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An assessment of the relationship between sweetener prices and high fructose corn syrup deliveries in the United States

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ABSTRACT

This paper uses an application of the Bertrand model to explain the relationship between HFCS deliveries and the prices of HFCS-42 and sugar. It finds that the HFCS deliveries and the prices of HFCS-42 and refined sugar are cointegrated over the period 1994:q1-2020:q1. The main results, based on the estimated long-run elasticities, show that a one percent increase in the price of HFCS-42 decreases HFCS deliveries by 0.153 percent. One implication of this result is that it would be helpful for the HFCS industry to prevent large increases in the HFCS price, which would prevent large decreases in HFCS deliveries and its share in the U.S. sweetener market. In addition, the price of sugar does not have a significant effect on HFCS deliveries.

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Deliveries; high fructose corn syrup; prices; sugar; United States

1. Introduction

High fructose corn syrup (HFCS) was commercially introduced to the U.S. sweetener market in 1967 (Barry, Angelo, Buzzanell, & Gray, 1990). The Clinton Company increased the fructose level of the corn syrup from 15 to 42 percent and introduced HFCS-42 to the U.S. sweetener market in 1968 (Bode, Empie, & Brenner, 2014). Then, in 1977, HFCS-55 (55 percent fructose) was commercially introduced and adopted by the beverage industry as a replacement for liquid sugar (Barry et al., 1990). The increase in HFCS deliveries and utilization in the U.S. sweetener market in the 1970s might have been associated with increases in the price of sugar. For instance, the price of sugar increased from 12.4 cents a pound in 1973 to 56 cents a pound in December 1974, which was associated with The Coca-Cola company replacing 25 percent of sucrose with HFCS-42 and other beverage companies replacing 25 to 50 percent of sucrose with HFCS-42 (Forrestal, 1982, as cited in Bode et al., 2014). The price of sugar increased again from 21 cents a pound in 1976 to 52 cents a pound in 1980 (Bode et al., 2014). This is associated with The Coca-Cola company and PepsiCo increasing their HFCS-55 utilization rates from 25 to 50 percent in 1980, and to 100 percent in

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1984 (Pendergrast, 1993). It has also been argued that the HFCS industry has strategically set the price of HFCS 10 to 30 percent below the price of refined sugar (Barry et al., 1990). In addition, Lord (1995) argued that the replacement of sugar with HFCS in the manufacturing of soft drinks was motivated by a 10 percent discount of the price of HFCS-55 relative to the price of sugar. However, there have been important changes in the U.S. sweetener market since the 2000s. The deliveries of sugar were more than those of HFCS from 2007 to 2009, which was associated with the price of HFCS being higher than the price of sugar (Haley & Dohlman, 2009). McConnell (2016) also reports that the annual decrease in HFCS deliveries over the period 2006–2015 is associated with higher costs of corn, a loss of competitiveness of the price of HFCS relative to the price of sugar, and changes in the preferences of food manufacturers. Hence, it is likely that the behavior of prices of HFCS and sugar affects HFCS deliveries to the U.S. sweetener market.

The behavior of the prices of HFCS and sugar represents important economic implications for these industries. In this regard, Barros (1992) found that the price of sugar had a positive effect on the growth rate of HFCS consumption. Other research has used cointegration analysis to explain the relationship between the prices of HFCS and sugar. Williams and Bessler (1997) suggest that the price of HFCS increases in period $t + 1$ after the price of sugar has been above its long-run equilibrium in period t. Moss and Schmitz (2002a) suggest that the price of HFCS is less than the price of sugar and find that these prices move together over a range of prices where the two products are perfect substitutes. Moss and Schmitz (2004) identify three different long-run relationships between the prices of HFCS and sugar over the period 1979–2003. They argue that these results may be due to changes in the HFCS industry reaction function because of changes in the price of sugar. Evans and Davis (2002) use a different methodology and recognize the existence of an HFCS price reaction function. They find that the price of sugar has a positive and significant effect on the price of HFCS. They also suggest that a simple decrease in the price of sugar might not be associated with a significant reduction in the pattern of sweetener use in the United States. However, the long-run relationship between HFCS deliveries and the prices of HFCS and sugar is an issue that needs to be explained.

Understanding the long-run relationship between HFCS deliveries and the prices of HFCS and sugar is important to HFCS producers, sugar producers, policy makers, and academics. However, we are not aware of a study that has focused on this issue. To fill this gap in the literature, this paper uses quarterly data for the period 1994:q1–2020:q1 and a Bertrand model application. The proposed framework implies that HFCS deliveries are a function of the prices of HFCS and sugar. The results show that the estimated long-run elasticity between HFCS deliveries and the price of HFCS-42 is negative and significant. Specifically, a one percent increase in the price of HFCS-42 decreases HFCS deliveries by 0.153 percent. However, the long-run elasticity between HFCS deliveries and the price of sugar is nonsignificant.

The remainder of this paper is organized as follows. The second section describes the relationship between HFCS deliveries and the prices of HFCS and sugar. The third section presents a review of the relevant literature. The fourth section describes the methodology and data. The next section is the discussion of the results. The final section presents the conclusions and policy implications.

2. Deliveries of HFCS and the prices of HFCS and sugar in the U.S. sweetener market

After being commercially introduced to the U.S. sweetener market in 1967, HFCS had a significant increase in commercial use in 1972 (Barry et al., 1990). In 1968, the Clinton Company increased the fructose level of the corn syrup from 15 to 42 percent and introduced HFCS-42 to the U.S. sweetener market (Bode et al., 2014). The introduction of HFCS to the sweetener market might have been related to the relatively higher price of sugar. Ballinger (1978) reports that the price of sugar increased during the period 1957–1974, while the price of corn syrup was not only below the price of sugar but decreased.

