

Article

# Long Distance Trade, Locational Dynamics and By-Product Development: Insights from the History of the American Cottonseed Industry

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**Abstract:** Using the historical development of the American cottonseed value chain as a case study, we show that the factors usually deemed significant in the spontaneous development of localized industrial symbiosis (e.g., high volumes of potentially valuable yet environmentally problematic residuals, an economically diverse industrial base, as well as personal interactions and short mental distances between economic actors) have long been observed at much larger geographical scales. Like cereal grains and livestock, but unlike unprocessed residuals (e.g., residual steam and gas), the development of by-products out of cottonseed further involved numerous intermediaries and steps through which a complex raw material was broken down into various components that were then often (re)combined with other materials in remote locations. Additionally, because of the insufficient size and/or demand by domestic consumers, distant markets proved crucial at an early stage. We suggest that self-organizing and market-driven long-distance recovery linkages warrant more attention on the part of industrial symbiosis theorists, especially in terms of the technical, economic, geospatial, social and institutional conditions required for their emergence.

**Keywords:** industrial symbiosis; cottonseed by-products; cotton industry; technological change; secondary materials; win-win innovations; long-distance trade

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## (Epigraph)

“If there is one aspect more than any other that characterizes modern commercial and industrial development . . . it is the utilization of substances which in a primitive stage of development of any industry were looked upon as worthless. They were secondary products incurred in the manufacture of the main commodity, for which the industrial acumen of the age found no use; or if a use were known, the prejudices and conservatism of society allowed them to languish in the shadow of a similar commodity already strongly entrenched.”

Leebert Lloyd Lamborn [1] (p. 16) (1904)

“Cotton-seed oil is a most conspicuous instance of an article once thrown aside as a nuisance. Originally it was only a byproduct in the manufacture of meal from the seed; and even after it was discovered that meal could be made, it was a question what should be done with the oil. That question has been answered in various ways. What was garbage in 1860 was a fertilizer in 1870, cattle food in 1880, and table food and many things else, in 1890.”

Frederic G. Mather [2] (p. 104) (1894)

## 1. Introduction

Pauline Deutz [3] (p. 3) defines “industrial symbiosis” (henceforth IS) as a “flow of underutilized resource(s) (comprising substances and/or objects and/or energy), from an entity which would otherwise discard them, to another entity which uses them as a substitute for new resources”. This characterization overlaps significantly with the older concept of “by-product” where one entity produces a residual (e.g., livestock materials other than meat and leather) often—albeit not always—used by another entity [4]. Inspired by localized recovery linkages of low value wastes too bulky and difficult to transport (e.g., sludge recovered from a fish farm and from a pharmaceutical plant, residual steam and fly ash from a power plant, and refinery gas once flared as waste) observed in the Danish city of Kalundborg, and in a few additional locations, IS—unlike by-products—has been mostly theorized as a local or regional phenomenon in which frequent interactions and short mental distances between key individuals often play a crucial role [3,5–10].

While local recovery linkages have a long history [11,12], limiting the analysis of IS to a small geographical scale arguably detracts from another long-standing and significant win-win reclamation practice, i.e., the trade in residual textile fibres, glass, paper, ferrous and non-ferrous metals, chemicals, leather and other substances that were collected, sorted and reprocessed by intermediaries at different geographical scales [13–15]. While some of these were consumer waste, many were production residuals. Furthermore, many commodities traded over long distances no longer thought of as production residuals were once such by-products (e.g., petroleum products other than kerosene, livestock products other than meat and leather).

Our main argument is that IS theorizing should be expanded to the trade in, re-processing of, and innovative reuse of secondary materials, particularly production residuals. As will be discussed, localized and long-distance recovery networks and activities of this kind share a number of characteristics and incentives with IS. On the other hand, the theorization of the long-range trade in, and reuse of, secondary materials will require factoring in considerations less relevant in the case of localized IS. For instance, over time many residuals dealers built or acquired collection, storage and processing facilities in separate geographical locations and launched or acquired ventures in other lines of work. Several decades ago Lipsett Inc. was thus active in many locations from New York City to Los Angeles in the wrecking, scrap and construction businesses [14]. National Lead was involved in the paint and primary lead marketing business, but also in the lead recovery business, including lead-acid batteries and battery plates, from which it manufactured a range of lead-based materials (e.g., pipes, wire, powder and alloys) [14]. These and many other similar businesses were the inspiration for once popular expressions such as “Mine Above Ground” [14] (p. 142) and “From a Needle to a Battleship” [15] (p. 37). Diversity of operations also obviously allowed for more flexibility in terms of generating profits from items in greater demand. Some profitable secondary material recovery efforts thus combined sorting out consumer refuse along with the recovery of industrial equipment and installations available as a result of wear, tear and obsolescence (e.g., collapsed steel bridges, surplus military equipment, etc.) [13–17]. By and large, however, our main argument for expanding IS theorizing to production residuals is the fact that most of these were the unavoidable joint-products of manufacturing activities and were exchanged between different corporate entities.

Despite a few exceptions [18–22], there has been little recent academic interest in the self-organizing development of the long distance trade in manufacturing by-products, and its attendant economic and environmental benefits. We nonetheless deem the issue important in the context of IS theorizing because, if local economic diversity is really the key to promoting IS development [23], then having economic access to distant—and therefore more diverse—markets inherently creates even more numerous win-win possibilities. An examination of the long distance trade in secondary production materials also provides a way to study the importance of other claims made about IS, such as the importance of short personal and mental distances in the development of innovation and/or trusting relationships. Because of the inherently more complex nature of the long distance trade in production residuals, including economies of scales, role and importance of intermediaries, creation of

numerous valuable by-products over time out of one type of residual, “creative destruction” through the development of substitute products, and the numerous trade-offs involved in these processes, our paper supplements insights to IS theorizing through a case study of the development of valuable by-products from American cottonseed over the last century and a half. In our opinion, this case serves as an interesting historical example of a market-driven and self-organized dynamic process that meets Deutz’s [3] criteria for industrial symbiosis even though, from its beginning, cottonseed by-product development was carried out on, and its success required, a very large geographical scale rarely seen in IS literature.

Our contribution is based on an extensive literature search. We selected the materials and arguments we deemed most relevant for the discussion of IS, and we organized these materials and arguments thematically rather than chronologically. Section 2 discusses the domestication and physical properties of the cotton plant and cottonseed along with the various environmental problems created by the latter in the early nineteenth century. This is followed by an overview of by-product development from cottonseed over the last century and a half. Section 4 discusses more specifically the benefits of long-distance trade and the broader geographical division of labor that made the cottonseed trade and industry possible. The last section raises a few additional considerations for IS theorizing, such as the unintended consequences of government policies and distant inter-industrial knowledge flows. Our conclusion synthesizes our main insights, reflecting them back onto the theoretical IS framework.

## 2. Cotton: Cultivation, Use and Environmental Issues

### 2.1. Domesticated Cotton Species: Advantage America

Cotton is both the world’s most significant textile crop [24] and its most industrialized [25]. Cotton belongs to the *Malvaceae* botanical family that includes other economically significant plants such as jute, cocoa, okra and durian [26,27]. There are four industrially significant domesticated cotton species in the *Gossypium* genus [24–26]. *Gossypium hirsutum*, also known as upland, short-staple or Mexican cotton, is the main commercially valuable species of cotton [24,26]. *Gossypium barbadense*, also known as Egyptian, sea-island, long-staple or pima cotton, is the second most valuable commercial cotton species [24–26]. Both upland and pima cotton are native to the Americas [24–27]. Old world cottons that were once dominant in Africa and Eurasia until the arrival of upland cotton in the historic era include *Gossypium herbaceum*, or African cotton, and *Gossypium arboreum*, also known as Indian, Asiatic or tree cotton [24–27]. To avoid confusion, we will use the following common names for the four main cotton species: upland, pima, African and Indian. These species were present on four continents [24,25] with three primary centres of genetic identity: Australia, north-eastern Africa and the Arabian Peninsula, and west-central and southern Mexico [25].

It is a testament to cotton’s remarkable fibres, and its eventual importance as “white gold” [24], that it was independently domesticated everywhere it occurred in the wild, starting with the Indus Valley Harappa civilization around 8000 BP (6000 BC) [24]. South American cotton domestication occurred between 5500 and 4500 years BP, with the most widely accepted dates being 5500 BP (3500 BC) in the Yucatan Peninsula (Mexico) for upland cotton and 5480 BP (3480 BC) in Peru for pima cotton [26]. African cotton [24] grew wild in the savannah of southern Africa and was domesticated in the Middle East and around the eastern Mediterranean [26]. The legacy of this domestication is preserved linguistically as the word “cotton” comes from the Arabic word “qutn” [24] (p. 156) variously transliterated as “qutun” or “kutun” [28] (p. 4). African cotton is still cultivated in parts of Africa and Asia, but the main Old World species is Indian cotton [24] whose wild progenitors have been lost to science [26] but were, most likely, evolved independently from African cotton ancestors [25]. In addition to the widely cultivated species of cotton, an additional 51 species are recognized [24,26], some remaining wild and some enjoying local importance as “dooryard” crops.

Upland cotton has readily acclimatized to very diverse environments giving rise to local varieties or, through selective breeding, to cultivated varieties botanically known as *cultivars*, but not to separate

species [29]. Wendel et al. [29] reported that there are seven geographical upland cotton “races”, each with many local varieties. In the US alone, for example, all the upland cultivars belong to four main types: the Acala grown in the Southwest, the Delta grown in Mississippi and California, the Plains grown in Texas and Oklahoma, and the Eastern [29] grown in the Southeast.

The main cotton cultivars today are upland cotton [24,26] and pima cotton [24–26,30]. Industrial cultivation of pima cotton accounts for between 1% to 8% of the cotton grown worldwide, now extending through parts of Asia (including China and Uzbekistan), Africa, the Middle East, South America, and the United States (eastern Carolinas and Georgia) [26,29]. While pima cotton fibres are strong, long and fine, hence ideal for superior products, its yield and resistance to pests and diseases are inferior, making the species less economically advantageous than upland cotton [25]. Upland cotton, now responsible for 90–96% of world cotton production [26,29,31], was introduced to the south-eastern United States in the 1700s from Mexico while simultaneously being transplanted to Spain, India, Africa, Cuba and Brazil [26]. Thus, by the early 1800s, the United States was home to two species of cotton that differ from one another in the morphology and properties of their lint and seeds, as well as in hardiness and adaptability of the plant as a whole. Upland and pima cotton do have an important trait in common, however, that differentiates them from their many wild and cultivated Old World relatives, as well as from some of their domesticated New World cousins. It is the number of sets of chromosomes upland and pima cotton plants inherit, and the evolutionary and commercial advantages those extra chromosomes confer. In the case of upland cotton especially, some of these advantages would prove problematic for the development of commercial seed by-products. Because cottonseed properties are key elements in our story of human ingenuity and industrial symbiosis, we will now briefly examine the genetic basis for these properties, and the resulting industrial challenges of working with upland cotton cultivars.

