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Industrial Symbiosis: Old Wine in Recycled Bottles? Some Perspective from the History of Economic and Geographical Thought.

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Abstract

‘Industrial symbiosis’ is a central concept in the industrial ecology literature that describes geographically proximate inter-firm relationships involving the exchange of residual materials, water and energy. Despite its obvious relevance to regional science, economic geography and urban economics, the issue is only beginning to be addressed in these sub-disciplines. This situation is paradoxical as both recovery linkages and the very concept of IS were discussed in some depth by numerous economists and geographers several decades ago. Our goals in this paper are to document this intellectual history, in the process gaining a better understanding of the phenomenon while shedding additional light on current controversies. In doing so, we further hope to re-stimulate economists, geographers, and regional scientists’ interest in the topic and to illustrate the long-standing importance of geographical co-location in facilitating the “internalization of externalities” of industrial operations.

JEL Codes: R11, Q53, Q57, B19

Keywords: industrial symbiosis, industrial ecology, agglomeration economies, by-products, by-product linkages

“We have shibboleths that must be employed in speech or documents for admission into the inner chambers of certain geography circles, such pass words as occupance (occupancy is tabooed because it is in the dictionary), cultural landscape, regional personality, pattern, locus, fundament, product-value, industrial symbiosis. This is another way of keeping our disciples in line.”

E. Parkins. 1934. “The Geography of American Geographers.” *The Journal of Geography* 33 (9): 229

‘Industrial symbiosis’ (henceforth, IS) is a concept used to describe geographically proximate inter-firm relationships involving the exchange of residual materials, water and energy. Despite its obvious relevance to regional science, economic geography and urban economics, the (mostly) engineering and business school-based IS literature and its attendant ‘eco-industrial development’ initiatives have generated little interest among economists, geographers and regional scientists.¹ As will be argued in this paper, this situation is paradoxical as both the processes described in the IS literature and the concept itself were discussed in some depth by several economists and geographers from the middle of the nineteenth century to the birth of the modern environmental movement in the 1960s. Unlike more recent contributions to the industrial ecology literature, however, earlier generations of analysts considered IS, or at any rate bilateral recovery linkages, a fairly common and spontaneous outcome of market processes. Our goals are to shed some light on this intellectual history in order to gain a better understanding of the drivers of the phenomenon; to stimulate geographers, economists and regional scientists’ interest in the topic; and to illustrate the historical importance of geographical co-location in helping profit-maximizing industrial actors spontaneously “internalize their externalities” in the absence of external incentives such as pollution taxes or environmental regulations.

The paper is structured as follows. The first section provides a brief overview of the recent IS literature. This is followed by a discussion of past uses of this metaphor. We then focus on the modern understanding of IS, i.e., geographically localized by-product linkages, and discuss past authors’ assessment of the extent of the phenomenon and of the market incentives and institutions that promoted its creation. Section four surveys the main analytical points made in past discussions of the geographical dimension of by-product linkages. This is followed by our reflective conclusion in which we suggest, among other things, that the early literature was less normative than the more recent one because its authors had a better understanding of the multi-faceted nature of industrial location dynamics.

1. Present Day Industrial Symbiosis and By-Product Linkages Discussions: An Overview

Industrial symbiosis is the most explicitly geographical concept of the perspective known as ‘industrial ecology’ (henceforth, IE). Industrial ecologists promote economic development and the simultaneous reduction of environmental impact through maximized efficiency of energy and material inputs, including waste reduction at the source and the creation of ‘loop closing’

¹ The few exceptions are Andrews (2001), Considine (2001); Deutz and Gibbs (2008), Gibbs (2008), Gibbs and Deutz (2005); Gibbs, Deutz and Proctor (2005); Hewes and Lyons (2008); Jacobsen and Anderberg (2004); Korhonen and Snäkin (2005); Kronenberg and Winkler (2009); Lyons (2007); Roberts (2004); Ruth (1998, 1999); Sterr and Ott (2004); and Van den Bergh and Janssen (2004).

linkages whereby the waste products of one line of work become the valuable input of another (Ayres and Ayres, 2002). This prescription is typically contrasted with the alleged ‘linear’ model that is said to have characterized past industrial development in which “the flow of material from one stage to the next is independent of all other flows,” creating both useful products and wasteful/polluting emissions in all production stages (Jelinski *et al.*, 1992: 793). Indeed, it seems fair to state that most pioneers in the field shared Ayres (2004: 427) belief that, overall, “the industrial system is very wasteful of materials and recycles very little.”

Within the IE perspective, IS has traditionally centered “on the notion of biological symbiotic relationships in nature, in which at least two otherwise unrelated species exchange materials, energy, or information in a mutually beneficial manner – the specific type of symbiosis known as mutualism” (Chertow, 2000: 314). More recently, however, IS is sometimes defined as involving complex as opposed to bilateral relationships (i.e., at least three different entities involved in the exchange of at least two different by-products) (Chertow, 2007). Be that as it may, IS differs from more mainstream ‘greening’ industrial initiatives that deliver both improved environmental and economic performances inasmuch as its main emphasis is “cooperation between firms as opposed to focusing on action at the level of the individual firm, seeing firms as nodal points within a networked ecosystem” (Gibbs, 2008: 1140).