Increases in the utilization of HFCS in the United States have been associated with large increases in the price of sugar. A decrease in U.S. sugar yields over the period 1972–74 made the price of sugar rise from 12.4 cents a pound in 1973 to 56 cents a pound in December 1974, which was associated with The Coca-Cola company replacing 25 percent of sucrose with HFCS-42 and other beverage companies replacing 25 to 50 percent of sucrose with HFCS-42 (Forrestal, 1982, as cited in Bode et al., 2014). In 1977, HFCS-55 (55 percent fructose) was commercially introduced and adopted by the beverage industry as a replacement for liquid sugar (Barry et al., 1990). Because of lower world sugar yields, the price of refined sugar increased again from 21 cents a pound in 1979 to 52 cents a pound in 1980 (Bode et al., 2014). This is associated with The Coca-Cola company and PepsiCo increasing their HFCS-55 utilization rates from 25 to 50 percent in 1980, and to 100 percent in 1984 (Pendergrast, 1993).

It seems that the relationship between the prices of HFCS and sugar has had an important influence on HFCS deliveries and utilization in the U.S. sweetener market. In this regard, it has been reported that a very important determinant of the price of HFCS is the price of sugar because of the substitutability between these two products in many industrial uses (Cubenas & Schrader, 1979; USDA-ERS, 1978). It is also argued that important contributions to the development of the HFCS industry and its share increase in the U.S. sweetener market have come from the higher sugar prices in 1974 and 1980 as well as from the guaranteed domestic price due to U.S. government sugar price support program (Barry et al., 1990). Further, the increase in HFCS capacity in the 1970s is associated with high sugar prices in 1974/75 (USDA-ERS, 1980).

The pricing strategy of the HFCS industry can also affect HFCS deliveries and utilization. In this regard, it has been argued that the HFCS industry has strategically set the price of HFCS 10 to 30 percent below the price of refined sugar (Barry et al., 1990). In addition, Lord (1995) argued that the replacement of sugar with HFCS in the manufacturing of soft drinks was motivated by a 10 percent discount of the price of HFCS-55 relative to the price of sugar. However, there have been important changes in the U.S. sweetener market. For instance, changes in the deliveries of HFCS in the 2000s are associated with changes in the price differential between HFCS and sugar. During the period 2002–04, HFCS deliveries were larger than sugar deliveries several times, which was related to the price of HFCS being 20–40 percent less than the price of sugar (Haley & Dohlman, 2009).

However, the deliveries of sugar were more than those of HFCS from 2007 to 2009, which was associated with the price of HFCS being higher than the price of sugar (Haley & Dohlman, 2009). McConnell (2016) also reports that the annual decrease in HFCS deliveries over the period 2006–2015 is associated with higher costs of corn, a reduction in the competitiveness of the price of HFCS relative to the price of sugar, and changes in the preferences of food manufacturers. In per capita terms, HFCS deliveries had an annual decrease rate of 2.7 percent over the period 1990–2016, while sugar deliveries annual growth rate was 0.5 percent during the same period (McConnell, 2017). Furthermore, McConnell (2018) reports a 2.2 percent decrease in HFCS deliveries in 2016/17 relative to 2015/16 HFCS deliveries, and that the price differential between HFCS and refined sugar vanished in the United States in 2015/16 and 2016/17 because the spot price of HFCS-42 was greater than the spot price of refined sugar. Therefore, it is likely that the behavior of the prices of HFCS and sugar has an important influence on the behavior of HFCS deliveries.

3. Literature review

The behavior of the share of HFCS in the U.S. sweetener market has been related to the relationship between the prices of HFCS and sugar. Based on a model of demand and supply of HFCS in the United States, Barros (1992) estimated a reduced form of the growth rate of demand for HFCS over the period 1971–1988. He found that the price of sugar had a positive effect on the growth rate of HFCS consumption and suggested permanent effects on the HFCS consumption growth rate from permanent changes in the price of sugar. In addition, Lord (1995) stated that the price of HFCS-55 was set 10 percent below the price of sugar to promote the substitution of HFCS-55 for sugar in the manufacturing of soft drinks.

Other research has focused on the influence of the HFCS firm on the price of HFCS. Froeb and Werden (1991, 1992) analyze the relationship between the residual demand elasticity and the delineation of the relevant market. To define a monopoly mark-up, these studies use the residual demand elasticity and assume a monopolist HFCS firm, but the elasticity associated with the delineated market can be different from the estimated demand elasticity. In addition, Froeb and Werden (1992) suggest that using the current market demand elasticity to delineate relevant markets overstates the monopolist market power. Cotterill (1998, 2001) analyzes price fixing in the HFCS industry. Cotterill (1998) reports that HFCS producers charge a price below the list price of HFCS to large purchasers, while Cotterill (2001) assumes that HFCS producers fix and raise the price charged to direct buyers, so these studies suggest that the HFCS industry can influence price. Furthermore, Brendstrup, Paarsch, and Solow (2006) control for the effects of HFCS short-run capacity and sugar as substitute in their estimation of a residual demand and a supply of HFCS. They find that the HFCS industry does not have market power when they control for these two factors in the residual demand equation. However, when they control

for the effect of sugar as substitute only, they find that the HFCS industry has market power, which means that the HFCS firm can charge higher prices given the government policy determined price of sugar.

The behavior of the prices of HFCS and sugar has also been analyzed by using cointegration analysis. Williams and Bessler (1997) report that the prices of HFCS and sugar are cointegrated over the period 1984–1991. Their cointegration results also suggest that the price of HFCS responds to deviations in the long-run equilibrium between HFCS and sugar prices, and that the price of HFCS increases in period $t + 1$ after the price of sugar has been above its long-run equilibrium in period t. They also find that the main determinant of the price of HFCS is the price of sugar. Moss and Schmitz (2002a) argue that one factor that has contributed to the establishment of the U.S. HFCS industry is the sugar price premium. Their models suggest that the price of HFCS is less than the price of sugar, and their cointegration analysis suggests that these prices move together over a range of prices where the two products are perfect substitutes. Specifically, they find that a long-run relationship between the prices of HFCS and refined sugar over the period 1983–1996. Similarly, Moss and Schmitz (2002b) apply cointegration analysis to the prices of HFCS, raw sugar, and wholesale-refined sugar over the period 1979–2001. Their model assumes that HFCS and sugar are perfect substitutes in the soft drink market, but not in non-soft drink markets. They find that the prices of HFCS and wholesale refined sugar moved together during the period 1983–1996. However, from 1997 to 2001, the price of HFCS did not follow the increases in the price of refined sugar. Specifically, these prices diverged during this period. They also find that in response to increases in the price of corn, the price of HFCS increases. In another study, Moss and Schmitz (2004) conduct cointegration analysis on the prices of HFCS and sugar over the period 1979–2003 and identify three different long-run relationships between these prices. They argue that these results may be due to changes in the HFCS industry reaction function due to changes in the price of sugar. They also find no correlation between the prices of HFCS and sugar during the period 1997–2001. They suggest that markup pricing of HFCS was still possible, and that the price of HFCS might have been different from the competitive price during this period.