## 2.2. *The Many (Mixed) Blessings of Tetraploidy*

During reproduction, many plant species may introduce significant changes to the genome of their offspring. Polyploidy, the property of having multiple sets of genes, is one such change, and it has far-reaching consequences for the offspring. A diploid sexually reproducing organism has one full set of genes (i.e., two sets of chromosomes) by inheriting one set of chromosomes from each parent. Humans are diploid; even limited polyploidy introduces serious challenges to human viability. Plants do not share these human limitations: A tetraploid plant has two full sets of genes (i.e., four sets of chromosomes, two from each parent) and, as we will see, it tends to use them to its advantage [32]. Hancock [32] (p. 79) provided a possible explanation for the evolutionary advantage of polyploidy: “The bottleneck of reduced fertility and low numbers could be partially ‘solved’ by the new polyploid being self-fertile and perennial; this would increase the new variant’s chances of producing enough viable offspring to avoid chance elimination.”

Researchers [25,26] now suggest the origins of upland and pima cotton may be traced to an unusual and highly fortuitous long-distance genetic crossing between two geographically far-flung cotton species: a wild diploid South American species native to Peru and a diploid trans-oceanic migrant originally from southern Asia, Australia and Oceania [25,26]. The progeny of this successful hybridization between the migrant and local diploid species gave rise to today’s most successful and most economically significant species of cotton, all of them tetraploid [25,26]. Since the rise of the tetraploid lineages of American cotton, the four widely cultivated domesticated species of cotton have further experienced “deliberate interspecific introgression” [25] (p. 4), or cross-species genetic mixing, as a result of targeted breeding to develop elite commercial cultivars.

Why would the tetraploid offspring of two distant diploid species be so successful? Hancock [32] analyzed the distinct evolutionary advantages that such hybridizing may have conferred on the native American cotton. He identified three mechanisms increasing the fitness of a tetraploid hybrid [32]: *nucleotypic effects*, through which the increase in the sheer quantity of genetic material correlates with an increase in plant size; *dosage effects*, having to do with increased enzyme production due to gene

multiplication; and *greater heterozygosity*, increasing the plant's hardiness and stability through the simultaneous presence of genes with distinct and complementary properties. In other words, tetraploid cotton plants grow larger and taller than their diploid cousins by virtue of having more genes in their nucleus, thus outcompeting smaller plants. Tetraploid cotton plants also develop beyond the innate limits of fibre production or photosynthetic efficiency as a result of higher concentration of enzymes and proteins. Finally, tetraploid cotton plants use their heterozygosity advantage to adapt to a greater variety of diverse habitats with disparate growing conditions and novel substrates by relying on the full complement of enzymatic output from complementary parallel genes. Hancock [32] gave an example of beneficial mutations in cotton via simple gene duplication: With two different enzymes performing the same function, where one enzyme may be less sensitive to salt than the other, the plant's tolerance to oceanic coastal or island areas may be extended, hence extending its growing range. We will see the consequences of some nucleotypic and dosage effects when examining the uniquely fuzzy surface of the tetraploid upland cottonseed. For now, it is important to remember that naturally occurring hybridization processes made upland and pima cotton into crops characterized by abundance and adaptability.

### 2.3. Physical Properties of the Cottonseed

The cotton fruit is known as a "boll". It is approximately 4 cm across, spherical in upland cotton but more pointed in the pima species [28]. Each boll contains three to five "loculi" or compartments in which five to 11 seeds mature [28]. The boll opens half-way through its approximately 100-day growth cycle as the lint, white in most commercial varieties, dries [28,33,34]. Cottonseeds are more ovoid than spherical, slightly pointed in the manner of blunt apple seeds, and 3–10 mm in length. (One exception is the kidney cotton of the Amazon Basin, *G. barbadense* var. *brasiliense*, a variety of pima cotton with a kidney-shaped seed that might have been the focus of selective breeding [25] as the kidney cottonseed is easier to gin manually than the typical seeds).

Seeds are 66% of the weight of a measure of seedcotton (cotton boll with seeds and lint). One hundred seeds may weigh between 5 and 10 milligrams [28]; conversely, one kilogram of delinted seeds contains approximately 8000 units [35]. They are characterized by a dark brown or ash-coloured husk which, particularly in the upland cotton species, is entirely encased in short, compact white fuzz typically called "linters" [24,28,35,36]. Pima cottonseed husks appear black and smooth instead of dark brown and rough [28]. While the pima cottonseed is much less fuzzy than the upland one, both tetraploid New World varieties present more fuzz than the smoother cottonseeds of the diploids [28].

The cellulosic fibres that make cotton desirable grow out of the seed's surface. The longer "lint" fibres are used in textile production [24,25]. The much shorter "fuzz hairs" or "linters" [24,25] are the protagonists of cottonseed by-product development, but as we will see they were among its greatest villains. Cottonseeds of more primitive cultivated varieties, even tetraploid ones, sometimes lack fuzz, but the presence of fuzz almost invariably translates into higher quality and more abundant lint [25]. The commercially important cotton such as upland produces cellulose-rich fibres out of approximately 30% of the seed coat epidermal cells [24].

At maturity, the cottonseed kernel stores comparatively little energy in starch form, but its prodigious ability to accumulate protein and oil make it a valuable product [24]. There are some physical barriers to seed utilization—many of them consequences of tetraploidy—and these loomed large in the early days of the cottonseed industry. One was the immediate deterioration of cottonseed after ginning [37]. Any long-term storage of the seed has to ensure cool and dry conditions to retard degradation such as free fatty acid production, odour release, and a darkening of the seed kernel and linters [37]. While cottonseed fuzz, or linters, is typically desirable as a correlate of high quality lint, it proved highly undesirable from the point of view of cottonseed processing and further utilization [38]. The problem was that while high quality lint and seed separation was greatly facilitated by Eli Whitney's invention of the cotton gin in 1793 and subsequent technological advances [39], the ginning process could not remove most of the fuzz from the seeds of upland cotton [28]. This had not been



a problem with the much less “fuzzy” pima cotton for which the gin was initially developed. In other words, upland cotton’s very success at producing great quantities of lint hampered the reuse of the seeds because they were encased in excess fuzz. As a result, cottonseed accumulation created significant localized environmental problems (discussed in Section 2.4) [37].

Another problem with adopting the cottonseed as a protein- and fat-rich nutritional package for both human and livestock consumption centered around the presence, and the effective removal, of gossypol [24,25,31,33,38,40–42]. Gossypol is a chemical compound in the dark red pigment glands present throughout the cotton plant but concentrated in its seed [24,25,41,43]. Gossypol contains terpenoid aldehydes [24,25] that, in larger concentrations, are toxic to people, non-mature ruminants, pigs, and poultry [24,25,38]. Gadelha et al. [43] and Rodman [40] (n.p.) explained the cotton plant’s evolution of gossypol in terms of its pesticidal function; tetraploid dosage effects may explain the large variance in the concentration of the substance between species and cultivars. Indeed, gossypol can do significant damage to animal tissues: The compound affects human and animal reproductive organs, as well as metabolism and nutrient uptake [33,37,43].

While modern cottonseed oil and meal extraction techniques discussed in Section 3 provide excellent ways of reducing gossypol content in refined cottonseed oil and desolventized meal, these are heavily industrialized methods not accessible to all growers, particularly in many developing countries. Eliminating gossypol from the plant would make cottonseed by-products much easier and more economical to adapt for human and animal consumption. Since gossypol is found in the pigment glands of the cotton plant, gossypol-free cotton is called “glandless” while regular cotton is called “glanded” [40]. Nearly glandless or variably glanded varieties of cotton have been cultivated, usually because of other adaptations such as drought resistance [44,45], and are now under intense scrutiny by agricultural researchers [40,42,43,46]. Gossypol removal, as well as the development of glandless cottonseed, will be discussed in Section 5.

#### 2.4. Environmental Problems of Cottonseed Disposal

Until the development and widespread use of the cotton gin, the limited volume of cottonseed available in the United States was either replanted (about 10% of the total [24–26]), fed to mature ruminants [38], or used as fertilizer on corn and cotton fields (having first killed the seeds by fermenting them in compost heaps, keeping them wet in large piles, or covering them in deep furrows [1,47]). Because of the poor state of land transportation at the time, however, these various uses were at first only economical within close proximity to ginning operations.

In short order, large heaps of cottonseed proved an unmitigated nuisance. One could burn them, but the seeds’ flammable oil and linters content meant that fires could get out of control and were very difficult to put out. Another complaint was that “land where piles of seed had remained for some time refused to bring forth any plants at all” [47] (p. 354). Because of the toxic gossypol, cottonseed killed all livestock saved mature ruminants, prompting some farmers to keep the seeds out of reach. According to Brooks [47] (p. 353), in “order to protect the hogs . . . the seed were inclosed [sic] in pens, and both cattle and hogs were carefully guarded to see that they did not feed on them”. Similar concerns about harming livestock were raised when cottonseed hulls were proposed as animal feed, although the burning of hulls for fuel provided an early, if insufficient, outlet for this residual product [47] (p. 357). One seemingly widespread disposal method was to dump cottonseed in flowing streams and let them be washed away [48]. Most planters, however, elected to “dump them into creeks or swamps where the cattle and hogs could not find them” [47] (p. 353), but the result was “a miasmatic stench which was not only very offensive, but was thought to produce malaria and other diseases” [47] (p. 353).

Interestingly, the problems of cottonseed disposal were once deemed so significant that “it was seriously considered” by some commentators “to discontinue the production of cotton, since the seed were injurious to man, beast, and plant” [47] (p. 354). Furthermore, some of America’s earliest environmental regulations can be traced back to cottonseed disposal [38] (p. xvi). For instance, the *Revised Code of Mississippi* of 1857 included a (significant) fine of \$200 (equivalent to \$5600 in 2017)

for “throw[ing] or permit[ting] to be thrown the cottonseed from [any cotton-gin] into any river, creek, or other stream of water which may be used by the inhabitants for drinking or fishing therein” (Article 19) while simultaneously containing a provision that prevented ginners from accumulating seed within half a mile of a city, town, or village so as to “not prejudice the health of the inhabitants” (Article 18) [49] (p. 207). Similar laws were also enacted in Alabama and Georgia at the time.

### 3. Cottonseed By-Product Development

#### 3.1. Overview of the Development of the American Cottonseed Industry

When confronted with the environmental impact of cottonseed described in the previous section, some individuals saw intractable problems and urged liquidating cotton production altogether. Others, however, suggested that profitable opportunities might be found in the huge heaps of linters-covered cottonseed.

For the first five decades of the nineteenth century many innovators tried in vain to create wealth out of waste. One problem was their reliance on crude oil extraction techniques that were further hampered by the propensity of upland cottonseed linters to absorb much of the extracted oil [30]. Other issues included the abundance and cheapness of animal fats and oils in the American market and a strong popular prejudice against vegetable oils [50,51]. As Ogden [50] (p. 3) put it, while creating value out of cottonseed was “a discovery of no slight magnitude and importance”, it came “as most great discoveries do, accompanied by pecuniary loss, delay and disappointment; and [the industry] was successfully established only after repeated failures”. Profitable operations eventually blossomed in the aftermath of the American Civil War and, from this point on, new uses for cottonseed-derived materials were developed for nearly a century (see, among others, [1,30,38,48,50–54]). By the 1950s, however, cottonseed products began to lose several markets to new substitute products such as other vegetable oils and plastics.

