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# On the combined estimation of technical efficiency and its application to agriculture

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**Abstract:** Assessment of efficiency of businesses has been considered an object of interest by economists since the 1950's. A number of methods have been developed, including the so-called parametric approaches, using the regression analysis, and the non-parametric approaches, connected with the mathematical programming techniques. However, the diversity of available methods, especially when supplying contradictory estimates, leads to confusion, hindering an objective interpretation of results. In this paper, we propose a procedure leading to the reduction of such discrepancies by the proper modification of a combined method linking the non-parametric approach with a parametric one. Usefulness of the proposed solution is shown by estimation of technical efficiency concerning the agricultural production in the USA and the selected regions of the European Union.

**Key words:** data envelopment analysis, elasticity, frontier production function, regression

Analysis of the efficiency of production processes became the focus of interest on the part of economists in the 1950's and this trend was initiated by the studies of Debreu (1951) and Farrell (1957), in which a measure of technical and overall efficiency of production was introduced. In the course of years, several analytical methods have been developed to evaluate technical efficiency. Many details on the early history of efficiency analysis may be found in an interesting study by Førsund and Sarafoglou (2002). These methods in terms of applied methodology represent two fundamentally different approaches. The first one, i.e. the parametric approach, initiated by the studies of Aigner and Chu (1968), Timmer (1971) and Afriat (1972), uses the concept of the production function and is based on a respectively modified regression analysis. It includes such methods as the corrected ordinary least squares (COLS), the modified ordinary least squares (MOLS), or the stochastic frontier analysis (SFA). In turn, the other approach, i.e. the non-parametric one, in its mature form appeared slightly later, with a study by Charnes et al. (1978), and it is based on the solution of an adequately formulated problem of mathematical programming. In this respect, we need to mention several variants of the data envelopment analysis (DEA).

A considerable number of methods dealing with the same problem suggest a natural question on the

consistency of results obtained using different analytical techniques based on an identical set of data. In such a situation, it is expected that all methods should lead to an identical or at least similar assessments of efficiency. However, it turns out that such a consistency is problematic. In the paper by Sharma et al. (1997), rather divergent estimates of technical efficiency were obtained. Similarly, in a study by Cubbin and Tzanidakis (1998), the authors showed that the application of the parametric and non-parametric approaches on the same data set can produce conflicting efficiency results.

The attempt to reduce the above mentioned discrepancies in the efficiency analysis has contributed to the creation of an intermediate method, combining the parametric and non-parametric approaches. Such a solution was proposed by Arnold et al. (1996). The suitability of such a combined approach was presented in the paper by Bardham et al. (1998), where the results of extensive simulation studies were presented, which aim was mainly to evaluate the production function in the view of observations of many inefficient units. In simulation studies, the sample size is usually large and when generating observations, a previously established form of the production function is used. In turn, in empirical investigations the form of the production function is not known and the size of the sample frequently is not large. Thus it

is still required to improve the estimation methods, so that reliable and objective estimates of efficiency may be obtained. This is possible after uncovering the sources of discrepancies and proposing methods of their elimination. The main aim of this study is to propose a new approach which combines and utilizes the strengths of the parametric and nonparametric methods. A special emphasis is placed on the simplicity of the analysis. Two empirical examples of the application of this proposed approach connected with the agricultural sector are presented, too.

## MATERIAL AND METHODS

### Parametric approaches

The main vehicle of parametric approaches is a production function. It reflects a direct relation between inputs and usually a single output. Although the production function does not describe any particular production process, it mimics some processes in the sense that some inputs, represented here by a vector variable  $\mathbf{x}$ , are indispensable in creating an output  $y$ . Thus, the production function describes only the technological conditions of the production process. Usually, it is expressed in the form

$$y = f(\mathbf{x}) = f(\mathbf{x}; \mathbf{b})$$

where  $\mathbf{b}$  is a vector of parameters characterizing the production technology of the given set of decision making units (DMUs).

The functional relation between inputs  $\mathbf{x}$  and an output  $y$  should fulfil some obvious and some desirable requirements. The most obvious one states that  $\mathbf{x} = \mathbf{0}$  implies  $y = 0$ , i.e.  $f(\mathbf{0}) = 0$ , and that  $f(\mathbf{x})$  is increasing in all inputs. The other conditions specify the functional form of  $f$  which reduces the choice to continuous, homogeneous and concave functions.

