Journal of Applied Economics and Business Research
JAEBR, 2(4): 184-211 (2012)

Is Jordan Petroleum Refinery Company a Natural Monopoly?

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The purpose of this paper is to asses whether breaking up the current monopolistic structure of the petroleum refining industry in Jordan could be empirically justified. This entails testing whether the industry is a natural monopoly or not. Testing natural monopoly requires evaluating the subadditivity of the cost function since it is both sufficient and necessary condition. Using time series data over the period 1961-2010, a system of multi-input and multi-output comprised of a translog cost function and two cost share equations was estimated using iterative seemingly unrelated regression method. The estimated cost function satisfied the regularity conditions including positive estimated cost, positive estimated marginal cost and monotonicity in input prices at all sample points while the curvature (quasi concavity) property in input prices was met at 86% of the sample points. The conclusion was that the cost function is subadditive and hence the industry was a natural monopoly over the period 1961-2010, indicating that the current market structure is an efficient one from a cost perspective. Accordingly, the Government of Jordan needs to take this result into consideration during its course of action to restructuring this industry after the conclusion of the concessionary agreement in 2008.

Keywords *Monopoly, Jordan, Petroleum.*

1. Introduction

Jordan Petroleum Refinery Company (JPRC, henceforth) is the sole petroleum refinery in Jordan. It managed all downstream activities during a 50-year concessionary period, including the import and refinement of crude oil.[2] In addition to the storage, transportation and distribution of petroleum products. The concessionary contract ended in 2008 and was replaced by a service provision agreement to be renewed when needed. The Government of Jordan (the GoJ, from now on) believes that competition will increase efficiency. Therefore it plans to establish a competitive environment by breaking up the current vertically integrated monopoly structure and eventually liberalizing the petroleum products' market entirely. To prepare the market for gradual movement into a more competitive environment, the Gov will allow JPRC to work on the basis of commercial competitiveness by establishing petroleum distribution companies, one of which will be owned by the JPRC.

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[2] The concessionary contract spanned over the period 1958-2008.

 ISSN 1927-033X

Although in the absence of any form of market failure, competition is the most efficient structure. However, monopoly could be more efficient from a cost perspective, if it was natural. Accordingly, this paper seeks to empirically test whether JPRC is a natural monopoly. This requires testing the subadditivity of the cost function. More specifically, we want to use subadditivity to assess the impact of vertical integration on the cost structure.3 If the cost function proved to be subadditive then JPRC is indeed a natural monopoly and consequently, ceteris paribus, introducing competition would not be an optimal policy option from a cost perspective.

The paper is organized as follows. Section 2 introduces the concept of subadditivity and how it relates to natural monopoly. Section 3 explains the research methodology. Section 4 derives Allen elasticities of substitution as well as price elasticities of inputs demand. Section 5 introduces dynamic specification of the cost structure. Section 6 shows how to model the cost structure of the JPRC. Section 7 discusses subadditivity testing. The construction of the data sets and the definition of variables are discussed in section 8. Empirical results are presented in section 9. In section 10 we test the Regularity Conditions of the cost function. The structure of technology is tested in section 11. Section 12 provides estimates of some important elasticities are estimated. The results of the subadditivity testing are presented in Section 13 and finally Section 14 concludes the paper.

2. Natural Monopoly and Subadditivity

Monopoly is natural if it could provide outputs at lower social costs (see, for example, Baumol, 1977). Usually, standard microeconomic textbooks link the definition of natural monopoly to economies of scale. However, Baumol (1977) shows that economies of scale are neither necessary nor sufficient for monopoly to be the least costly structure. Rather, necessary and sufficient conditions are, by definition, implied by strict subadditivity of the cost function. Strict subadditivity means that the cost of the sum of any output vectors is less than the sum of the costs of producing these vectors separately. More formally, a cost function $\mathrm{C(y)}$, where y is a vector of outputs, is strictly and globally subadditive if for any m output vectors $\mathrm{y}^1, \dots, \mathrm{y}^{\mathrm{m}}$, the following condition is satisfied:

$$\mathrm{C}(\mathrm{y}^1 + \cdots + \mathrm{y}^{\mathrm{m}}) < C(\mathrm{y}^1) + \cdots + \mathrm{C}(\mathrm{y}^{\mathrm{m}}) \quad (1)$$

Therefore, any firm whose cost function exhibits subadditivity over the relevant range4 by satisfying condition (1) can produce a given output at a cost less than that incurred by two or more firms producing the same level of output. Moreover, Baumol (1977) shows that economies of scale are sufficient but not necessary for subadditivity to exist in the single-product environment. But in the multi-product case, he shows that sufficient conditions for subadditivity must include some sort of complementarity in the production of different outputs. As shown by Baumol (1977), subadditivity requires global information about the cost function, i.e., information is needed about the shape of the cost function from the origin up to the output level under study, which is rarely available. Moreover, Baumol, Panzar and Willig (1982) declare that there are no necessary and sufficient conditions for subadditivity that are simpler, from analytical perspective, than the definition itself. Therefore, Baumol et al. (1982) suggest an indirect test of subadditivity by developing separate necessary and sufficient conditions such that if the necessary condition is rejected then subadditivity is

[3] See Gilsdorf (1994).
[4] Baumol (1977) shows that it is possible for some output vectors an industry will be a natural monopoly while for others it will not.

 ISSN 1927-033X

rejected and if sufficient conditions are not rejected then subadditivity is accepted. On another front, Evans and Heckman (1984) propose a test of necessary conditions for natural monopoly that does not require global information about the cost function. This local test works as follows: if subadditivity is rejected in one region then global subadditivity should be rejected. Clearly, this test cannot be used to prove the existence of natural monopoly rather it can be used to reject its existence. This limitation is among the most important critiques against this test. Therefore, to avoid this limitation associated with this test, we will evaluate the necessary and sufficient conditions recommended by Baumol et al. (1982), although as mentioned in Viscusi, Harrington and Vernon (2005) "It is a complex matter to specify the necessary and sufficient conditions for costs to be subadditive". If we found that the cost function is subadditive, then the JPRC would be a natural monopoly and hence it could alone carry out all the activities most cheaply. Accordingly, ceteris paribus, it is not efficient, from a cost perspective, to disintegrate the current vertical structure. The opposite would be true if the cost function was not subadditive.

3. Research Methodology

Both Baumol et al. (1982) and Evans and Heckman (1984) conduct their analyses in terms of cost functions rather than the production function because the theoretical literature on natural monopoly relies on the cost function rather than the production function. Moreover as noted by Christensen and Greene (1976), duality theory made the estimation of cost functions easier than the estimation of production or transformation functions.[5] The principle of duality between cost and production functions ensures that, for every transformation function which is nonnegative, twice-continuous differentiable, monotone and concave in inputs, there exists a dual cost function:

$$C(y,w) = C(y_1, y_2, \dots, y_m, w_1, w_2, \dots, w_n) \qquad (2)$$

Where $w_1, w_2, \dots, w_n$ represent factor prices corresponding to the factor inputs $x_1, x_2, \dots, x_n$, respectively. If $C(y,w)$ is minimized with respect to input prices w, the principle of duality also ensures the existence of a transformation function $T(y,x)$ dual to $C(y,w)$ (see, for example, Diewert, 1982).

Baumol et al. (1982) identify a set of desired properties that a multi-product cost function should possess, including properness and flexibility. A proper cost function must be nonnegative, nondecreasing (monotone), concave and linearly homogenous in input prices and nondecreasing in its outputs (Varian, 1992). A functional form is flexible if it can provide a second-order (differential) approximation to an arbitrary twice continuously differentiable function (Diewert, 1982). Empirical literature on subadditivity shows that the transcendental logarithmic (translog) functional form developed by Christensen, Jorgenson and Lau (1973), is the most widely used functional form. The translog form provides a local second order approximation (expansion by second order Taylor series around the vector 0) to any production frontier. It imposes no a priori restrictions on production characteristics. A serious limitation of the translog cost function is that it does not allow zero values since it is measured in logarithms. However, this shortcoming could be eliminated using a Box-Cox

[5] Christensen and Greene (1976) states that "Direct estimation of the production function is attractive when the level of output is endogenous…Furthermore, since electric utilities compete with other industries for factors of production, the specification that input prices are exogenous variables is also reasonable". Since this setup is similar to the one of the petroleum refining industry in Jordan, then the use of cost function approach, in this paper, is plausible.

