Multi-plant Coordination in the US Beef Packing Industry

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Multi-plant Coordination in the U.S. Beef Packing Industry

Abstract. U.S. beef packers openly began employing multi-plant coordination during the last decade. Using the Salop Circular City framework, we demonstrate that this leads to wider spreads between downstream beef prices and upstream fed cattle prices. Taken together with market concentration, geography and transportation costs, alternative marketing arrangements, and cattle cycles and related beef packer capacity utilization, multi-plant coordination helps explain farm-to-wholesale beef price spreads that have remained wide absent any obvious market shocks. We find that, as cattle inventories decline, a multi-plant coordinator will permanently shut down a plant before a plant run as an individual profit center will shut down, which is consistent with packer behavior in recent years. We further demonstrate that adding a strategically-located packing plant, owned by a different firm, can narrow the price spread. Our results add new underpinnings to ongoing policy discussions.

1. Introduction

On February 1, 2013, Cargill, Inc. shut down its very large beef processing plant near Plainview, Texas. The permanent closure reduced the company's steer and heifer slaughter capacity by 4,650 head per day, which represented roughly 4% of U.S. fed cattle capacity at the time (Daily Livestock Report, 2013). Cargill, Inc. (henceforth Cargill) cited tight cattle supplies regionally, and in North America more broadly, as the primary motivation. A Cargill press release read:

> Given the over-capacity that exists with four major beef plants in the Texas Panhandle and a dwindling supply of cattle in the region, idling Plainview will allow Cargill to operate its other beef plants in Texas, Colorado and Kansas more consistently on a five-day-per-week basis to meet our customers' requirements, while helping us maintain our position in the U.S. beef sector (Cargill, 2013).

Cargill was not the only large beef packer to reduce capacity in response to cyclically lower cattle inventories. On August 18, 2015, Tyson Fresh Meats, Inc. announced it would cease operations at its beef slaughter facility in Denison, Iowa, "to better align its overall production capacity with current cattle supplies" (Tyson, 2015*a*). Steve Stouffer, then-president of Tyson Fresh Meats, Inc. (henceforth Tyson), said in a statement, "We believe the move to cease beef operations at Denison will put the rest of our beef business in a better position for future success" (Tyson, 2015*a*). The closure of the Denison plant further reduced U.S. slaughter capacity by an estimated 2,150 steers and heifers per day (Daily Livestock Report, 2015).[1]

While troubling to the cattle producers and communities that rely on these plants, and easy to criticize given the present-day capacity constraints, these closures were prudent business decisions at the time. Persistently tight cattle supplies in the mid-2010s drove up fed cattle prices, putting downward pressure on packer profits. Securities and Exchange Commission filings indicate higher live cattle expenses increased input costs by an astounding \$1.7 billion from 2013 to 2014 and another \$1.1 billion from 2014 to 2015 for Tyson's parent company Tyson Foods, Inc., and their beef segment reported an operating loss of \$66 million in 2015 (Tyson, 2015*b*). Plant closures brought slaughter capacity more in line with cattle inventory, allowing the remaining packing facilities to run more efficiently.

The above quotations from U.S. beef packing firms reveal that plant closures were executed

[1] According to Cattle Buyers Weekly, in the mid-2010s, Cargill closed two plants, Tyson closed one plant, JBS S.A. closed no plants, National Beef Packing Company, LLC closed one plant, and American Foods Group, LLC (primarily a non-fed beef processor) closed one plant. Cattle Buyers Weekly lists no other firms as operating multiple plants.

with company-wide capacity utilization and profits in mind. In particular, Cargill's mention of capacity utilization concerns at "other beef plants" reveals an increased use of multi-plant coordination in the beef packing sector. In this study, multi-plant coordination is defined as the firm-level coordination of procurement and slaughter activities across plants by multi-plant beef packers with the goal of maximizing corporate-level—as opposed to plant-level—profits.[2] Available empirical evidence suggests that as recently as 2005, beef packing companies did not appear to be coordinating fed cattle procurement and slaughter activities across plants in any meaningful way (Crespi and Sexton, 2004; Koontz and Lawrence, 2010). Subsequent implementation of multi-plant coordination is surely related to the adoption of modern information management systems.

Hence, the question is not *if* or even *when* beef packers shifted to completely implementing multi-plant coordination—their own statements confirm the use of this practice, and the uptake must have begun sometime after 2005. Instead, the relevant question to ask is, *what are the possible implications* of this business practice for the different segments of the beef supply chain? As will be demonstrated, the beef packing industry's move to multi-plant coordination helps explain recently-observed price dynamics. Namely, U.S. Department of Agriculture (USDA) Economic Research Service beef price spread data indicates that from January 2010 until August 2015, when Tyson closed its Denison plant, aggregate farm-to-wholesale beef price spreads averaged \$34/cwt.[3] From September 2015 through the end of 2021, the farm-to-wholesale price spread averaged \$88/cwt. Price spreads in 2021 were especially high, averaging \$156/cwt. These price spreads initially widened temporarily following the August 2019 fire at the Tyson packing plant near Holcomb, Kansas, and again in 2020 due to packing plant disruptions in the wake of COVID-19 (USDA-AMS, 2020*a*; Lusk, Tonsor, and Schulz, 2021). Both Lusk, Tonsor, and Schulz (2021) and Azzam and Dhoubhadel (2021) find evidence that price spreads following COVID-19 disruptions were consistent with perfect competition, and even producer organizations acknowledge it is "not unreasonable to expect ripple effects from these

[2]This is similar to the definition implicitly used by Koontz and Lawrence (2010). It is also similar to the definition used by Chen (2002) in a study of the U.S. petroleum refining industry, but differs slightly from the definition provided by Bhatnagar, Chandra, and Goyal (1993), who emphasize operation of multiple plants that are vertically integrated.

[3]The USDA Economic Research Service farm-wholesale-retail meat price spread series is widely used for informing producers, retailers, food service, consumers, analysts, consultants, investors, academics, government agencies, market regulators, and policymakers about livestock and meat price relationships (Schroeder et al., 2019). Schroeder et al. (2019) and Lusk, Tonsor, and Schulz (2021) provide definitions, measurement details, and interpretation of price spread data. Recent data is available online at https://www.ers.usda.gov/data-products/meat-price-spreads/meat-price-spreads/, with historical data being compiled and made available by the Livestock Marketing Information Center.

events" (Hoffmann, 2021). That said, conspicuously wide farm-to-wholesale beef price spreads have persisted without any analogous exogenous market shock.