Probably the most popular in terms of the number of applications is the Cobb-Douglas production function which, when the elasticity of scale is not greater than one, fulfils all the aforementioned requirements. Moreover, modelling with the Cobb-Douglas function leads to simple models which are parsimonious in parameters having direct economical interpretations. This feature is especially important when a set of DMUs is small. The next in popularity is the *translog* production function, which, however, fulfils the basic requirements under very specific additional data dependent conditions.

A deterministic frontier production function is defined as the theoretical maximum output that a producer can obtain from the given vector of inputs. Having chosen the form of the frontier production function  $y = f(\mathbf{x})$ , the output oriented technical efficiency is measured by the quotient  $TE = y/f(\mathbf{x}) \leq 1$ . This quantity, referred to the  $i$ -th unit which produces an output  $y_i$  from a vector  $\mathbf{x}_i$  of inputs, can be interpreted as the factor rescaling the value of the frontier production function to obtain the actual level of output, i.e.  $y_i = f(\mathbf{x}_i)TE_i$ .

The simplest way of establishing the frontier production function is the COLS method. It is performed in two steps. First, using the observations  $(y_i, \mathbf{x}_i)$ ,  $i = 1, 2, \dots, n$ , of the given set of DMUs, the estimate of  $f(\mathbf{x}; \mathbf{b})$  is evaluated. It can be done by the ordinary least squares regression, because the production function is usually linear in the logs of the variables. Then, the resulting function  $\ln f(\mathbf{x}; \mathbf{b})$  is shifted upwardly with respect to the largest positive residual  $a = \max(e_i)$ . In consequence, the log of the frontier production function has the form

$$\ln f(\mathbf{x}) = \ln f(\mathbf{x}; \mathbf{b}) + a$$

and

$$TE_i(a) = \exp(\ln y_i - \ln f(\mathbf{x}_i)) = \exp(-u_i)$$

where  $u_i = a - e_i \geq 0$  is the measure of the output-oriented technical inefficiency in the COLS method.

The shifting term may also be chosen according to a different rule, taking into account some specific assumptions about the distribution of  $u_i$ . If it is assumed that they follow an exponential distribution, then  $\ln f(\mathbf{x}; \mathbf{b})$  should be shifted by the standard deviation of residuals,  $s_D$ , following from the regression analysis (e.g. Greene 2008: 106). This is the simplest variant of the MOLS method. In such a case, however, not all estimated inefficiency measures are positive, since  $s_D < \max(e_i)$ . As a result, some units can appear to be technically over-efficient. These over-efficiencies may be caused by some specific conditions of the production process, which were beyond the control of the DMUs. Therefore, to preserve the sense of the technical efficiency concept, the over-efficiency must be truncated, i.e.  $TE_i(s_D) = \min\{\exp(-s_D + e_i), 1\}$ .

Note, moreover, that rescaling all  $\exp(-s_D + e_i)$ ,  $i = 1, 2, \dots, n$ , by their maximal value is useless in this matter, because such a rescaling leads to the efficiencies of the COLS approach. It is so, since a shift of  $\ln f(\mathbf{x}; \mathbf{b})$  by any scalar  $s$  gives efficiencies proportional to  $TE_i(a)$ . Indeed  $TE_i(a)/TE_i(s) = \exp(s - a) = \text{constant}$ .

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An idea of incorporating into the model the conditions not controlled by the DMUs resulted in the stochastic frontier analysis (SFA). In this approach, initiated by Aigner et al. (1977) and Meeusen and van den Broeck (1977), the frontier production function, contrary to the previous deterministic case, is assumed to be stochastic,

$$y = f(\mathbf{x})\exp(v)$$

where  $v$  is a random variable representing disturbances that are not dependent on the DMUs. To obtain the level of the output observed, it must be again rescaled by an additional term  $TE = \exp(-u)$ , where  $u$  is now a nonnegative random variable representing the technical inefficiency. In consequence, the stochastic frontier production function is estimated in presence of the standard disturbance term  $v$ , as in the regression model, and the technical inefficiency  $u$ , the latter term introducing into the model some additional and specific assumptions concerning the form of the probability distribution. The change in the form of the frontier production function, which is now a random variable, also causes a change in the understanding of the measure of the technical efficiency. In the stochastic approach, it is related with the quotient of two conditional expected values,  $TE = E(y|u)/E(y|u = 0)$  (e.g. Battese and Coelli 1992). The expectation  $E(y|u)$  represents the averaged level of output  $y$  (averaged with respect to the conditions not controlled by the producer), while  $E(y|u = 0)$  also represents the averaged output  $y$ , but for the production process being technically the most efficient.