The heyday of cottonseed by-products is nonetheless worth examining in the context of IS theorizing. As industrialist and former President of the Interstate Cottonseed Crushers’ Association Luther A. Ransom [48] (pp. 9–10) put it over a century ago, this is the story “of a raw material practically without value” that, within two decades, was converted “into products worth one hundred million dollars” and brought much economic prosperity in regions desperate for it. As Ransom [48] (pp. 9–10) observed over a century ago, significant investments ultimately delivered an increase in

the transportation business of the country, the payment of many thousands of dollars in wages, the employment of thousands of men, the annual increase in the export business of the United States, the great financial and economic value to the country of the production of cotton oil, thus giving to the consumer a sweet and wholesome product, and supplying a deficiency in the world’s shortage of olive oil and butter, the enrichment of the soil by the use of Cottonseed Meal, a by-product of the seed, the greatly increased development of the dairy and live-stock interests of the South by the use of the meal and hulls, the establishment of mattress factories by the use of the linters, and the erection of plants for the manufacture of machinery used in operating cotton oil mills.

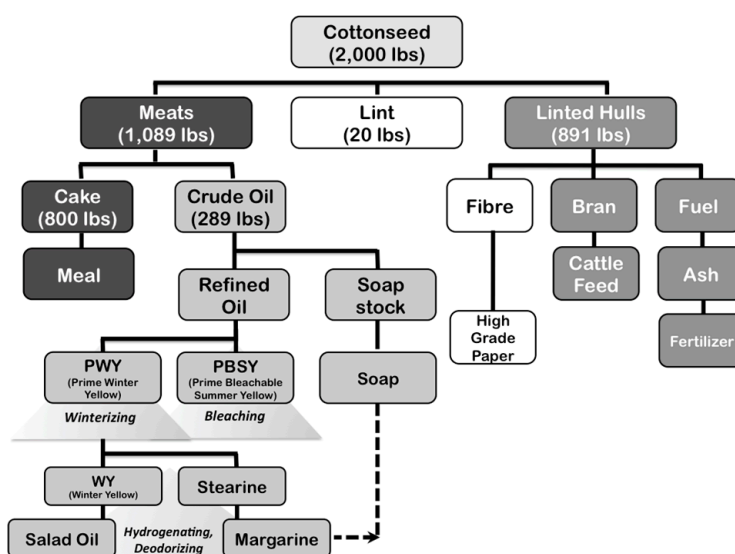
One can also convey a glimpse of these developments by tracking the number of crushing mills in operation, with the caveat that they became larger, more efficient and more versatile over time, thus eventually mandating significant consolidation. Looking back on the previous century, Carlson [53] (pp. 404–405) thus observed in 1956 that from seven in 1859 (and only three that survived the American Civil War), the number of cottonseed oil mills climbed to 26 in 1870, 45 in 1880, 119 in 1890 and reached its peak of nearly 900 on the eve of the First World War.

#### 3.2. Historical Overview of By-Product Development

With Writing in 1889, Grimshaw [55] (pp. 191–192) observed that cottonseed was long “considered a refuse for which there was no use; long burned or thrown away”, but that “its main and by-products

are now very important elements in our national industries. The garbage of 1800 became the fertilizer of 1870, the cattle food of 1880, and is now made to yield table food and useful articles of industrial pursuits". The oil, "more widely known throughout the world and used for a greater variety of purposes than any other oil", was by then most valuable, but the "residuum after its expression" was a valuable fertilizer and the "best cattle food", the ashes of the hulls delivered "potash of high commercial value", and the refuse from the refining of crude oil provided a "most excellent stock for laundry and toilet soaps". Truth be told, cottonseed oil pioneers had originally set their eyes on the whale oil market despite the inferior nature of their product for illumination, but by the early 1860s petroleum-derived kerosene proved too formidable a competitor [52,55].

Grimshaw [55] (p. 202) illustrated the main cottonseed by-products of his time as shown in Figure 1.

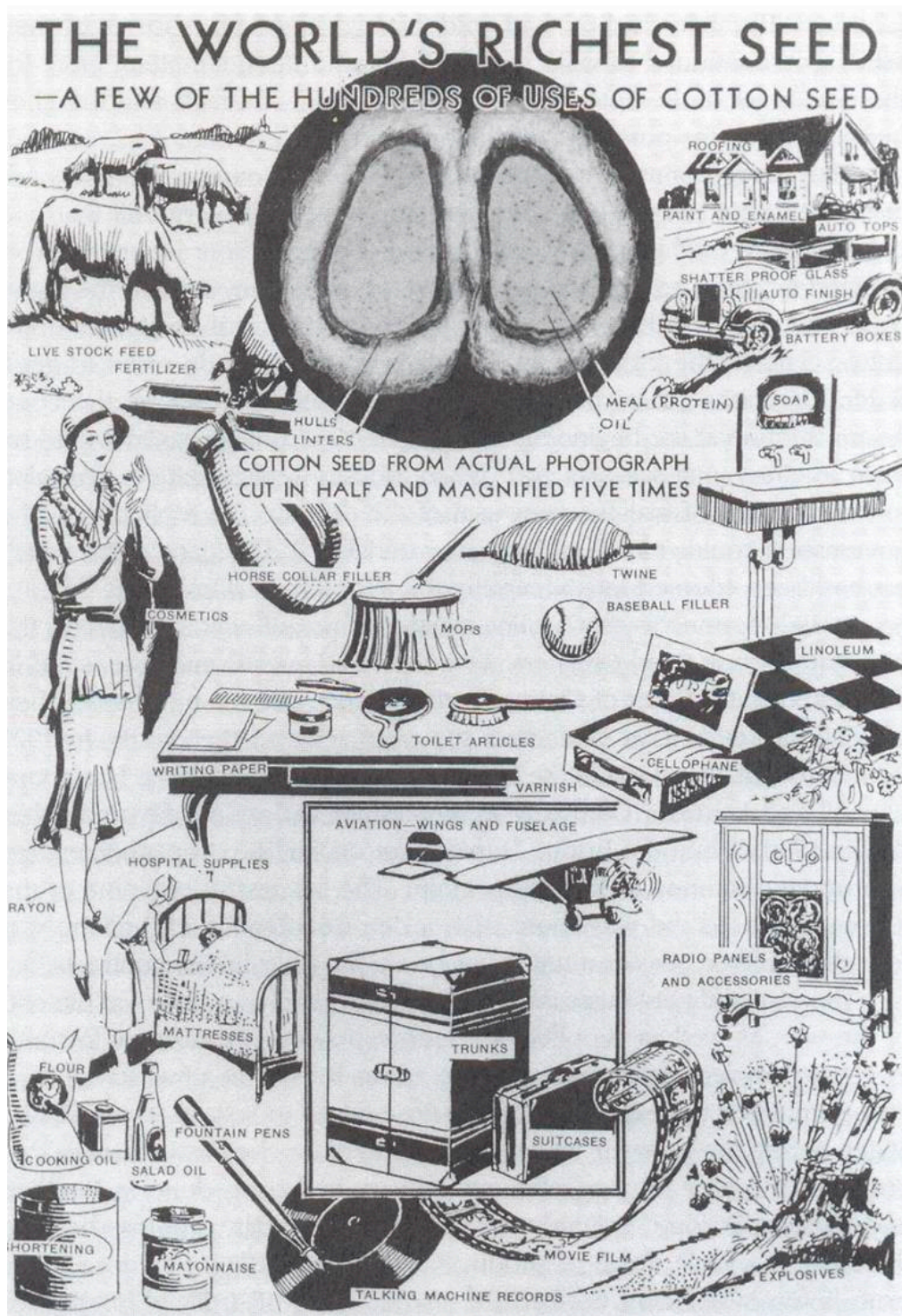


**Figure 1.** Cottonseed by-products derived from each part of the seed (circa 1889). Based on Grimshaw [55] (p. 202).

Two decades later, Ransom [48] (p. 53) described how the seeds grown "on the hillsides and in the valleys of old Georgia" had made possible the creation of "edible oil without olives; medicinal oil without codfish; butter without cows; ice cream without cream; lard without hogs; fertilizers without blood; mattresses without hair; stock feed without corn or oats and explosives without powder", the result being "as good or better articles than the originals". In her history of the cottonseed industry up to 1955, Wrenn [38] (p. xviii) listed some of the main cottonseed-based consumer products of the time: "shortening, salad oil . . . Ivory Soap, the Gold Dust Twins washing powder, Wesson Oil, Crisco, Spry, and Snowdrift." Perhaps the most iconic was Procter & Gamble's popular shortening *Crisco*—short for "Crystallized Cottonseed Oil"—introduced in 1911. These developments are especially impressive in light of Brooks's [47] (p. 363) comment the same year that "practically every cotton planter in the South remembers the time when cotton seed were piled high in the fields and were considered almost a useless product".

In their 1928 economic geography textbook, Galloway Keller and Longley Bishop [56] (p. 246) listed cottonseed by-products and their relationships to the parts of the seed from which they were in another detailed figure. Much of this information, however, is conveyed even more effectively in a 1930 promotional poster *The World's Richest Seed* produced by the National Cottonseed Products Association and reproduced as Figure 2.





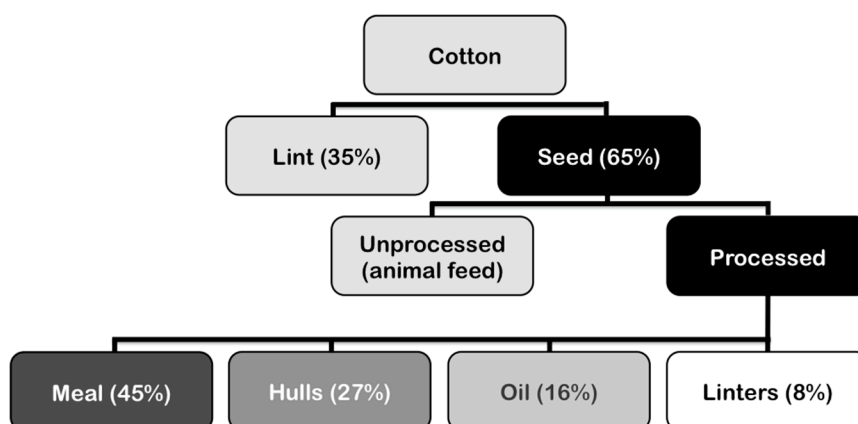
**Figure 2.** A 1930 promotional poster *The World's Richest Seed* produced by the National Cottonseed Products Association. Reproduced from Wrenn [57] (p. 126). (Original Source: [58]; Image reproduced with permission of the NCC).

Because of its composition, cottonseed oil proved inadequate for a number of uses, be it as an industrial lubricant, a wood filler, a leather treating agent and a component in paint [2,55].