While multi-plant coordination alone does not explain these persistently wide price spreads, the business practice is right at the nexus of a host of hot-button features of the U.S. beef supply chain, including concentration, geography and transportation costs, alternative marketing arrangements (AMAs), and cattle cycles and packing capacity. There is no shortage of academic literature pertaining to these cattle industry characteristics, but none of these features alone has been demonstrated to cause such price spread behavior. Accordingly, this study proposes that it is multi-plant coordination in conjunction with these salient features that is the cause of observed trends in beef price spreads. Simply put, given packing plants were optimizing independently before 2005, and then the largest processors subsequently began coordinating procurement and slaughter activities across plants, it is as if more than 20 separate economic agents suddenly consolidated into four. While not necessarily the motivation for packers employing multi-plant coordination, this undoubtedly has implications for beef price spreads and the competitiveness of fed cattle pricing in aggregate. Hence, this business practice must be taken into careful consideration as producers, beef packers, government entities, and other stakeholders consider consequential actions for the industry and its future.

This study proceeds as follows. Section 2 discusses key features of the U.S. beef supply chain and provides a review of relevant literature. In section 3, we develop theoretical models from a Salop Circular City framework that feature cattle producers who supply fed cattle to beef packing plants. The baseline model in section 3.1 considers processing plants that maximize profits at the plant level, with the key insight being that prices offered to cattle producers are a function of downstream (boxed) beef prices, a transportation cost parameter, and variable costs such as labor. In section 3.2, we present a multi-plant coordination model, which is the same as the baseline model except that beef packer profit maximization occurs at the firm level as opposed to the individual packing plant level. The primary result from this model is that multi-plant coordination results in beef price spreads that *ceteris paribus* are wider than when multi-plant coordination is not being employed. Section 3.3 demonstrates that as cattle inventories decline a multi-plant coordinator will permanently shut down a plant before a plant run as an individual profit center will shut down. This finding is consistent with packer shutdown decisions observed in recent years. Section 3.4 presents a scenario that is

extremely relevant for current policy deliberations, showing that a new beef packing plant opened by a different firm can lead to a narrowing of the spread between the downstream beef price and fed cattle prices. Section 4 concludes and draws a connection between packers effectively implementing multi-plant coordination and the adoption of computing technology for supply chain management.

2. Industry Background and Literature Review

A far cry from the cowboys and cattle drives enshrined in Americana, the U.S. beef supply chain has changed over time in response to demand, labor markets, and technology (MacDonald, 2003). In 2020, the United States ranked first internationally in beef and veal production with nearly 12.4 million metric tons produced, and first in domestic beef and veal consumption with more than 12.5 million metric tons consumed (USDA-FAS, 2021). In 2020 alone, U.S. cattle marketed for slaughter generated \$63.1 billion of receipts and resulted in \$123.3 billion (retail equivalent value) of beef produced (USDA-ERS, 2021*a*). The industry changes that have taken place to support such levels of production, processing, trade, and end-user consumption, however, have not come without controversy.

Beef packing consolidation occurred rapidly in recent decades. The beef packing industry had a four-firm concentration ratio of 36% in 1980 (USDA-GIPSA, 2006). However, by 1995, four-firm concentration for beef packers exceeded 80% and has remained near or above that level ever since (USDA-AMS, 2020*b*; USDA-GIPSA, 2006). Consider Figure 1, which depicts U.S. beef packing plants with more than 500-head-per-day of fed cattle slaughter capacity. In Figure 1, dot size indicates slaughter capacity while dot color indicates firm ownership. As can be seen, the largest plants are owned by the four largest firms, and each of the four largest firms owns more than one large plant.

Operating multiple plants in different geographic regions has long been recognized as a potential source for economic advantages in a variety of industries including beef packing (Azzam and Schroeter, 1995; Scherer et al., 1975). That said, there has been limited work regarding the economic rationale of operating multiple plants in the beef packing industry specifically, with advantages typically being assumed (Ward, 2010). One theorized advantage is that beef packing firms with multiple plants can avoid diseconomies of scale due to transportation costs (MacDonald, 2003). Another theorized advantage is the opportunity for multi-plant firms to optimize capacity utilization across plants. As described by MacDonald (2003), packers "that own multiple plants can direct livestock flows among them in such a way as to keep plant labor and capital fully

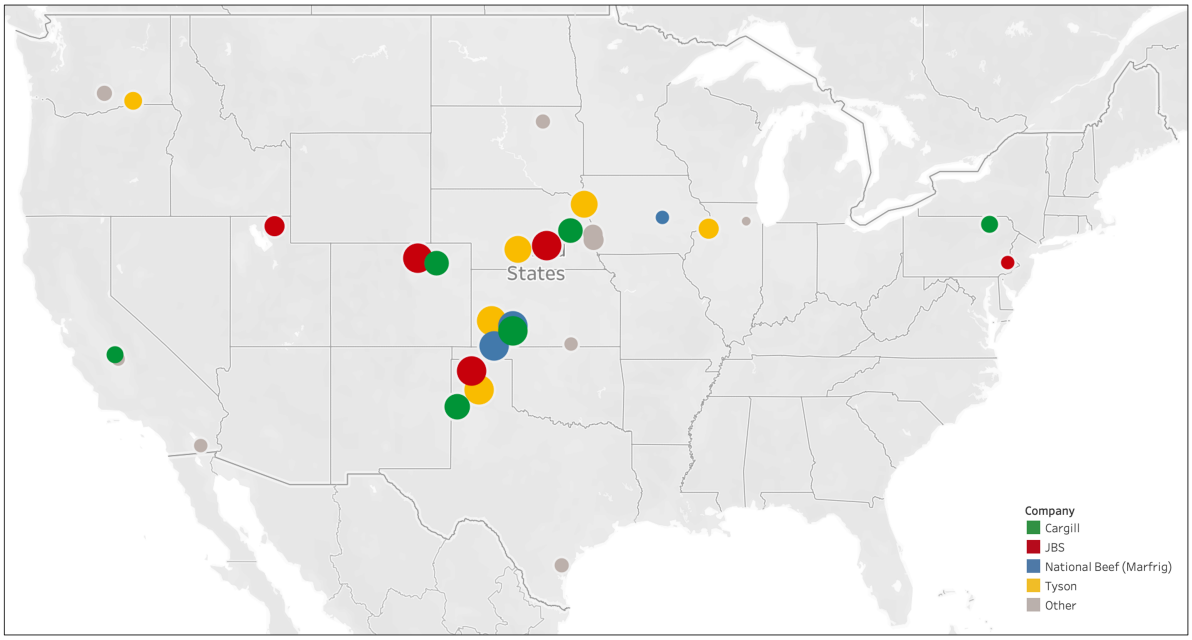

Figure 1: Beef packing plants by daily capacity (size) and firm (color) (Map created using Tableau Desktop and authors' calculations from a compilation of industry data)