Evans and Davis (2002) also recognize the existence of a HFCS price reaction function. They estimate a price equation and a derived demand for the HFCS for the period 1977–1998, and they find that the price of sugar has a positive and significant effect on the price of HFCS. They also find a nonsignificant cross-price elasticity of HFCS with respect to sugar and suggest that a simple decrease in the price of sugar might not be associated with a significant reduction in the pattern of sweetener use in the United States.

The above literature review suggests that the relationship between the prices of HFCS and sugar can affect the share of the HFCS in the U.S. sweetener market. It also reports that the HFCS industry can affect the price of HFCS. Further, it suggests that the price of HFCS reacts to changes in the price of sugar. However, we did not find a study that focuses on the long-run relationship between HFCS deliveries to the U.S. market and the prices of HFCS and sugar, which is the focus of the current paper.

4. Methodology

4.1. Model

We consider the HFCS and sugar industries and assume that there is one firm with several plants in each industry. For each industry, we assume that each plant uses the same technology, and that costs are the same across plants. It has been reported that the unit costs among HFCS producers are about the same and that they have similar pricing strategies (Butler, 1981). This can be associated with the use of the same technology in the production of HFCS (Brendstrup et al., 2006). We also assume that HFCS and sugar are substitutes, so changes in the prices of HFCS and sugar affect HFCS deliveries in the U.S. sweetener market.

The model is a Bertrand duopoly application that considers price as the strategic variable. The model assumes that the demand for HFCS is a function of the prices of HFCS and sugar. The demand for HFCS can be specified as a residual demand (Brendstrup et al., 2006; Froeb & Werden, 1992). As in Brendstrup et al. (2006), we specify a residual demand for HFCS as a function of the prices of HFCS and sugar only. That is,

$$D_h(P_h, P_s) = \begin{cases} d(P_h) \ if \ P_h < P_s \\ d(P_h)/2 \ if \ P_h = P_s \\ 0 \ if \ P_h > P_s \end{cases} \tag{1}$$

where $D_h(P_h, P_s)$ is the residual demand for HFCS, P_h is the price of HFCS, and P_s is the price of sugar.

Equation (1) implies that the HFCS oligopolist captures the entire market by setting the price of HFCS below the price of sugar. In addition, when the price of sugar is below the price of HFCS, the sugar oligopolist captures the entire market. However, the price of sugar has been above the world price of sugar because of the U.S. government sugar price support program (USDA-ERS, 2020) and the minimum domestic sugar price guarantee of the Agricultural Act of 2014 (Beghin & Elobeid, 2017). It has also been argued that HFCS faces limited competition from sugar because of the U.S. sugar price support program (Moss & Schmitz, 2004). Further, Barry et al. (1990) suggest that the price of HFCS has not only been below the price of sugar but also followed the price of sugar at a discount rate of 10 to 30 percent.

Equation (1) also implies that when the price of HFCS is less than the price of sugar $(P_h < P_s)$ and equal to the average cost of sugar $(P_h = AC_s)$, there is a Nash equilibrium. In addition, if the price of HFCS generates profits for the HFCS oligopolist, then there is a Bertrand equilibrium (Varian, 1992, p. 291–295).

The residual demand for HFCS can also be defined as $Q_h = f(P_s, P_h)$, where Q_h is quantity of HFCS. It can also be written as

$$Q_h = aP_s - bP_h \tag{2}$$

Equation (2) suggests that an increase in the price of sugar increases HFCS deliveries $(\partial Q_h/\partial P_s > 0)$, and that an increase in the price of HFCS decreases HFCS deliveries $(\partial Q_h/\partial P_h < 0)$. The derivative $\partial Q_h/\partial P_s$also implies that HFCS and sugar are substitutes.

In addition, given that quantity supplied of HFCS is also a single point on the HFCS residual demand curve that equals quantity demanded of HFCS, HFCS deliveries equal HFCS total utilization or domestic disappearance.

Equation (2) is a flexible functional residual demand curve for HFCS as suggested by Froeb and Werden (1992). Equation (2) is similar to Brendstrup et al.'s (2006) residual demand for HFCS, in which the quantity of HFCS depends on its own price and the price of sugar. Residual demand curves are different from Marshallian demand curves. For residual demand curves, the endogenous prices of substitutes and complements are replaced with best-response functions of the prices of substitutes and complements, and the endogenous own price of the commodity is instrumented by a measure of marginal cost (Brendstrup et al., 2006; Froeb & Werden, 1992). Froeb and Werden (1992) use quarterly data for the period 1981–89, conduct a 2SLS estimation of a residual demand for HFCS, use the price of corn as an instrument for the price of HFCS, and estimate residual demand elasticities for HFCS. They include seasonal dummies and a time trend to eliminate autocorrelation in the reduced-form equations, and they report a Durbin-Watson statistic. Brendstrup et al. (2006) also use quarterly data for the period 1980–2000, conduct a full-information maximum likelihood estimation of a system of a residual demand for HFCS and a supply of HFCS, use the price of liquid corn starch as an instrument for the price of HFCS, and estimate residual demand elasticities for HFCS. These two studies, even though they use time series data to estimate residual demand elasticities for HFCS, do not consider the time series properties of the data.

The focus of the current paper is to estimate a long-run relationship between HFCS deliveries and the prices of HFCS and sugar. Then, based on equation (2) and given the availability of quarterly spot prices for HFCS-42 for the period 1994:1–2020:1, we conduct cointegration analysis on HFCS deliveries, the spot price of HFCS-42, and the price of sugar.[1] This adds to the understanding of the economics of HFCS while considering the time series properties of the data, which is explained in the following sections.