The paradigmatic case in this literature is the small Danish industrial city of Kalundborg where numerous bilateral, gradual, voluntary and economically profitable residual and energy linkages were created over a period of three decades between local businesses including a refinery, a power plant, a pharmaceutical plant, an aquaculture operation, the local city administration, a wallboard manufacturer and nearby agricultural producers. For example, farms use sludge recovered from pharmaceutical processes and the fish farm as fertilizers. Residual steam from the power plant is piped to the refinery which, in exchange, pipes back refinery gas previously flared as waste. Gypsum produced by the power plant’s desulphurization process is sent to a company producing wallboard while power plant fly ash is used by a cement company. Kalundborg symbiotic linkages were estimated a few years ago to comprise some 2.9 million tons of materials annually and to have reduced local water consumption by 25%.

The Kalundborg recovery linkages, however, were not planned by environmental management consultants or bureaucrats, but were rather the result of multiple bilateral transactions between private sector employees looking for some lucrative uses for their residuals or, alternatively, for cheaper inputs. As interest in IS grew, geographically proximate market-driven by-product linkages were uncovered in locations ranging from Western Europe and North America to Australia and China. As Korhonen *et al.* (2002: 179) observed early on: “The emergence of industrial ecosystem-type developments has been natural or spontaneous development. In other words, such diverse regional networks seem to self-organize rather than arise out of a specific planning process.” Meanwhile, beginning in the mid-1990’s, US, EU and other governmental agencies sponsored so-called ‘eco-industrial park’ policy initiatives designed to foster (often from scratch) the development of symbiotic recovery relationships. Despite a few successes, the dominant opinion now seems to be that “the vast majority of these projects [were] consigned to the dustbin of history [and] vanished as soon as their funding sources dried up” (Lowitt, 2008; 498) and that “uncovering” existing symbioses has led to “more sustainable industrial development than attempts to design and build eco-industrial parks incorporating physical

exchanges” (Chertow, 2007: 11). Still, much debate remains as to the nature, extent and drivers of IS, along with the role that governmental interventions can or should play in this respect, especially in terms of nurturing nascent symbiotic linkages out of simple bilateral exchanges (sometimes designed as ‘kernels’ or ‘precursors’ to potentially more complex IS), and “whether there is any stage at which government intervention might be effective” (Chertow, 2007: 23) (Chertow, 2000; Chertow et al., 2008; Gibbs, 2008; Gibbs and Deutz, 2005; Jacobsen, 2006; Karlsson and Wolf, 2008; Ristola and Mirata, 2007).

Somewhat remarkably in light of the scope of these research efforts, very little thought has been given to the idea of identifying precedents in this respect, both in terms of actual cases or previous intellectual analysis of the phenomenon. As will be illustrated in the remainder of this essay, what is now labeled IS actually describes long established industrial practices that were discussed by a surprisingly large number of economic geographers, urban economists and regional scientists who, in some cases, even used this specific label to describe the phenomenon. This intellectual history is of more than archeological interest, inasmuch as it provides additional evidence that the development of geographically-localized by-product linkages is a very typical feature of industrial economies and an under-appreciated way through which industrial actors have long “internalize their environmental externalities.” These past contributions will now be summarized along the following axes: 1) conceptual discussions of IS; 2) assessments of the extent of and incentives that promoted by-product development and linkages; 3) impact of geographical space on the formation and outlook of by-product linkages.

2. Early Discussions of Industrial Symbiosis and Geographically-based Recovery Linkages

In light of some obvious similarities between natural and industrial systems, it is perhaps not surprising that the IE analogy was formulated as far back as the middle of the nineteenth century and was used by several writers in the following decades (Desrochers, 2005; 2009). To our knowledge, the history of IS as a concept (as opposed to actual practices) is slightly less ancient while its exact meaning varied more between analysts.

One meaning of the term was to describe what would later be known as ‘agglomeration economies.’ For example, a mention of the “remarkable degree of industrial symbiosis” in Chattanooga (TN) referred to local connections between “the iron and steel, hosiery, woolen, and lumber industries, and their mutually dependent plants. Foundries and pattern shops are complementary to the machinery industries; textile machinery production, tram and silk throwing, mercerizing, bleaching and dyeing to the hosiery industry; and raw works, wood-working machinery, and wagon skein manufactories to the lumber industries” (Ohio State University, 1932: 45-46). The geologist E. Mitchell Gunnell (1939: 140) similarly characterized the linkages between the mining and smelting industries of Leadville (CO) as a case of IS while the entry under that name in the 1944 and later editions of the *Dictionary of Sociology* (Fairchild, 1964: 314) defines the concept as the “grouping within a community of independent manufacturers, who are able to benefit by using each other’s products,” in the process eliminating “unnecessary cross hauling and transport costs.” Such uses of IS can also be found in the later work of geographers Eyre (1963), Banerjee and Roy (1967), Ogendo (1967), Chaudhuri (1971a; 1971b) and Hamilton (1968), among others.

Another historical meaning of IS describes the labor market peculiarities of locations characterized by the presence of heavy industries employing a predominantly male workforce and of nearby lighter industries transplanted there because of the resulting availability of a female labor pool. For example, Miller and Parkins (1928: 153) observed that in eastern Pennsylvania's industrial cities "numerous factories employed in producing knit goods or in dyeing and finishing textiles give work to the more delicate hands of women." Such cases included Scranton (mining machinery, locomotive manufacturing and other iron and steel products on the one hand; cottons, laces, woollens and buttons on the other); Wilkes-Barre (forged axle and wire rope works, machine shops; silk and lace mills); Allentown (coal mining, iron furnaces, rolling mills, foundries, cement plants, shoe factories; silk and knitting mills) and Hazleton (mining and pumping machinery, pianos; silk, hosiery, knit goods, overalls). This specific meaning of IS to describe the industrial geography of Eastern Pennsylvania was still used decades later by the geographer Walter A. Browne (1965).