employed at a planned level of hours of use" (p. 431). This multi-plant coordination of slaughter volumes allows for firm-level profit maximization—beef packers can maximize profits by allocating cattle among packing plants in order to supply optimal levels of beef to downstream users while making best use of processing capacity. Operating in such a way has benefits for beef packers, since when "one plant is closed for food safety reasons, other plants can continue operating, both purchasing cattle and supplying beef and by-products to customers" (Ward, no date, p. 2). The high-profile packing plant closures in 2019 and 2020 were not related to food safety, but the intuition holds nonetheless. This reallocation occurred after the closure of the Tyson plant in Holcomb, Kansas, following the August 2019 fire, when "Tyson appears to have shipped a significant portion of the cattle it would have previously processed at the Holcomb plant to its other plants" (USDA-AMS, 2020*a*, p. 4). Finally, moving toward multi-plant coordination could allow for smaller packer procurement staffs if procurement activities are conducted at the firm level rather than the plant level. Procurement staffs are a source of significant costs to individual plants, and while often attributed to the development and use of AMAs, packers have cut procurement staffs by one-half to two-thirds in recent years (Koontz, 2015).

MacDonald (2003) makes the qualitative statement that not all packers "operate their plants as

integrated systems" (p. 431), but very few quantitative studies perform an empirical evaluation of multi-plant optimization in beef packing. Crespi and Sexton (2004) use transaction-level data for February 1995 to May 1996 to estimate packer bid functions for four beef-processing plants in the Texas Panhandle region and present evidence suggesting that plants were making cattle procurement decisions independently even though two of the plants were owned by the same firm. Koontz and Lawrence (2010) use plant-level profit and loss (i.e., accounting) data for the four largest beef packers in the United States to measure the effects of AMAs on packer profits, gross margins, and costs. In the course of doing so, they demonstrate that plant-level average total cost curves are declining, nearly linear, and notably steep. Most relevant for our study is their assertion that for the October 2002 through March 2005 period, "Very few firms appear to conduct any degree of multiplant [*sic*] coordination. For the firms that did, volumes appeared to be reduced most frequently at one or two specific small plants" (Koontz and Lawrence, 2010, p. 21). In particular, they point out that monthly slaughter volumes are highly positively correlated across plants within multi-plant firms both in levels and in first differences. Many of the plants operated at low capacity levels and experienced losses during this time period, leading them to claim that individual plants "operated as separate profit centers" (Koontz and Lawrence, 2010, p. 21). Koontz and Lawrence (2010) do admit that, from their analysis, it is difficult to make strong claims regarding multi-plant coordination since transportation costs were not considered. Despite that, available empirical evidence regarding multi-plant coordination indicates that as of 2005, it "was simply not strong" (Koontz and Lawrence, 2010, p. 21). This stands in stark contrast to the multi-plant coordination that major packers have since embraced for decisions regarding even the largest of plants.

Many studies of the beef supply chain focus on features of the fed cattle market that are theoretically distinct from, but related to, multi-plant coordination. Here we discuss literature examining four of the more salient topics and their connection with our study.

Market Concentration. Given the degree of concentration in beef packing, it should not come as a surprise that "the U.S. beef-packing sector has been the subject of more empirical studies of market power than any other industry in the world" (Sexton, 2000, p. 1092). Nevertheless, nearly every study arrives at more-or-less the same conclusion as Schroeter's (1988) seminal work on the topic—beef packing companies exert little monopsony power in the fed cattle market and little monopoly power in the beef market. Put succinctly in a recent review by Wohlgenant (2013),

"Despite the preponderance of evidence that producers are not worse off from increased concentration in livestock industries, there still remain much skepticism and allegations that anticompetitiveness by meatpackers influences prices and returns of producers" (p. 2). The near consensus in opinions among economists past and present is noteworthy. Germane to the present study is that, though concentration and multi-plant coordination are not necessarily related other than tautologically, they are still related (Scherer et al., 1975).

Geography and Transportation Costs. Many studies of the fed cattle industry recognize the nearly definitional nature of geography, and consequentially transportation costs, in fed cattle marketing. Several studies evaluate market integration in U.S. cattle feeding regions, both before the implementation of Livestock Mandatory Reporting (LMR) (Goodwin and Schroeder, 1991) and after (Pendell and Schroeder, 2006). Generally speaking, these studies suggest regional markets have become more integrated over time, particularly after LMR was enacted. More recently, the literature attempts to account for region-specific geography effects. Crespi and Sexton (2005) find that fed cattle prices in the Texas Panhandle region were $5\% - 10\%$ below prices in a competitive setting. They attribute these lower prices in large part to transportation costs that make shipping cattle to other regions prohibitive. Pudenz and Schulz (2021) show that basis for fed dairy cattle widened by as much as $\$15$/cwt (depending on the transaction type) in the Iowa-Minnesota reporting region following the decision by Tyson in late 2016 to stop procuring fed dairy cattle, many of which were slaughtered at its plant in Joslin, Illinois. McKendree, Saitone, and Schaefer (2021) demonstrate the national implications of this change in procurement practices, finding that national fed Holstein prices decreased 5.5% for cattle marketed on a live weight basis (3.5% on a dressed weight basis) as a result of Tyson's decision. The fact that procurement practice changes largely impacting a single plant could have such a large price impact highlights a broader point made by Crespi, Saitone, and Sexton (2012), which is the "ever-increasing importance of shipping costs in defining regional procurement markets" (p. 678). In fact, survey data suggests that fed cattle are travelling further to slaughter facilities than they have in the past. In 2011, cattle from U.S. feedlots with more than $1,000$ head capacity traveled an average of 166 miles (USDA-APHIS-VS, 2013). This is an increase from 1999, during which comparable surveys

indicated that cattle travelled an average of 132 miles to slaughter (USDA-APHIS-VS, 2000).[4] Geographical and transportation considerations matter greatly for the fed cattle industry and can have notable price impacts for fed cattle producers. That said, none of these studies suggest that geography by itself has enough of an impact to explain current price spread behavior.