Beginning in the middle of the twentieth century, however, palm-seed oil, soybeans, petroleum by-products and other alternatives progressively displaced cottonseed and ushered in a decline in the percentage of American cottonseed sent to crushing mills, from a high of nearly 90% in 1950 to

approximately 45% in 2000 [41] (p. 1). Whole cottonseed was not wasted though, for despite being “a rather inconvenient feedstuff to handle” [41] (p. 8), it was increasingly added to the diet of (mostly) lactating dairy cows and beef cattle, a practice once frowned upon. Indeed, as Lamborn [1] (p. 20) wrote over a century ago, “[w]hole cottonseed has been used in the past to some extent as a feeding-stuff, but its use for this purpose has now been practically abandoned in the vicinity of oil-mills, because of the facts that (1) the lint on the seed and the dusts it collects are likely to be injurious; (2) it is not easy to mix the seed thoroughly with other coarse feeds; and (3) the seed is disposed of to better advantage at the oil-mills.” Brooks [47] (p. 354) further added that if it was discovered long ago that “seed might be boiled with other foodstuff and fed to cows without injury”, it was then “claimed that the butter made from cows eating that food was not nutritious”.

Baffes [59] (p. 3) provided the following breakdown by weight of the current uses of cottonseed products, as shown in Figure 3.



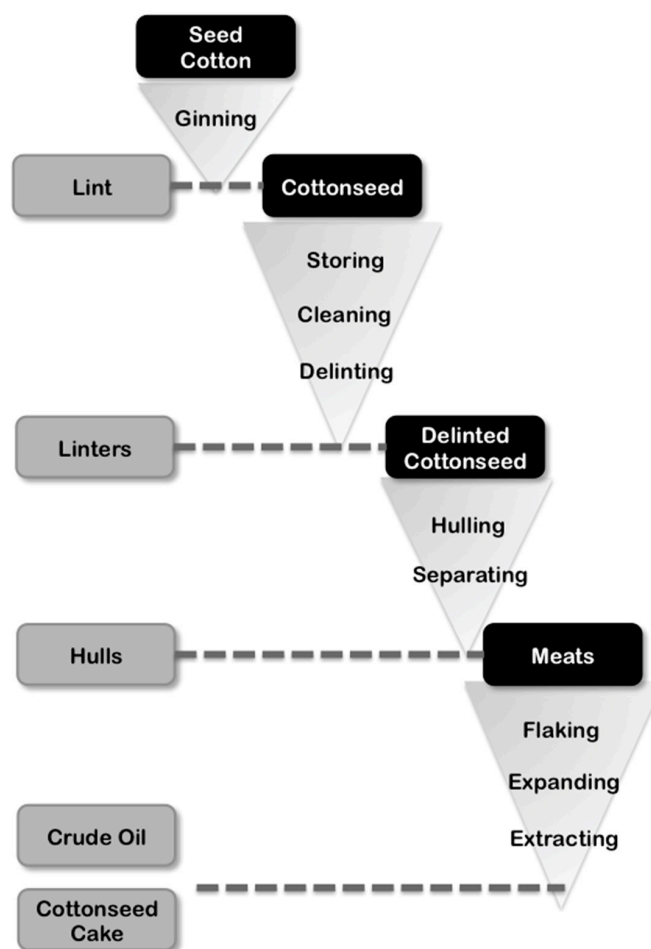
**Figure 3.** Current (2010) breakdown by weight of the uses of cottonseed products based on Baffes [59] (p. 3) and NCPA [60] (n.p.).

While providing a comprehensive coverage of the historical development and the current uses of cottonseed by-products is beyond the scope of a single article, the following sections provide a few relevant highlights and illustrate the often significant amount of time, efforts and resources involved.

### 3.3. Cottonseed By-Products: The Basics

Cottonseed has been called both “white gold” [24] and the “golden goose” [31] by historians and industry analysts for its ability to offer innovative, versatile and inexpensive alternatives to many scarce resources. Blasi and Drouillard [41] (p. 3) provided the basic schematic for modern cottonseed processing in Figure 4.

The first golden egg of the cottonseed golden goose may be the great efficiency with which cottonseed can be turned into by-products: In one ton of cottonseed, by weight, only 4% (80 lbs.) of material cannot be used commercially and is consigned to waste [60]. The remaining 96% is used as follows, by weight: 45% (900 lbs.) become cottonseed meal, 27% (540 lbs.) are hulls, 16% (320 lbs.) are extracted as crude oil, and 8% (160 lbs.) constitute the highly versatile (and light) linters [60]. Because delinting, hulling, oil and meal extraction are tightly controlled for maximum industrial efficiency, cottonseed-based by-products remain numerous and wide-ranging, feeding into a variety of markets not affiliated with livestock, agriculture, or direct food production [37,61].



**Figure 4.** Main stages in industrial cottonseed processing culminating in oil extraction, as of 2002, based on Blasi and Drouillard [41] (p. 3).

### 3.3.1. Meal and Hulls

Cottonseed meal, or dried and pulverized cottonseed cake (itself the leftover material once oil has been squeezed out of husked kernels), has long been a valued by-product as it contains “about nine times as much of the important plant foods—phosphoric acid and potash—as does the fibre produced by the plant” [62] (p. 509). Galloway Keller and Longley Bishop, writing in 1928 [56] (p. 245), noted appreciatively that the cake and the meal were of “almost as great a value in this country as the oil”, that, apart from their use as livestock feed, they were also used on a large scale in the preparation of fertilizers, and that they could also be used to “make bread, crackers, and other such foods”.

In 2016, as in 1928, cottonseed meal was used as livestock and aquaculture feed, and as fertilizer protein source [37,40,63]. Unless it has been treated in modern mills using expander technology and heat-based solvent extraction, the meal is typically mixed with other feed products because of its residual gossypol content [37,40]. In addition to industrially treated meal, only glandless cottonseed meal is virtually free of gossypol and can be used without restrictions in all feed and food products [11,40]. Hence, Galloway Keller and Longley Bishop’s [56] (p. 245) suggestion of making cottonseed meal baked goods can only be realized if either industrial refining has neutralized or removed the gossypol, or the seeds have been harvested from glandless cotton. This remains a focus of research around the world, particularly in India and China, and in parts of the United States [40,42,43].

The main uses of cottonseed hulls are in livestock feed, fertilizer and soil conditioner industries, furfural production in the plastics industry, and as oil-well packing material [37]. Galloway Keller and Longley Bishop, among others, revealed that there is a long history of utilizing the hulls as fertilizer,



but also as fuel [56] (p. 245): “The hulls used to be burned in the oil mills and their ashes used as fertilizers. But some one found out that by mixing the hulls with cottonseed meal a good stock feed could be produced, and there is now so great a demand for this mixture by stock raisers and dairymen that the husks are no longer used for fuel.” As with the meal, modern technology has expanded the range of historical use of all cotton by-products.

### 3.3.2. Cottonseed Oil

Cottonseed oil is versatile, economically valuable, and has long been used in a variety of domestic and industrial contexts going back at least several centuries in China [31,37,56,63]. Galloway Keller and Longley Bishop also pointed out that “[t]he English people seem to have been the first of western nations to make oil from cottonseed; in [the United States] the industry dates from about 1870. In a recent year there were about six hundred cottonseed-oil mills in this country, and a number in the United Kingdom, India, Egypt, Russia and other countries . . . ” [56] (p. 244).

Historically, cottonseed oil extraction started in the 1800s using hydraulic presses [37] and screw and lever, or wedge, presses [30] although “[t]he more primitive French oil mills employed a vertical wooden screw attached to a heavy beam” [30] (p. 5). The hydraulic plate process involved wrapping cottonseed meal in cloths and compressing it between parallel plates [37]. In her history of the early cottonseed industry in America, Wrenn [30] (p. 4) included a description of the earliest commercial cottonseed oil mill, adapted from, or shared with, the better-developed oilseeds of the time, such as the flaxseed and the sesame, then known as benne [64]. Once cottonseed processors started hulling the seeds, as described in Section 3.4.2, the presses of the 1820s and 1830s, many built after a design by Francis Follett and Jabez Smith, employed horses to crush cottonseed kernels “like olives by millstones on edge running over them in a space hollowed out of a flat rock. Follett and Smith derived their press design from that used to create linseed oil. Crushed cottonseeds were enveloped in haircloth, placed in a mortar, and mashed with a heavy pestle, moved by animal or water power, until the oil flowed out” [30] (p. 5).

By the early twentieth century new advances resulted in the building of ever larger and more complex mills. The more efficient solvent extraction began with small-scale kettle process refining in the early parts of the 20th century, progressing to continuous refining by the 1940s [37]. Even though Ransom [48] gave evidence of industrial refining in or before the 1910s, the mature technology for solvent extraction and the refining of miscella (a mixture of solvent, such as hexane, and condensed oil, together with impurities and by-products [37]) in the oilseed industry developed from the 1957 patent for what became known as the Ranchers Process [37]. Most cottonseed mills in the United States now use a variation of the Ranchers Process continuous solvent extraction [37]. One of the efficiencies of the solvent extraction process is its step-wise refining of the useful cottonseed by-products from the oil-solvent mix before completely separating the miscella into reclaimed solvent and refined cottonseed oil. This seemingly counterintuitive process allows for the extraction equipment to stay cleaner, and for higher flow processing due to the superior flow properties of the miscella with respect to the more viscous refined oil [37]).

While world production of cottonseed in the late 1990s was second only to world production of soybeans, as a source of vegetable oil cottonseed was sixth, at 3.75 million metric tons, outranked by soybean, palm, sunflower, canola, and peanut oils [31,37]. The primary reason for this disparity is the lower oil content of the cottonseed, at 18%, as compared to the alternatives [31,37]. In addition, cottonseed is diverted into animal feed or fertilizer directly, although that is also true of soybean or peanut, both highly prized and versatile food staples for people as well as livestock. In the same time frame, cottonseed oil production ranked third in the United States, behind soybean and corn oils [37]. As of 2013, the world’s top cottonseed oil producers were China, India, Pakistan, Brazil and the United States [31], with the top two outstripping all the rest with 1,500,000 tonnes and 1,250,000 tonnes, respectively, as compared to Brazil and the U.S. at 380,000 and 327,000, respectively [31]. Since 2006, when health authorities in New York City announced that trans-fat oils would be banned from the

city's restaurants, demand for cottonseed oil increased dramatically, leading the National Cottonseed Products Association (now the NCC) to predict that more cottonseed will be crushed for oil than fed to livestock for the first time in a decade [31].

Cottonseed oil is chemically composed of fatty acids bonded to glycerol, a combination common in vegetable oils and known as triglyceride [37]. The fatty acids most abundant in cottonseed oil, by weight, are the linoleic acids (up to 54%), palmitic acids (up to 27%), and oleic acids (around 18%) [31,37]. Since the linoleic and oleic acids are both unsaturated, they raise the nutritional profile of cottonseed oil to the highly prized 70% unsaturated fatty acid level, one of the highest among vegetable oils [31]. This makes cottonseed oil suitable for reducing saturated fat intake [31]. Cottonseed oil has an appreciable tocopherol content (1000 ppm), including the most valued of these natural anti-oxidants, alpha-tocopherol commonly known as vitamin E [37]. These prized antioxidants may be left in the oil to prolong its shelf life and to add nutritional value [31], may be extracted from cottonseed oil miscella during refining to be mixed back into the liquid product, or diverted to the pharmaceutical industry [37]. Refined cottonseed oil has almost no flavour (Niemi [31] (p. 26) described the flavour as "mild, nutty"), even when heated to deep-frying temperatures [37,65], and is more stable than canola or soybean oil at high temperatures because of its chemical composition [37]. While enhancing the flavour of the food cooked in it, cottonseed oil does not pollute due to its high smoke point of 232.2 °C [37] (p. 803).