A similar use of IS was made in the Japanese context by the Columbia University economic geographer John E. Orchard (Orchard and Orchard, 1930: 172) who nonetheless doubted the prospects of its rapid growth in the heavily industrialized area of Northern Kyushu in light of the fact that women there had "continued to work with their husbands in the steel mills, preferring the higher wage even with the heavier work to the lower wages offered in the spinning mill." Mares (1953: 359-360) later wrote that the phenomenon was centuries-old in Czechoslovakia and that in industrial towns where coal, steel and cement were produced, some textile mills and other consumer goods industries were often found that "from the viewpoint of their labor requirements, were complementary to their basic industry." Linen and poplins; gloves and embroideries; and rhinestones and jewelry were thus manufactured by, respectively, the wives and daughters of steelworkers and foundry men; of miners; and of lumbermen. Of course, Alfred Marshall (1898: 351) had earlier observed in the English context the nearby growth "of industries of a supplementary character" in heavy industry districts, but without using the IS label.

To our knowledge, the most elaborate conceptual discussion of IS and the one closest to its current meaning can be found in the work of geographers Charles Langdon White and George T. Renner (1936) who learned from the botanists of their days that symbiosis could be either antagonistic (parasitic) or mutualistic, with the latter being further separated into disjunctive (for example, the reciprocal benefits in insect pollination) and conjunctive (for example, lichen) symbiosis.² They defined the concept as "the establishment of two or more basic industries in an area" (p. 18). IS could be *disjunctive* when economic adjustments were "mutually independent and [bore] no relation to each other," such as date-growing and sheep-herding in the Sahara or dairying and fishing in western Washington.³ In certain instances, symbiotic activities of this type could "even be competitive and disruptive." *Conjunctive industrial symbiosis* was observed when industries "apparently separate and distinct... actually depend upon one another for raw

2 Renner later used the IS metaphor repeatedly on its own, while Langdon White apparently never did, thus suggesting that this section of the book was written by the former. This is not surprising, inasmuch as Renner is considered the first economic geographer to have adopted an ecological approach to industrial location (Sit, 1980: 413).

3 One critic observed that "the use of the word 'industrial' to include human activities in the Sahara Desert and Pennsylvania" was objectionable (TWF, 1937: 144).

materials,” in which case “proximity is thus distinctly beneficial to all concerned” (idem). An example of this was the coal-mining, iron-smelting and wire-manufacturing complex that could then be observed in Pittsburgh region. Finally, industrial symbiosis sometimes exhibited “actual parasitism” such as in the case of the textile industry of eastern Pennsylvania (idem).

A decade later, Renner (1947: 180-181) further defined IS as “the consorting together of two or more dissimilar industries.” He again distinguished disjunctive and conjunctive symbiosis on the basis of the absence or presence of “organic connections,” but added that in the latter case industries that existed side by side not only because one was the supplier of another or because they used a common source of raw materials, but also some “industries [which] utilize [the] waste products of other industries,” such as a manufacturer of wood alcohol whose main input was the sawdust produced by a nearby saw mill. These quotes were later reproduced *verbatim* in Renner et al.’s (1953: 642-643) influential textbook.

That this perspective on IS had some traction among geographers is attested by its frequent use in prominent outlets.⁴ For example, Lezius (1937) described the use by Toledo glass plants of low-cost gas available as a by-product from nearby petroleum refineries as a case of “conjunctive industrial symbiosis” (p. 406), while Cotterill (1950: 77) referred to Renner’s IS discussion in the context of “main product and by-product in the material field” in the zinc smelting industry. The President of the Geography section of the British Association for the Advancement of Science, A. Austin Miller (1956: 65), described the “praiseworthy examples of paper mills making use of hot waste water from chemical works wisely located nearby” as a “form of industrial symbiosis much to be encouraged.” Smith and Basile (1971: 237) wrote that the term IS “implies that one [industry] lives off, or utilizes the waste products of another.” To our knowledge, Renner’s IS writings were last discussed by Seth (1987: 119).

Some regional scientists similarly elaborated on the potential applications of the concept of symbiosis in ecosystems to urban economic development (Lambooy, 1973) and the specific topic of localized by-product linkages in early models of industrial location and Soviet territorial production complexes (Hamilton, 1968; Kolosovskiy, 1961) (indeed, by-product linkages were often an integral part of central planning efforts in Soviet-style economies) (Gille, 2000; Sathre and Grdzlishvili, 2006). Perhaps because of the general orientation of the field and of the fact that the concept was never co-opted by economists, however, discussions of localized by-product linkages by regional scientists were quickly relegated to anecdotal entries in broader discussions of “agglomeration economies” or “joint production.”⁵

For example, Thompson (1968: 12) observed that “local slaughtering produces hides and this encourages shoe firms to locate nearby to save transportation costs on their chief material.” Isard (1960: 377) identified one type of industrial complex as deriving “from the joint production of two or more commodities from a single class of raw materials – such as diverse food, fertilizer, and industrial products from livestock.” Friedmann (1956: 225) wrote that “[by-product]

4 Some of these authors referred to Renner’s work, while others didn’t. In our opinion, the latter cases probably reflect the relatively well-known character of the concept at one point in time.