We apply the natural logarithm to equation (2) and get

$$LQ_h = aLP_s - bLP_h \tag{3}$$

where a and b are elasticities, and L is the natural log operator. The econometric specification of equation (3) is given as

$$LQ_{h,t} = \beta_0 + \beta_1 LP_{s,t} + \beta_2 LP_{h,t} + e_t \tag{4}$$

where the variables are defined above and e_t is the error term that represents random shocks. We expect $\beta_1 > 0$ and $\beta_2 < 0$.

We assume that the price of sugar is exogenous because it is mostly determined by the U.S. sugar program (Brendstrup et al., 2006; Froeb & Werden, 1992). In addition, Froeb and Werden (1992), based on a Granger causality test, do not find any feedback of the price of HFCS on the price of sugar. Furthermore, Williams and Bessler (1997) found that the price of sugar was weakly exogenous and that there was no long-run feedback of the price of HFCS on the price of sugar.

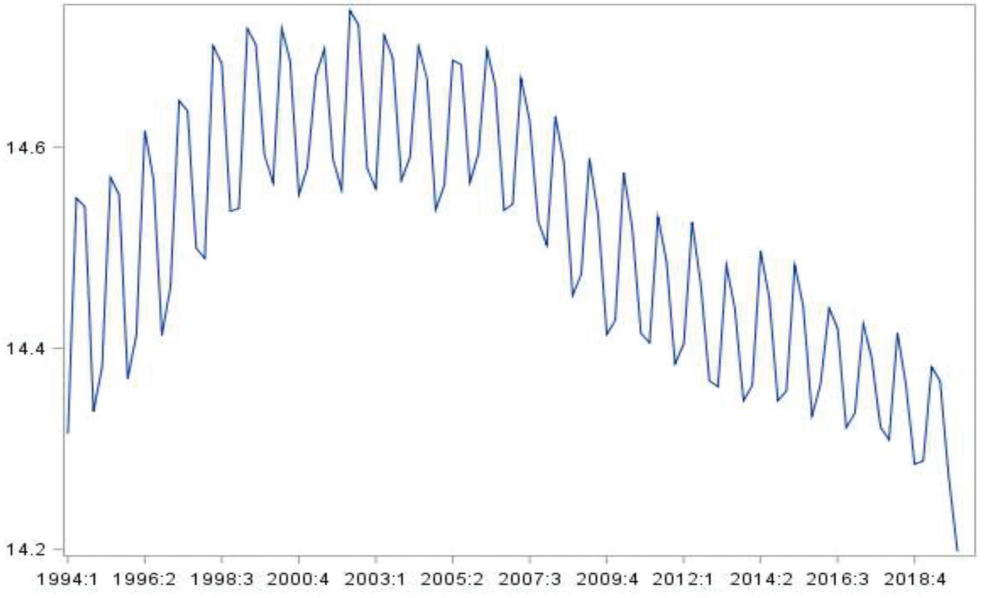
[1]List prices are higher than spot prices, so spot prices are more accurate.

4.2. Data and econometric methodology

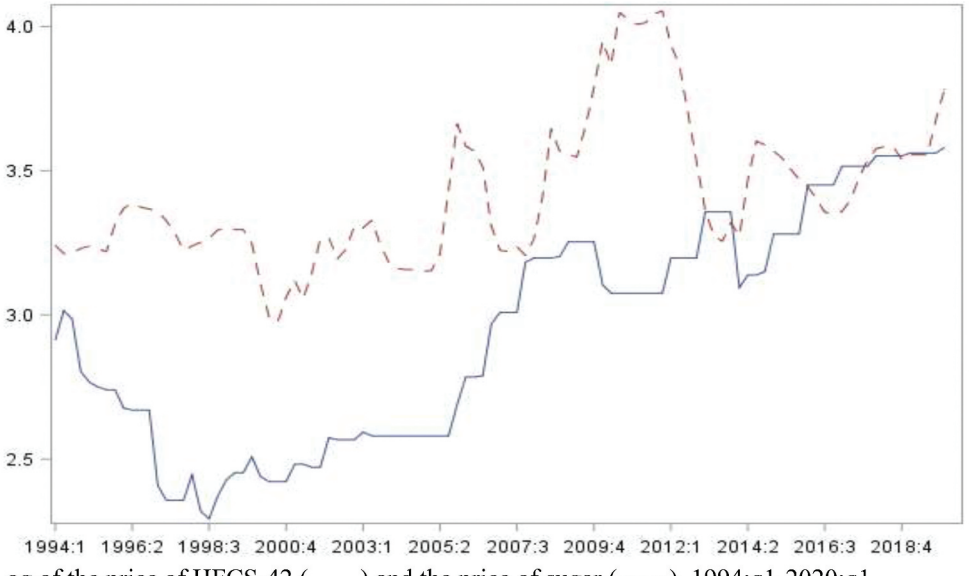
This paper uses quarterly data for HFCS deliveries, the spot price of HFCS-42, and the price of wholesale refined sugar that covers the period from 1994:q1 to 2020:q1. Specifically, HFCS deliveries are short tons (dry weight), the spot price of HFCS-42 is cents per pound (dry weight), and the wholesale price of refined sugar is cents per pound. The data are obtained from the USDA/ERS. Data sources and variable definitions are in the Appendix A, and descriptive statistics are in Appendix B.

Figure 1 plots the logarithms (logs) of HFCS deliveries, the price of HFCS-42, and the price of sugar for the period from 1994:q1 to 2020:q1. The increase in HFCS deliveries from 1994:q1 to 2002:q2 is associated with a decrease in the price of HFCS-42 from the 1994:q1 to 1998:q3 and a relatively large price differential between HFCS-42 and sugar. In addition, Figure 2 shows that the annual growth rate of total HFCS production (HFCS-42 plus HFCS-55) rose from 3.91 percent in 1995 to 6.37 percent in 1997. Thus, it is likely that the increase in HFCS deliveries was influenced by the decrease in the price of HFCS-42. The decrease in the price of HFCS-42 has been associated with a significant increase in production capacity between 1995 and 1997 and a growth rate of HFCS production that was greater than the U.S. consumption rate (Haley, Suarez, & Jerardo, 2004; Lord, Suarez, Salsgiver, & Napper, 1997). However, HFCS deliveries decreased from 2002:q2 to 2020:q1. This is associated with increases in the price of HFCS-42 from 9.90 cents a pound in 1998:q3 to 35.92 cents a pound in 2020:q1. Also, the price differential between HFCS-42 and sugar decreased from 2013:q1 to 2020:q1. Figure 2 also shows that the HFCS annual production growth rate not only decreases from 1998 to 2019, but also it has been negative from 2011 to 2019. It has been reported that the decrease in HFCS deliveries during the last decade is associated with higher corn costs, the price of HFCS being less competitive relative to the price of sugar, and changes in the preferences of customers and food manufacturers (McConnell, 2016).

