlined as follows. In 1826, the chemist Otto Unverdorben (1806-1873) obtained a liquid based by the distillation of indigo that had the property of forming crystalline salts. What would later be called “aniline” was eventually obtained from coal tar derivatives (by nitrating benzene and then reducing the nitrobenzene). In 1845, a coal-tar based dye, yellow picric acid, was used for dyeing silk by Guinon in Lyon and was later found applicable to wool. In 1856, in a series of experiments which included an attempt to synthesize the anti-malarial drug quinine (until then derived from the bark of cinchona trees), a teenage chemist by the name of William Henry Perkin (1838-1907) obtained a brilliant purplish substance while oxidizing some crude aniline. After much developmental work, Perkin and his associates offered the world the first commercially successful synthetic dye, best known as *mauve* from 1859 onward. This new dyestuff triggered much chemical research in the preparation of aniline-based dyes and, in the process, launched the modern organic chemical industry and the development of coal-tar based products ranging from explosives, medicines, and

perfumes to flavoring materials, sweeteners, disinfectants, antitoxins and tracing and photographic agents.^{xix}

The supremacy of British dye manufacturers, however, would be short-lived. Beginning around 1870, German producers would begin to take over this branch of manufacturing and achieve almost complete dominance by the turn of the twentieth century, accounting for almost 90% of the world production of dyestuffs by 1913. A short version of this story can be told as follows. In 1868, the German chemists Carl Graebe (1841-1927) and Carl Liebermann (1842-1914) succeeded in preparing alizarin from the coal tar derivative anthracene (first identified in coal tar in 1832 and representing between 0.25% and 0.5% of the tar's weight), in the process synthesizing the first natural dye molecule. Under the direction of Heinrich Caro (1834-1910) of the Badische Anilin and Soda-Fabrik (BASF), the development of large-scale manufacturing techniques for the production of synthetic alizarin and other coloring substances followed within a few years and quickly put madder producers out of business.^{xx} In the process, anthracene was turned almost overnight from a cheap residual that could be bought for a few shillings per ton in order to be burned or used as a lubricant grease, into a critical input that sold for more than two hundred times its former value (Meldola, 1905, p.171). Indeed, this input became so valuable that, in the early stages of the industry, an anthracene manufacturer reportedly proposed to the Paris authorities to remove the asphalt used as street pavement in order to distill crude anthracene from it (Gardner, 1915).

The road to synthetic indigo, while similar in its basic outline, proved much more arduous because of the absence of a suitable "carbon skeleton" in the coal tar hydrocarbon molecules. One of the main pioneers in this respect was the German chemist Adolf von Baeyer (1835-1917), who began working on the issue in 1865 and eventually succeeded in producing it in three different ways from various coal tar derivatives. After much investment and developmental work, scientists and engineers working for BASF eventually put naphthalene-based synthetic indigo on the market in 1897. During the first twenty years of synthetic indigo manufacturing, the decision as to which coal tar derivatives to use depended on the availability of benzene and naphthalene that could respectively be turned into aniline via nitrobenzene and anthranilic acid via phthalic anhydride (Findlay, 1917; Green, 1902; Travis, 1993a).

Synthetic dyes had several advantages over plant-derived alternatives, the most obvious being their much greater range of colors (along the lines of a 10 to 1 ratio by the turn of the twentieth century) and cheaper prices. For example, the value of the amount of alizarin used in the world in 1880 was around \$8,000,000, while the cost to manufacture the same amount of dye from madder roots would have been near \$28,000,000 (Noyes, 1907). This price difference could be explained by the abundance and reliability of the coal tar supply and by the fact that the preparation of synthetic dyes was much less labor and input-intensive than the cultivation and extraction of coloring matter from plants. Synthetic dyes were also of better quality because plants often exhibited weather-related changes of color and contained many impurities, while growers and natural dye-makers also had much more incentive to adulterate their products because of the lack of uniformity of their raw materials. Plant supplies were also less reliable, as they required a significant growing period and were only harvested periodically; were regularly prone to failure or lower yields because of diseases, insects or bad weather; or might simply not be planted if other crops proved more lucrative.