transformation as suggested by (Caves, Christensen and Tretheway, 1980).[6] Nonetheless, the translog function should meet the above regularity conditions so that it matches a well-behaved transformation function.[7] Since it is very difficult to impose monotonicity and concavity on the model, the common practice in the empirical research is to estimate the parameters of the model, then to test whether these conditions are met or not. The monotonicity condition is satisfied, by definition, if the cost function is increasing in input prices for given y. For the translog function, since input prices and costs are always positive, this condition is met provided that the fitted cost shares are positive. The concavity of the cost function in input prices is achieved if the Hessian matrix of the second partial derivatives of the cost function with respect to input prices is negative semidefinite.[8] Linear homogeneity is usually treated as a maintained (untested) hypothesis since it is a precondition for the existence of duality between cost and transformation functions. Therefore it is imposed prior to estimation; see Christensen and Green (1976) and Brown, Caves and Christensen (1979) for the set of linear restrictions needed to ensure this condition. The condition that the cost function must be increasing in y is achieved if the fitted marginal costs are positive. Given that the translog multiproduct cost function is given by:[9]

$$ln\, C = \alpha_0 + \sum_i^m \alpha_i\, ln\, y_i + \sum_j^n \beta_j\, ln\, w_j + \frac{1}{2}\sum_i^m\sum_j^m \alpha_{ij}\, lny_i\, ln\, y_j + \frac{1}{2}\sum_i^n\sum_j^n \beta_{ij}\, lnw_i\, ln\, w_j + \sum_i^m\sum_j^n \gamma_{ij} lny_i\, ln\, w_j \qquad (3)$$

Where, ln denotes the natural logarithm, while α, β and γ are the parameters to be estimated. Moreover, $\alpha_{ij} = \alpha_{ji}$ and $\beta_{ij} = \beta_{ji}$ are imposed as symmetry conditions, the cost share equations are derived using Shephard's Lemma. In logarithmic form, Shephard's Lemma can be expressed as:

$$\frac{\partial\, ln\, C}{\partial\, ln\, w_j} = \frac{\partial C}{\partial w_j}\frac{w_j}{C} = S_j, \quad j = 1,2, \dots n \qquad (4)$$

Where $S_j = w_j x_j / C$, is the share of total cost associated with input j. Once the input share equations are found, the input demand equations can be derived as:

$$x_j = S_j \frac{C}{w_j}, \qquad j = 1,2, \dots n \qquad (5)$$

By logarithmic differentiation of the translog cost function (3), the input cost share equations take the form:

[6] In this paper, this limitation is not important since none of the petroleum products assumes zero value; therefore Box-Cox transformation will not be used.
[7] Barnett and Pasupathy (2003) and Barnett (2002) note that "Regularity requires satisfaction of both the curvature and the monotonicity conditions. Without both satisfied the second order conditions for optimization behavior fails and the duality theory fails. The resulting first-order conditions, demand functions and supply functions become invalid".
[8] See Christensen and Greene (1976).
[9] This specification is used by Shoesmith (1986, 1988 & 1990), Al-Mutairi and Burney (2002) and Mohammed and Burney (2006). For further details about this functional form see Brown et al. (1979) and Caves et al. (1980)

 ISSN 1927-033X

$$S_j = \beta_j + \sum_i^n \beta_{ij}\, ln\, w_i + \sum_i^m \gamma_{ij}\, ln\, y_i, \qquad (j = 1,2,\dots,n) \tag{6}$$

Therefore, the monotonicity in input prices is satisfied if S_j given by equation (6) is positive.

The marginal cost for each output is defined as:

$$MC_i = \frac{\partial C}{\partial y_i} = \frac{C}{y_i}\frac{\partial\, ln\, C}{\partial\, ln\, y_i} = \frac{C}{y_i}\varepsilon_{Cy_i} \tag{7}$$

Where MC_i is the marginal cost of the *i*th output and ε_{Cy_i} is the elasticity of cost with respect to the ith output and calculated as:

$$\varepsilon_{Cy_i} = \alpha_i + \sum_j^m \alpha_{ij}\, ln y_j + \sum_j^n \gamma_{ij}\, ln\, w_j\,, \quad i = 1,2,\dots,m \tag{8}$$

Since C and y_i are always positive, then MC_i is positive if ε_{Cy_i} is positive. Therefore, the condition that the cost function is nondecreasing in its outputs is satisfied if ε_{Cy_i} given by equation (8) is positive.

For the translog cost function, the elements of the Hessian matrix are:

$$\frac{\partial^2 C}{\partial w_j^2} = C_{jj} = \frac{C}{w_j^2}\left(\frac{\partial\, ln\, C}{\partial\, ln\, w_j}\left(\frac{\partial\, ln\, C}{\partial\, ln\, w_j} - 1\right) + \frac{\partial^2\, ln\, C}{\partial\, ln\, w_j^2}\right)$$
$$= \frac{C}{w_j^2}\left(S_j(S_j - 1) + \beta_{jj}\right) \tag{9.a}$$

$$\frac{\partial^2 C}{\partial w_j \partial w_i} = C_{ji} = \frac{C}{w_j w_i}\left(\frac{\partial\, ln\, C}{\partial\, ln\, w_j}\ \frac{\partial\, ln\, C}{\partial\, ln\, w_i} + \frac{\partial^2\, ln\, C}{\partial\, ln\, w_j\, \partial\, ln\, w_i}\right)$$
$$= \frac{C}{w_j w_i}\left(S_j S_i + \beta_{ji}\right) \tag{9.b}$$

Where β_{jj} and β_{ji} are the coefficients of the own and cross product terms of the input prices from the estimated translog cost function. Therefore, the concavity in input prices is met if the elements of the Hessian matrix given by (9.a) and (9.b) are negative semidefinite. Alternatively, (Shoesmith, 1988) shows that concavity is satisfied provided that the principal minors are of alternating signs beginning with $C_{jj} \leq 0$, where C_{jj} denotes second partial derivatives of the cost function with respect to input prices.[10]

As noted by Berndt and Wood (1975) and Diewert and Wales (1987), the translog cost function does not satisfy these restrictions globally, therefore monotonicity and concavity must be checked at every data observation.

[10] Since total cost and input prices are always positive, it suffices to check the elements inside the brackets of equations (9.a) and (9.b). See Diewert and Wales (1987), Salvanes and Tjøtta (1998a), Bloch, Madden and Savage (2001), Bloch, Madden, Coble-Neal and Savage (2001) and Casarin (2002).

4. Allen Elasticities of Substitution and the Price Elasticities of Input Demands

As implied by equation (5), the demand for each input depends upon its price, other input prices and outputs. Hence, it is useful to know the change in demand for each input in response to changes in other inputs prices and outputs. The most commonly used elasticities are the Allen (partial) elasticities of substitution and the price elasticities of input demands. The own price elasticity of demand for input j is given by:[11]

$$\eta_{ii} = \frac{1}{S_i}(\beta_{ii} + S_i) \qquad (10)$$

Those elasticities should be negative.

The cross price elasticity of demand for input $i$with respect to the price of input j is defined as:

$$\eta_{ij} = \frac{1}{S_i}\left(\beta_{ij} + S_i S_j\right) \qquad (11)$$

The Allen elasticities of substitution are related to the own and cross price elasticities of input demand in the following way (Christensen and Greene, 1976):

$$\sigma_{ii} = \frac{1}{S_i}\eta_{ii} = \frac{1}{{S_i}^2}\left(\beta_{ii} + S_i(S_i - 1)\right) \qquad (12)$$

$$\sigma_{ij} = \frac{1}{S_j}\eta_{ij} = \frac{1}{S_i S_j}\left(\beta_{ij} + S_i S_j\right) \qquad (13)$$

By the symmetry condition implied by (3), $\sigma_{ij} = \sigma_{ji}$ although η_{ij} does not necessarily equal η_{ji} (Berndt and Wood, 1975). A positive elasticity of substitution implies that the inputs are substitutes, while a negative elasticity implies that the inputs are complements. The existence of substitution possibilities among inputs have interesting implications on investment decisions. More specifically, as noted by Chambers (1988), elasticities of substitution provide information on relative input responsiveness to changes in relative input prices.

5. Dynamic Specification of the Cost Structure

Anderson and Blundell (1982) argue that studies involving estimation of systems of demand equations either of commodities or factors of production, suffer from serial correlation in residuals. They believe that the main source of the problem is that these systems do not incorporate dynamic component. To tackle this problem, Anderson and Blundell (1982) incorporated dynamic structure into the systems of equations of demand and cost studies. Unfortunately, because Anderson and Blundell (1982) modeled only cost share equations without the cost function, an identification problem, which Urga (1996) later solved, has

[11] See Berndt and Christensen (1973a), Berndt and Wood (1975) and Christensen and Greene (1976) for details. Also see Kim (1982) for derivations.