### 3.3.3. Linters

Cottonseed linters give rise to the most diverse array of goods and industrial uses. In 1963 Charles Lipsett [17] showed a particular enthusiasm for linters processing in his *Industrial Wastes and Salvage* work. He noted that if multiple cuts were attempted to remove the linters (each new cut requiring an adjustment of the delinter), the first four generated the more valuable "chemical grades", i.e., longer and more uniform linters utilized in the manufacture of plastics, fine fibres such as rayon, and high quality papers. Grades five and up were considered "felter grades" and were used in upholstery, mattresses, stuffing, and in roofing and building papers. When linters were in short supply, Lipsett observed, the seeds were passed through as many as ten cuts with the product coming out of the last two being almost dust [17] (p. 230).

In addition, linters are employed by the fibre, furniture and cleaning product industry as felts, yarns, or fibre pulp; they become essential reagents in the chemical industry where they facilitate the synthesis of cellulose products such as cellulose acetate, cellulose nitrate, viscose, rayon and cellulose esters and ethers [37,60,63]. The paper industry, in particular, has found chemical grade linters extremely valuable over time, using them as a raw material for rag content papers. Linters were deemed especially valuable because of their uniformity, lack of colour, and absence of contamination by other matter such as "adhesives, cellophane or synthetics that are often impossible to remove from other form of papermaking raw materials even by cooking and bleaching, which give untold trouble to the papermakers" [17] (pp. 230–231).

Because of their uniform quality and near 100% cellulose content, linters make possible the economical production of such diverse and seemingly unrelated goods as solid propellants, dynamite, pharmaceuticals, paint and emulsions, plastics, X-ray and photography film, adhesive tape, ice cream and edible food casings [37]. Like "liquid gold", or petroleum, cottonseed linters exemplify the concept of "white gold"—or, indeed, the "golden goose"—in that their cellulose fibres can lend their hydrocarbons to a myriad uses.

### 3.4. Extracting Cottonseed By-Products

The preceding section provided a quick introduction to cottonseed by-products. Reviewing the extraction and by-product creation in some detail may make more sense if, instead of listing by-products by weight, we progress, in cottonseed mill fashion, from the outside to the inside of the fuzzy upland cottonseed.



### 3.4.1. Getting Rid of the Fuzz

While the pronounced presence of linters on the ginned upland cottonseed was a major problem in the early days of cottonseed processing, modern industrial methods have been designed to deal with this seed feature, balancing linters quantity, quality and processing time by means of utilizing multiple pass high speed saws [37].

The most common modern delinting practice is to remove all of the linters in two passes, the first cut resulting in a longer fibre and the second cut being done to remove the remaining linters, with the possibility of nicked hull segments hanging in the balance [37]. Shaved hull fragments in the second pass linters yield are difficult to remove from the fibre and affect the quality of the cellulose product [37]. Modern mills attempt to leave no more than 2.5–3.5% lint on what is called the fully delinted seed [37] as lint left on the seed soaks up oil during further processing [37,38], in addition to taking up more storage space [37]. Delinting is a delicate process, but, as mentioned earlier, linters have found diverse uses in the plastics, petroleum, explosives, cosmetics, paper, food, and other industries, so increasing their yield and quality is an end in itself [17,37]. In fact, some cotton industry spokespeople no longer refer to linters as a cottonseed by-product; instead, linters are often called a co-product [65].

### 3.4.2. Cottonseed Hulling

As Wrenn [30,38] noted, large scale delinting and hulling were two seed processing steps not previously needed, thus not developed, in the European cotton processing industry based on pima cotton cultivation, and European, Chinese and Indian experience with Old World cotton species. In the 1850s, a wealthy New Orleans merchant hoping to get into the cottonseed by-product trade, Paul Aldigé, “visited Marseilles, the great European center of oil and soap making, to study French methods of processing pima cottonseed. Aldigé may also have viewed oil-mill machinery at the Crystal Palace Exhibition in London. [ . . . ] In his travels Aldigé would have seen the latest advances in pressing and refining technology, but nothing helpful in the critical area of cottonseed hulling” [30] (pp. 7–8). In the same vein, Wrenn [30] (p. 4) provided us with the story of Williams’ first cottonseed mill as a perfect segue into cottonseed hulling:

A mill built in about 1814 by planter and political leader David R. Williams of Society Hill, South Carolina, failed, because Williams tried to press oil from the whole seed as flaxseed processors did. [ . . . ] Williams must have been working with seed from short-staple, or upland, cotton. [ . . . ] Seed from upland cotton, even after ginning, are covered with short fibers and fuzz, which absorb too much oil. The tough, lint-covered hulls must be removed from the kernels before pressing.

Carlson [53] (p. 405), summarized early attempts to crush whole upland cottonseed as resulting in a “low yield of oil . . . poor quality meal, and unprofitable operations”. In 1857, however, “the first huller employing the present-day cutting principle was developed and it was twelve years later that the principle of the gin was applied to the removal of linters from the seed. This type of equipment paved the way for economical processing” [53] (p. 405).

Thus, the fuzzy, rough seed exterior of upland cotton in the United States drove the need for innovative approaches, including borrowings from the cereal and oilseed industry [37,38]. One of them, as noted by Carlson [53], was seed hulling, a technique common in processing grains [38] and perfected for the cottonseed industry by William Fee in 1857 [31,53]. Yet Fee, although he is often credited with developing hulling for the cottonseed oil industry, was not the first to introduce the idea into cottonseed processing:

The first practical cottonseed huller was designed by Francis Follett and Jabez Smith of Petersburg, Virginia. Follett patented a huller in 1829, and Smith patented an improved huller the same year. With financial backing from Follett, Smith built and marketed hullers

and an improved oil press during the late 1820s and early 1830s. In an 1829 letter describing the machines, David Williams said that it had not occurred to him fifteen years earlier that the seed ‘might be hulled, like rice, so as to separate the kernels which contain all the oil’ [30] (pp. 4–5).

Another huller design developed in the mid-1830s by Lancelot Johnson was based, in principle, on a large coffee mill with a vertical tooth-lined beam turning in a circular, tooth-lined hopper [30]. Smith’s mid-1830s designs were still similar to his mortar-and-pestle original, with a stone cylinder turning in a cavity and cracking seeds caught in the gap between them [30]. Until Smith improved this design by introducing more refined machined parts to lower the 10–15% seed losses, “[o]thers considered the Follett and Smith huller ‘imperfect,’ because in the process of cracking the hulls it crushed too many seeds to permit efficient separation of the meats from the hulls” [30] (p. 6). It is in this context that in 1857 William R. Fee finally patented the first truly modern cottonseed huller design that paved the way for bar-type industrial hullers that dominated the industry for decades [30].

Ball and decorticator hullers are used in the modern cottonseed industry [37]. The bar type is older but still effective, using two bars attached to closely spaced rotating cylinders to cut the seed coat [37]. After being scored, the seed falls onto a shaker screen that stops the now detached hulls, but lets the seed meat fall into a processing area below [37]. The hulls still often harbour meat pieces, or entire attached kernels, so they are moved to an air column separator that sends the empty hulls to a hull beater, a screen cylinder with moving parts that ensure meat removal [37]. The protein content of cottonseed meal is closely related to the efficiency of hull removal [37]; conversely, the efficiency of meal production is related to the effectiveness of hull–meat separation. Typical industry average for cottonseed meal is 41% protein [37] (p. 797).

### 3.4.3. Cottonseed Oil and Meal Extraction

Cottonseed meat assembled from the hull–meat separation process must be processed as rapidly as possible because free fatty acids evolve from the oil, and both the meat and oil darken due to the release of gossypol from ruptured pigment glands [37]. The first step prior to oil extraction is flaking the meat, which consists of rolling it out to a very fine layer between 0.25 and 0.38 mm [37]. This step is crucial to oil extraction; unrolled meat fragments will not participate well in further processing [37]. After flaking, oil may be extracted in a variety of ways. The most common technique in use in the United States and increasingly around the world is direct solvent extraction. The use of solvent extraction with expanders has been the main innovation in US cottonseed processing since the 1980s [37]. Other methods common around the world, particularly in smaller mills operating for local use, are prepress solvent extraction, direct extraction without expanders, and even direct screw press extraction [37]. Some of the older methods, by forgoing heat and vacuum treatments of meal and oil, limit further processing and application of cottonseed products by failing to deactivate and extract a sufficient amount of the toxic gossypol compound to allow liberal use of products in the food and feed industry [31,40].

## 4. Secondary Materials and Long Distance Trade: The Case of Cottonseed

### 4.1. Historical Perspective on the Secondary Materials Trade

When we now think about long distance trade in secondary materials, electronic waste reprocessing in China or scuttling old ships in Bangladesh often come to mind. Needless to say, numerous production and consumption residuals (e.g., scrap steel, waste paper, plastic and electronics) are now traded between continents. What is less appreciated is how old these trade and innovation patterns are, involving, from their inception, both the production and consumption side of secondary materials trade and re-use.

To give but a few historical examples, the journalist and publisher Peter Lund Simmonds [13] (pp. 4–7) commented in 1876 that the recovery of shoddy (an inferior quality yarn or fabric made

from the shredded fibre of waste woolen cloth or wool clippings), paper, scrap iron and lead was then practised on a very large scale in New England. In his book *Industrial Wastes and Salvage: Its Production, Marketing and Utilization* published over half a century ago, the writer and publisher Charles Lipsett covered, among other secondary commodities, the trade in plastic, glass, metal, copper, brass, nickel, stainless steel, lead, zinc, tin, magnesium, iron and leather scrap; wood, fruit, vegetable, brewery, chemical, distillery, textile, cotton and citrus waste; and automobile wrecking and ship breaking. He observed that, owing to geographic imbalances between the production of secondary materials and appropriate processing sites and markets, there was “a large import and export business” in production residuals in “every industrialized nation” [17] (p. v). West Germany was a large importer of scrap metals, Japan of scrap iron and Italy of woollen rags. U.S. textile manufacturers produced wastes “for export around the globe, as well as being reprocessed and recycled into industry in the United States” [17] (p. v) (see also Lipsett [14] (p. 10)). Labor costs often proved significant enough to ensure the profitability of shipping “certain mix scrap to foreign countries for segregation and return[ing] [it] to the generating nation, the cheaper labor costs more than paying for freight both ways” [17] (p. v). Without the widespread utilization of waste materials, he added, there wouldn’t be sufficient raw materials in the world to supply the needs of industries. Lipsett [17] (p. 355) further commented that “Yesterday’s waste has become today’s new product or chemical or food, with its own waste which through research and development will become tomorrow’s new economic resource”.