Synthetic dyes further exhibited a number of technical advantages. One pound of artificial alizarin had the tinctorial power of at least 90 pounds of madder (Meldola, 1905).^{xxi} Their application was simpler because their quality was more uniform. Materials colored with synthetic dyes therefore tended to be of much better quality. For example, in Germany, the results obtained from synthetic indigo were said to be so much brighter than the drab natural color that it led the military authorities responsible for the color of the uniforms to wonder whether the factory-made product was really genuine indigo (Travis, 1993a, p.224).^{xxii} Interestingly, MacRae (1880), reflecting one perspective that was not so uncommon at the time, thought that aniline dyes would never completely overtake madder because of the limited amount of coal-tar produced in gas works, whereas plants were renewable resources. This argument is still sometimes being used today as dyes are now ultimately derived from scarce resources such as petroleum (Balfour-Paul, 1998, p.231), but are probably just as mistaken.

3.3 Geographical Impact of Synthetic Dyes

Once the problems of large-scale production had been worked out, synthetic dyes quickly displaced most common madder and true indigo production. The inevitability of this outcome was apparently never in doubt. As Perkin's teacher, the German chemist A. W. Hofmann, put it in 1862 (although he couldn't anticipate the dominant role that his native country would soon play in this process): "England will, beyond question, at no distant day become herself the greatest colour-producing country in the world, nay, by the strangest of revolutions, she may, ere long, send her coal-derived blues to indigo-growing India, her tar-distilled crimsons to cochineal-producing Mexico, and her fossil substitutes for quercitron and safflower to China, Japan, and the other countries whence these articles are now derived" (quoted in Findlay, 1917, p.56).

Indeed, for both madder and indigo, several political attempts to protect plant producers through tariffs and government contracts, the creation of crash research programs to improve both agricultural and dye-making productivity, and even military conflicts that temporarily blocked synthetic dye exports, proved futile in the end.^{xxiii} Overall, it has been estimated that, at their peak, madder cultivation required between 300 000 and 400 000 acres (or between 1212 and 1616 km²) in 1868 (Findlay, 1917; Roscoe, 1915/1881), while indigo plants required more than 1,583,808 acres (or approximately 6400 km²) in 1897 (Findlay, 1917; Steingruber, 2004). Much agricultural land in Europe, India, East Asia and the Americas was thus liberated for other types of agricultural production, ranging from food-stuffs to plants cultivated for their fibers. For example, in Avignon, madder plantations were replaced by grapevines, while in India and Java indigo cultivation eventually gave way to sugar plantations and other crops. Interestingly, Perkin eventually took up madder cultivation in order to ensure the survival of the plant (Travis, 1993b), while the Masters Golf Tournament, held annually in Augusta, Georgia, is staged on a former indigo and cotton plantation (Balfour-Paul, 1998). Of course, the same process could also be observed for other inputs in the manufacture of natural dyes. For instance, the introduction of artificial scarlets resulted in the abandonment of the cultivation of cochineal in the Canaries and its replacement by sugar and tobacco, while pressures on dyewoods and logwood were similarly relieved (Gardner, 1915).^{xxiv} Interestingly, with the annual worldwide consumption of synthetic indigo now approximating 20 000 tons, several million acres would be required to manufacture the equivalent using traditional methods (Balfour-Paul, 1998, p.231).

While the phasing out of coloring plants created short-term economic hardship in production areas, it was part of a series of processes, which included substitute product developments and increased productivity in the agricultural, forestry and wood product sectors, that ultimately resulted in the expansion of the forest cover in over fifty countries in the world (mostly advanced economies, but also developing economies such as India and China) in the last century and a half (Rudel et al., 2005; Kauppi et al., 2006). As such, it provides an illustration that the use of non-renewable resources can greatly benefit both the environment and the economy although transition periods might prove difficult for some individuals. As Zimmermann (1933, p.9) observed: “Progress always means a net gain but seldom a pure gain. Creating the better, we must often destroy the good.” While “many examples could be cited to illustrate this point,” the German-born economist chose, not surprisingly, a “direct and self-evident” case, the “invention of synthetic indigo [which] added new resource value to coal, but destroyed or lowered the resource values of large stretches of land in the tropics and sub-tropics where once the indigo plant grew” (idem).