 ISSN 1927-033X

arisen. Urga (1996) suggests a general cost function that contains both equilibrium and disequilibrium terms. The suggested short-run cost function takes the following form:[12]

$$ln\, C_t = m\, ln\, C_t^* + (1-m)\, ln\, C_{t-1}^* + (1-m)\left(\sum_i^n S_{i,t-1}\, ln\, w_{it} - \sum_i^n S_{i,t-1}^*\, ln\, w_{i,t-1}\right) + \sum_i^n \sum_j^n b_{ij}\,(S_{j,t-1}^* - S_{j,t-1}) ln\, w_{it} \qquad (14)$$

Where m is scalar, C^* is the equilibrium cost and C is the effective cost, S_t^* is the optimal (target) share, where the star indicates the long-run, S_t is the short-run (actual) share and b_{ij} are the elements of an ($N \times N$) matrix of coefficients called B. In equilibrium $S_{it} = S_{it}^*$

The corresponding cost shares system to (14) is given by:

$$S_t = mS_t^* + (1-m)S_{t-1} + B(S_{t-1}^* - S_{t-1}) \qquad (15)$$

Reparameterization of (15) by subtracting IS_{t-1}, where I is the identity matrix, from both sides and adding and subtracting mS_{t-1}^* from the right-hand side, produces what is called partially generalised error correction mechanism.

$$\Delta S_t = m\Delta S_t^* + K(S_{t-1}^* - S_{t-1}) \qquad (16)$$

Where $K = mI + B$

Because of singularity, one equation has to be deleted from (16). Consequently, the joint estimation of (14) and (16) eliminates the parameters identification problem and allow for estimating short-run elasticities. The short run own price and cross price elasticities of demand for factors of production are respectively given by:[13]

$$\eta_{ii}^s = \frac{m\beta_{ii}}{S_i} + S_i - 1 \qquad (17)$$

$$\eta_{ij}^s = \frac{m\beta_{ij}}{S_i} + S_j \qquad (18)$$

Where the superscript (s) means short-run

6. Modeling the Cost Structure of the JPRC

The cost function will be modeled under the assumptions that the JPRC is a regulated firm/industry that minimizes cost for a given level of outputs (exogenously determined) and the market of inputs is competitive.[14] An additional useful assumption would be to view

[12] As shown by Moss, Erickson, Ball and Mishra (2003), *m*, is interpreted as the adjustment factor or parameter while b_{ij} are interpreted as the dynamic parameters of the cost share equations.

[13] Compare with long-run elasticities as given by (10) and (11) above.

[14] It is worth noting that the JPRC is required to supply all petroleum products which are demanded at regulated prices. Consequently, revenues of the JPRC depend on the rates set by the GoJ. Furthermore, since petroleum refinery industry competes with other industries for factors of production, then the assumptions that input prices and level of production are exogenous variables are reasonable (see footnote 6). Among the authors who adopt the assumption of cost minimization and competitive input markets are Berndt and Wood (1975), Christensen and Greene (1976), Roberts (1986), Gilsdorf (1995) and Coble-Neal (2005).

labor, capital and crude oil as a group weakly separable from other inputs of production. The importance of this assumption is that it allows the inclusion of the inputs that are the most important for the production process. Weak separability means that the marginal rate of substitution between any two of these three inputs is independent of changes in the quantity of other inputs.[15]

Ideally, the cost model as described by the general form (3) should include all petroleum products as well as all factors of production under consideration. However the inclusion of too many variables would considerably reduce the number of degrees of freedom and consequently might produce poor estimates of the model. Therefore we will preserve the multiproduct nature of the model; however, the number of products will be reduced by grouping them into bundles of products. The common practice in empirical studies is to aggregate products into a small number of bundles (usually 2 or 3 bundles) according to some plausible criterion. Following Shoesmith (1986, 1988 & 1990), 3-bundle specifications were attempted.[16] But unfortunately, under these specifications, the cost function violated the quasi-concavity condition at a great number of the sample points despite that it satisfied the monotonicity condition in input prices almost at all the sample points.[17] In view of that, other specifications of 2 bundles were attempted. Among these only one combination gave rise to plausible empirical results. Under this combination, the first bundle contains (gasoline, liquefied petroleum gas, Jet fuel, kerosene, diesel and white spirits) while the other contains the heaviest products (asphalt and fuel oil).[18] Indeed, while achieving the monotonicity property at all the sample points, this specification has substantially improved data compliance with quasi-concavity condition where this condition was respected at 86% of the data points versus 36% under the 3-bundle specification.[19]

An additional important virtue of the 2-bundle specification over the 3-bundle specification is lessening the severity of multicollinearity resulting from the reduction in the number of independent variables. This consequently increases the number of degrees of freedom. On the other hand, the assumption of weak separability allows us to include the most important inputs into the model, i.e., labor, capital and crude oil. Accordingly, our model will contain 2 outputs and three inputs ($m = 2,\ n = 3$) and can be represented as:

[15] Another definition of weak separability is given by Berndt and Christensen (1973b) which implies that Allen partial elasticities of substitution between a factor in the separable group and some factor outside the group are equal for all factors in the group. For formal treatment of weak separability see (Denny and Fuss, 1977).
[16] It should be noticed that the technical experts in the JPRC recommended aggregating the products into 3 bundles based on the value of those products which is related inversely to their degree of volatility. More specifically, the following aggregation was recommended: the first bundle to contain gasoline and LPG, the second bundle to contain kerosene, diesel, white spirits and jet fuel, while the third to contain asphalt and fuel oil.
[17] It is worth mentioning that it was tried to impose concavity at a single point as recommended by Ryan and Wales (2000) on the hope that concavity will be achieved at more points. Unfortunately, although this method was tried at many points including the point of approximation (the sample mean) but this procedure did not enhance the concavity at all. Hence, this option was neglected as well. Therefore there was a need to find an alternative way of aggregating petroleum products into 2 bundles.
[18] Two other combinations were tried out. In one of these combinations, one bundle included gasoline and LPG, while the other one contained diesel, kerosene, Jet fuel, white spirits, asphalt and fuel oil. In the other combination, one of the bundles contained gasoline, LPG, diesel, asphalt and fuel oil, while the other contained diesel, kerosene, Jet fuel and white spirits. But none of these combinations was compatible with all the desired theoretical properties of a cost function.
[19] It is true that Wales (1977) shows that the translog function provides good estimates even if several violations of this condition occur, however compared to other studies this violation is severe and inferences based on such a cost function are highly suspect (Chua, Kew and Yong, 2005).

 ISSN 1927-033X

$$ln\, C = \alpha_0 + \alpha_1\, ln\, y_1 + \alpha_2\, ln\, y_2 + \beta_1\, ln\, w_1 + \beta_2\, ln\, w_2 + \beta_3\, ln\, w_3 + \frac{1}{2}\alpha_{11}(ln\, y_1)^2$$
$$+ \alpha_{12}\, ln\, y_1\, ln\, y_2 + \frac{1}{2}\alpha_{22}(ln\, y_2)^2 + \frac{1}{2}\beta_{11}(ln\, w_1)^2 + \beta_{12}\, ln\, w_1\, ln\, w_2$$
$$+ \beta_{13}\, ln\, w_1\, ln\, w_3 + \frac{1}{2}\beta_{22}\,(ln\, w_2)^2 + \beta_{23}\, ln\, w_2 ln\, w_3 + \frac{1}{2}\beta_{33}\,(ln\, w_3)^2$$
$$+ \gamma_{11}\, ln\, y_1\, ln\, w_1 + \gamma_{12}\, ln\, y_1\, ln\, w_2 + \gamma_{13}\, ln\, y_1\, ln\, w_3$$
$$+ \gamma_{21}\, ln\, y_2\, ln\, w_1 + \gamma_{22}\, ln\, y_2\, ln\, w_2 + \gamma_{23}\, ln\, y_2\, ln\, w_3 + \varepsilon_C \qquad (19)$$

The disturbance, ε_C, reflects the fact that the translog specification is merely an approximation of the true cost function. To get the cost share equations $S_i, i = 1,2,3$ associated with equation (19), the translog cost function is differentiated with respect to $ln\, w_1$, $ln\, w_2$ and $ln\, w_3$, respectively and the following cost share equations are derived:

$$S_1 = \beta_1 + \beta_{11}\, ln\, w_1 + \beta_{12}\, ln\, w_2 + \beta_{13}\, ln\, w_3 + \gamma_{11}\, ln\, y_1 + \gamma_{21}\, ln\, y_2 + \varepsilon_1 \qquad (20.\text{a})$$

$$S_2 = \beta_2 + \beta_{12}\, ln\, w_1 + \beta_{22}\, ln\, w_2 + \beta_{23}\, ln\, w_3 + \gamma_{12}\, ln\, y_1 + \gamma_{22}\, ln\, y_2 + \varepsilon_2 \qquad (20.\text{b})$$

$$S_3 = \beta_3 + \beta_{13}\, ln\, w_1 + \beta_{23}\, ln\, w_2 + \beta_{33}\, ln\, w_3 + \gamma_{13}\, ln\, y_1 + \gamma_{23}\, ln\, y_2 + \varepsilon_3 \qquad (20.\text{c})$$

$S_i, i = 1,2,3$ are calculated by dividing their respective cost component by total cost.

Following the literature, the disturbances of the cost share equations are assumed to have joint normal distribution, see, for example, Christensen and Greene (1976) and Seabra (1993), among others. Furthermore, the disturbances are assumed to be temporally uncorrelated but contemporaneously correlated across equations.