5 For instance, Marshall Smith (1971: 99) describes Renner’s concepts of industrial symbiosis and con-industrialization as “merely elaborate expressions for externalities and agglomeration tendencies.”

technical linkages represent a special factor of agglomeration” that arise “where the products of one industry become the raw materials of another” and that “this relationship can be consummated with greatest efficiency by a clustering of complementary production processes.” Linkages of this type were numerous in the meat, oil refining and chemical industries “where flow processes encourage the proximate locations of ‘linked’ industries” and, along with the tertiary services that arise in the process, “may give rise to rather important urban concentrations” (idem). Isard (1960) also wrote much about petro-chemical recovery linkages in Puerto Rico and even anticipated the later rationale for eco-industrial parks in the following passage:

For months [in the 1950s in Puerto Rico] we tracked down false leads. Then one day, in unpredictable fashion, an idea came up. If no *one* manufacturing activity by itself could be profitably located in Puerto Rico, perhaps we could find some *combination* of activities that together might be profitably operated. Perhaps this possibility could be nurtured because the location of such activities next to one another would provide additional advantages to each. If one activity were to produce an output that was an input to a second, there would be savings on transport costs on the output of the first activity. Conversely, if an operation could locate next to one that provided it with an input, then it would get that input at a lower delivery price. Further, an operation might produce a by-product that ordinarily is scrapped – dumped on the environment. (Recall that at that time the pollution-absorption capability of the environment was considered almost infinite, way beyond the foreseeable reach of man.) If we could arrange to place another operation close by that could use the by-product, then that by-product might fetch some revenue (Isard, 1975: 437).

Brief discussions of IS can also be found in the writings of scientists influenced by the early ‘systems analysis’ literature.⁶ The geophysicist and oceanographer Athelstan Spilhaus (1967: 1131; see also Spilhaus 1966) thus discussed “examples of industrial symbiosis where one industry feeds off, or at least neutralizes, the wastes of another.” Among other instances, fly ash from smokestacks were used in the preparation of cement and bricks; a Florida city’s garbage was turned into fertilizer; sulfur dioxide from factory chimneys was combined with sulfur from oil refineries to prepare sulfuric acid; and dust from grain elevators was made into pellets for cattle feed. The authors of a US National Research Council (1975: 38) report similarly observed cases of IS in which “the waste generated by one organization can be a valuable input of another, so that by establishing close physical, economic and managerial relationships between the two industries the costs of both can be reduced” in which waste was defined as including “industrial waste and effluents from processes and manufacturing, scrap equipment, products and junk, generally, and even municipal waste.”

In short, the concept of IS has long been used to describe different relationships between co-located industries, including, but not limited to, geographically localized by-product linkages. As will now be illustrated, a much broader literature studied or described localized by-product linkages without using this particular label.

⁶ The roots of IE can also be traced back to this literature (Erkman, 1997), although no reference to these previous uses of IS can be found in IE writings.

3. Past Assessments of By-Product Linkages

3.1 Extent of Past By-Product Linkages

Numerous books and articles published between the first decades of the Industrial Revolution and the birth of the modern environmental movement document and analyze the development of profitable industrial waste recovery linkages between otherwise unrelated firms (Desrochers, 2007). For example, the journalist and publisher Peter Lund Simmonds (1862, 2), a writer who belonged to several geographical societies (Greysmith, 1990), documented that “in every manufacturing process there is more or less waste of the raw material, which it is the province of others following after the original manufacturer to collect and utilize”. In his opinion, this was already the case throughout most of Europe and becoming increasingly so even in the United States and other resource-rich economies (Simmonds, 1876). Later authors of general treatises on the topic would independently document the widespread nature of this phenomenon (Koller, 1918; Kershaw, 1928; Lipsett, 1963; Razous, 1937/1921/1905).

This assessment was also shared by many past economists and geographers. It is probably fair to say, however, that if some economists devoted a few lines to the development and extent of by-product linkages - as opposed to already existing cases of joint production (Kurz, 1986, 2006; Baumgärtner et al., 2006) -, they rarely discussed their geographical expression. For example, Karl Marx (1909: 120-1) observed that with “the advance of capitalist production the utilisation of the excrements of production is extended” and that the “so-called waste plays an important role in almost every industry.” Alfred Marshall wrote that “many of the most important advances of recent years have been due to the utilizing of what had been a waste product” (1898: 358) and that modern industry was successfully generating a demand for by-products while simultaneously improving their quality (1932: 238-9). The agricultural economist Rudolf Alexander Clemen (1927: 2 and vii) similarly observed that “at the present time, profitable by-products are derived from numerous farm crops and industrial operations” and that the “development of by-products in [all] industry is one of the most outstanding phenomena in our economic life... From the viewpoint of individual business, this manufacture of by-products has turned waste into such a source of revenue that in many cases the by-products have proved more profitable per pound than the main product.” In his textbook *Economics*, John Ise (1950: 111) observed that “in recent years there has been rapid progress in the use of by-products.”

Perhaps the best concise general treatment on the issue can be found in Erich Zimmermann’s (1933) *World Resources and Industries*. The German-born and trained American economist - who also belonged to the Association of American Geographers and was probably more influential among this latter group⁷ - observed that while nature used to be the only reservoir out of which humans drew the raw materials of production, a growing number of industries were relying on “secondary sources of supplies, salvaged from the waste heap and the junk pile, or artificial substitutes, especially synthetic products” whose raw materials often used to be wasted (p. 762). Because he felt that “a comprehensive survey of waste elimination would fill volumes” (p. 769), Zimmermann limited the portion of his chapter on “resources from test tubes, waste heaps, and junk piles” to the description of a few outstanding examples, such as cottonseed,

⁷ Zimmermann discusses his stance as a contributor to both disciplines in the forewords to the various editions of his *magnum opus*.

bagasse (a by-product of sugar extraction from sugar cane) and (mostly) packing house wastes. From these and other cases he inferred some general patterns, such as the fact that “the boundary lines between waste products and by-products are vague,” that “the transfer from one category to the other is an almost daily occurrence” (p. 768), and that resource recovery would in time help equalize the distribution of economic activities on the globe “through synthetic chemistry, by-product utilization, waste elimination, and the recovery of secondary materials” (p. 763).