3.4 Agglomeration Economies and Synthetic Dye Production

Although the German supremacy in the synthetic dye industry has often been attributed to a better educational system, patent monopoly and strong marketing techniques,^{xxv} German producers in time came to benefit from localization considerations, agglomeration economies and localized by-product linkages.^{xxvi} First, inputs were much more significant consideration than proximity to markets for final products, as dyes were high-valued commodities for which transportation costs were not very significant. Beer (1981/1959, p.53) points out that, even though they might have started elsewhere, the most successful dye manufacturers ended up being located on the banks of the Rhine or its tributaries “where they had easy access to bulky raw materials and an adequate water supply” for it took “great quantities of coal oil, acids, alkalis, pyrite ores, salts, fuels, ice and cool, fresh water to make a relatively small quantity of dyestuffs.” With the exception of the Agfa of Berlin, “other firms that had been founded during the early 1860’s in central and Southern Germany... failed to grow because of their unfavorable geographic location and most of them went out of the dye business” (p.54)

Perhaps as important, however, were the regional linkages between complementary lines of work, including by-product linkages. In short, dye preparation in the early years of the twentieth century involved some primary constituents of coal tar, such as toluene, benzene, phenol, xylene, naphthalene, anthracene, cresol, and catchol which were converted into some three hundred intermediate compounds through the action of various chemical reagents such as sulphuric acid, nitric acid, caustic soda and chlorine. By combining these in various ways, usually through manufacturing processes that involved three to six steps apart from separation, but sometimes as many as fifteen or twenty (anthraquinone vat dyes), almost nine hundred commercially successful dyes were prepared by the First World War (Findlay, 1917). Although such production processes required much accumulated know-how, Findlay (1917, p.50) points out that “a further very serious complication is introduced owing to the fact that in the preparation of many of the intermediates, ‘by-products’ are produced in varying amounts, and for these by-products a remunerative outlet must be obtained.” He added:

The problem of working up, completely and remuneratively, without waste and without over-production, all the by-products formed in the manufacture of the intermediates, is one of the utmost importance for the success of the industry. Owing to the enormous development of her organic chemical industry, embracing the manufacture of dyes, drugs, perfumes, and “fine” organic chemicals generally, the solution of this problem has become more easy for Germany than for any other country (Findlay, 1917, pp.50-51).

When asked at the beginning of the First World War about the possibility of manufacturing locally the more than 700 synthetic dyes previously imported from Germany, the American chemist Bernhard Hesse commented that the German synthetic dye industry could not be isolated from its local connections to other lines of work. The coal tar industry could thus be best understood as being organized along three divisions: 1) products obtained from coal tar through distillation and other operations; 2) productions obtained from 1 by chemical transformation, although not themselves dyes; 3) dyes made from 2. In his opinion, the crucial fact was that German producers controlled much of the second division of the world’s markets. This control was due to the facts that while the growth of this division had been relatively slow, it had become tightly interwoven, with “each of its hundred or more products being dependent upon or made up of one or more other products, so that no one of them is of use without still others.”

These commercial and industrial relations had grown to such an extent over time that “the coal-tar dye industry is really a conglomerate of many separate parts acting and reacting upon each other, commercially and industrially” (quoted in Stansfield and Carter, 1915, p.42). As he put it:

Not a single one of the 22 factories in Germany is wholly independent of other factories in Germany, whereas together they are independent of sources outside of Germany, or can very readily be so should occasion arise. It would not do merely to transplant even the largest German works to this country; a part of probably each German works would be necessary to produce here or anywhere a complete and self-contained industry. Such a transplanting of the coal-tar dye industry would be comparable to an attempt to transplant to this country *every single branch* of say, the textile industry or any other highly ramified and diversified art (quoted Stansfield and Carter, 1915, pp.42-43).

Of course, the First World War led to a revival and/or significant expansion of the synthetic dye industries in countries ranging from the United Kingdom and Switzerland to the United States, and to a temporary respite for British India’s (nonetheless doomed) indigo producers.

4. Reflective Conclusion

Reflecting on the causes of the division of labour, the Scottish economist Adam Smith (1904/1776, book I, chapter 2, non-paginated) observed that it could ultimately be traced back to a propensity to “truck, barter and exchange one thing for another” that is “common to all men, and to be found in no other race of animals, which seem to know neither this nor any other species of contracts.” As a result of this unique propensity, humans long ago began to engage in long distance trade, resulting in a more efficient use of scarce resources. As Smith (1904/1776, book IV, chapter 2, non-paginated) further observed, while it would be possible with “glasses, hotbeds, and hot walls,” to grow “very good grapes... in Scotland and to produce “very good wine” out of them, this would entail “about thirty times the expense for which at least equally good [wine] can be brought from foreign countries.” It would have been, however, a “manifest absurdity” to employ thirty times more capital to achieve the same result and similarly absurd, “though not altogether so glaring, yet exactly of the same kind, in turning towards any such employment a thirtieth, or even a three-hundredth part more of either.”