The condition of linear homogeneity in input prices implies that the sum of $S_i, i = 1,2,3$ must be one. Consequently, the following linear restrictions on the parameters of the cost and input share equations are specified.

$$\beta_2 = 1 - \beta_1 - \beta_3 \qquad (21.\text{a})$$

$$\beta_{12} = -\beta_{11} - \beta_{13} \qquad (21.\text{b})$$

$$\beta_{23} = -\beta_{13} - \beta_{33} \qquad (21.\text{c})$$

$$\beta_{22} = \beta_{11} + \beta_{33} + 2\beta_{13} \qquad (21.\text{d})$$

$$\gamma_{12} = -\gamma_{11} - \gamma_{13} \qquad (21.\text{e})$$

$$\gamma_{22} = -\gamma_{21} - \gamma_{23} \qquad (21.\text{f})$$

Substituting the homogeneity restrictions (21) into the translog cost function (19) yields:

$ln\,C = \alpha_0 + \alpha_1\,ln\,y_1 + \alpha_2\,ln\,y_2 + \ \beta_1\,ln\,w_1 + (1 - \beta_1 - \beta_3)\,ln\,w_2 + \beta_3\,ln\,w_3 +$
$12\alpha11(lny1)2+\alpha12lny1lny2+\ 12\alpha22lny22+12\ \beta11(lnw1)2-(\beta11+\beta13)lnw1lnw2+$
$\beta13lnw1lnw3+12(\beta11+\beta33+2\beta13)\ lnw22-(\beta13+\beta33)lnw2lnw3+\ 12\,\beta33(lnw3)2+$
$\gamma_{11}\,ln\,y_1\,ln\,w_1 - (\gamma_{11} + \gamma_{13})\,ln\,y_1\,ln\,w_2 + \ \gamma_{13}\,ln\,y_1\,ln\,w_3 + \gamma_{21}\,ln\,y_2\,ln\,w_1 - (\gamma_{21} +$
$\gamma23lny2lnw2+\gamma23lny2lnw3+\varepsilon C$
(22)

Similarly, by substituting the homogeneity restrictions into the cost share equations S_1, S_2 and S_3in (20), we get the following share equations:

$$S_1 = \beta_1 + \beta_{11}\,ln\,w_1 - (\beta_{11} + \beta_{13})\,ln\,w_2 + \beta_{13}\,ln\,w_3 + \gamma_{11}\,ln\,y_1 + \gamma_{21} + \varepsilon_1 \qquad (23.a)$$

$$S_2 = (1 - \beta_1 - \beta_3) - (\beta_{11} + \beta_{13})\,ln\,w_1 + (\beta_{11} + \beta_{33} + 2\beta_{13})\,ln\,w_2 + \beta_{23}\,ln\,w_3 - \gamma11 + \gamma13lny1 - \gamma21 + \gamma23lny2 + \varepsilon2 \qquad (23.b)$$

$$S_3 = \beta_3 + \beta_{13}\,ln\,w_1 - (\beta_{13} + \beta_{33})\,ln\,w_2 + \beta_{33}\,ln\,w_3 + \gamma_{13}\,ln\,y_1 + \gamma_{23}\,ln\,y_2 + \varepsilon_3 \qquad (23.c)$$

The system comprised of the equations (22) and (23) represents the constrained multivariate regression system to be estimated.

7. Testing Subadditivity

Baumol et al. (1982) show that economies of scope is the only necessary condition for subadditivity while different sets of sufficient conditions are available. However, all of these conditions are excessively strong in the sense that they contain elements that are not necessary for subadditivity. Among these are the following two conditions which together guarantee strict subadditivity of costs at an output vector y^0 are:[20]

(Non-strict) transray convexity along any one hyperplane $H = \{y \backslash w.y = w_0, w > 0\}$ through y^0.

Strictly declining ray average costs up to the hyperplane H.

Before discussing these conditions we will introduce the concepts of transray convexity and declining ray average costs in turn.

Transray convexity characterizes the behavior of costs as output proportions vary. Mathematically, a cost function is called a transray convex through $y^* = (y_1^*, \dots, y_n^*)$ if there exists any set of positive constants $w_1, \dots w_n$, such that for every two output vectors $y^a = (y_1^q, \dots y_n^a)$, $y^b = (y_1^b, \dots y_n^b)$ lying in the same hyperplane $\sum_{i=1}^{n} w_i y_i = w$ through y^*(so that they satisfy $\sum_{i=1}^{n} w_i y_i^a = \sum_{i=1}^{n} w_i y_i^b = \sum_{i=1}^{n} w_i y_i^*$), we have

[20] Gordon Gunsch and Pawluk (2003) and Squires (1988) employ these conditions in testing subadditivity.

$C(y^*) = C(ky^a + (1-k)y^b) \leq kC(y^a) + (1-k)C(y^b)$

For any k, $0 < k < 1$.[21]

Ray average cost (RAC) is the generalization of single product average cost.[22] According to this concept, the proportionate changes in output is observed along a ray from the origin in output space and then the shape of the cost function is observed as we move along the ray (Berg and Tschirhart 1988). In the multiproduct case, decreasing ray average cost can be used to express the analogue of decreasing average cost in the single-product case. Declining ray average cost can be expressed as (Baumol, 1977):

$$\frac{C(vy_1, \dots, vy_n)}{v} < \frac{C(wy_1, \dots, wy_n)}{w}$$

For v $> w$, where v and w are measures of the scale of output along a ray through output vector $y = (y_1, \dots, y_n)$.[23]

Squires (1988) notes that it is very difficult to test overall transray behavior with the cost function. However testing for pairwise transray convexity is simple. If pairwise transray convexity does not exist then transray convexity does not hold. Pairwise transray convexity can be tested by calculating second-order partial derivatives.

Baumol et al. (1982) show that any of the following two conditions is sufficient for transray convexity between two outputs *i* and *j*:

$$Cy_iy_i \geq 0, \quad Cy_jy_j \geq 0, \quad Cy_iy_j = Cy_jy_i \leq 0 \qquad (24.\text{a})$$

$$Cy_iy_i \leq 0, \quad Cy_jy_j \leq 0, \quad Cy_iy_j = Cy_jy_i \leq 0, \quad Cy_iy_j \leq -\left(Cy_iy_i\, Cy_jy_j\right)^{1/2} \qquad (24.b)$$

Where Cy_iy_i is the second order partial derivative of the cost function with respect to the *i*th output. Note that $Cy_iy_j \leq 0$ implies weak cost complementarity. As shown by Baumol et al. (1982), a twice-differentiable multiproduct cost function exhibits weak cost complementarities over the product set N up to output level y, if:

$$\frac{\partial^2 C(y^\wedge)}{\partial y_i \partial y_j} = C_{ij}(y^\wedge) \leq 0, \qquad i \neq j$$

For all $y^\wedge$ with $0 \leq y^\wedge \leq y$. The presence of weak cost complementarities implies that the marginal cost of producing any one product decreases with increases in the quantities of all other products.

Also note that that decreasing marginal cost implied by $Cy_iy_i \leq 0$ suggest the presence of product-specific scale economies and is calculated as follows:

[21] See Baumol (1977).
[22] See Bailey and Friedlaender (1982).
[23] In other words, declining ray average cost exists whenever a small proportional change in output leads to a less than proportional change in total cost (Baumol et al., 1982).

$$\frac{\partial^2 C}{\partial {y_i}^2} = Cy_i y_i = \frac{C}{{y_i}^2}\left(\frac{\partial \ln C}{\partial \ln y_i}\left(\frac{\partial \ln C}{\partial \ln y_i} - 1\right) + \frac{\partial^2 \ln C}{\partial \ln {y_i}^2}\right) \quad (25.a)$$

$$= \frac{C}{{y_i}^2}\left(\varepsilon_{Cy_i}\left(\varepsilon_{Cy_i} - 1\right) + \alpha_{ii}\right) \quad (25.b)$$

Where ε_{Cy_i} is defined as in (8). At the point of approximation (normalization)[24] equation (25.b) becomes:

$$\frac{\partial^2 C}{\partial {y_i}^2} = Cy_i y_i = \frac{C}{{y_i}^2}\left(\alpha_i(\alpha_i - 1) + \alpha_{ii}\right) \quad (26)$$

Gilsdorf (1994) shows in detail how to derive the formula for weak cost complementarity. The final equation that concerns us is:

$$\frac{\partial^2 C}{\partial y_i \partial y_j} = C_{ij} = \frac{C}{y_i y_j}\left[\left(\frac{\partial \ln C}{\partial \ln y_i}\frac{\partial \ln C}{\partial \ln y_j}\right) + \frac{\partial^2 \ln C}{\partial \ln y_i \, \partial \ln y_j}\right] \quad (27)$$

Within the translog structure (equation 3) we have the following:

$$\frac{\partial \ln C}{\partial \ln y_i} = \alpha_i + \sum_j^m \alpha_{ij} \ln y_j + \sum_j^n \gamma_{ij} \ln W_j \quad (28)$$

$$\frac{\partial^2 \ln C}{\partial \ln y_i \, \partial \ln y_j} = \alpha_{ij} \quad (29)$$

At the point of approximation (normalization) equation (27) becomes:

$$\frac{\partial^2 C}{\partial y_i \partial y_j} = C_{ij} = \frac{C}{y_i y_j}\left(\alpha_i \alpha_j + \alpha_{ij}\right) \quad (30)$$

As noted by Baumol et al. (1982), weak cost complementarity is sufficient condition for economies of scope, which in turn is a necessary condition for subadditivity.