Thus, the case of cottonseed processing, once the initial hurdles were overcome through inter-industry borrowing and innovation, has fit the pattern described by Lipsett [17]. While certain cottonseed products needed to be processed rapidly over short time spans and geographical distances, thus feeding localized IS linkages, (for example refined cottonseed oil and by-products before winterization and hydrogenation), other cottonseed by-products such as linters were perfectly poised to travel long distances to be processed into a variety of cellulose-based products.

#### 4.2. Industry Structure and the Profit Motive

Similar to petroleum, livestock and cereal grains—and unlike unprocessed residual materials as observed in Kalundborg—the development of most by-products out of cottonseed involved numerous steps through which a complex raw material was broken down into components that were often (re)combined with other materials. Because of the insufficient size and/or early reluctance of domestic consumers, finding profitable markets for cottonseed further implied moving large quantities of material over long distances. The result, in Mullendore’s [66] (p. 282) words, was that “cottonseed must go through an unusually large number of steps in its passage from the producer to the consumer” and “each step of manufacture and distribution represents a separate and distinct phase of the industry, in many instances as to both location and ownership”.

At the risk of oversimplifying, from its early days the cottonseed value chain was built around the following actors, often physically distant from each other (based on [30,48,66,67]):

- *Cotton producers* (both large ones who employed seasonal cotton pickers or tenant farmers and smaller independent ones)
  - produced field cotton;
  - might have historically taken a portion of cottonseed back home for planting or sold them to an intermediary, or directly to a cottonseed oil mill.
- *Ginners*
  - separated the fibre from the cottonseed;
  - acted as intermediaries between cotton producers and cottonseed processors.
- *Cottonseed buyers* (a.k.a. dealers, brokers or wholesalers)
  - traded in cottonseed.

- *Crushing mill operators* (a.k.a. cottonseed oil mill operators)
  - collected and stored cottonseed;
  - produced crude cottonseed oil, cake/meals, hulls, and linters.
- *Refiners*
  - refined the crude oil;
  - produced other by-products in the process.
- *Manufacturers of cottonseed products* (from livestock feed to a wide range of consumer and industrial products)
  - derived their products wholly or partly from the output of crushing mills and oil refiners.
- *Wholesalers*
  - distributed finished product to consumer retail outlets and/or industrial customers.

Because of the seasonal nature of cotton ginning and cottonseed crushing, the high cost and difficulty of storing cottonseeds, and the cyclical nature of cotton harvests and markets that determined the volume of cottonseed produced any given year, countless southern entrepreneurs “combined farming, merchandising, ginning, and buying cotton and cottonseed. In order to control seed supplies, many oil mill companies owned cotton gins and loaned money to finance the building of new gins and the modernization of old ones . . . ” [38] (p. xvii). Some also added other ventures such as cattle feeding, feed and fertilizer mixing, and ice making [38] (p. xvii). Others yet combined a variety of oilseed milling with cottonseed milling, often moving laterally from work with oilseeds whose fortunes were waning towards the ascendant cottonseed [30].

As in other lines of work, intermediaries were sometimes vilified by cotton producers and final consumers as parasitical and untrustworthy. Over a century ago Jenkins [67] (p. 2) observed that cottonseed meal was often sold as a fertilizer “to dealers in [Connecticut] chiefly by commission houses, which in turn buy it from large and small mills in the cotton-growing regions”. An employee of the Connecticut Agricultural Experiment Station that inspected some of this material, Jenkins was critical of this system because the “houses which sell it to the Connecticut trade never see the meal or have it in their possession. As to its quality they rely on the statements of the mills with which they trade, a confidence which frequently appears to be vain” [67] (p. 3).

As always in market economies, however, the solution to such problems was the creation of grades, standards and brands. Grades and standards helped ensure that producers of quality output obtained maximum value. Buyers of commodified by-products knew exactly what they were getting for their money without having to inspect every shipment. Handling and transportation could also be accomplished more efficiently by combining the production of similar goods from different producers. In the United States cottonseed came to be graded upon purchase according to a process based on two indexes established by the National Cottonseed Products Association [37,61,68]. The first index is the quantity index for oil and ammonia content (calculated differently for upland and pima cottonseed). The second is the quality index for impurity content, seed moisture content, and amount of free fatty acids that, in addition to a numerical value, comes with labels such as Prime Quality, Below Prime Quality, Off Quality and Below Grade (which does not get a numerical grade) [61] (pp. 60–61). The grade is then determined by “multiplying a quantity index by a quality index and dividing the result by 100” [61] (p. 60) with high grades of cottonseed scoring above 100 and low grades scoring below, always within their quality bracket. In 2016 US *prime quality cottonseed* was defined to contain, by analysis, “not more than 1.0 percent of foreign matter, not more than 12.0 percent of moisture, and not more than 1.8 percent of free fatty acids in the oil in the seed” [68]. Thus, a Prime Quality batch of upland cottonseed may get a grade of 92.40 if its oil content is low, and a Below Prime Quality batch of upland cottonseed may be graded at 97.5 if it is high in oil but also high in moisture and free fatty acids

index [37,61,68]. The development of modern brands for mass-produced commodities and products (e.g., Crisco) similarly allowed final consumers to economize on the time they would have otherwise been required to spend establishing the trustworthiness of multiple anonymous producers.

Although addressing past nuisance problems and avoiding fines probably played a role in the very early days of the industry, the creation of value out of cottonseed was primarily driven by competitive pressures, be they from other cottonseed-related businesses or else producers of substitute products. Ransom [48] (p. 145) thus noted that, from the perspective of Georgia cottonseed oil refiners, competition between a large number of interests was involved in the “purchase of the seed and the sale of the by-products” and that they had to compete “with each other for the crude oil, and with the refineries operated in other parts of the United States, the packers of the West and European buyers”. However, while competition might have been fierce (and thus insured that useless intermediaries were eliminated), at the turn of the twentieth century it was often the case that “nothing but the utilization of the cotton-seed waste saved the industry from bankruptcy [as many] a cotton grower secured enough extra for the cotton seeds just to make both ends meet” [69] (p. 457) (see also Deasy [51] (p. 347)).

Reflecting on the “many useful things about the cotton plant besides the fibers”, geographers Galloway Keller and Longley Bishop [56] (p. 245) considered it yet another successful case of by-product development in which “much that originally went to waste and was a great nuisance to the producer has now become of value and a source of profit”. “The more keen the competition between industries”, they observed, “the more necessary does it become to save in every possible way, in order to make profit” [56] (p. 245). The various uses of the cotton plant, including cottonseed, provided thus yet another “excellent illustration of the tendency in modern industry to let nothing go to waste, but to find uses for what was hitherto been looked upon as of small value” [56] (p. 247).

#### 4.3. Long Distance Trade

From the origins of the trade (i.e., relatively small scale shipments of pima cottonseed cake from the US Atlantic coast to British mills), distant markets proved extremely significant in the development of the cottonseed value-chain. In an age when unpaved land transportation was at best slow, ineffective and extremely costly (Deasy [51] (p. 348) described roads as being “little more than trails”) and warehouses lacking climate control machinery, much of the movement of cottonseed between plantations, ginning and crushing operations first centered along the waterways—especially around the Mississippi River and its navigable tributaries—and only proved profitable over relatively short distances because of the perishability of the cottonseed. Nixon [52] (p. 81) thus observed that, for a couple of decades after the industry took off, cottonseed-oil operations “hug the lines or points of water transportation” with the mills being concentrated in locations such as New Orleans, Memphis, Nashville, Natchez, Savannah and Charleston (see also Deasy [51] (p. 348)).

Some early processing operations, however, were located far from cotton fields, a result of their owners having first gained experience with, and then progressively moving away from, crushing other materials such as flaxseed, and taking advantage of the transportation routes of the time. As Wrenn put it [30] (p. 8): “For several decades flax cultivation had been declining in the United States because of the widespread availability of inexpensive, easy-to-clean cotton textiles. Linseed-oil mills began to experiment with various oil seeds in their search for additional raw materials.” Once the extant oil mills could be retrofitted with efficient hullers to handle upland cottonseed, that is, between the late 1850s and 1860s, little stood in the way of re-tooling an oilseed mill for cottonseed processing. Notably, shifting from processing one type of seed to another took ample advantage of other industrial linkages established for the flax, sesame or castor bean oil trade, such as warehousing logistics, mill workforce contracting, by-product sales, and the all-important transportation to and from the mills via the waterways. For instance, in New Orleans the entrepreneur A. A. Maginnis switched from manufacturing linseed oil from flaxseed to cottonseed crushing in 1856 while a St. Louis producer of linseed and castor oils followed suit the next year. In short order, western Ohio linseed-oil manufacturers, the center of flax growing up to that point in time, bought cottonseed and had it



shipped up the Mississippi and Ohio Rivers in boats that had previously carried goods from Cincinnati to southern ports and plantations. Flaxseed mills in the New York City and Providence areas also switched to cottonseed processing and oil refining at the time as they could also benefit from reasonable freight rates from ships returning from southern ports. In short order though, most northern operations either closed or relocated closer to their main input [30] (pp. 8–9).

As could be expected, much valuable material was left to rot far from navigable water ways. Ogden [50] (p. 12) thus insisted at the time that the claim of a large surplus of cottonseed available for processing was “true in the abstract [but] false in the concrete” because its existence owed to “the lack of transportation facilities and their unequal distribution over the broad area of cotton culture”. He was nonetheless confident that “sooner or later this difficulty [would] be remedied [when] the South [became] netted and fretted with railroads” and that, when this was the case, “every tonne of surplus seed will be utilized and help to swell the tide of general prosperity”.

In time the railroad came and new cottonseed mills were built at railroad centers in order to gather inputs from a wider catchment area. Interestingly, Brooks [54] (p. 312) observed that in the early years of the industry “river cotton seed produces a little more oil than railroad seed, and there is often a corresponding difference in their values”. He added that while seed could be shipped by rail in bulk, bags were required for river shipping which added to this mode of transportation costs.

The financial arrangements between cotton growers and ginners varied over time. Ransom [48] (p. 23) observed that in the early stages of the industry the mill operator would return “to the farmer the products of his seed, after deducting an amount sufficient to cover the cost of production and a reasonable profit”. Three decades later, Deasy [51] wrote that cotton producers would usually get bales of lint back upon completion of ginning operations to dispose of as they wished, while the bulk of the seed was bought on the premise by the ginner. Seed would then be purchased from many other small operations, gathered until one or more railroad cars were filled, and shipped in bulk to crushing mills. From there crude oil was barreled and shipped to more distant refineries.

In the early twentieth century demand for cottonseed was sufficiently strong that, for a time, “many small mills [were] erected near the cotton fields, and these get their seed from the neighboring producers” ([56] (p. 245); see also [48] (p. 68)). Ransom [48] (p. 19) believed that smaller operations would prove viable on account of their proximity to cotton fields that would allow them to market their seed locally “without freights . . . where they are needed by the farmers, stock-raisers and dairymen, at least expense than their larger competitors” and that these advantages would “probably be sufficient to sustain these small mills in any competition coming from the larger interests”. This being said, many “operating refineries at centrally located points” controlled crude oil plants “located at the sources of the seed supply” [47] (p. 37) and, as Carlson [53] (p. 405) observed a few decades later, “like all new industries, cottonseed processing appears to have attracted many who expected to make quick fortunes” but ignored broader logistical and commercial considerations. Over time a number of these small mills did not survive the consolidation that followed changing market demand, improved processing technologies and the advent of trucking. By the early 1950s, all processing plants in the cotton belt states were distributed on the basis of the local volume of seed production. As a result of the low density, bulkiness and perishability of cottonseed, it was then typically uneconomic to ship them “for crushing purposes more than 200 to 300 miles as a maximum” [53] (p. 405).