Numerous geographers also noticed these patterns. For example, in their textbook *Commercial and Industrial Geography* Galloway Keller and Longley Bishop (1928: 74 and 245) commented that “there are nearly three hundred and fifty different kinds of manufactures in the United States. Some of these have a great number of what are known as ‘by-products’” and further added that “one of the great developments in modern industry is the use of such [waste] products, which are known as by-products. Much that originally went to waste and was a great nuisance to the producer has now become of value and a source of profit.” In his textbook *Economic Geography* Bernhard Ostrolenk (1941: 416-417) observed that the “term ‘by-product’ no longer has the same meaning it formerly had, a waste or semi-waste, for there are few products wasted in modern industry.”

Interestingly, the database JSTOR lists 82 articles published in the journal *Economic Geography* between 1925 and 1960 that contain the term ‘by-product’ in their main text. Among other illustrations, Zierer’s (1941) description of the “Industrial Area of Newcastle, Australia” mentions the opening of a by-product coking plant and the recovery of sulphuric acid from a zinc concentrating operations. In his discussion of the “Iron and Steel Industry of the Middlesbrough District” (UK), Frey (1929: 180) wrote that in one local operation “the utilization of by-products is well developed, the slag is transformed into fertilizer, road metal, and cement; the flue dust goes through an extraction plant for potash recovery.” In a description of the iron industry of the Cleveland (UK) district, Appleton (1929: 314) observed that the phosphatic slag proved to be an “excellent fertilizer” when finely ground and was also used extensively in the manufacture of bricks prompting the establishment of large plants “in connection with some of the steel plants.” Morrison (1945) observes that the Michigan Alkali Co. (MAC) was established in 1899 to use a waste product from the manufacture of caustic soda, calcium carbonate sludge. In 1908, a subsidiary of this firm, Huron Portland Cement Co., was launched to provide an outlet from residual stone (i.e., too small in size) produced from the MAC operated quarry that had previously been wasted or sold to other cement companies.

Numerous cases were also discussed to some extent in economic geography textbooks (Table 1).

Table 1 (around here)

3.2 Factors Favoring the Development of By-Product Linkages

Two main types of incentives were thought to promote the development of by-product linkages. The first was the search for increased, or at any rate constant (in a dynamic world), profitability. In short, faced with innovative competitors, entrepreneurs, managers and technicians have always had some incentive to extract as much value as possible from their costly inputs and, as a result, to incidentally reduce emissions in their backyards, local rivers and surrounding atmosphere by developing lucrative by-products out of wasted (and often polluting) substances.

The second was the necessity of removing nuisances that could result in legal actions and their attending costs and/or injunctions.

Geographers Galloway Kelley and Longley Bishop (1928: 245-246) explained the first incentive in the following terms: “The more keen the competition between industries, the more necessary does it become to save in every possible way, in order to make profit. As the processes of the industries are studied ever more carefully, in the effort to do better in both earning and saving, more chances appear to make use of what seemed nearly valueless before.” Another geographer, Landon (1939: 324), observed that, “by speeding up many processes,” advances in chemical know-how saved “labor and other expense” and also conserved “raw materials, utilizing them more completely, substituting the cheaper for the more expensive ones, increasing the durability of manufactured products, and utilizing waste.”

A century earlier, the American economist Wayland (1838: 383-384) had similarly stressed that, in order to increase profitability, manufacturers should strive to consume entirely “every utility possessed by any substance;” that much care should be devoted to insure that “all the fragments and remnants should be, so far as possible, employed to some valuable purpose;” and that “all the values must be consumed in the most profitable manner.” For example, the residuum left over after the extraction of flax seed was a valuable food for cattle and therefore both lessened the price of oil and increased its demand. The agricultural economist Clemen (1927: 2) put forth a similar argument: “The materials from which the by-products in nearly all industries are manufactured today were formerly partially or wholly wasted, and the change to intensive utilization of these materials for by-product manufacture has been brought about by the ever-increasing force of competition in American business, both between individual concerns within a single industry and among different ones.”

Interestingly, even authors otherwise known for their hostility to the profit motive recognized its beneficial impact in terms of by-product development. To give but one example, Karl Marx (1909: 95-96) wrote that the creation of by-products out of waste “reduce the cost of the raw material to the extent that they are saleable;” that the “reduction of the cost of this portion of constant capital increases to that extent the rate of profit;” and that industrial waste recovery was “the second great branch of economies in the conditions of production” after economies of scale.

By-product recovery was also sometimes triggered by legal actions, or the threat of such actions, based either on the common law doctrines of negligence, trespass, nuisance and strict liability for abnormally dangerous conditions and activities, or specific governmental regulations. For example, like other analysts before him and long before Porter (1991) who is now credited with formulating this insight (Desrochers, 2008), Zimmermann (1933: 768) observed that not all businesses were “free to strive from the maximization of profit without social interference” and that “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 (idem.).”