### Non-parametric approaches

The main idea of non-parametric approaches focuses on formulating a series of appropriate linear programming problems, in which the most efficient producers are identified in the observed set of DMUs. This idea, first pointed out by Farrell (1957), was fully elaborated by Charnes et al. (1978) and since then it has been known as the data envelopment analysis (DEA). In this method, the efficiency of each producer is evaluated with respect to the given group of them, by comparing the observed outputs and vectors of inputs characterizing all producers under investigation.

A particular formulation of the linear program depends on the initial assumptions. They concern the type of orientation, which can be focused on the

outputs maximization given the values of inputs, or on the inputs minimization given the values of outputs, and the type of technology restrictions, which can be the constant returns to scale (CRS) or the variable returns to scale (VRS). Many other formulations of the DEA are reviewed by Thanassoulis et al. (2008) (see also Coelliet al. 2005; Cooper et al. 2007).

In the case of a single output oriented DEA, which corresponds to the considerations of Section 2, and under the CRS assumption, an estimate of the technical efficiency of the  $i$ -th producer follows by solving a linear program of the form:

$$\text{Max}_{\mathbf{q}, \lambda} q, \text{ subject to: } -qy_i + \mathbf{y}\lambda \geq \mathbf{0}, \mathbf{x}_i - \mathbf{X}\lambda \geq \mathbf{0}, \lambda \geq \mathbf{0}$$

where  $y_i$  and  $\mathbf{x}_i$  represent the output and the vector of inputs, respectively, of the  $i$ -th unit, while  $\mathbf{y}$  and  $\mathbf{X}$  are the vector of outputs and the matrix of inputs, respectively, of all producers in the sample. The score of technical efficiency of the  $i$ -th unit is the inverse of solution  $\theta$ ,  $TE_{ci} = 1/\theta$ . When  $TE_{ci}$  is equal to one, the  $i$ -th producer is a frontier, i.e. the most efficient producer in the whole set of the DMUs.

When the CRS restriction is replaced by the VRS, the above formulated linear program changes by adding the condition that all  $\lambda$ 's sum to one. This convexity constraint envelops the data set more tightly, which now is covered by the convex hull rather than the convex cone only, as in the case of the CRS. In consequence, the corresponding estimate of the technical efficiency  $TE_{vi}$  is not less than  $TE_{ci}$  for each DMU.

The results of the DEA procedures are often employed as the dependent variable in the further analysis searching socioeconomics sources of differences between the units' efficiency (Assaf and Matawie 2009; Hu et al. 2009; Olson and Vu 2009; Assaf and Agbola 2011). However when comparing the non-parametric approaches with those based on the regression analysis (RA), which are presented in Section 2, the differences between them are easily visible. The RA methods require many specific assumptions concerning the form of the production function as well as they are related with the type of the probability distributions of random variables involved in the model. Moreover, the estimation of unknown parameters and efficiency scores is possible when the sample size, i.e. the set of the DMUs, is large, which is especially important for the SFA.

The DEA approach is completely different. The assumptions are minimal and the sample size may be small. However, the DEA does not provide any explicit formula relating the output to inputs. Instead, it produces only some measures of efficiency or in-

efficiency, which are related exactly with the set of DMUs under considerations. Some other differences between these two techniques are discussed by Cubbin and Tzanidakis (1998) and Sena (2003). These authors observed also that the DEA and RA approaches may give very different results. The other arguments supporting this observation can be found in papers by Ferrier and Lovell (1996), Sharma et al. (1997) as well as Sahoo et al. (1999).

### The combined approach and its modification

In the paper by Arnold et al. (1996), a combined method of estimating the production function was proposed. This method is accomplished in two stages. First, the DEA is used to identify the frontiers in a set of DMUs. Next, the RA with a selected form of the production function is applied to all DMUs, but the regression model is supplemented by a dummy variable distinguishing between the efficient and inefficient units. In consequence, two production functions, for the frontiers and non-frontiers, are established. Having estimated the frontier production function, the estimates of the technical efficiencies of all DMUs may be obtained. Of course, some truncations of over-efficiency of some units are necessary. We will furthermore denote this approach as the DE+RA.