[24] Normalizing the regressors is one method used to tackle the multicollinearity problem. This is undertaken by dividing the outputs and factor prices by their respective means in the sample, thus regressors will have a mean of one and a standard deviation of zero, see (Caves et al., 1980, Kim, 1982; Shoesmith, 1986 and Shin and Ying, 1992). The normalization reduces the high correlations among variables for models involving quadratic or higher order terms. It also facilitates the interpretation of the coefficients. Moreover using the additional information contained in the cost share equations to increase the efficiency of the parameter estimates and then jointly estimate the cost equation and the cost share equations as a system of equations is a second method to reduce multicollinearity.

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Baumol et al. (1982) show that increasing or decreasing returns at y imply that (RAC) is decreasing or increasing at y. As shown by Panzar and Willig (1977), a local measure of overall or aggregate scale economies, $SL(y,w)$, can be computed as: [25]

$$SL(y,w) = \frac{C(y,w)}{\sum_i y_i MC_i} = \frac{1}{\sum_i \varepsilon_{Cy_i}} \tag{31}$$

Where $MC_i = \frac{\partial C(y,P)}{\partial y_i}$ denotes the marginal cost and ε_{Cy_i} as defined by (8) above. At the approximation point, $(\sum_i \alpha_i)^{-1}$ represents overall scale economies. Remember that returns to scale are said to be increasing, constant or decreasing if $SL > 1$, $SL = 1$ or $SL < 1$, respectively.

Based on the above, the sufficient conditions for natural monopoly can be summarized by: $SL > 1$; $\frac{\partial^2 C}{\partial {y_i}^2} \geq 0$; $\frac{\partial^2 C}{\partial y_i \partial y_j} \leq 0$; for all i, j, with $i \neq j$.

8. Constructing the Data Sets and Defining the Variables

As implied by equation (22), the translog cost function expresses the total cost as a function of the produced quantities of petroleum products and the prices of the factors of production. Hence we need data about these variables. The major source of these data is the annual reports of the JPRC spanned over the period 1961-2010.[26] Additional data which is not published in the annual reports were provided by the JPRC. Those include the amounts and the prices of imported crude oil in addition to the amounts of crude oil used in the production. Missing data about wages for the period 2005-2010 were also provided by the JPRC. The data on the consumer price index (CPI) was taken from the database of the Central Bank of Jordan. The Jordan dinar exchange rate against US dollar was taken from the United Nations database.[27] Total cost is calculated by adding up the cost of goods sold, the sales expenditures and the administrative expenditures. These three cost items were extracted from the income statements included in the annual reports and were adjusted by the CPI. The prices of domestic crude oil were provided by JPRC. The prices of labor and capital were calculated based on the data in the annual reports. More specifically, the average wage per worker was used as a proxy for the price of labor. It was calculated by dividing annual wages by number

[25] Among the authors who calculate this measure are Kim (1985, 1987, 1995), Diewert and Wales (1991), Seabra (1993) and Bloch, Madden, Coble-Neal and Savage (2001).

[26] It is worth mentioning that in 1983 the GoJ decided to entrust the JPRC to pay the full price of the crude oil on its behalf to the Tapline Company, and later on, any financial settlements to be resolved between the government and the company. This change has been reflected on cost items in the financial statements starting from 1983 and thereafter. Therefore to ensure consistency in the data, the prices of crude oil have been adjusted before 1983 to reflect this change, consequently the cost of crude oil used in production and total costs have been adjusted as well. On the other hand it deserves mentioning that the inclusion of the year 2010 data has distorted the results of the analysis considerably especially the regularity conditions of monotonicity and concavity. A possible reason for this could be the volatility in world prices of crude oil which caused a jump in the price of crude oil from $62 per barrel in 2009 to $82 in 2010, as demonstrated in the annual report 2010 of the JPRC. This has adversely affected the cash flows which are used by the JPRC to finance the purchase of crude oil and refined products which represent the main cost components of the company. To fix the distortion caused by the inclusion of the year 2010, a dummy variable with value 1 for 2010 and 0 otherwise has been added to the model. Adding this variable to the model has improved the results considerably. The dummy variable is found to be statistically significant and different from zero (see Table 1).

[27] http://statisticaldb.cbj.gov.jo/index?lang=en, http://data.un.org/Data.aspx?d=IFS&f=SeriesCode%3a.

of employees.[28] Calculating the price of capital is more complicated compared to calculating the price of labor. Adding to this difficulty the relative scarcity of subadditivity literature on petroleum refining industry. To tackle this difficulty, methodologies used in other industries were investigated to aid in constructing a suitable measure that can be adopted in the petroleum refining industry taking into consideration the limitation of data. Taking into consideration these different methodologies of calculating the price of capital coupled with relative scarcity of much of the data needed for the calculations, it was found that a suitable measure that could approximate the price of capital might be constructed by dividing the residual cost (total cost minus costs of labor and crude oil) by the fixed assets. Among the authors who use this methodology are Barakat (2003), Rezvanian, Mehdian and Elyasiani (1996), Altunbas and Molyneux (1996) and Gropper (1991). It is worth mentioning that Al-Alwani (1995) and Al-Momani (1996) use this proxy as well.

9. Empirical Results

Following Christensen and Greene (1976), the Iterative Zellner Efficient method (IZEF) is employed by jointly estimating the translog cost function and the cost share equations. This method is similar to the Zellner Efficient method (ZEF) or the Seemingly Unrelated Regression (SUR) method of Zellner except that the estimates are iterated until the estimated variance-covariance matrix is diagonal and the parameter estimates converge (Denny and Pinto, 1978). However, since the sum of the cost share equations adds to one, this will cause a problem in estimating the system of equations comprised by the cost function (22) and the cost share equations (23). The problem is caused by the fact that the disturbance terms across the share equations must sum to zero, which means that the covariance matrix of the share disturbance terms is singular. This problem can be overcome by arbitrarily excluding any one of the cost share equations and then jointly estimating the remaining two with the translog cost equation. If feasible generalized least squares (FGLS) method is used to estimate the new nonsingular system, then the estimates will depend on which equation has been dropped. To make estimates invariant to which equation has been deleted, the maximum likelihood estimates should be used instead of FGLS, which can be obtained by iterating FGLS or using direct maximum likelihood estimation see, (Greene, 2003).

Before introducing the results of the Iterative Seemingly Unrelated Regression (ISUR) estimates, it is useful to compare the estimates under OLS with the results under SUR.[29] The static translog cost equation (22) was estimated using OLS method while the system of equations (22) and (23.a, b) was estimated using SUR method without imposing linear homogeneity restrictions. Under the two methods 18 out of 21 parameters estimates are significant at 5% level. Moreover, the estimates under OLS and SUR are very close in terms of magnitude. However as expected, the efficiency measured by the standard error, is greater for all the estimates under SUR compared with OLS. It is worth mentioning that not all estimates, especially the second order ones, have the correct sign that comply with the economic theory including β_{11}which has incorrect sign under SUR.[30]

[28] Among the authors who use this proxy are Christensen and Greene (1976), Seabra (1993), Salvanes and Tjøtta (1998b), Bloch, Madden, Coble-Neal and Savage (2001), Kwoka (2002), Barakat (2003), Fraquelli, Piacenza and Vannoni (2004), Mohammed and Burney (2006), Wills-Johnson (2008), Farsi, Fetz and Filippini (2008) and Fetz and Fillipini (2010).
[29] Results can be provided upon request from the authors.
[30] However, as shown below when linear homogeneity is imposed, the iterative SUR estimate yield estimates consistent with the economic theory including $\beta_{11}$with the correct sign (positive) see Table 1. One possible explanation for this could be based on Greene (2003) who notes that the unconstrained model does not comply

 ISSN 1927-033X

Next, we impose the restriction of linear homogeneity in factor prices and we also added $AR(1)$ terms to the three equations to remove serial correlation. Furthermore, a dummy variable was added to remove distortion in results caused by the inclusion of the data of 2010 (see footnote 27). Moreover, time trend was added to the cost equation to remove the effect of the trend.[31] Using ISUR technique, the parameters estimates were obtained through an iterative process which converged after 15 weight matrices and 86 iterations. Table 1 presents the parameter estimates of the system of equations (22) and (23.a, b). The estimates of the restricted parameters not contained in Table 1 can be derived from the following set of equalities:

$\beta_2 = 1 - \beta_1 - \beta_3$= 0.083010, $\beta_{12} = -\beta_{11} - \beta_{13} =$ - 0.002983

$\beta_{22} = \beta_{11} + \beta_{33} + 2\beta_{13} = 0.026231$, $\beta_{23} = -\beta_{13} - \beta_{33}$ = - 0.023248

$\gamma_{12} = -\gamma_{11} - \gamma_{13} =$ - 0.067233, $\gamma_{22} = -\gamma_{21} - \gamma_{23}$ = 0.069693

As the Table 1 shows, the value of R-squared for the cost equation is extremely high (0.998747) indicating that large proportion of variation in the system is explained by the translog and cost share equations.32 Out of 19 parameters estimates, 15 are significant at 5% level. These include the most important estimates in the model (the elasticities of cost with respect to the quantities of production and prices of inputs) which are highly significant with probability zero. It is clear that modeling the error terms as autoregressive processes of degree one is proper as well since the significance of the estimates associated with these terms are extremely high with zero probability for each. The time trend variable is significant but negligible. The dummy variable is also significant. One possible explanation for the dummy variable could be that it captures the effect of volatility in world crude oil prices (As noted in footnote 27) which is not explained explicitly by the regressors in the model. The constant term which represents the fixed costs is positive as expected. The cost elasticities with respect to the produced quantities and input prices have the correct sign and are of plausible magnitude.

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with the economic theory. However, we decided not to impose the linear homogeneity restriction at this stage for two reasons. First, to highlight any differences caused by imposing and not imposing restrictions and second because we want to hold another comparison between SUR estimates and fully modified ordinary least square (FMOLS) and since FMOLS does not allow for restriction; therefore restrictions were not imposed so that results are comparable under OLS, FMOLS and SUR.

[31] Following Ray (1982), the time variable was modeled in this way. A more complex strategy of modeling time variable in the context of translog function, as a proxy for the technological development, was pioneered by Stevenson (1980) using truncated third-order Taylor series expansion and it was used extensively in the empirical work especially the one aiming at measuring the effect of technological change on cost structure. However, this model exhausts a substantial additional number of degrees of freedom. In our model this will lead to additional loss of 7 degrees of freedom compared with a loss of only one degree of freedom with the less sophisticated specification. Moreover this truncated specification was tried and produced unsatisfactory results.

[32] This is not unusual in this kind of studies, the following list shows some of the studies alongside with the associated R-squared value: Bloch, Madden and Savage (2001) ; ($R^2 =$ 0.9998), Sánchez (2000), Serafica (1998);
($R^2 =$ 0.993), Gilsdorf (1995); ($R^2 =$ 0.98), Shin and Ying (1992); ($R^2 =$ 0.9977), Diewert and Wales (1991); ($R^2 =$ 0.9999), Shoesmith (1988); ($R^2 =$ 0.9994) and Evans and Heckman (1984); ($R^2 =$ 0.9999), among others.

Table 1 ISUR Estimates of the Static Translog Cost Equation and Two Cost Share Equations

Parameter	Coefficient	Std. Error	t-Statistic	Prob.
α_0	19.87645	0.0472	421.1089	0.0000
α_1	0.381602	0.063593	6.00066	0.0000
α_2	0.522986	0.042206	12.3913	0.0000
β_1	0.074962	0.00913	8.210911	0.0000
β_3	0.842028	0.011261	74.77311	0.0000
α_{11}	0.296463	0.357458	0.829366	0.4084
α_{12}	-0.34135	0.297884	-1.14591	0.2540
α_{22}	0.447857	0.258297	1.733883	0.0853
β_{11}	0.032249	0.003895	8.280051	0.0000
β_{13}	-0.02927	0.00328	-8.92363	0.0000
β_{33}	0.052514	0.007133	7.362383	0.0000
γ_{11}	-0.04658	0.009697	-4.80331	0.0000
γ_{13}	0.11381	0.027579	4.126641	0.0001
γ_{21}	-0.01231	0.007573	-1.62533	0.1066
γ_{23}	-0.05738	0.02329	-2.46382	0.0151
$AR(1)$ coefficient of the cost equation	0.563398	0.055398	10.17001	0.0000
$AR(1)$ coefficient of the share equations	0.913448	0.014611	62.51642	0.0000
Time trend coefficient	0.004437	0.001723	2.575262	0.0112
Dummy variable coefficient	0.07667	0.023786	3.223348	0.0016

	Cost equation	Labor share equation	Capital share equation
R-squared	0.998747	0.948611	0.779487
Adjusted R-squared	0.998061	0.942635	0.728599
S.E. of regression	0.048165	0.005323	0.052423
Durbin-Watson stat	2.464378	2.148282	2.487768
Mean dependent var	19.73216	0.052449	0.24102
S.D. dependent var	1.093687	0.022223	0.100628
Sum squared resid	0.071916	0.001218	0.10718

More specifically, the cost elasticities with respect to the production of the first and second bundles of petroleum products are approximately 0.38 and 0.52, respectively. On the other hand, the elasticities of cost with respect to the prices of labor, capital and crude oil are approximately 0.07, 0.08 and 0.84, respectively. The remaining interaction parameters are also of the correct sign. However, Moon (1999) notes that for the classical SUR model in which the regressors are stationary and errors are independent and identical over time a feasible generalizes least squares (FGLS) estimator is efficient. But this is not true in general if the system of equations has nonstationary time series that allow for endogenous regressors and serially correlated errors. In this case FGLS has a non-standard limit distribution that is skewed and shifted away from the true parameter due to the asymptotic endogeneity of the regressors and the serial correlation of the errors, although the estimate is consistent. Moon (1999) shows how to correct for asymptotic endogeneity and serial correlation by fully-modifying the integrated seemingly unrelated regressions model following Phillips and Hansen (1990) approach.33 Therefore the natural next step would be testing the stationarity of the time series. To that end, the standard unit root tests of Dickey and Fuller and Phillips-Perron were undertaken. The results showed that none of the series was stationary at the level even at 10% level. However, all the series became stationary at the first difference. To check

[33] On the other hand, Balcombe and Tiffin (2002) argue that Moon's (1999) approach does not allow for the imposition of cross-equation restrictions. Therefore they suggest other two methods to take cross-equation restrictions into account.

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for the possibilities of the existence of long run equilibrium relation. The Johansen test for cointegration was conducted. The results show that there exists one cointegration equation. Based on the results of the stationarity and cointegration tests, the variables have a (static) long-run equilibrium and consequently the possibility of spurious correlation between the variables is ruled out. Based on these results, the static translog cost equation (22) was estimated using fully modified ordinary least squares (FMOLS) without imposing linear homogeneity constraint.34 The estimates under FMOLS were compared with those under SUR. Under FMOLS, 19 out of 21 parameters estimates are significant at 5% compared with 18 under SUR. The results are also very close under the two methods except for β_{11}. However like OLS estimates, not all parameters estimates, especially the second order ones, have the correct sign that comply with the economic theory (see footnote 31 for a possible explanation). Since FMOLS yielded similar results to SUR estimates, then the ISUR estimates can be confidently

9.1. Multicollinearity

Most cost and demand systems suffer form the second type of multicollinearity (Hill and Adkins 2001), i.e. when two variables exhibit a large correlation. In fact, it was found that the data suffers from this type of multicollinearity since the correlation between the two groups of products Y_1 and Y_2 is 99.1%.35 Moreover, the Variance Inflation Factor (VIF) which measures the increase of variance caused by the existence of multicollinearity shows that the two variables y_1 and y_2 are collinear.36 As shown earlier (see footnote 25), among the remedy measures taken to lessen the effect of multicollinearity is normalizing the independent variables by dividing them by their means to reduce the degree of multicollinearity. Indeed the Variance Inflation Factor (VIF) declined significantly after normalization.

9.2. Autocorrelation

Time series data often exhibit autocorrelation or serial correlation of the disturbances across different periods. In the presence of autocorrelation, OLS estimators are no longer efficient. Portmanteau test for system autocorrelation show that the hypothesis of no autocorrelation was rejected up to 12 lags.37 To reduce autocorrelation, first order autoregressive disturbances were modeled and added to each equation in the system, see Evans and Heckman (1984).38 After adding the AR(1) term, the hypothesis of no autocorrelation was not rejected at all lags up to 12 lags.

9.3. Heteroskedasticity

Tests of heteroskedasticity have been applied to the OLS residuals of the translog cost equation. White test has been used to test the null hypothesis of no heteroskedasticity. The results showed no evidence of heteroskedasticity. The results of Breusch-Pagan-Godfrey test,

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[34] Results can be provided upon request from the authors.