Based on Figure 1, it is likely that the series are nonstationary. This implies that differencing may be needed to achieve stationarity. We determine the order of integration of the series by conducting the Augmented Dickey-Fuller (ADF), the Phillips-Perron (PP), and the Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) unit root tests. The unit root tests suggest that the series are integrated of order one or $I(1)$. This means that OLS estimation of equation (4) is not appropriate due to spurious regression problem (Granger & Newbold, 1974). However, e_t in equation (4) is $I(0)$ if Q_h, P_s and P_h are cointegrated (Lutkepohl, 2007 p. 301). Then, the convergence rate in terms of order of probability of the OLS estimates of equation (4) is $\left(\hat{\beta}-\beta\right)=\mathrm{O}_p(T^{-1})$, so the OLS estimates are not only consistent but superconsistent (Stock, 1987). In this case, the convergence rate of the OLS is faster than $\mathrm{O}_p\left(T^{-1/2}\right)$, which is the convergence rate of most estimators for stationary time series (Hamilton, 1994 p.460). However, the OLS estimators have nonnormal limiting distributions (Stock, 1987). We address this problem by using the dynamic OLS (DOLS) developed by Stock and Watson (1993). Given this methodology, we add leads and lags of the first differences of the $I(1)$ variables to equation (4), which makes the OLS estimators become asymptotically normally distributed (Stock & Watson, 1993).



Log of HFCS deliveries, 1994: q1-2020: q1.



Log of the price of HFCS-42 (——) and the price of sugar (------), 1994:q1-2020:q1.

Figure 1. Plots of the time series (LQ_h, LP_S, LP_h),1994:q1–2020:q1.

Having determined that the series are integrated of order one, we test for the existence of a long-run relationship among Q_h, P_s and P_h. Based on the Johansen cointegration method (Johansen, 1995), we identify one cointegrated relationship among Q_h, P_s and P_h. Therefore, we conduct a one-step error correction model (ECM) and DOLS estimations of equation (4), which allows for estimating the long-run elasticities between Q_h and P_s and P_h.

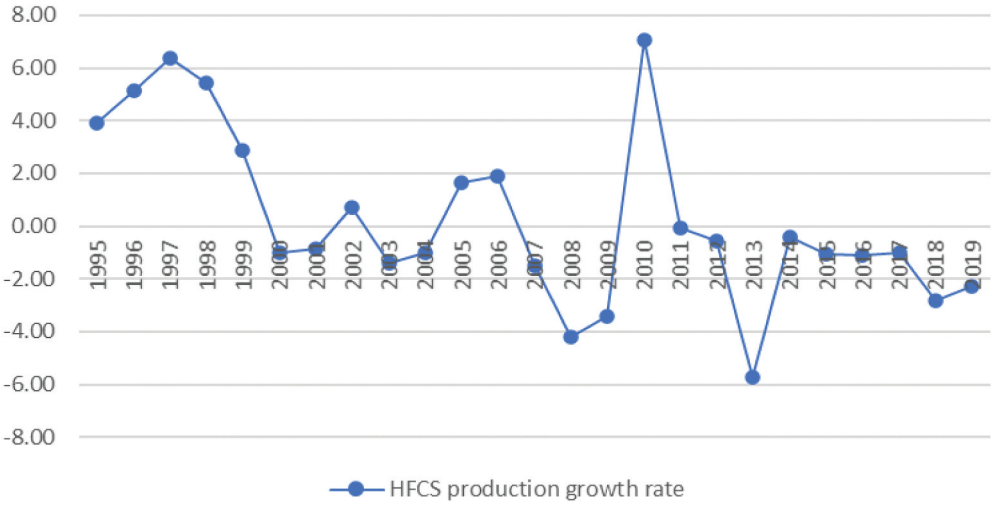


Figure 2. HFCS production annual growth rate, 1994–2019. Source: Authors' computations. Total HFCS is HFCS-42 plus HFCS-55. Growth rates for the period 1994–2003 are computed based on data from Table 6: U.S. high fructose corn syrup supply and use, calendar year of the Sugar and Sweetener Outlook, May 2004. Growth rates for the period 1994–2003 are computed based on data from Table 29: U.S. high fructose corn syrup (HFCS) production, quarterly, by fiscal and calendar year of the Sugar and Sweeteners Yearbook Tables, USDA, ERS.

5. Empirical analysis

5.1. Unit root tests

We conduct the Augmented Dickey-Fuller (ADF), the Phillips-Perron (PP), and the Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) unit root tests to determine the order of integration of the series. Table 1 presents the unit root tests. Based on the ADF, PP, and KPSS tests, the logs of the levels of the price series are integrated of order one or $I(1)$. However, the unit root tests suggest that first differences of the series are stationary or $I(0)$.[2] In the next section, we discuss the results of the cointegrating relationship among Q_h, P_s and P_h.

5.2. Cointegration test

Having identified that the time series are integrated of order one, we use the Johansen cointegration method (Johansen, 1995) to determine if there is a cointegrated relationship among Q_h, P_s and P_h. The method identifies the number of long-run relationships in the time series system. First, the method defines an unrestricted vector autoregressive (VAR) process for the time series system. That is,

$$y_t = c + \sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i} + \varepsilon_t \tag{5}$$

[2]The unit root tests do not include a deterministic trend, but inclusion of a deterministic yielded the same results.

Table 1. Unit root tests, 1980:1–2017:12.