The method presented above, however, does not guarantee that the efficiencies obtained will be in full agreement with that following from the DEA. Although small differences may be easily explained by the differences in the computational procedures, large disagreements, if they take place, must have more severe causes. At this point, first of all note that the definitions of technical efficiency in the case of stochastic and deterministic frontier production functions are different, which causes difficulty in a direct comparison of efficiencies following from the SFA with those following from the other approaches.

As to comparisons between the non-parametric approaches and those based on the deterministic frontier production function, it should be noted that in general the model assumptions of the RA, of the DEA(CRS) and of the DEA(VRS) are different. In consequence, they will produce different estimates of technical efficiencies for the same data set. They will provide similar results only in special cases. Since the CRS assumption corresponds with the linear homogeneity of production function, we

can expect similar efficiencies following from the DEA(CRS) and the standard regression approaches. They will be very close, if the data actually support this specific assumption. The question appears what if it is not the case.

If the condition of constant returns to scale is not satisfied, then the DEA(VRS) may produce efficiencies much more different from those following from the RA. To explain this, note that the VRS output oriented linear program, as observed by Pastor (1996), is invariant with respect to any translation of the input vectors, provided that the shift is the same for all DMUs. It is not a property of the production function, since by the standard assumptions, it is increasing in all inputs and  $f(\mathbf{0}) = 0$ . These assumptions imply in particular that even small non-zero inputs lead to a positive quantity of an output, while in practice, to obtain a positive amount of the output, some critical non-zero, unfortunately unknown, quantities of all inputs are necessary. This divergence can be reduced by a proper translation of the production function, i.e. by subtracting from the input vector  $\mathbf{x}$  some vector  $\delta$  of positive constants. Note that a shift of the production function from  $f(\mathbf{x};\beta)$  to  $f(\mathbf{z};\beta)$ , where  $\mathbf{z} = \mathbf{x} - \delta$ , does not change its shape. Of course, the role of the parameter vector  $\beta$  is not the same in both cases, and some attention should be paid when interpreting parameters in the economic sense.

To estimate the shifted production function, it suffices to subtract the vector  $\delta$  from input vectors of all DMUs. The choice of  $\delta$  is an independent task. It can be treated as an additional vector of the parameters and estimated together with the vector  $\beta$ . But then the number of unknown parameters increases substantially and, moreover, the resulting model cannot be easily transformed to the linear form, even in the case of the Cobb-Douglas function. The other extreme possibility is an arbitrary choice of  $\delta$ . However, a compromising solution is that based on results of the DEA(VRS). It can be achieved by shifting the input vectors along the vector  $\delta$  composed of the minimal inputs observed in the data set. In consequence, the problem reduces to the choice of the length of  $\delta$ . Since the set of frontiers following from the DEA(VRS) is invariant with respect to any shift of the input vectors, the precise length of  $\delta$  can be determined in such a way that the corresponding regression model following from the second stage of the analysis proposed by Arnold et al. (1996) will be the best fitted to the data. This can be done by fitting a series of regression models in which the length of the shift along  $\delta$  successively increases.

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In consequence, the resulting frontier production function  $f(\mathbf{z}; \mathbf{b})$  enables the estimation of technical efficiencies of all DMUs. This method will be denoted by the DE+RAs.

Finally, note that the equation  $f(\mathbf{x}) = f(\mathbf{z})$  implies the equality of the corresponding partial derivatives, which means that the marginal efficiencies following from both functions are the same. It is not in the case of elasticities. However, for the  $j$ -th input they can be simply recalculated as follows:

$$\varepsilon(x_j) = \frac{\partial f(\mathbf{x})}{\partial x_j} \frac{x_j}{f(\mathbf{x})} = \varepsilon(z_j) \frac{x_j}{z_j}$$

where  $z_j = x_j - \delta_j$ . Summing up elasticities  $\varepsilon(x_j)$  over all inputs, the elasticity of scale can be obtained. Note also that here elasticity  $\varepsilon(x_j)$  is a function of  $x_j$ , even in the case of the Cobb-Douglas production function.