Apart from these two broad types of incentives, other specific conditions had to be met for commercially successful waste utilization. Clemen (1927: 1) identified five factors: (1) a practical commercial process of manufacture; (2) actual or potential market outlets for the new proposed by-products; (3) adequate supplies of the waste used as raw material, gathered in one place or capable of being collected at a sufficiently low cost; (4) cheap and satisfactory storage; and (5) technically trained operatives. These pre-conditions were implicitly understood by most authors who wrote knowledgeably on the topic. Not surprisingly, this typically led them to emphasize either the importance of large-scale production, whether in a single firm or in a large city, as a prerequisite for commercial success. We now turn to the importance of the latter issue through an overview of the impact of geographical proximity and/or long distance trade on successful industrial waste recovery.

4. Geographical Space and By-Product Linkages

4.1 Case studies

Many past discussions of by-product linkages allude to the importance of close geographical proximity to their main supplier as a prerequisite for their profitability. As an anonymous (1873: 11) writer observed in the second half of the nineteenth century: “*ceteris paribus*, the waste matter has generally the advantage of being at or near the spot where it can be utilized, while often the mere fact of its easy disposal is an absolute gain.” Decades later, the geographer and economist Malcom Keir (1919: 39) observed that localization “attracts to itself plants whose business is the utilization of waste products. In order to insure a plentiful supply of raw material upon which to work, these shops must be where there are many factories creating the same sort of waste. For the factories, the presence of the waste-using shops turns a loss into a profit, a charge into a credit or a liability into an asset.” Such linkages “add an increment to the importance of a locality as the center of an industry; for by transforming liabilities into assets, and turning costs into profits, they aid in the defense of the community against the onslaughts of outside competition. Hence they augment the growth of the industry in the location where it is already rooted” (p. 40). Keir illustrated these processes by discussing, among others, the cases of a great cement plant in Buffington, Indiana, that fed upon the slag of the largest steel mill in the United States located in the nearby town of Gary and a glue and mucilage manufacturer in Gloucester, Massachusetts, whose main supply was the heads and tails of fish from what was then one of the most important fishing ports in the world.

Numerous observations of this type can be found in the writings of contemporary economists and geographers. For example, the American economist Edward Ross (1896: 256) explained the geographical concentration of industries at least in part by “the cluster of side industries that grow up about packing establishments, refineries, or gas-works, engaged in turning refuse into byproducts.” The British political economist Charles Devas (1901: 98) similarly attributed some of the increased size of urban agglomeration to the “greater growth of subsidiary industries, such namely as supply materials and utilize refuse, to do which for a single factory would not be worthwhile.” In a classic study, the American economist Robert Murray Haig (1926: 191) explained the agglomeration of New York City’s canning and meat packing firms by the perishable nature of their inputs. New York’s canneries thus proved to be, for the most part, “salvage plants designed to preserve the surplus supplies of temporarily glutted markets, supplies which would otherwise decay and be wasted.” In his discussion of “Cement Production and Trade on the Great Lakes,” the American geographer Paul Cross Morrison (1944: 40) observed that in some cases, cement plants

were supplied with blast furnace slag and alkali waste as substitutes for limestone and that in these cases slag became “a very cheap raw material instead of a troublesome waste;” that, “as might be expected, those plants using [these by-products] are located adjacent to the iron and steel mills or the alkali plants which furnish them with their principal raw material”; and that being so situated “they also automatically inherit the favourable location of the blast furnaces and alkali plants to important market areas.”

Perhaps no other case of localized by-product linkages was more discussed in the first half of the twentieth century than the Chicago meat packing district (Table 1; Marshall, 1932; Zimmermann, 1933). The most detailed treatment of the issue can be found in Clemen’s (1927: 2-3) work who described how in the early decades of the industry there “grew up around the larger packing plants a number of separate satellite industries, which bought the unfinished by-products of the plants.” As he further added:

This process of integration in the packing industry and its by-products differs from what is normally understood as integration by the professional economists. While many of the products ... are manufactured by certain of the national packers themselves, or through subsidiary corporations such as leather and tanning companies and fertilizer companies, in many instances by-products processed to a certain degree within the packing industry proper are transferred to other subsidiary industries over which individual packers have no control, for further elaborate and expensive processing into final, highly finished articles (Clemen, 1927: 27).

Among other linkages, large refineries took the non-uniform, steam-rendered lard of packers, refined and bleached it, and sold it on the open market. Glue works made glue from bones, sinews, and various other packing plants materials. Fertilizer plants carted off the pressed tankage and raw or pressed blood, dried and sold it as such, or manufactured mixed fertilizer. Soap factories bought various grades of tallow. Butterine manufacturers used neutral lard and oleo oil from packing plants for manufacturing oleomargarine. Other non-edible portions were turned into pharmaceutical products and lubrication oil (Clemen, 1927). In time, however, “the production of these by-products was taken over by the packer himself, until a packing plant was a self-contained institution, performing a series of integrated services” thus profoundly transforming what could have previously been described as a case industrial symbiosis (Clemen, 1927: 3). (This issue will be addressed in more detail in a later section.)

Hunker and Wright (1963) later touched upon other cases in their broader discussion of the ‘economies of location integration’ in Ohio that resulted from the “contiguous location of two or more plants, usually of different companies, which either buy or sell to one another” finished products and raw materials, but also in many cases “by-products, or even waste materials” (p. 109). Among illustrations of the latter type, a Columbus fertilizer plant was linked to the sulfuric acid wastes of a neighboring zinc oxide facility while in Toledo linkages between a petroleum refinery and an adjacent plant making powdered iron products could be observed.