Economic agglomerations have also always been nexuses of trade in which individuals interact in different ways and on different geographical scales, a point that is not necessarily well-conveyed by the industrial symbiosis metaphor which tends to skew analysis towards localized linkages at the expense of broader trade networks. Unlike people influenced by conventional economic teachings who view a wider division of labor as a necessary condition for greater wealth and economic growth, sustainable development theorists and environmental activists often consider a regional economy's high reliance on interregional and international trade as a sign that inhabitants of such a region are living beyond their ecological means (Rees, 2006). The evidence presented in this paper, at least inasmuch as it demonstrates that market processes probably factor in environmental considerations (such as resource use) better than is often thought to be the case, suggests a more cautious analysis. While perhaps not always true, a case can nonetheless be made that the existence of large and diversified industrial agglomerations dependent on long-distance trade (including by-products) can not only result in a better allocation of scarce resources than systems based on localized linkages and renewable inputs, but also in a potential reduction of the environmental impact of economic activities per unit of output.

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Notes

ⁱ Of course, some analysts, such as Andrews (2001) and Chertow (2000) have not shied away from the issue.

ⁱⁱ Barnett (undated) and McDonald (1995) are biographies of Zimmermann, while Bradley (2007) and DeGregori (1985) are discussions of his key insights. Zimmermann is perhaps most famously remembered for his statement that "resources are not, they become."

ⁱⁱⁱ This chapter was omitted in later editions of this book.

^{iv} For concise introductions to these intellectual movements, see *The History of Economic Thought Website* <<http://cepa.newschool.edu/het/>>

^v Zimmermann (1933, p.vii) acknowledges as much in the foreword to his book. Also worthy of note is that he belonged to both the American Economic Association and the Association of American Geographers (Barnett, n.a.), that his work probably proved much more influential among economic geographers (subsequent editions of his main book were often mandatory readings in graduate geography programs until the late 1960s) and that *World Resources and Industries* is classified as a work of economic geography rather than resource economics in North American academic libraries.

^{vi} Harvard University Professor Michael Porter (1991) suggests that “well-designed” environmental regulations can stimulate innovations that would increase private and social benefits by enhancing productivity and reducing waste.

^{vii} To my knowledge, Zimmermann’s only addresses this issue in a brief comment on the displacement of indigo production which is reported in the main text. Later developments in this industry, from environmental problems to industrial relocation, are discussed in Forter (2000) and Travis (2004).

^{viii} Numerous books and websites are devoted to the topic. Among the sources of well-known (and therefore unreferenced) facts used in this essay are Balfour-Paul (1998), Chenciner (2000), Clow and Clow (1970/1952), Fairlie (1965), Gardner (1915), Miall (1931), Morris and Travis (1992), Russell (2000); Schetky (1964), Simmonds (1854), Travis (1993b) and the research annual *Dyes in History and Archeology*.

^{ix} For example, lichens, annatto, safflower, turmeric and barberry.

^x Chenciner (2000) is a detailed recent account of various aspects of madder’s past cultivation, harvest, dye extraction and trade. Schot (1992) contains much information on nineteenth century Dutch and French madder production and preparation.

^{xi} This author also provides a good description of the 19th century madder boom, including several trade statistics, although, as he points out, “there appear to be no convenient tables showing the history of the madder trade or of the dye” (p.247). According to Perkin (1915/1879), Dutch ground madder was usually recognized as being of the best quality, while Schot (1992) is more critical and discusses Dutch attempts to catch up with new French industrial production methods in the middle of the nineteenth century. See also Simmonds (1854) for a contemporary perspective.

^{xii} Lecturing on the same topic in 1890, Meldola (1905, p.168) states that annual madder production peaked at about 70,000 tons, a figure probably borrowed from Perkin (1915/1879), although Perkin would later be credited for providing a figure of 90,000 tons (Roscoe 1915/1881). According to Simmonds (1876), the greatest annual amount of madder ever consumed in the UK was 47,500 tons. Estimates on the amount of madder consumed in the rest of the world at the time involved much more guesswork.

^{xiii} Although Playfair’s text reads as though the innovation was local, he might be referring to the work of Léonard Schwartz of Mulhouse (France) who, in 1843, filed a patent for a somewhat similar treatment of spent madder.

^{xiv} For more details on madder preparation and related advances in 19th C, see Chenciner (2000) and Travis (1993b).

^{xv} Balfour-Paul (1998) is recent survey of the past cultivation, preparation, trade and political problems associated with indigo production. For earlier assessments, see, among others, Asiaticus (1912) and Brunck (1900).