Variable Levels	ADF(τ)	PP(τ)	KPSS(η)	Result
LQh	−0.15	−0.15	0.58**	*I*(1)
LPs	−1.42	−1.42	0.48**	*I*(1)
LPh	−0.07	−0.07	0.76***	*I*(1)
First differences				
ΔLQh	−10.53***	−10.53***	0.47	*I*(0)
ΔLPs	−6.46***	−6.46***	0.07	*I*(0)
ΔLPh	−9.54***	−9.54***	0.27	*I*(0)

Notes: ADF is the Augmented Dickey-Fuller test, PP is the Phillips-Perron test, and KPSS is the Kwiatkowski, Phillips, Schmidt, and Shin test. The null hypotheses of the ADF and PP tests are that the series are not stationary. The null hypothesis of the KPSS test is that the series is stationary. *** and ** means significant at the 1 and 5 percent, respectively. The tests do not include a deterministic trend.

Table 2. Johansen trace test for cointegration: *LQh, LPs, LPh.*

Null hypothesis	Alternative hypothesis	Trace statistic	*P*-value
r = 0	r > 0	87.71	0.0001
r = 1	r > 1	16.02	0.1726

where y_t is a (k × 1) vector that contains the integration of an order one time series, c is a (k × 1) vector that contains the constants, Γ_i is a (k × k) matrix of the coefficients on the lags of the first differences of the time series, and ε_t is a (k × 1) white noise or innovation process with expected value $E(\varepsilon_t) = 0$ and variance $E\left(\varepsilon_t \varepsilon_t^{'}\right) = \Sigma$. The vector error correction representation of equation (5) is given as

$$\Delta y_t = c^* + \Pi y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i^* \Delta y_{t-i} + \varepsilon_t \tag{6}$$

where $\Pi = \alpha\beta'$, α and β are (k × r) matrices, and Γ_i^* is a (k × k) matrix of the coefficients on the lags of the first differences of the time series.

The rank (r) of the matrix Π determines the number of cointegrating relationships in the time series system y_t. When Π is full rank or $r = k$, the series in the system y_t are $I(0)$. When the $r = 0$, the first differences of the series in the system y_t are $I(0)$. And the number of cointegrating relationships in the time series system y_t is given by r as defined by 0 < r < k. When $r = 1$, the error correction term in equation (6) is given as $\Pi y_{t-1} = \alpha\beta' y_{t-1}$, where β' is the cointegrating vector, and α is the matrix that contains the adjustment coefficients that restore equilibrium. Therefore, the product $\beta' y_t$ defines the cointegrating relationship. This cointegrating vector is stationary despite the fact that the vector y_t is nonstationary.

We use the trace statistic to determine the number of cointegrating relationships in our time series system as in Williams and Bessler (1997), Moss and Schmitz (2004), and Herzer and Felicitas (2006). The null hypothesis defines the number of cointegrating relationships $r = i$ such that $i \in [0, k]$, where k is the number of time series in the system. The alternative hypothesis defines that $r > i$. To conduct the test, we determine the lag order of the VAR process based on the Akaike information, Hanna-Quinn, and Schwarz Bayesian criteria. Therefore, the cointegration tests presented in Table 2 are based on a four-lag VAR process. The second row in Table 2 shows that the null hypothesis that

defines one cointegrating relationship in the time series system cannot be rejected. Therefore, *LQh, LPs* and *LPh* are cointegrated, so there is long-run relationship among HFCS deliveries, the price HFCS-42, and the price of sugar. In the next section, we discuss the estimation of the long-run elasticities between Q_h and P_s and P_h.

5.3. Estimation of the long-run elasticities between Q_h and P_s and P_h: error correction model

The purpose of our investigation is to estimate the long-run relationship between the HFCS deliveries and the prices of HFCS-42 and sugar. This also allows for estimating the responsiveness of HFCS deliveries to changes in the prices of HFCS-42 and sugar based on the corresponding long-run elasticities. Thus, we conduct a one-step error correction model estimation based on the method of Stock (1987) to estimate the long-run relationship between HFCS deliveries and the prices of HFCS-42 and sugar. We estimate a transformed single equation form of equation (4) according to Bewley (1979). Specifically, we regress ΔLQh_t on LQh_{t-1}, LPs_{t-1}, LPh_{t-1}, the lags of ΔLQh_t up to lag four, ΔLPs_t and ΔLPh_t and their lags up to lag four,[3] dummy *Dic*, dummy *Dpi*, dummy *D08*, and quarterly dummies.[4] By successively eliminating the least significant variables, we obtain equation (7) as the estimated one-step error correction model.[5] That is,

$$\begin{aligned}\Delta LQh_t = {} & 3.153 - \underset{(6.55)}{0.201}\, LQh_{t-1} - \underset{(6.44)}{0.014}\, LPs_{t-1} - \underset{(2.00)}{0.073}\, LPh_{t-1} - \underset{(8.04)}{0.642}\, \Delta LQh_{t-1} \\ & - \underset{(8.92)}{0.723}\, \Delta LQh_{t-2} - \underset{(19.78)}{0.585}\, \Delta LQh_{t-3} + \underset{(7.95)}{0.051}\, \Delta LPs_{t-3} + \underset{(2.40)}{0.011} Dic + \underset{(2.08)}{0.047} q2 + \underset{(4.38)}{0.030} q3 \\ & \underset{(2.83)}{}\end{aligned}$$

$$\begin{aligned}&Time{=}105(1994{:}1{-}2020{:}1), R^2{=}0.972, SE{=}0.017, DW{=}1.775, Q(4){=}0.418(0.981), \\ &ARCH(4){=}0.832(0.934), LM(4){=}1.411(0.842). The number in parentheses es are t{-}ratios.\end{aligned} \tag{7}$$

Equation (7) shows that the coefficient on the lag of HFCS deliveries is significant at the one percent level, as well as the coefficient on the price of HFCS-42. However, the coefficient on the price of sugar has an unexpected sign and is significant at the 5 percent level. Given that the cointegration test identified a long-run relationship, we obtain the long-run relationship among Q_h, P_s and P_h by normalizing on the coefficient of LQh_{t-1} in equation (7). That is,

[3] The lag order is the same as that used in the cointegration test.