Their most striking example, however, could be found in the port city of Ashtabula where nine plants were “mutually dependent upon an exchange of products in an expanding chemical industry complex,” illustrating once more that that “the chemical industry is its own best

customer” (pp. 109-110). This local industrial complex could be traced back to a ferro-alloy plant established in 1943 (operated by Union Carbide and Carbon, henceforth UCC) that produced ferro-alloys for nearby steel centers as well as chemical by-products that were not utilized by another concern until 1950. In 1949, National Distillers Products Corporation (NDPC) established a local division to produce sodium (Na) by utilizing local power, local water and Michigan salt. While an anticipated market for the detergent failed to materialize, in 1950 Detrex Chemical Industries located a plant adjacent to the NDPC operations in order to manufacture a variety of chlorinated solvents. The plant purchased chlorine, a by-product of sodium production, from NDPC and acetylene from UCC, an input which could not be transported over long distances. By 1952, Linde Air Products, a division of UCC, located adjacent to the ferro-alloys plant to use calcium carbide in the production of acetylene and liquid oxygen for sale to steel mills. Linde also markets argon to the titanium plants which were built in the late 1950’s. In 1954, the General Tire and Rubber Company built a plant in this complex to use a Detrex by-product, hydrochloric acid, along with acetylene and lime from UCC, in order to produce polyvinyl resins. This plant made no further exchanges with its local neighbors, but rather shipped its main product to other plastic plants in other location.

In 1955, National Distillers found a local market for its sodium when Archer-Daniels-Midland (henceforth, ADM) built an \$8-million plant across the street from its facility. Despite this close proximity, sodium was shipped by tank car rather than by pipeline because of its dangerous character. At the time they wrote their case study, Hunker and Wright (1963: 111) observed that one of ADM by-products, caustic soda, “might form the basis for further chemical linkage in the future; currently, it is shipped out of the region.” In 1956, UCC completed the erection of a titanium plant which, among other things, utilized sodium from National Distillers that reverted to sodium chloride through its manufacturing process and was then piped back for recycling to National Distillers. After asking the rhetorical question “Why have so many chemical companies built their plants in Ashtabula?,” Hunker and Wright (1963: 112) answered “because of each other” and of ‘permissive’ factors, such as “lake, rail, and highway transport, plentiful electric power, abundant water, and adequate space.”

We now turn to an examination of the simple geographical economics of by-product linkages as discussed several decades ago by numerous analysts.

4.2 Simple Geographical Economics of By-Product Recovery and Linkages

In his classic *Theory of the Location of Industries*, Alfred Weber (1929: 201-203) observed that some connections between otherwise independent productive processes could be due to either economic (use of a main product) or technical (“the material of one process is the by-product of the second main product of any one of the stages of another process” (pp. 201-202)) factors. The latter case included the synthetic dyes industry whose main basic input was coal tar, a by-product of coke producers. Obviously, the main product determined the primary location of industrial operations which, in turn, determined “the material deposit of the other industries which use the by-product” (p. 203). There nonetheless remained a problem if “all the products that are produced at the junction point are of importance from a locational point of view” because of either their weight or value. If this was the case, “all of these lines of production influence the location of the junction point which is their common initial stage of production. Consequently, the location of this junction point is not apparent without further analysis” (idem).

Although Weber did not elaborate on the issue, much historical evidence illustrate how technological change, whether in the form of the development of a new by-product from waste, new lucrative markets for existing by-products, or new transportation technologies, profoundly affected locational constraints or opportunities. For example, the advent of trucking greatly facilitated the delivery of livestock and in time, following the “well-established trend of decentralization toward the source of raw materials” (Langdon White et al., 1974: 322), led to the relocation of meat-packing plants much closer to fattening grounds to “prevent loss of weight en route and to avoid freight charges on waste material that forms a large part of each animal” (Russell Smith et al., 1961: 228).

Decades earlier, Langdon White (1928: 121) had observed that the replacement of bee-hive coke ovens that kept “the sky dark with the clouds of smoke they belch forth day and night” in the “gloomy, unhealthful Connellsville [PA] region” by by-product ovens - which, as the name implies, allowed the recovery of gaseous and liquid residuals of coking operations - should have many environmental and economic benefits, for the latter yielded “a greater amount of coke per ton... [made] coke of better quality, and [yielded] by-products that are nearly as valuable as the coke itself.” Writing a quarter of a century later, however, Willard-Miller (1953: 153) observed that the advent of the by-product coke oven had actually accelerated the decline of the Connellsville economy. In short, the beehive process which reduced the bulk of raw coal by about 40 percent before transportation mandated the production of coke close to the coal mine. The by-product oven, on the other hand, allowed the recovery of gases which were then used for heating open hearts, blast furnaces, power stations, and other plants. As a result, the by-product ovens were nearly always built close to iron and steel industry operations. Furthermore, by-product ovens had also allowed the economic use of lower grade coal fields in better geographical locations, i.e., closer to industrial centers.

If the importance of geographical proximity for the profitable recovery of some type of waste products (bulky, low value and difficult or dangerous to transport) has long been understood, it has also been obvious for quite some time that certain residuals, such as scrap steel (Carlson and Gow, 1936; Maher, 1999; Pounds, 1959) and cottonseed (Deasy, 1941), are less subjected to the friction of distance. Writing over four decades ago, Lipsett (1963, v) observed that because of geographic imbalances in terms of waste production and demand, there was “a large import and export business in such products in every industrialized nation.” For example, West Germany was a large importer of scrap metals, Japan of scrap iron, Italy of woollen rags and U.S. textile manufacturers produced wastes “for export around the globe, as well as being reprocessed and recycled into industry in the United States.” Lipsett added that labour costs were often an important factor in international trade and that it had proved “economic to ship certain mix scrap to foreign countries for segregation and return to the generating nation, the cheaper labor costs more than paying for freight both ways (idem).”