Alternative Marketing Arrangements (AMAs). The impacts of cattle procured through AMAs—formerly called captive supplies—have also been frequently studied. Two early studies of AMAs in cattle markets are Hayenga and O'Brien (1991) and Elam (1992). While the former provides mixed results regarding the impact of forward contract deliveries in other states on Colorado cattle market prices, the latter uses correlation coefficients and price transmission equations to show that contracting volume has a negative impact on cash prices. Xia and Sexton (2004) present a theoretical model that demonstrates how, in certain situations, use of a specific type of AMA can lead to lower spot market prices. Even so, AMAs continue to increase in prevalence and prominence, with roughly 20% of national fed cattle trade occurring in the negotiated cash (i.e., spot) market in any particular week.[5] These AMAs are a cost-reducing innovation that provide benefits to beef packers and the cattle producers who adopt them. Specifically, AMAs reduce packer and producer costs of participating in the cash market (Koontz, 2015). AMAs also help producers secure beef market program premiums and meet customer demand specifications (Schroeder, Coffey, and Tonsor, 2021). Federal legislation addressing low spot market volumes by forcing a certain percentage of transactions (e.g., 50%) has been discussed for nearly 20 years (Grassley, 2021), but some economists argue that such policies are welfare reducing for cattle producers as a whole (Anderson, Mitchell, and McKenzie, 2022; Koontz, 2021). Hence, the literature does not support the notion that AMAs by themselves are responsible for observed farm-to-wholesale price spread dynamics, though the supply chain and packing capacity management benefits of AMAs may allow for effective multi-plant coordination.

Cattle Cycles and Packer Capacity. Cattle cycles have long been recognized as a prominent feature of the U.S. cattle industry (Rosen, Murphy, and Scheinkman, 1994). Packer capacity is not unlimited, so as cattle supplies vary throughout the cattle cycle, packer procurement decisions do

[4] Conversations with individuals familiar with the industry lead us to believe these distances are even longer today than they were in 2011, suggesting transportation costs could have an even greater impact.

[5] Current and historical data is available in the National Weekly Fed Cattle Comprehensive reports at https://usda.library.cornell.edu/concern/publications/c534g2593?locale=en.

as well (McKendree, Saitone, and Schaefer, 2021; Pudenz and Schulz, 2021). Separate research demonstrates that higher cattle inventories can lead to lower fed cattle prices, and that increased beef packer market power in cattle procurement amplifies this effect (Crespi, Xia, and Jones, 2010). The current cattle inventory cycle began in 2014 and is just past its peak. Many market analysts view persistently wide beef price spreads as being primarily a result of cattle supplies being out of step with slaughter capacity, and that the spread will narrow as cattle supplies contract and slaughter capacity increases in coming years. In Congressional testimony in June 2021, then RaboResearch Animal Protein Analyst Dustin Aherin asserted:

> With any luck we will work through the long tail of 2020's cattle backlog in Q3 2021. As such, year-over-year cattle prices will rise in 2H 2021 and beyond. In conjunction with tightening cattle supplies, capacity expansion will come online over the next several years and new technologies will reduce labor constraints, further shifting margins to the benefit of cattle producers (Aherin, 2021).

This explanation is sound, but less than complete. Large cattle supplies and correspondingly high beef packing capacity utilization at the peaks of cattle inventory cycles are not a new phenomenon (Tonsor and Schulz, 2020). In fact, two cattle cycles have had peaks (i.e., 1996 and 2007) since beef packer concentration more or less leveled out in 1995, but in neither case were such wide price spreads observed. Exogenous market shocks like the 2019 Holcomb packing plant fire and the 2020 COVID-19 induced packing plant disruptions certainly did not work to narrow the price spread, but something must have changed since the last cattle cycle peak in 2007 to cause such extraordinary price spreads to persist without any obvious precipitating market shock.

These four concepts overlap and are frequently discussed together. What has not yet been addressed in the literature, however, is how multi-plant coordination is directly related to all of them. Koontz and Lawrence (2010) get the closest to doing so, but the authors themselves admit that, from their analysis, it is difficult to make strong claims regarding multi-plant coordination since transportation costs were not considered. Crespi and Sexton (2004) also discuss these features and do account for transportation costs, but their reported results on the subject of multi-plant coordination are limited due to nondisclosure requirements.

Theoretical studies are not uncommon in the robust literature focusing on the U.S. beef supply chain. These studies typically are of the "applied theory" variety, and often focus on producing a "possibility result" for a non-obvious research question. In many cases, empirical evaluations of

these research questions are difficult because of the lack of publicly available data. For instance, Xia and Sexton (2004) use a two-period model to demonstrate that a specific kind of AMA in the first period can lead to depressed spot market prices in the second period. This particular study created its own sub-literature, with Zhang and Brorsen (2010), Crespi and Xia (2015), and Xia, Crespi, and Dhuyvetter (2019) developing the model further. Other theoretical studies abound, and our study takes a similar approach.

3. Theoretical Models

We adapt our theoretical models from the standard Salop Circular City framework (Belleflamme and Peitz, 2015). We make two primary modifications to the Salop framework. First, while location in the Salop framework typically represents location in quality or characteristic space, location in our models represents location in geographic space. Second, a situation with many buyers and few sellers usually motivates the Salop framework, while in our models there are many sellers and few buyers. These are similar to the adaptations Zhang and Sexton (2001) made to the Hotelling Linear City model, but the Salop model is more appropriate for modeling entry and exit.

3.1. Baseline Model

Let N beef packing plants be distributed equidistantly on a circle with circumference equal to 1. Let these packing plants be indexed by $n \in \{1, ..., i-1, i, i+1, ..., N\}$. Each beef packing plant offers the same plant-gate price for fed cattle (input) to all producers.[6] In regard to processing technology, each plant converts fed cattle into boxed beef (output) according to a fixed proportions technology in cattle and variable inputs, which precludes substitution between cattle and other variable inputs (e.g., labor) for beef production (Lusk, Tonsor, and Schulz, 2021; Ma and Lusk, 2021; Xia and Sexton, 2004; Zhang and Sexton, 2001). Let units of fed cattle be chosen such that fed cattle prices and boxed beef values are directly comparable.

In the baseline model, assume that, as asserted by Koontz and Lawrence (2010) regarding the 2002–2005 time period, packing plants are not employing multi-plant coordination. Clearly, the degree of implementation of multi-plant coordination falls on a spectrum, but to illustrate the point most distinctly, we assume the case here that individual plants are "operated as separate profit

[6] Fed cattle are marketed in various ways, including according to animal sex (i.e., steers, heifers, mixed lots), selling basis (i.e., live FOB, live delivered, dressed FOB, dressed delivered), and transaction type (i.e., negotiated, formula, forward contract, negotiated grid). This model assumes a single equilibrium plant-gate cattle price for each plant, which is reasonable in light of optimizing behavior in response to arbitrage opportunities across cattle marketing methods.

centers" (Koontz and Lawrence, 2010, p. 21). Hence, the ownership structure of the N plants does not impact the results of the baseline model and will be left undefined.