If whole cottonseeds did not travel far, their by-products typically would. From an early date cottonseed cake and meal not only found a ready market both in the south and other sections of the USA, but also in much of Western Europe. Brooks [54] (p. 330) thus observed that “much of the Chicago and Kansas City dressed beef shipped to all parts of America in refrigerator cars is simply concentrated cotton seed meal and hulls” while “many farmers near enough to the mills” were then feeding cottonseed products to dairy cows in “dairies near the larger southern cities”. Additionally, many early purchasers of cottonseed meal were located in northern European countries such as Denmark, England and The Netherlands where cheap American livestock feed (that included both cottonseed products and other cereal grains), combined with other animal feed from Eastern Europe,

profoundly altered the nature of local agricultural productions. The case of Denmark is illustrative in this respect (see Brandt [70] and Henriksen [71] for a more detailed treatment).

In the second half of the nineteenth century Danish farmers reacted to the availability of cheap animal feed imports by specializing in more lucrative livestock and dairy productions, in the latter case imported feedstuff proving absolutely essential to expand production from summer to year-round dairying. Although limited quantities of American cottonseed meal had been bought before, Danish imports took off after a near failure of the Russian sunflower crop and a drastic reduction in the availability of sunflower cake [48]. A few years later Ransom [48] (p. 57) could thus write admiringly of the “famous *Trifolium* dairy in Denmark”, at the time the largest in the world, where “15,000 head of milk cows are fed on cottonseed meal”.

As a result of this open-trade policy, between the mid-1870s and the mid-1920s, the Danish cattle herd doubled, the pig herd increased six-fold and the chicken flock fourfold. By 1938, the British (56%) and German (20%) markets absorbed more than 76 percent of Danish exports, then mostly consisting of butter, eggs, lard and bacon. By embracing free trade Danish farmers not only discovered “the fields of production in which they had the best opportunity to compete successfully with the farmers of the world, but they also were able to develop their own abilities, their agricultural production and marketing plants to almost functional perfection”, the result being “a most remarkable degree of culture and the art of decent living” [70] (pp. 271–273).

Foreign markets played an even more significant role in providing early outlets for American cottonseed oil. As mentioned before, American consumers were originally not fond of vegetable oil. On the plus side, upland cottonseed oil had many advantages over alternatives (including pima cottonseed) then available to European mills and consumers. Furthermore, parts of Europe were then struggling with a shortage of vegetable oils and dairy products. As Ransom [48] (p. 35) put it, a “butter shortage, almost a famine, already exists, and it is said that in some parts of Europe the people have not seen real butter in twenty years”. As a result, “during the early years of its manufacture cottonseed-oil was almost entirely exported to foreign countries, and export figures for those years represent very nearly the production of the country” [47] (p. 23). Ransom [48] (pp. 10–11) later observed that, despite increased home consumption (albeit more than made up for by increased domestic supply), cottonseed products had “invaded the great olive groves of Europe and Asia” and were then “competing on equal terms” with their production. Brooks [47] (p. 362) further observed that the best grade of upland cottonseed oil (“summer yellow”) was used in many European countries (at first mostly Holland) in the preparation of dairy and lard substitutes and in salad oil while the inferior grade were converted into soap (at first mostly in France).

Although the evidence presented in this section is but a glimpse of the rich history of the development of the cottonseed by-product industry, access to distant markets provided consumers in many locations with superior products than would have been the case if recovery linkages had remained local. Long-distance trade also made food production and provisioning more resilient overall while lessening the environmental impact of residual materials otherwise destroyed locally and substituted by (if at all possible) less efficient alternatives in other locations. Baffes [59] (p. 4) provided additional evidence for these claims by observing that until the mid-1980s in most West and Central African cotton producing countries the cottonseed typically “went to waste with no value attached”, but that as a result of improved transportation and a more diverse economic base cottonseed oil is now consumed by humans and the cottonseed meal by animals.

Another way to look at some of these issues is the tension in Chad, Burkina Faso and Benin between ginners who “believe they can sell seed at a higher price if they export” and crushers who argue that “government should mandate that ginners sell only to local industries at prices they can afford” [72] (p. x). Although not a perfect antecedent, one can get a glimpse of the negative impact of a coerced local use of residuals by examining earlier calls for greater consumption of cottonseed products in the American South. Ransom [48] (pp. 10–11) thus believed that doing so would “make the South the great cattle-raising section of the Union” and argued that “if a general policy of feeding some

cattle on every farm was adopted by our farmers it would lead to the establishment of packing-houses, and this would make the South the great livestock section of America" rather than being a net importer of beef. (Ransom also suggested how, by relying on abundant cottonseed meal, Georgia could become a top producer of mules and work horses, a proposal that would soon be put to rest by Henry Ford and other automobile pioneers...) Ransom's vision became a reality in the Southwest (i.e., Texas), but not in the Southeast as the region would eventually specialize in other types of meat animals. Suffice it to say that in recent years Georgia, Alabama, Arkansas, North Carolina, Mississippi and Texas have been the top US states in terms of (chicken) broiler production [73]), but that as of 2015 only Texas was a significant beef cattle producing state (13.14% of total US production, the largest in the nation), while Alabama (27; 1.36%), Georgia (30; 1.16%), Mississippi (31; 1.01%) and other southern states were marginal producers [74]. Texas also turned out to be the only southern state of significance in terms of milk cows [75]). Devising policy interventions on the basis of a single input would have thus arguably ignored the importance of many other factors and alternative use of scarce resources, in this case from land use (reflected in its price) and climate to the proximity to markets. Had resources been arbitrarily diverted to cattle rearing, both cottonseed producers and consumers of cottonseed-based products would have been unnecessarily harmed.

## 5. Other Considerations

What follows are a few additional lessons from the history of the cottonseed industry we believe provide useful suggestions for IS theorizing and research.

### 5.1. Political Interference

In a free market, the value of cotton by-products is determined by supply and demand considerations, including the harvest of field cotton, production location, demand for whole cottonseed, ginning and crushing technologies and competing alternatives for cottonseed by-products. In practice, however, the market for cottonseed by-products has long been affected by a range of government interventions, both in terms of the cotton crop itself and various measures that affected cottonseed products and their alternatives.

Policy interventions in cotton production have historically ranged from water and other production subsidies that favor greater output to other measures, such as production restriction schemes, that had the exact opposite goal in an attempt to artificially inflate fibre prices. Mali, Benin, Burkina Faso and Chad thus filed a complaint against the United States and European Union for unfair trade practices associated with production subsidies that benefit their cotton farmers [72]. Other government schemes that directly impacted cotton production and cottonseed by-products include recent US biofuel subsidies that have artificially increased the acreage devoted to corn and soybean at the expense of cotton [31], historical restrictions on the manufacture of dairy and animal fat substitutes such as oleomargarine, and tariffs that restricted their import in other jurisdictions where other vegetable oil producers (e.g., olive oil) were politically powerful. As Ransom [48] (pp. 68–69) observed a century ago, cottonseed oil producers had to struggle with numerous competing interests that included the "olive growers of Italy, Spain and France", the "producers of copra of the Pacific islands", the "cocoanut, peanut and sesame oil manufacturers of Europe", the "packers of the world", the "butter makers of Europe", the "Western growers of corn and hay" and "hog raisers", the "European growers of low grade cotton and cotton factory waste" and the "manufacturers of soap of all kinds, wherever located". Of course, American producers of similar commodities, such as the olive growers of California, were similarly hostile to cottonseed. It was therefore not surprising that "the development of this industry has been retarded because it met with so much opposition from so many different and conflicting interests" [48] (p. 69).

Sometimes, too, government policies designed to benefit cotton growers proved remarkably counterproductive to cottonseed interests. Boyle [76] (p. 171) thus observed that the US Tariff Act of 1921 put a high duty on soybean oil and peanut oil in an effort to support cotton farmers. Almost

overnight, however, American export of cottonseed oil dropped considerably, from 100,000 tons to 28,000 tons per year as the peanut and soybean tariff drove these commodities to the European market where they displaced American cottonseed oil. In other words, far from eliminating competition for American producers, protectionist policy shifted it to another market. A few years later, New Deal policies aimed at curbing cotton production in an effort to raise lint prices limited the supply available to cottonseed processors and thus benefitted the industry's local and international competitors [51].

While the complexity of market economies is nothing short of mind-boggling, a world where cotton prices and alternatives to cottonseed products were entirely determined by market forces would arguably deliver both increased economic and environmental benefits by allocating scarce resources ever more efficiently among competing uses. At any rate, much historical evidence suggests that market competition will result in a constant war on waste that will incidentally address environmental problems rather than create ever more damaging environmental externalities.

## 5.2. Importance of Industrial Diversity and Innovation

Several IS scholars have emphasized the importance of economic diversity at the local scale in the development of by-product linkages [12,23,77,78]. As illustrated in earlier sections, however, the broader economic diversity delivered by long-distance linkages provides even more potential and actual win-win opportunities. What can be further emphasized through the history of cottonseed by-product development, however, is that long-distance trade and interactions can often be as crucial as physical proximity and “short mental distances” between local actors. What follows are a few illustrations of such instances.

### 5.2.1. Interindustrial Borrowing in the Oil and Meal Extraction: The Case of the Migrating Expanders

The most interesting innovation in cottonseed oil processing, continuous solvent extraction with expanders, dates back to a 1965 US innovation in cereal grain processing [37]. The U.S. rice industry was looking for a way to stabilize rice bran for shipping, and the use of expanders allowed just that by inactivating an enzyme involved in spoilage of rice bran [37]. The enzyme was susceptible to the high temperatures and pressures achieved in the expander, but the heat could be controlled so as not to destroy the bran [37]. The rice industry in South America imported the US-developed expanders and made significant use of them [37]. As it often happens with industrial innovation, technical crossover from rice bran processing into oilseed processing made the somewhat adapted expander a prized part of the oil extraction process in Brazil in the early 1970s [37]. This innovation made such a difference in the Brazilian oilseed extraction industry that the originally American device found its way back to the United States in the late 1970s where it was applied to the perennially tough problem of efficiently extracting oil from cottonseed [37]. Between the late 1970s and the late 1990s, 95% of cottonseed extraction plants in the United States converted to using expanders as the *de rigueur* step preceding solvent oil extraction [37].