[35] The high degree of correlation is not unusual in petroleum refining since the percentage of producing each product remains constant unless the configuration of the refinery is changed.

[36] The centered VIF is the ratio of the variance of the coefficient estimate from the original equation divided by the variance from a coefficient estimate from an equation with only that regressor and a constant. The uncentered VIF is the ratio of the variance of the coefficient estimate from the original equation divided by the variance from a coefficient estimate from an equation with only one regressor (and no constant).

[37] Portmanteau autocorrelation test computes the multivariate Box-Pierce/Ljung-Box Q-statistics for residual serial correlation up to the specified order.

[38] Following Diewert and Wales (1991), and to ensure that the results are invariant to the share equation deleted when the $AR(1)$ process is assumed, the serial correlation coefficients for the share equation disturbances are restricted to be the same.

which is more powerful test of heteroskedasticity did not show evidence of heteroskedasticity too.

9.4. Test for Structural Change or Parameter Stability

The years 1973 and 1979 were chosen as structural breaks to capture the effect of oil embargos in those years and assess their impact on the cost function estimation. However, due to the large number of regressors involved in the translog model and consequently the small number of degrees of freedom, the Chow test for breakpoints could not be performed for 1973. On the other hand, the null hypothesis of no structural break could not be rejected for the year 1979, implying that there is no evidence against the stability of the model. The year 1989 was also chosen to reflect the impact of the financial crisis in 1989 on the cost structure of the JPRC. Likewise, there was no evidence to reject the hypothesis of no structural break.

10. Testing the Regularity Conditions of the Cost Function (Static Specification)

This section highlights the regularity conditions that a proper cost function needs to adhere to. Those include positive cost, positive marginal cost, monotonicity and concavity in input prices, in addition to linear homogeneity in input prices and symmetry conditions which are imposed a priori during estimation. Each of these conditions will be discussed respectively in turn. Since exp $(\ln (C(y))$ is strictly positive for all y, then the estimated production cost is positive for all y at all observations. The positive marginal cost condition requires the elasticities of cost with respect to outputs to be positive; this condition is satisfied for all sample points.39 As remarked earlier, the sufficient condition for monotonicity in input prices40 is positive fitted cost share equations; the results support the monotonicity condition since the three fitted cost share equations were positive at every observation. The final regularity condition is that the cost function is (quasi) concave in input prices. This condition requires the Hessian matrix of the cost function to be negative semidefinite. This condition was met at 43 points out of 50 comprising 86% of all the data set.41 As mentioned earlier, according to Wales (1977), the translog function provides good estimates even if several violations of this condition occur.42 By satisfying the above conditions, the cost function is proper in the sense that it can be used to investigate further properties of multi production including economies of scope, economies of scale and subadditivity.

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[39] This finding contradicts the finding of Evans and Heckman (1984) which was criticized later by Diewert and Wales (1991) and Salvanes and Tjøtta (1998b) for violating positive marginal cost condition for one of the outputs at 21 observations of 31 observations.

[40] Monotonicity implies that the costs of production are nondecreasing in input prices.

[41] It was tried to impose concavity at a single point as recommended by Ryan and Wales (2000) on the hope that concavity will be achieved at more points or even at all the points as it occurred with Ryan and Wales (2000) themselves. Unfortunately, although this method was tried at many points including the point of approximation (the sample mean) but it did not enhance the concavity at all. Hence, this option was abandoned.

[42] In this context, it is worth mentioning that Roberts (1986) states that concavity is satisfied at the expansion point and at 54of the 65 sample observations, equivalent to approximately 83% of the sample. Shoesmith (1988) indicates that concavity was met at 51 of the 67 sample points or equivalent to 76% of the points. Gilsdorf (1994) reports that concavity condition was violated at 16 cases out of 72 cases; i.e., the percentage of conformity is approximately 78%. Gilsdorf (1995) declares that concavity condition was violated at 20 observations out of 72, which means that approximately 72% of the observations satisfy the condition. On the other hand, as shown in footnote 98, following the procedure of Ryan and Wales (2000) increased the percentage of points that satisfied concavity from 39.3% to 83.1% in Chua, Kew and Yong (2005). Alternatively, Gervais, Bonroy and Couture (2008) report that imposing concavity at one point made concavity to be respected at more than two thirds of the observations in the sample.

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11. Testing the Production Structure

The relevancy of choosing the translog functional form to represent the production structure of petroleum refining industry in Jordan will be tested in this section. More specifically, tests concerning some specialized production structures including input output separability, Cobb-Douglas functional form, constant returns to scale technology and nonjointness in production will be carried out.43 These tests will be performed by imposing some restrictions on the static translog cost structure and using Wald test to assess the validity of these restrictions.

11.1.Input Output Separability (Homotheticity)

Input output separability is important as it can be used to assess whether it is plausible to aggregate all the outputs into a single aggregator or not (see, for example, Brown et al., 1979 and Hall 1973).44 Using Wald test, the hypothesis of the following restrictions:
$\gamma_{11} = 0, \gamma_{13} = 0, \gamma_{21} = 0, \gamma_{23} = 0$, was tested.45 These restrictions were rejected, indicating that it is inappropriate to aggregate all the products into one single measure. This in turn provides evidence that the technology of refining industry in Jordan is better understood if it is treated empirically as a multi-product industry.46

11.2 Testing the Hypothesis of Cobb-Douglas Technology

Since Cobb-Douglas functional form is a special case (or nested) into the translog form, therefore it is appropriate to check whether the production technology of the JPRC can be represented by Cobb-Douglas or not. This can be done by testing that all the second-order parameters are zero (see, Diewert, 1982).47 Using Wald test, this functional form was rejected.48 This suggests that it is inappropriate to model the technology of JPRC by the restrictive Cobb-Douglas technology as done in some previous studies.49

11.3 Testing the Hypothesis of Constant Returns to Scale (CRTS) Technology

Technology can exhibit either decreasing, constant or increasing returns to scale. Constant returns to scale imply that entrepreneur is indifferent between centralization and decentralization of the production process (Chambers, 1988). Following Denny and Pinto

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[43] The overwhelming research tests for input-output separability, Cobb-Douglas and constant returns to scale technologies. Nonjointness is not much tested in empirical studies especially, as shown below, it is subject to much debate and has been used mistakenly to test for economies of scope. However this dissertation finds it convenient to test for nonjointness in porduction for two reasons. First, in order to give a complete picture of the underlying technology structure of JPRC. Second, as Squires (1987) notes, nonjointness has implications for regulation policies. In such case each production process can be separately regulated without affecting production of the other processes because there are no technological or cost tradeoffs between the output of one activity and that of another.

[44] In the words of Christodoulopouls (1995) "separability, crucial as to whether an aggregated output index is permissible".

[45] The other restrictions $\gamma_{12} = 0$ and $\gamma_{22} = 0$ are implicitly considered by the linear homogeneity in input prices constraint, see equations (21.e, f). For more details see Berndt and Christensen (1973a & 1974).

[46] Among the authors who test for this restriction are Evans and Heckman (1984) Gilligan, Smirlock and Marshall (1984), Kim (1985) and Burns and Weyman-Jones (1998).

[47] The other restrictions $\beta_{12} = 0$, $\beta_{22} = 0$, $\beta_{23} = 0$, $\gamma_{12} = 0$, $\gamma_{22} = 0$ are implicitly considered by the linear homogeneity in input prices constraint, see equations (21.b, c, d, e, f).

[48] For an application of this test see Fuss and Waverman (1981), Gilligan, Smirlock and Marshall (1984), Gilligan and Smirlock (1984) and Kim (1985), among others.

[49] Taraweneh (1991) and Al-Alwani (1995) used Cobb-Douglas functional form to represent the technology of JPRC.

(1978), the hypothesis of constant returns to scale as nested into the translog cost model was tested by imposing the restrictions:

1) $\alpha_1 + \alpha_2 = 1$,
2) $\alpha_{11} + \alpha_{21} = 0$ and $\alpha_{12} + \alpha_{22} = 0$. Utilizing the symmetry condition $\alpha_{12} = \alpha_{21}$, the constraint reduces to $\alpha_{11} = \alpha_{22}$
3) $\gamma_{11} = -\gamma_{21}$, $\gamma_{13} = -\gamma_{23}$.

The constraint $\gamma_{12} = -\gamma_{22}$ is implicitly implied in the linear homogeneity in input price constraint (21.e, f). Based on Wald test criterion, the hypothesis of CRTS is rejected.50 This conclusion is expected since the JPRC has experienced increasing returns to scale during the period 1961-2010 although strictly declining all over the period. Increasing returns to scale has an important implication from a public policy perspective. If there is increasing returns to scale then it is beneficial from an economic point of view to have one big firm rather to have many small firms producing at relatively high cost (Pindyck and Rubinfeld, 2005).