Let mass M of cattle producers be uniformly distributed on the circle. These producers are identical aside from location on the circle, which represents geographical location and is denoted by index $m \in [0, 1]$. Each of the M producers supplies one unit of fed cattle inelastically as long as the farm-gate price the producer receives is greater than reservation price f (Crespi and Sexton, 2004). For producers supplying cattle to plant n, this farm-gate price equals the plant-gate price r_n less transportation costs, which are a linear function of the distance from plant n to producer m's position on the circle. Assume that transportation costs are entirely passed through to the producer (Koontz and Lawrence, 2010). Hence, producer m faces the following decision problem:

$$\max_{n \in \{i, i+1\}} \{r_n - \tau |l_n - m|, f\} \tag{1}$$

where plants $n = i$ and $i+1$ are the plants on either side of cattle producer m, with plant n's location being $l_n = n/N$. Let producer $m_{i,i+1}$ be the cattle producer who is indifferent between supplying their cattle to packing plants i and $i + 1$. This indifferent producer is defined by:

$$r_i - \tau \left(m_{i,i+1} - \frac{i}{N} \right) = r_{i+1} - \tau \left(\frac{i+1}{N} - m_{i,i+1} \right) \tag{2}$$

This expression can be solved for $m_{i,i+1}$:

$$m_{i,i+1} = \frac{r_i - r_{i+1}}{2\tau} + \frac{2i+1}{2N} \tag{3}$$

Substituting $i - 1$ for i, producer $m_{i-1,i}$ is the cattle producer who is indifferent between supplying their cattle to packing plant $i - 1$ and i. This producer is defined as:

$$m_{i-1,i} = \frac{r_{i-1} - r_i}{2\tau} + \frac{2i-1}{2N} \tag{4}$$

Assuming in equilibrium that r_i is sufficiently high relative to reservation price f (i.e., the market is "covered"), plant i attracts all fed cattle located between indifferent producers $m_{i-1,i}$ and $m_{i,i+1}$.

Given there is mass M of producers, this means that the quantity supplied to plant i is:

$$q_i\left(r_{i-1}, r_i, r_{i+1}\right) = \left(m_{i,i+1} - m_{i-1,i}\right) * M = \left(\frac{2r_i - r_{i-1} - r_{i+1}}{2\tau} + \frac{1}{N}\right) * M \tag{5}$$

Let all plants $n \in \{1, ..., N\}$ have a large fixed cost associated with fixed processing inputs (e.g., capital), and constant marginal costs in variable processing inputs (e.g., labor). Constant marginal costs in processing inputs is a standard assumption in studies of the beef packing industry (Crespi, Xia, and Jones, 2010; Xia, Crespi, and Dhuyvetter, 2019; Xia and Sexton, 2004; Zhang and Brorsen, 2010). Furthermore, constant marginal costs with a large fixed cost is consistent with Koontz and Lawrence (2010), who show that for 2002-2005 average total cost functions were decreasing and "were not U-shaped, or at least plants never operate on the increasing cost portion, nor was there a flat spot reflecting a minimum" (p. 6). This is also consistent with Morrison Paul (2001), who finds "incentives on the margin for firms to expand utilization of existing capacity if allowed by demand conditions, but otherwise to remain in an equilibrium situation on a downward sloped portion of the average cost curve" (p. 75). Hence, the cost structure for each beef packing plant is appropriately modeled as $C(q_n) = \gamma + c * q_n$. Without loss of generality, let plant i choose r_i to maximize profits while taking producer supply q_i into account:

$$\max_{r_i} \Pi\left(r_i\right) = \left(p - r_i\right) * q_i - \gamma - c * q_i \tag{6}$$

$$\text{subject to } q_i\left(r_{i-1}, r_i, r_{i+1}\right) = \left(\frac{2r_i - r_{i-1} - r_{i+1}}{2\tau} + \frac{1}{N}\right) * M$$

Substituting the constraint into the maximization problem, we have:

$$\max_{r_i} \Pi\left(r_i\right) = \left(p - r_i\right) * \left(\frac{2r_i - r_{i-1} - r_{i+1}}{2\tau} + \frac{1}{N}\right) M - \gamma - c * \left(\frac{2r_i - r_{i-1} - r_{i+1}}{2\tau} + \frac{1}{N}\right) M \tag{7}$$

Taking the first order condition with respect to r_i, equating it to zero, and simplifying yields:

$$p - 2r_i + \frac{r_{i-1}}{2} + \frac{r_{i+1}}{2} - \frac{\tau}{N} - c = 0 \tag{8}$$

N such equations, one for each plant n, implicitly define optimal prices r_n^*. Recalling that plants are distributed equidistantly, and that plants have identical cost structures, the focus here is on the

symmetric equilibrium in which the plants, though operating as their own profit centers, each find it optimal to offer the same price for fed cattle. Setting $r_n = r$ for $n = 1, ..., N$, we first note that the optimal supply function simplifies to:

$$q^* = \frac{M}{N} \tag{9}$$

This means that all plants slaughter an equal quantity of cattle in equilibrium. Next, we solve for the following expression for symmetric equilibrium price r^*:

$$r^* = p - \frac{\tau}{N} - c \tag{10}$$

This price has a straightforward interpretation—the plant-gate fed cattle price offered by the packing plants is the downstream beef price less the so-called packer margin, which in this case is a combination of costs related to transportation and processing. When $N = 4$, as will be the case in the following section, optimal price and quantity are, respectively:

$$r^* = p - \frac{\tau}{4} - c \tag{11}$$

$$q^* = \frac{M}{4} \tag{12}$$

3.2. Multi-plant Coordination Model

In section 3.1, we develop a baseline model in which, as Koontz and Lawrence (2010) suggest, packing plants operate as independent profit centers even though they may be owned by the same firm. In this section, we construct a model that incorporates multi-plant coordination of procurement and slaughter activities to maximize packing firm profits.

For concreteness, suppose there are two packing firms, A and B, as in figure 2. Let these packing firms each own two plants, with packing firm A (dotted circles) owning plants 1 and 2 and packing firm B (diagonally-striped circles) owning plants 3 and 4. Assume all $n \in \{1, ...4\}$ plants are equidistant as they are in the baseline model. Let plants 1 and 2 be located next to each other on the unit circle, and let plants 3 and 4 also be located next to each other. This market arrangement is depicted in figure 2.[7]

[7] An alternative market alignment is possible in which no two plants owned by the same firm are located next to each other. That arrangement, however, does not allow for multi-plant coordination in the context of the Salop framework. Since multi-plant coordination is the focus of study, we proceed with the specification shown in figure 2.