Without getting into too much detail, expanders improved cottonseed oil extraction efficiency by allowing the transformation of cottonseed meal into a substrate ideal for the solvent extraction of oil. Flaked and cooked cottonseed meal is fed into the expander where it is subject to high temperature and pressure. The steam rising from the pressure-cooked meal is collected and allowed to cool and condense into a porous material called “collet” [37]. The oil-collecting solvent, typically hexane, passes through the filigreed surface of the collet quickly, collecting oil along the way without saturating the collet [37]. In comparison to cottonseed flake, which retained up to a third of the hexane solvent, collet retains no more than 20% of the solvent [37]. Thus, expanders use less solvent and make the oil collection more efficient. Once the cooled collets arrive at the extractor, they are subjected to a process that creates two types of products, or fractions: the “miscella”, or oil mixed with solvent, and the “meal”, which is the extracted protein [37]. Both fractions need to undergo further solvent extraction, usually in a heated environment under a slight vacuum [37]. The meal is cooled and ground while the miscella is usually partially refined on site into semirefined cottonseed oil at up to 75% oil

content [37]. The efficiency of the extraction and refining process is greatly improved by the use of the expander technology.

One more advantage of the expander in cottonseed processing is the fact that the humid heat to which it exposes cottonseeds binds the gossypol toxin [37]. Gossypol glands, the pigment centres of the cottonseed, are distributed throughout the seed kernel like peppery flecks. Cutting and rolling the seed exposes them and allows them to become susceptible to the water and steam present during processing, particularly in the expander. The heat and humidity of the expander ensure that many of the gossypol glands rupture and render the toxic substance within them inactive [37]. Excessive unbound gossypol discolours the cottonseed oil and renders the cottonseed meal toxic in large quantities to all but ruminants [37,38].

Initial processing of the cottonseed oil at the mill is done in the miscella form [37]. The initial step in processing is refining, which adjusts the amount of hexane solvent in the miscella and removes free fatty acids, pigments released from the gossypol glands, and various mucilaginous impurities [37]. Bleaching with clay may follow refining to improve the colour of the product [37]. If the cottonseed oil is bound for the table as frying oil, salad dressing, margarine, shortening, or any other edible product, it may be hydrogenated to increase its melting point, although the natural properties of the oil and its lack of cholesterol have recently become a marketing feature of their own [37]. Table-grade cottonseed oil may be winterized to remove the stearin compounds that solidify at low temperatures and give a cloudy appearance to the product [37]. Processes such as winterization and inter-esterification [37] are beneficial to the efficiency of cottonseed oil utilization as they assist in separating and sorting cottonseed oil components according to hardness, melting point, and chemical composition, thus yielding a larger and better defined spectrum of specialized items, from high quality liquid oil to solids with stable crystallization properties and tailored melting points. This is reflected in the variety of grades of crude and refined cottonseed oils (there are nine types of crude cottonseed oil and 13 grades of refined cottonseed oil determined by clarity, colour, flavour, free fatty acid content, moisture and volatile matter content, unsaponifiable matter content, initial peroxide value, and fat stability [37,61]), and in the exact specification of colour and chemical content of each grade [37,61].

### 5.2.2. Interdisciplinary Borrowing and Research: Low-Gossypol and Glandless Cottonseed

A crucial problem with the use of the cottonseed as a source of nutritious by-products in both the food and the feedstock industry can be traced back to the seed's strong survival mechanisms [36,40–42]. While cottonseed has long offered a potent nutritional package rich in protein and fat, its use has been problematic because of difficulties in finding ways to effectively remove gossypol, a phenolic compound present in the dark red pigment glands scattered liberally through the cotton plant but concentrated in its seed kernel [24,25,31,33,38,40–43]. Rodman [40] (n.p.) explained the cotton plant's evolution of gossypol in terms of the pesticidal advantage of the compound: "It acts as a natural defense, helping to limit damage from chewing insects." There are two gossypol isomers that are mirror images of each other: the  $-$ gossypol and the  $+$ gossypol [41,43]. The  $-$ gossypol is more toxic than its mirror image as it is eliminated more slowly by living organisms [41,43]. Upland cotton produces between 33% and 47% of the  $-$ gossypol as compared to the  $+$ gossypol, but pima cotton produces up to 78% of the more harmful  $-$ gossypol. Typically, a pima cottonseed will yield up to 34 g of all gossypols per kg [43] and it has higher overall gossypol concentrations than upland cotton [43].

Gossypol can do a lot more damage than causing digestive trouble. The compound contains terpenoid aldehydes [31,43] that react with a range of bioactive compounds and amino acids such as lysine [43], thus making these materials less available in the body for vital functions. Gossypol affects metabolism and the reproductive organs [33,37,41,43]. Yafa [33] (p. 3) explained: "Low doses of gossypol have also been used for centuries in China as a male contraceptive: it destroys the lining of tubules in the testicles where sperm are produced." In light of this information, effectively eliminating, and not just lowering, the gossypol content in human and animal cottonseed food products should be



the preferred course of action in cottonseed product development. In non-trace concentrations, both gossypols are harmful to all but mature ruminants [24,25,38,41–43].

While modern cottonseed oil and meal extraction techniques provide excellent ways of reducing gossypol content in refined cottonseed oil and desolventized meal, these are heavily industrialized methods not accessible to all small growers, particularly in the developing countries growing cotton. Eliminating gossypol from the plant would, thus, render cottonseed by-products much easier, and more economical, to adapt for human and animal consumption. Since gossypol is found in the pigment glands of the cotton plant [24,25,40], gossypol-free cotton is called “glandless” while regular cotton is called “glanded” [40]. Nearly glandless or variably glanded varieties of cotton have been cultivated historically and are now under intense scrutiny by agricultural researchers.

A promising American variety of glandless hybrid cotton, Acala-GLS, is being developed at the New Mexico State University (NMSU) [40]. It is a hybrid between upland cotton and a plant provisionally known as *Gossypium hopi* Lewton, or Hopi cotton, a cotton indigenous to Arizona whose taxonomic identity is still not settled [79]. *G. hopi* was described as a distinct species in 1912 by Frederick Lewton [44]. By the time Lewton was working with it, Hopi cotton had been experimentally studied by the U.S. Department of Agriculture as its seeds had been, in fact, available since the late 1880s [44]. Rodman [40] wrote: “Seeds from that variety, dubbed *Gossypium hopi*, were actually used in U.S. Department of Agriculture upland cotton breeding projects beginning as early as 1905. However, the issue back then was not the lack of gossypol, but rather Hopi cotton’s early maturation and its viability in arid environments. Introducing those characteristics into upland varieties, with their larger bolls and longer, thicker lint, was the breeding goal.” As Lewton [44] pointed out in his descriptive paper, Hopi cotton had rather low lint content and smooth, linters-free seeds, even though such lint as was available was of good colour, length and quality.

Serious American interest in glandless cotton did not arise until the 1950s [40,42] and may be seen as trailing worldwide trends. Chinese research into the topic has yielded workable glandless cultivars as early the 1990s, but Chinese and African glandless cottons, widely grown and hybridized primarily as sources of gossypol-free food and feed products, did not fare well economically as pressure from upland cotton, among other factors, kept demand down [40]. Rodman concluded that pest pressures, lower yields and lack of a robust market for gossypol-free seeds have deterred producers from using glandless varieties. The ability of the cotton plant to vary the number and distribution of its pigment glands is, however, an important advantage in further development of new varieties.

Gossypol itself may have some benefits when it comes to its industrial uses. Since extracting gossypol from pima cotton would be relatively efficient, it could be used as a natural bio-toxin as long as careful refining could be assured. Gadelha [43] offers a wide array of medicinal and anti-viral uses of gossypol: HIV, H5N1 influenza, yeast and bacteria. Moving beyond the use of gossypol to combat invading microorganisms, Gadelha et al. [43] suggest carcinogenic application of the compounds. In their review, Gadelha et al. [43] also found evidence of gossypol use in treating female reproductive issues in some trials in the 1970s.

Clearly, eliminating gossypol from cottonseed and food and feedstock may allow for more targeted uses of cottonseed by-products, and of gossypol itself, in less advanced economies and the pharmaceutical industry. As with other agricultural commodities, advances in this respect will come from a global rather than local intellectual and industrial community. Research and development of glandless cottonseed, in parallel with its trade and innovation, have been truly international, relying on work carried out in Brazil and China [42,43]. New ways of thinking about improved cotton cultivars and the energetic requirements of their growth, transportation and processing should be part of a long-range linkage system [42,43,78,80].

## 6. Reflective Conclusions

Inspired by the discovery of several spontaneous, economically profitable, intermediary-free and geographically proximate residual and energy recovery linkages in the Danish city of Kalundborg and

later on in a wide range of locations and policy contexts [78] IS theorists have strived to achieve an understanding of the key elements leading to their emergence. By and large, attempts at theorizing have been framed at the local scale and have emphasized the local embeddedness—or sustained personal interactions and short mental distances—of economic actors. While certainly representative of many past and present recovery linkages, perhaps the initial “Kalundborg template” led many researchers and theorists to overemphasize the local scale at the expense of long-distance transactions and to underestimate the valuable contribution of intermediaries in gathering, processing, and finding lucrative markets for production residuals. In other words, perhaps a few large trees have hidden a rather significant forest from the sight of IS theorists.

Using the development of the American cottonseed value chain as a case study, we illustrated that the main factors usually deemed necessary for the development of industrial symbiosis can be observed at a much larger geographical scale, be they a high volume of potentially valuable (in terms of physical and chemical components) but otherwise problematic (high disposal costs) residuals and an economically diverse industrial structure that allowed for the development over time of inter-industrial linkages. As with any other commodity (e.g., produce, vegetable oils, transportation fuels) widely traded by intermediaries, however, grades and standards came to be developed as a substitute for local trust and embeddedness in order to address information barriers and reduce transaction costs. Of course, regulatory and other barriers to successful by-product development (e.g., protectionism, negative marketing campaigns) could also be observed and were perhaps even more significant at a larger geographical scale.

While continental and inter-continental recovery linkages developed around residuals amenable to, and sufficiently valuable to, be transported over long distances (and ultimately dependent on both the development of adequate transportation infrastructure and trade liberalization), they could also deliver a much more complex division of labor. In other dimensions, however, the outline of cottonseed by-product development revolves around a familiar narrative in which profitability considerations delivered both greater wealth and incidental environmental benefits. Although we did not expand on this point, it is difficult to conceive how a few well-intentioned and environmentally conscious minds could have delivered positive advances of such variety and on such a scale. What seems certain, however, is that an undue emphasis on dealing locally with large heaps of valueless cottonseed would have resulted in overall greater environmental impact and reduced wealth creation.

While the evidence presented in this essay is partial and limited to one secondary commodity, it does suggest that much conceptual confusion and debate surrounding industrial symbiosis might be the result of an undue emphasis on the local/regional scale. This is not to say, of course, that the study of localized recovery linkages is not valuable, but rather that it is insufficient to grasp the true scale and scope of such linkages, including the crucial role played by a much larger division of labor (e.g., intermediaries and distant processing/production centers). As such, we suggest that the long-distance trade in secondary materials and international (often intercontinental) flows in ideas and technologies that pave the way to by-product development warrant more attention by IS theorists.

While the evidence presented in this paper is focused on one set of by-products and commodities, it arguably sheds some light on what could be considered old and new in the field of IS. It can also challenge some assumptions as to the conditions required to promote innovative resource recovery while inviting a re-examination of the role played by international collaboration and inter-disciplinary innovation.

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