11.4 Testing the Hypothesis of Nonjointness in Production

The hypothesis of nonjointness was accepted implying that the production process can be summarized by individual production functions. Christodoulopoulos (1995) comments that if the condition of nonjointness is accepted then the cost function does not exhibit economies of scope. Altunbas and Molyneux (1996) report that nonjointness was not rejected for two countries in their sample implying that cost complementarities do not exist. However they assert that the nonjointness test based on the translog cost-function is only a local test and does not necessarily imply absence of global jointness.51
In sum, building on the results of the above tests of input-output separability, Cobb-Douglas functional form, constant returns to scale technology and nonjointness in production, it can be inferred that the translog cost model sufficiently describes the technology of petroleum refining industry in Jordan.

12. Estimates of Important Elasticities

12.1 Own and Cross Price Elasticities

Own and cross price elasticities are used to measure the effect of price change on the input usage. Long-run own price elasticity which is given by equation (10) measures the change in demand for input because of change in the price of the input itself. Long-run cross price elasticity given by (11) measures the change in demand for input i due to change in the price of input j. These elasticities were estimate for each year; most of the own price elasticity of demand for labor, capital and crude oil are of the correct sign (negative) with values less than one indicating that the demand for factors of production is inelastic with respect to changes in input prices. More specifically, 92% and 94% of the own price elasticities for labor and capital, respectively, were of the correct sign, while all of own price elasticities for crude oil were of the correct sign. At the point of approximation, own and cross price elasticities of inputs were estimated under the static and dynamic specifications. As shown in Table 2, in

[50] Fuss and Waverman (1981) could not reject the hypothesis of constant returns to scale except at the begging of the sample period. Burns and Weyman-Jones (1998) did not find evidence against the constant returns to scale.
[51] Note that Fuss and Waverman (1981), Christodoulopoulos (1995) and Altunbas and Molyneux (1996) use the nonjointness to assess cost complementarity and economies of scope in contradiction to what Mester (1986) argue.

 ISSN 1927-033X

the long run, the demand for capital is the more responsive to changes in its own price while demand for crude oil is the least responsive to change in its own price. The cross price elasticities are all positive indicating substitutability between factors of production but with different degrees. More specifically, in the long run an increase of 1% in the price of crude oil results in an increase of almost 0.5% and 0.6% in demand for labor and capital, respectively. These are reasonable estimates since crude oil comprises the largest proportion of the production cost, therefore the increase in the price of this cost item induces the JPRC to increase its investments in new technologies including replacement of old equipment and machinery to increase efficiency in production. Consequently, investment in new technologies often creates the need for people with special technical skills capable of running and operating such technologies. On the other hand, substitutability of crude oil towards labor and capital is almost negligible since the cross price elasticities of crude oil with respect to labor and capital prices are very small (0.04 and 0.055, respectively). These are also reasonable estimates because crude oil is essential factor in the refining process and therefore is least affected by changes in the prices of labor and capital.

Table 2 Estimates of Own and Cross Price Elasticities of Inputs at the Point of Approximation under Static and Dynamic Specifications[52]

	Static Specification			Dynamic Specification					
				Short- Run			Long-Run		
	η_l	η_k	η_o	η_l	η_k	η_o	η_l	η_k	η_o
l	-0.495	0.043	0.452	-0.469	0.141	0.328	-0.516	0.149	0.367
k	0.039	-0.601	0.562	0.045	-0.277	0.233	0.047	-0.329	0.281
O	0.040	0.055	-0.096	0.032	0.070	-0.102	0.035	0.085	-0.120

Source: Ebsco Business Source Premier (2012a), Emerald (2012), JSTOR (2012a) and ScienceDirect (2012a)

12.2 Elasticities of Substitution

Elasticities of substitution which are given by (12) and (13) can be used to examine the substitutability or complementarity between different pairs of inputs. Two factors are substitutes (complements) if σ_{ij} is positive (negative). Elasticities of substitution essentially contain the same information of cross price elasticities since they are normalized elasticities such that normalization ensures symmetry of these elasticities (see Chambers 1988). Except for some data points, all the elasticities are positive indicating that all inputs are substitutes. At the point of approximation, the elasticities of substitution are placed in Table 3. Since these cross elasticities are positive, then labor, capital and crude oil are all substitutes in the production process.

[52] The entries in the table are read as follows: each element in the row represents price elasticity of demand for the input following a change in the price of the input in the column. For example 0.043 represents the cross price elasticity for the demand for *labor* following a price change in *capital.* The diagonal elements are the own price elasticities of demand for labor, capital and crude oil, respectively. The structure of the table is based on Kim (1982).

Table 3 Estimates of Elasticities of Substitution between Inputs at the Point of Approximation

Elasticity of substitution	Static Specification	Dynamic Specification	
		Short- Run	Long-Run
Between labor and capital	0.624	0.984	0.687
Between labor and crude oil	0.49	0.723	0.514
Between capital and crude oil	0.664	0.655	0.393

13. The Results of the Subadditivity Test

As noted earlier, subadditivity of the cost function is both necessary and sufficient for the existence of natural monopoly to exist. To reiterate, rejection of the necessary condition implies that subadditivity does not hold, while failure to reject the sufficient conditions provides evidence of subadditivity. It was shown before that economies of scope is a necessary condition for subadditivity, while transray convexity coupled with decreasing ray average costs is one of the sufficient conditions for subadditivity. Therefore, testing the existence of a natural monopoly will be carried out using these conditions. Gilsdorf (1994) comments that direct calculation of scope economies is impossible using the translog cost function since it does not allow zero value for any of its variables. Nonetheless, economies of scope can be indirectly tested by examining whether or not weak cost complementarities exist. Our estimates show that cost complementarity between the two bundles of petroleum products exist at all the sample points. At the point of normalization, the cost complementarity exists if the following condition is satisfied,
$(\alpha_i \alpha_i) + \alpha_{ij} < 0$. Indeed, at the point of normalization this condition is satisfied with a value of (-0.14).[53] This means that marginal cost of producing one bundle of petroleum products decreases with the production of the other bundle. Hence the necessary condition for subadditivity is satisfied. The next step will be testing the sufficient condition of declining ray average cost coupled with transray convexity.
Economies of scale are calculated at each point according to equation (31); the mean value of this measure is 1.15 with a range from 1.03 to 1. 37. At the point of approximation (the sample mean), overall scale economies is 1.11, indicating the existence of increasing returns to scale.[54] As shown previously, increasing returns to scale implies decreasing ray average cost. So the conclusion is that JPRC has experienced decreasing ray average cost during the period 1961-2010. To test for transray convexity, all second order derivatives with respect to outputs should be evaluated at each data point. Transray convexity requires second-order own derivatives to be positive and cross derivatives to be negative.[55] This condition holds true at all the sample points. Also, at the point of approximation, the cost function exhibits transray convexity. Therefore, the sufficient condition of subadditivity displayed by transray convexity together with declining ray average cost is satisfied at all the sample points as well

[53] Although as shown above, no statistical evidence was found to reject the hypothesis of nonjointness, however as shown by Baumol et al. (1982), Gorman (1985) and Gilsdorf (1994), economies of scope might still exist even in the absence of cost complementarity, according to them economies of scope might arise because of a shared fixed cost among the outputs. Notably, Seabra (1993) comments that economies of scope arise because there are large fixed cost (α_0=13.48). Likewise Gordon et al. (2003) assure that large fixed costs common to the production of multiple outputs will suffice to ensure the existence of economies of scope. It is also important to note that under the dynamic specification the hypothesis of nonjoint production was rejected (the value of chi-square under Wald test is 4.858456 with probability 0.0275) providing evidence that fixed costs are possible source of economies of scope even if the nonjointness hypothesis was not rejected under the static specification.
[54] Remember that returns to scale are increasing, constant or decreasing as $SL(Y, W)$ is greater than, equal to, or less than 1, respectively.
[55] For empirical application see Fraquelli, Piacenza and Vannoni (2004, 2005), Gordon et al. (2003), Buehler (2000), Seabra (1993), Squires (1988) and Wang (1981), among others.

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as at the point of approximation during the period 1961-2010. Hence the cost function satisfies the necessary and sufficient conditions for subadditivity at all the sample points as well as at the point of approximation.

14. Conclusion

In sum, the results of the natural monopoly test suggest that the JPRC was a natural monopoly during the period 1961-2010 indicating that the current market structure is cost efficient. Accordingly, the Government of Jordan needs to take this result into consideration during its course of action to restructuring this industry after the conclusion of the concessionary agreement in 2008. However, in the absence of economic regulation this structure could be inefficient from the consumer perspective. So the public policy dilemma that rises is how society can benefit from least cost production (natural monopoly) without suffering from monopoly pricing.[56] Therefore a regulatory rule has to be designed to reflect the regulator's objective of maximizing a linear social welfare function of the consumers' surplus and the producer's profit.

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[56] Most of this discussion hinges on Viscusi et al. (2005) and to a lesser extent on Pindyck and Rubinfeld (2005).

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