Reflective Conclusion

Much evidence suggests that by-product linkages are a long established, spontaneous and important feature of market economies that once attracted the attention of a remarkably large number of economists and geographers. In our assessment, these pioneering contributions differ from more recent IS writings in a few respects. First, they were much more inclined to think that

the phenomenon (whether bilateral or multilateral) was widespread. They were also more keen to emphasize that it occurred at different geographical scales and that it was subject to much creative destruction. It also seems fair to state that they more inclined to think of the ‘win-win’ potential of by-product development. Last, their writings were essentially descriptive rather than normative. Indeed, instances in which an analyst argued that public planning could improve upon the IS results fostered by market processes were few and far between (Desrochers, 2007). While this latter feature can perhaps be explained in some instances by personal inclinations towards *laissez faire*, it is also probably the case that earlier geographers and economists had a better sense of the multiple factors affecting the locational decisions made by industrial managers than later writers who typically came to the topic without any background in spatial analysis. Interestingly, it is perhaps not a coincidence that some recent discussions of IS written by individuals who were not trained as spatial analysts are becoming increasingly undistinguishable from descriptions of agglomeration economies. A prime example of this can be found in the work of Chertow (2007: 12) who now describes, among other things, the main benefits of IS as consisting of

- (1) By-product reuse- the exchange of firm-specific materials between two or more parties for use as substitutes for commercial products or raw materials.
- (2) Utility/infrastructure sharing—the pooled use and management of commonly used resources such as energy, water, and wastewater.
- (3) Joint provision of services—meeting common needs across firms for ancillary activities such as fire suppression, transportation, and food provision.

And yet, the question remains: If localized by-product linkages remained important features of modern economic geography landscapes, why did the topic essentially disappeared from the radar screen of most spatial analysts in the last few decades until it was independently rediscovered by academics with appointments in engineering, environment and business schools?

One can think of a few reasons. The first is that while the underlying economic and geographical logics of by-product linkages are relatively straightforward, they are not easily amenable to strict quantification, a point acknowledged by the Chief Statistician for Manufactures of the US Census of 1900 in the preface to a bulletin on *The Utilization of Wastes and By-Products*. As he put it, “it is impossible to measure statistically the addition of wealth of the country created by turning to some useful purposes the residues and by-products which were formerly thrown away or left to rot,” but then immediately added that “the volume thus preserved and turned to some useful account must be enormous” (Kittredge, 1902: 1). Indeed, as later acknowledged by Isard (1998: 217) himself, the serious consideration of by-product linkages would dramatically increase the level of complexity faced by input-output analysts. Of course, by the time Isard made these observations, the inherent complexity of modelling spatial processes had long led to their purging from mainstream economics.

Another possible explanation might be the rise of the modern environmental movement and its core belief that the search for increased corporate profitability is fundamentally incompatible with improved environmental performance. Looking for examples of ‘win-win’ innovations such as IS was therefore not on the radar screen of scholars more strongly attracted to egregious cases

of industrial pollution or whose analytical outlook implicitly assumed that, in the absence of environmental regulations or taxes, industrial operators lack incentives to internalize their externalities.

It may also be the case that, as illustrated by the evolution of the Chicago meat-packing district, over time several successful inter-firm recovery recycling linkages were brought back within the confines of specific firms. Clark (1930: 129) thus described the progressive “internalization” of by-product recovery in preceding decades: “The utilizing of by-products has progressed from the stage in which only the more important materials are recovered and, in most cases, sold to separate concerns for manufacture, to the present stage in which substantially every material is typically worked up into finished form in departments of one concern.” He added that this process gave a “powerful stimulus” to large scale production, “since the gains are only available when even the least plentiful constituents are present in quantities sufficient to pay for processes of recovery which are often more complex than the main process and involve a larger minimum investment in capital” and that they “must also often reimburse the heavy expenditures on organized chemical research which have made the modern developments possible (idem).” Similar points were also made by Ise (1950: 111). It may be the case, however, that the refocusing of many firms on their core competencies in the last two decades has re-opened the doors to external symbiotic relationships, or is at any rate making it more likely in the future.

While the evidence presented in this essay is by no means comprehensive, it does suggest that market incentives often spontaneously resulted in increased wealth and improved environmental conditions through the systematic rewarding of more efficient manufacturing process and the transformation of waste into valuable products. These processes, in turn, were often dependent on the close geographical proximity of otherwise unrelated industrial operations which allowed the profitable development of by-product recovery linkages. As such, we suggest that the topic warrants more attention than it was given in recent decades by geographers, economists and regional scientists.

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Table 1: Discussions of By-Product Development and Linkages in Selected Economic Geography Textbooks⁸

Textbook	Petroleum refining residuals	Coal gasification and coking residuals	Steel production residuals	Meatpacking residuals	Cotton residuals
Russel Smith (1922; et al. 1961)	X	X	X	X	X
Galloway Keller & Longley Bishop (1928)	X	X		X	X
Whitbeck (1929)				X	
Landon (1939)	X			X	X
Carlson (1956)	X	X			X
Estall & Buchanan (1961)	X	X			

⁸ The cases discussed in these textbooks usually entail a few paragraphs. Shorter allusions to other types of linkages were omitted.