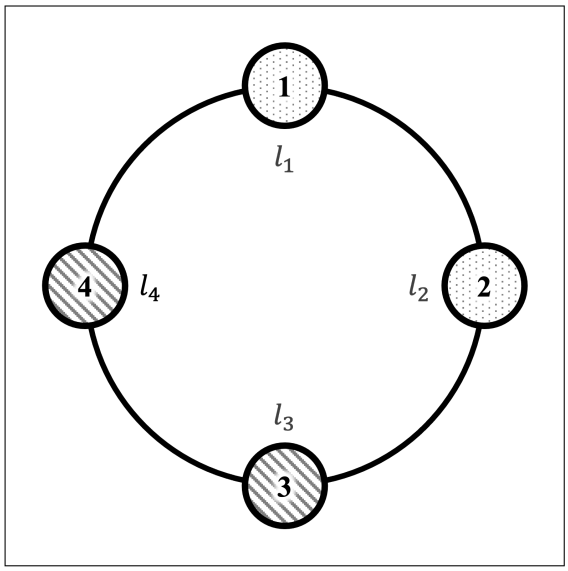

Figure 2: Beef packing plant locations for firm A (dotted circles) and firm B (diagonally-striped circles) in the multi-plant coordination model

The fed cattle producer problem remains the same as in the baseline model, but now we consider the case for beef packers in which each packing firm is maximizing profits at the firm—rather than the plant—level. Without loss of generality, consider firm A's profit maximization problem:

$$\max_{r_1^A, r_2^A} \Pi\left(r_1^A, r_2^A\right) = \left(p - r_1^A\right) * q_1 - \gamma - c * q_1 + \left(p - r_2^A\right) * q_2 - \gamma - c * q_2 \tag{13}$$

$$\text{subject to } q_1 = \left(\frac{2r_1^A - r_2^A - r_4^B}{2\tau} + \frac{1}{4}\right) * M$$

$$\text{and } q_2 = \left(\frac{2r_2^A - r_1^A - r_3^B}{2\tau} + \frac{1}{4}\right) * M$$

where r_1^A is firm A's plant-gate price for plant 1, r_2^A is firm A's plant-gate price for plant 2, and expressions for q_1 and q_2 are found by adapting cattle supply equation (5) for $N = 4$ plants. Plugging q_1 and q_2 into the maximization problem, we take the first order conditions with respect to r_1^A and r_2^A, set them equal to 0, and simplify to obtain:

$$r_1^A : \frac{p}{2} - 2r_1^A + r_2^A + \frac{r_4^B}{2} - \frac{\tau}{4} - \frac{1}{2}c = 0 \tag{14}$$

$$r_2^A : \frac{p}{2} - 2r_2^A + r_1^A + \frac{r_3^B}{2} - \frac{\tau}{4} - \frac{1}{2}c = 0 \tag{15}$$

By analogy, first order conditions can also be found for firm B, which operates plants 3 and 4:

$$r_3^B : \frac{p}{2} - 2r_3^B + r_4^B + \frac{r_2^A}{2} - \frac{\tau}{4} - \frac{1}{2}c = 0 \tag{16}$$

$$r_4^B : \frac{p}{2} - 2r_4^B + r_3^B + \frac{r_1^A}{2} - \frac{\tau}{4} - \frac{1}{2}c = 0 \tag{17}$$

Since the previously built plants are equidistant and have identical cost structures, it follows to once again focus on the solution where prices are equal across all plants. Let this multi-plant coordination price be $\tilde{r}$. Notice that this again leads to a much simpler expression for optimal quantity supplied to each of the four plants:

$$\tilde{q}^* = \frac{M}{4} \tag{18}$$

Substituting $\tilde{r}$ into the first order conditions where appropriate, and simplifying, we are left with four identical first order conditions of the following formulation:

$$p - \tilde{r} - \frac{\tau}{2} - c = 0 \tag{19}$$

Solving for $\tilde{r}$, we obtain the following optimal plant-gate price under multi-plant coordination:

$$\tilde{r}^* = p - \frac{\tau}{2} - c \tag{20}$$

The optimal multi-plant coordination plant-gate fed cattle price $\tilde{r}^*$ is strictly lower than fed cattle price r^* when packers are not employing multi-plant coordination. This means that, all else equal, all producers receive lower farm-gate prices and the average farm-to-wholesale beef price spread is wider after packers effectively implement multi-plant coordination. Multi-plant coordination plant-gate price $\tilde{r}^*$ is less than r^* by $\frac{\tau}{4}$, which is clearly a function of transportation cost parameter τ. That said, the larger price spread after the implementation of multi-plant coordination is *not* reflective of beef packers or producers paying higher costs, transportation or otherwise. Instead, the wider price spread is simply the result of multi-plant coordinators capitalizing on reduced "competition" in the market to decrease their own fed cattle input costs.

This does not mean, however, that other factors such as increased transportation and labor costs are irrelevant for recently observed price spread behavior. Farm-gate prices equal $\tilde{r}^*$ less

transportation costs, and simple comparative statics further show that $\tilde{r}^*$ itself is a decreasing function of both transportation costs and variable input costs. Given that transportation costs increased in the United States in 2021 relative to 2020, and labor challenges continue to plague the U.S. economy, these increased costs have contributed to wider price spreads that have already been made wider by multi-plant coordination.

3.3. Optimal Plant Closure

Suppose that beef packing firm A closes plant 2. Assume that the cattle previously slaughtered at plant 2 must be slaughtered at the remaining three plants. This is consistent with the inelastic supply of cattle in the short– to medium–run (USDA-ERS, 2021*b*). Importantly, since the remaining packing plants cannot be moved, the packing plants are not equidistant from each other as they have been thus far. This means that the profit maximization problem will need to be considered explicitly for each firm. Consider first the profit maximization problem for firm A:

$$\max_{r_1^A} \Pi\left(r_1^A\right) = \left(p - r_1^A\right) * q_1 - \gamma - c * q_1 \tag{21}$$

$$\text{subject to } q_1 = \left(\frac{2r_1^A - r_3^B - r_4^B}{2\tau} + \frac{3}{8}\right) * M$$

Notice that the expression for q_1 in firm A's maximization problem after the shutdown is similar in formulation but not exactly analogous to q_1 in firm A's profit maximization problem (13) before the shutdown. This stems from there being a new indifferent cattle producer (i.e., producer $m_{1,3}$) following the shutdown of plant 2. Producer $m_{1,3}$'s location is found by starting with a maximization problem akin to indifferent producer problem (1).