^{xvi} Travis (1993a) is usually considered the best book on the topic, while Beer (1981/1959) is an influential account of the emergence of the German synthetic dyes industry. Meldola (1905) is a contemporary popular account that covers most of these developments, with the exception of commercially successful synthetic indigo production methods. Travis (2006) is a more detailed analysis of Meldola writings and policy advocacy on the issue. Other valuable resources include Findlay (1917) and special issues of the *British Journal for the History of Science* (March 1992) and *History and Technology* (June 2006).

^{xvii} Coal gas, including different varieties of town gas and producer gas, was produced by heating coal, where various gases, including steam and small amounts of air, were added, yielding a gas whose heating value was about 50% of natural gas. It was used as an illuminant until electricity proved a better alternative at the end of the 19th century, and as a fuel until the growing availability of natural gas in the 1940s. For a brief history of coal gasification, see, among others, Boyle et al. (2003). For more detailed treatment of the development of by-products derived from coal gas residuals, see Findlay (1917), Gluud (1932), Meldola (1905), Stansfield and Carter (1915) and Shadle et al. (2005).

^{xviii} This being said, the great bulk (as much as 95% of the volume) of coal tar was used for creosoting, lubrication and fuel (Wright 1886). Dye production only consumed a minute fraction of this residual.

^{xix} Mauve's main input was aniline obtained from the nitration and reduction of benzene derived from coal tar. For recent scholarship on these events, see the aforementioned special issue of *History and Technology*. Mauve's popularity declined rapidly from 1864 onward with the emergence of better alternatives. Its last use was for coloring the postage stamps of the late Victorian era (Findlay 1917).

^{xx} For example, between 1858 and 1868, the average value of the annual import of madder roots in the UK was over a million sterling, a figure which had dropped to £24,000 in 1880. Artificial alizarin, however, originally proved inadequate for wool dyeing, a problem that helped protect the market for Dutch madder for a few more years until the development of so-called azo-dyes. Various statistics on this transition can be found in Perkin (1915/1879). Interestingly, Perkin (1915/1879, p.55) observed: "Up to and during 1876 considerable quantities of artificial alizarin were imported from the Continent, and entered at the Customs as garancine or madder, and this having been brought to the notice of the officials, the returns made subsequently are more reliable." According to Beer (1981/1959, p.118): "By 1876 the madder growers were in ruin and alizarin-makers began to encroach on each other's markets."

^{xxi} Roscoe (1915/1881, p.72) is more explicit on this point: "Last year [1880] the estimated production of the artificial colouring matter was 14,000 tons, but this contains only 10 per cent. of pure alizarin. Reckoning 1 ton of the artificial colouring matter as equal to 9 tons of madder, the whole artificial product is equivalent to 126,000 tons of madder. The present value of these 14,000 tons of alizarin paste, at £122 per ton, is £1,568,000. That of 126,000 tons of madder at £45 is £5,670,000, or a saving is effected by the use of alizarin of considerably over four millions sterling. In other words, we get our alizarin dyeing done now for less than one-third the price which we had to pay to have it done with madder." Furthermore, according to Beer (1981/1959, p.118): "Commercial madder contained only about 1 per cent alizarin whereas coal tar derived alizarin could be made in any degree of purity up to 100 per cent."

^{xxii} Although Travis doesn't raise the issue, this endorsement should perhaps be viewed as part of the larger marketing battle then opposing German synthetic dye producers to foreign growers and natural dye makers.

^{xxiii} Kumar (2007) is a recent treatment of some of these factors in the context of indigo production in British India.

^{xxiv} As early as 1750, 8000 tons of logwood were cut annually in Honduras to supply the English market (Russell, 2000, p.205).

^{xxv} Discussions of this issue can be found in virtually every early twentieth century British essay on the topic. See, among others, Meldola (1905) and Miall (1931).

^{xxvi} Economists and geographers explain the geographical concentration of economic activities through two types of positive externalities known as "agglomeration economies." The first, localization economies, are related to the agglomeration of firms of the same industry in one area. The second, urbanization economies, are related to the agglomeration of various industries in one location. In the former case, firms in such agglomerations benefit of advantages ranging from specialized labour pooling, intermediate inputs and suppliers, while in the latter case firms benefit from more generic intermediate inputs, such as law, accounting and software service, along with the operation of transport infrastructures. In both cases, geographical proximity also facilitates face-to-face interactions. Surprisingly, by-product linkages are virtually absent from this literature. For a more detailed examination of these issues, see, among others, Loveridge (1999).