[4] *Dic* is 1 from 1994:q1 to 1998:q3 and zero otherwise, and it is included to control for the effect of the increase in HFCS capacity. *Dpi* is 1 from 1998:q3 onwards and is included to control for the increase in price of HFCS-42 over this period. *D08* is 1 from 2008:q1 to 2009:q2 and is included to control for the 2008–09 recession. *q2, q3*, and *q4* are quarterly dummies to control for seasonally.

[5] The number in parentheses below the coefficients are t-ratios. The number in parentheses next to diagnostic statistics are p-values. *SE* is standard error, *DW* is Durbin-Watson statistic, *Q* is the Portmanteau test for heteroskedasticity, *ARCH* is test for autocorrelated conditional heteroskedasticity, and *LM* is the Godfrey test for autocorrelation based on four lags. For the *Q* and *ARCH* tests, the p-values up to lag 12 are more than 10 percent, and for the *LM* test the p-values up to lag 8 are more than 10 percent.

$$LQh_t = -0.070LPs_t - 0.363LPh_t \tag{8}$$

Based on equation (8), HFCS deliveries decrease by 0.36 percent when the price of HFCS-42 increases by one percent. However, HFCS deliveries decrease by 0.07 percent when the price of sugar increases by one percent. This result is contrary to our expectations.

The validity of the estimations based on equation (8) depends on the assumption that the prices of HFCS-42 and sugar are weakly exogenous. If this assumption does not hold, the estimates in the ECM equation (equation (6)) are biased and the *t*-tests are misleading. This means that we are not sure about the effects of the prices of HFCS-42 and sugar on HFCS deliveries in equation (8). Because of this, we conduct a weak exogeneity test within the Johansen framework. The last row in Table 3 shows that the null hypothesis of weak exogeneity of the price of sugar is rejected. Therefore, the estimation based on equation (8) is not reliable, so we prefer the dynamic OLS estimation. The dynamic OLS (DOLS) estimation is presented in the next section.

5.4. Estimation of the long-run elasticities between Q_h and P_s and P_h: dynamic OLS model

In this section, we use the DOLS methodology (Saikkonen, 1991; Stock & Watson, 1993) to estimate the long-run elasticities between HFCS deliveries and the prices of HFCS-42 and sugar. Given this methodology, the elasticity estimates are valid even if some of the regressors in equation (8) are endogenous (see Saikkonen, (1991) about the relationship between the DOLS estimator and instrumental variable estimators). In addition, the DOLS estimator is asymptotically equivalent to the Johansen's (1995) maximum likelihood estimator (Herzer & Felicitas, 2006). The DOLS specification is given as

$$\begin{aligned} lnQh_t = {} & \beta_0 + \beta_1 lnPs_t + \beta_2 lnPh_t + \sum_{i=-4}^{i=4} \Phi_1 \Delta LPs_{t+i} + \sum_{i=-4}^{i=4} \Phi_2 \Delta LPh_{t+i} \\ & + \delta_1 dIc + \delta_2 dPi + \delta_3 d08 + \delta_4 q2 + \delta_5 q3 + \delta_6 q4 + \varepsilon_t \end{aligned} \tag{9}$$

where β_1 and β_2 are the long-run elasticities, and Φ_1 and Φ_2 are the coefficients of the lead and lag differences of the prices of HFCS-42 and sugar (the $I(1)$ series) and are considered as nuisance parameters. The nuisance parameters capture the short-run dynamics of the process (Stock & Watson, 1993). These parameters adjust for potential endogeneity, autocorrelation, and nonnormality of the residuals, so the elasticity estimates are consistent. The lag order is four, as in the error correction model in equation (7).

The results of the DOLS estimation are presented in Table 4. Based on the diagnostic test statistics, the residuals have no problems of autocorrelation, heteroskedasticity, or nonnormality. Note that the p-values for these tests are more than 10 percent. Therefore, the hypothesis tests on the estimated long-run elasticities are valid.

Table 3. Weak exogeneity test on HFCS deliveries, HFCS price, and sugar price.

Variable	Chi-Square	*P*-value
HFCS deliveries	0.78	0.3773
HFCS-42 price	0.20	0.6533
Sugar price	7.29	0.0069

Table 4. DOLS Estimation of the long-run elasticities between *LQh, LPs, LPh*, 1994:q1–2020:q1.

$\widehat{\beta_0}$	$\widehat{\beta_1}$	$\widehat{\beta_2}$	$\widehat{\delta_1}$	$\widehat{\delta_2}$	$\widehat{\delta_3}$	$\widehat{\delta_4}$	$\widehat{\delta_5}$	$\widehat{\delta_6}$
15.068[a]	− 0.060	− 0.153[a]	0.006	0.024	−0.001	0.134[a]	0.101[a]	−0.012[b]
(61.71)	(1.17)	(2.85)	(0.22)	(0.82)	(0.05)	(22.35)	(13.53)	(2.05)

Notes: *Time* = 105 (1994:q1–2020:q1). The DOLS estimation is based on an *AR*(1, 7)-model. The number in parentheses are *t*-ratios. *a* and *b* represent significance at the 1% and 5% level, respectively. Diagnostic statistics: R^2 = 0.968, *SE* = 0.026, *DW* = 1.78, *Q*(1) = 0.030 (0.862), *Q*(7) = 6.077 (0.531), *ARCH*(1) = 0.016 (0.900), *ARCH* (7) = 4.376 (0.736), *LM*(1) = 2.131 (0.144), *LM*(7) = 8.327 (0.305). The numbers in parentheses next to the diagnostics statistics are *p*-values.