Proceeding, we substitute the expression for q_1 into the objective function, and take the first order condition with respect to r_1^A. Setting the first order condition equal to 0, we simplify to obtain:

$$r_1^A : p - 2r_1^A + \frac{r_3^B}{2} + \frac{r_4^B}{2} - \frac{3\tau}{8} - c = 0 \tag{22}$$

Hence, firm A's optimal pricing decision rule depends on the prices set by firm B. Turning now to firm B's maximization problem, multi-plant coordinator firm B chooses prices r_3^B and r_4^B in the following profit maximization problem:

$$\max_{r_3^B, r_4^B} \Pi\left(r_3^B, r_4^B\right) = \left(p - r_3^B\right) * q_3 - \gamma - c * q_3 + \left(p - r_4^B\right) * q_4 - \gamma - c * q_4 \tag{23}$$

$$\text{subject to } q_3 = \left(\frac{2r_3^B - r_1^A - r_4^B}{2\tau} + \frac{3}{8}\right) * M$$

$$\text{and } q_4 = \left(\frac{2r_4^B - r_1^A - r_3^B}{2\tau} + \frac{1}{4}\right) * M$$

Plugging q_3 and q_4 into firm B's problem, we then take first order conditions with respect to r_3^B and r_4^B. Equating these first order conditions with 0, the following optimal decision rules can be derived:

$$r_3^B : \frac{p}{2} - 2r_3^B + \frac{r_1^A}{2} + r_4^B - \frac{3\tau}{8} - \frac{1}{2}c = 0 \tag{24}$$

$$r_4^B : \frac{p}{2} - 2r_4^B + \frac{r_1^A}{2} + r_3^B - \frac{\tau}{4} - \frac{1}{2}c = 0 \tag{25}$$

Taken all together, first order conditions (22), (24), and (25) give us a three equation system with three unknowns, yielding the following solutions:

$$r_1^{A*} = p - \frac{22\tau}{48} - c \tag{26}$$

$$r_3^{B*} = p - \frac{27\tau}{48} - c \tag{27}$$

$$r_4^{B*} = p - \frac{25\tau}{48} - c \tag{28}$$

These optimal plant-gate prices can be easily verified by plugging them back into first order conditions (22), (24), and (25) and simplifying to show that the first order conditions hold. To calculate optimal quantities of cattle flowing to each plant, we use our expressions for q_1, q_3, and q_4 and plug in optimal post-shutdown prices (26) through (28) where appropriate:

$$q_1^* = \frac{44M}{96} \tag{29}$$

$$q_3^* = \frac{29M}{96} \tag{30}$$

$$q_4^* = \frac{23M}{96} \tag{31}$$

Optimal plant-gate prices and plant quantities are not symmetric as they were before due to the fact

that plants are no longer located equidistantly from each other. Both r_3^{B*} and r_4^{B*} are lower than $\tilde{r}^*$, which means that firm B's plant-gate prices are lower than they were before the shutdown. Firm A's plant 1 offers a slightly higher plant-gate price than it did before the shutdown, but straightforward calculations verify that the (weighted) average plant-gate price for the whole market is slightly lower than it was before the shutdown. Furthermore, the average farm-gate price is lower after the shutdown than before since the producers located most closely to where plant 2 used to be located are now netting much lower prices once transportation costs are considered. This means that the average farm-to-wholesale price spread is wider than it was before the shutdown. In regard to optimal quantities, plants 1 and 3 slaughter more cattle after plant 2 shuts down than before. Plant 1, which is still owned by firm A, harvests a much larger volume of cattle than previously, while plant 3 slaughters only marginally more cattle. Plant 4 harvests fewer cattle, however, due to competition between plants 1 and 3 for the cattle previously slaughtered by plant 2. That said, firm B overall slaughters more total cattle than it did before plant 2 shut down, and it does so while offering lower plant-gate prices.

Thus, it has been shown that firm A shutting down plant 2 results in a situation in which firm A slaughters more fed cattle but must offer a higher plant-gate price at plant 1 to procure those cattle. This raises the question—when will multi-plant coordinator A permanently shut down plant 2? Total profit before and after the shutdown, respectively, can be used to calculate the following shutdown condition:

$$\begin{aligned} 2\left(p-\tilde{r}^*\right)*\tilde{q}^*-2c*\tilde{q}^*-2\gamma &< \left(p-r_1^{A*}\right)*q_1^*-c*q_1^*-\gamma \\ \implies \left(\frac{1}{4}\right)\tau M-2\gamma &< \left(\frac{11}{24}\right)^2\tau M-\gamma \\ \implies \left(\frac{23}{576}\right)\tau M-\gamma &< 0 \end{aligned} \tag{32}$$

Shutdown condition (32) describes when firm A shutting down plant 2 is more profitable than keeping it running. Several features of this shutdown condition are noteworthy. First, the left hand side is increasing in both transportation costs τ and cattle inventories M. In regard to cattle inventories, this means that a multi-plant coordinator is more likely to shut down a plant when fed cattle supplies cyclically decline. How does this compare with the condition for shutting down

plant 2 when firm A is not using multi-plant coordination? Comparing plant 2's profit when it is optimizing independently to 0, the following shutdown condition is derived:

$$(p - r^*) * q^* - c * q^* - \gamma < 0$$

$$\implies \left(\frac{1}{16}\right) \tau M - \gamma < 0 \tag{33}$$

Comparing shutdown conditions (33) and (32), we see that as M decreases, the shutdown condition for the multi-plant coordinator holds (i.e., becomes negative) before the shutdown condition for the independent plant does. This means that as cattle inventory falls, a multi-plant coordinator will shut down one of its plants before a plant operating on its own will shut down. This finding corroborates the timing of the implementation of multi-plant coordination—Koontz and Lawrence (2010) tell us beef packing firms did not shut down plants in the 2002-2005 period at the bottom of the cattle cycle, but after effectively implementing multi-plant coordination, some packers did choose to shut down plants in the 2013-2015 period during the trough of the subsequent cattle cycle.

3.4. New Plant

Let a new plant owned by firm E be built in location $l_2 = \frac{2}{4}$. Being owned by an entrant firm, the new plant has a potentially different cost structure from the preexisting plants owned by incumbent firms A and B. This cost structure for firm E's plant is denoted as $C_2(q_2) = \gamma_2 + c_2 * q_2$. This new-plant entry is very similar to how Cattlemen's Heritage Beef Company is planning to build a packing plant with capacity for $1{,}500$ head per day near Glenwood, Iowa, which is less than 80 miles from the closed plant previously operated by Tyson in Denison, Iowa (Iowa Cattlemen's Association, 2021). Firm E's maximization problem for this new plant involves the choice of r_2^E:

$$\max_{r_2^E} \Pi = \left(p - r_2^E\right) * q_2 - \gamma_2 - c_2 * q_2 \tag{34}$$

$$\text{subject to } q_2\left(r_1^A, r_2^E, r_3^B\right) = \left(\frac{2r_2^E - r_1^A - r_3^B}{2\tau} + \frac{1}{4}\right) * M$$