The results in Table 4 show that the prices of HFCS and sugar have negative effects on HFCS deliveries. The negative sign on the estimate of the elasticity of HFCS deliveries with respect to the price of sugar is unexpected. However, this elasticity estimate is nonsignificant. The loss in significance of the estimate of this elasticity can be due to the price of sugar not being weakly exogenous. In the case of the long-run relationship between HFCS deliveries and the price of HFCS-42, the elasticity estimate is negative and highly significant. It implies that a one percent increase in the price of HFCS-42 decreases HFCS deliveries by 0.153 percent. Specifically, one standard deviation increase (8.02 cents) in the price of HFCS-42 relative to the average price (20.46 cents) represents a 39 percent increase in the price of HFCS-42, and it causes a decrease in HFCS deliveries of 120,232.02 metric tons ($0.39 \times 0.153 \times 2014.95 \times 1000 = 120{,}232.07$ tons). Given these results, it would be better for the HFCS industry to prevent large increases in the price of HFCS, so this would prevent large decreases in HFCS deliveries and large reductions in its share of the U.S. sweetener market. This gives support to the arguments that the setting of the HFCS-55 price at 10 percent below the price of sugar contributed to promoting the replacement of sugar with HFCS-55 in the manufacturing of soft drinks (Lord, 1995), and that the sugar price premium is a factor that has contributed to the establishment of the U.S. HFCS industry (Moss & Schmitz, 2002a). The results also give support to the arguments that the deliveries of sugar in the United States have been greater than HFCS deliveries when the price of HFCS has been higher than the price of sugar (Haley & Dohlman, 2009), and that the reduction in the competitiveness of the price of HFCS relative to the price of sugar has been associated with decreases in HFCS deliveries over the period 2006–2015 (McConnell, 2016).

Cointegration analyses have found that the price of HFCS and sugar move together (Moss & Schmitz, 2002a, 2002b), and that the price of HFCS increases following increases in the price of sugar above its equilibrium level (Williams & Bessler, 1997). In addition, Moss and Schmitz (2004) and Evans and Davis (2002) suggest that the price of HFCS reacts to changes in the price of sugar. Cotterill (1998, 2001) suggests that the HFCS industry can influence the price of HFCS, which can affect HFCS sales. Therefore, given this past research's results and the results of our paper, if increasing HFCS deliveries can contribute to increasing HFCS profits, it would be better for the HFCS industry to prevent large increases in the HFCS price, which would prevent large decreases in HFCS deliveries and its share in the U.S. sweetener market. However, the increase in the price of HFCS also depends on the cost of corn (Froeb & Werden, 1992; Moss & Schmitz, 2002b), but we do not assess the effect of the cost of corn on the price of HFCS.

Our results show that increases in the price of sugar does not affect HFCS deliveries. This may be related to Evans and Davis (2002) suggestion that a simple decrease in the price of sugar might not be associated with a significant reduction in the pattern of sweetener use in the United States. However, Evans and Davis (2002) used a different methodology and found a nonsignificant cross-price elasticity of HFCS with respect to sugar.

6. Conclusion

This paper uses an application of the Bertrand model to analyze the long-run relationship between HFCS deliveries and the prices of HFCS-42 and refined sugar. It finds that HFCS deliveries, the price of HFCS-42, and the price of sugar are cointegrated over the period 1994:q1–2020:q1. The main results, based on the estimated long-run elasticities of HFCS deliveries with respect to the price of HFCS-42, show that a one percent increase in the price of HFCS-42 decreases HFCS deliveries by 0.153 percent. This result is robust to two different specifications. In addition, this result is in line with the implications of the Bertrand model used. Further, this finding gives support to the arguments that changes in the U.S. sweetener market have been associated with decreases in the deliveries of HFCS when the price of HFCS has increased (Haley & Dohlman, 2009; McConnell, 2016). In addition, we did not find a significant effect of the price of sugar on HFCS deliveries. This may be related to Evans and Davis (2002) findings of a nonsignificant cross-price elasticity between HFCS and sugar, and who suggest that a simple increase in the price of sugar might not be associated with a significant reduction in the pattern of sweetener use in the United States.

One implication of our results is that if increasing HFCS deliveries can contribute to increasing HFCS profits, it would be beneficial for the HFCS industry to prevent large increases in the HFCS price, which would prevent large decreases in HFCS deliveries and its share in the U.S. sweetener market. However, the increase in the price of HFCS also depends on the cost of corn (Froeb & Werden, 1992; Moss & Schmitz, 2002b), but we do not assess the effect of the cost of corn on the price of HFCS. Assessing the relationship between HFCS deliveries, the price of HFCS, and the price of corn is left for further research. In addition, the results of this paper can contribute to future studies that focus on price relationships between HFCS and sugar, as well as other interdependent industries.

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Appendix A Variable definitions and data sources

Variable name	Variable definition	Source
HFCS deliveries	HFCS deliveries in metric tons (dry weight)	USDA/ERS, Sugar and Sweeteners Yearbook Tables, Table 28: U.S. high fructose corn syrup (HFCS) deliveries, quarterly, by fiscal and calendar year. Accessed at https://www.ers.usda.gov/data-products/sugar-and-sweeteners-yearbook-tables/sugar-and-sweeteners-yearbook-tables/#Corn%20Sweetener%20Supply,%20Use,%20and%20Trade.
Price of HFCS-42	Nominal spot price in cents per pound of dry weight	USDA/ERS, Sugar and Sweeteners Yearbook Tables, Table 9: U.S. prices for high fructose corn syrup (HFCS), Midwest markets, monthly, quarterly, and by calendar and fiscal year. Accessed at https://www.ers.usda.gov/data-products/sugar-and-sweeteners-yearbook-tables/sugar-and-sweeteners-yearbook-tables/#Corn%20Sweetener%20Supply,%20Use,%20and%20Trade.
Price of refined beet sugar	Nominal wholesale price of refined beet sugar in cents per pound.	USDA/ERS, Sugar and Sweeteners Yearbook Tables, Table 5: U.S. wholesale refined beet sugar price, Midwest markets, monthly, quarterly, and by calendar and fiscal year. Accessed at https://www.ers.usda.gov/data-products/sugar-and-sweeteners-yearbook-tables/sugar-and-sweeteners-yearbook-tables/#Corn%20Sweetener%20Supply,%20Use,%20and%20Trade.

Appendix B Descriptive statistics, 1994:q1–2020:q1

Variable	*N*	Mean	Std Dev	Minimum	Maximum
HFCS deliveries tons	105	2014.95	257.66	1466.00	2510.00
HFCS-42 price (cents/pound)	105	20.46	8.02	9.90	35.92
Refined sugar price (cents/pound)	105	31.56	8.91	19.57	57.62