Substituting the supply function into the maximization problem, taking the first order condition with respect to r_2^E, and setting it equal to 0, we derive:

$$p - 2r_2^E + \frac{r_1^A}{2} + \frac{r_3^B}{2} - \frac{\tau}{4} - c_2 = 0 \tag{35}$$

Though firm A's plant 1 was preexisting, equidistant plant locations mean the first order condition for firm A's plant 1 can still be found by analogy:

$$p - 2r_1^A + \frac{r_2^E}{2} + \frac{r_4^B}{2} - \frac{\tau}{4} - c = 0 \tag{36}$$

Now all that remains is the maximization problem for multi-plant coordinator B. Firm B chooses prices r_3^B and r_4^B to maximize profit in the following problem:

$$\max_{r_3^B, r_4^B} \Pi\left(r_3^B, r_4^B\right) = \left(p - r_3^B\right) * q_3 - \gamma - c * q_3 + \left(p - r_4^B\right) * q_4 - \gamma - c * q_4 \tag{37}$$

$$\text{subject to } q_3 = \left(\frac{2r_3^B - r_2^E - r_4^B}{2\tau} + \frac{1}{4}\right) * M$$

$$\text{and } q_4 = \left(\frac{2r_4^B - r_1^A - r_3^B}{2\tau} + \frac{1}{4}\right) * M$$

Substituting the supply equations into the objective function, we take the first order conditions with respect to r_3^B and r_4^B, and simplify:

$$r_3^B : \frac{p}{2} - 2r_3^B + r_4^B + \frac{r_2^E}{2} - \frac{\tau}{4} - \frac{1}{2}c = 0 \tag{38}$$

$$r_4^B : \frac{p}{2} - 2r_4^B + r_3^B + \frac{r_1^A}{2} - \frac{\tau}{4} - \frac{1}{2}c = 0 \tag{39}$$

The four first order conditions given by (35), (36), (38), and (39) give us a four-equation system with four unknowns. This four-equation system can be solved for the following optimal plant-gate prices:

$$r_1^{A*} = p - \frac{3\tau}{10} - \frac{117}{145}c - \frac{28}{145}c_2 \tag{40}$$

$$r_2^{E*} = p - \frac{3\tau}{10} - \frac{57}{145}c - \frac{88}{145}c_2 \tag{41}$$

$$r_3^{B*} = p - \frac{4\tau}{10} - \frac{111}{145}c - \frac{34}{145}c_2 \tag{42}$$

$$r_4^{B*} = p - \frac{4\tau}{10} - \frac{121}{145}c - \frac{24}{145}c_2 \tag{43}$$

Once again, optimal prices (40) through (43) are readily verified by plugging them into the first order conditions and showing that the first order conditions hold. The optimal plant-gate prices yield several notable takeaways. First and foremost, if the marginal costs of operation at the new plant are equal to or less than the existing plants, it can be shown that average plant-gate and farm-gate fed cattle prices are higher, and the average farm-to-wholesale price spread is narrower, after the entry of firm E compared to after firm A shut down plant 2. This suggests that planned new plants like Cattlemen's Heritage Beef Company strategically locating near Glenwood, Iowa, could lead to narrower price spreads in the present market environment. This is directly relevant for current policy discussions since on January 3, 2022, the White House announced that it would be allocating $\$1$ billion to expand "independent" meat and poultry processing capacity in the United States. According to the fact sheet released by the White House, the additional slaughter capacity will result in "better earnings for producers" (White House, 2022). Our study speaks primarily to relative prices and not absolute prices, but if the definition of "better earnings" involves fed cattle prices that are closer to beef prices, this policy could be effective in achieving that goal.

Optimal prices (40) through (43) also show that the cost structure of the new plant enters into all cattle prices. Since new plant cost structures could follow from federal subsidies the plants receive, subsidy details will be consequential for both packers and producers. This finding is not unlike that of Azzam (2022), who shows that small packers must have equal market share with large packers for the USDA policy to work. Therefore, the U.S. federal government should think carefully about the intended and unintended impacts of subsidy dispersion.

4. Conclusion

At some point since 2005, the largest beef packers in the United States began moving toward multi-plant coordination. This business practice is highly related to other often-discussed industry features such as concentration levels, geography and transportation costs, alternative marketing arrangements, and cattle cycles and packing capacity. As we show, beef packers employing multi-plant coordination leads to wider spreads between downstream beef prices and upstream fed cattle prices. Increased employment of this business practice by individual packing firms helps

explain persistently wide farm-to-wholesale price spreads at the aggregate level.

Economists and others may wonder why, if multi-plant coordination is optimal behavior from a profit-maximization standpoint, beef packing firms have not always performed multi-plant coordination. Previous literature sheds some light on this puzzle. Summarizing surveys of 12 industries representing six countries, Scherer et al. (1975) find production cost savings opportunities associated with multi-plant coordination in most of the industries. These opportunities were not always capitalized on, however, with one provided explanation being that many firms were not able to overcome managerial difficulties associated with optimizing production across multiple plants.

The rise in capability and use of computing technology in supply chain management since 1975, and especially since 2005, is likely the impetus for the effective implementation of multi-plant coordination in beef packing. Amazon Web Services' Elastic Compute Cloud made cloud computing more accessible starting in 2006, and machine learning and artificial intelligence tools have since gained traction (Varghese, 2019). The world is also indescribably more connected electronically than in was in 2005—for frame of reference, Apple, Inc.'s world-changing first generation iPhone was introduced in 2007 (Eadicicco, 2017). It is no accident that beef packers today are more vulnerable to cybersecurity attacks such as the attack on JBS S.A. in the spring of 2021 that shut down all of its U.S. beef slaughter plants (Polansek and Mason, 2021). Firm-wide cybersecurity attacks are not possible where there are no firm-wide information technology systems, and firm-wide systems are not implemented without reason. This increased use of computing technology by multi-plant firms was predicted by Scherer et al. (1975) decades ago:

> As the capacity of electronic data processing equipment grows and as persons trained to use that capacity analytically flow from the universities into industry, the ability of multi-plant, multi-product firms to solve complex production assignment and scheduling problems is bound to increase. One significant by-product may be an increase in the cost savings realizable through multi-plant operation... We nevertheless believe that there is much unmined gold left in the hills, and that multi-plant firms are going to develop better ways of extracting it" (p. 397-398).

It seems that since 2005, beef packers have finally struck the mother lode and have figured out how to employ multi-plant coordination to extract it. As policymakers, politicians, and industry participants consider consequential actions for the beef supply chain, our study provides a launching point for future research to account for multi-plant coordination.

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