## Data

To illustrate the considerations of the previous sections, we will examine two data sets. The first one concerns the production in the year 2001 of 34 regions from Belgium (1 region), France (22), The Netherlands (1), Luxemburg (1) and the western part of Germany (9). The data were taken from the Farm Accounting Data Network. The value of the total agriculture production was used as the output variable. As the input variables, we had initially selected total the utilized agricultural area, labour and materials, but the first variable, land, appeared to be insignificant and was eliminated from the analysis.

In the second example, we used the data set which was analysed by Farrell (1957) when he introduced the main idea of the DEA approach. This data set characterizes the agriculture production in the United States in the year 1952. Farrell has estimated the technical efficiencies of 48 states using, in particular, cash receipts from farming, with the home consumption included, as the output, and various sets of input variables. In particular, he used the following: land, labour and materials.

Technical efficiencies were calculated by two nonparametric methods, the DEA(CRS) and the DEA(VRS), two regression methods, the COLS and MOLS, the combined method DE+RA and the proposed one, the DE+RAs, with a shift of input vectors. In parametric approaches as well as in the combined ones we used the Cobb-Douglas function, which ensures the smallest number of free parameters.

## RESULTS

Estimates of technical efficiencies for the first data set related to the EU agriculture are presented in Table 1. In the last columns, the elasticity of labour and materials as well as of scale are contained. They were calculated using the proposed DE+RAs method. The averages of these elasticities,

$$\varepsilon(\text{labour}) = 0.145, \varepsilon(\text{materials}) = 0.992, \varepsilon(\text{scale}) = 1.137$$

indicate that the second input, materials, is the most effective and that the constant returns to scale assumption is disturbed.

The last two rows of Table 1 present Pearson's coefficients of correlation between the results following from the non-parametric and the remaining methods. The correlation between efficiencies obtained from DEA(CRS) and DEA(VRS) is not very high, which means that the constant returns to scale assumption significantly influences the resulting efficiencies. On the other hand, observe quite a high correlation between efficiencies following from DEA(VRS) with those following from DE+RAs, which is in harmony with the established scale elasticity  $1.137 > 1$ . Moreover, observe very high correlations between results of the DEA(CRS) and of COLS, and of MOLS, which means that in these methods the elasticity of scale is near to one. Indeed, the estimated logs of this function are as follows:

$$\begin{aligned} \text{COLS: } \log f(\mathbf{x}) &= 0.563 + 0.127 \log x_1 + 0.907 \log x_2 \\ &\quad (0.581) \quad (0.022) \quad (0.052) \\ \varepsilon(\text{scale}) &= 1.034 (0.051) \quad R^2 = 0.929 \end{aligned}$$

$$\begin{aligned} \text{MOLS: } \log f(\mathbf{x}) &= 0.475 + 0.127 \log x_1 + 0.907 \log x_2 \\ &\quad (0.581) \quad (0.022) \quad (0.052) \\ \varepsilon(\text{scale}) &= 1.034 (0.051) \end{aligned}$$

where  $x_1$  here represents labour,  $x_2$  denotes materials,  $R^2$  the coefficient of determination, while in parentheses the standard deviations of estimated parameters are given.

On the other hand, frontier production functions following from the combined approaches take the forms:

$$\begin{aligned} \text{DE+RA: } \log f(\mathbf{x}) &= -0.573 + 0.146 \log x_1 + 0.983 \log x_2 \\ &\quad (0.637) \quad (0.022) \quad (0.057) \\ \varepsilon(\text{scale}) &= 1.130 (0.057) \quad R^2 = 0.952 \end{aligned}$$

$$\begin{aligned} \text{DE+RAs: } \log f(\mathbf{z}) &= 3.893 + 0.126 \log z_1 + 0.636 \log z_2 \\ &\quad (0.365) \quad (0.017) \quad (0.033) \\ \varepsilon(\text{scale}) &= 1.136 (0.035) \quad R^2 = 0.958 \end{aligned}$$

where  $z_1 = x_1 - 53.18$ ,  $z_2 = x_2 - 33420.60$ . The translation vector  $\delta$  in the DE+RAs method was equal to 60% of the vector (88.63, 55701.00) composed from the minimal values of both inputs. The minimal shift in the case of labour is not less than 2% (of the maximal observed labour), while in the case of materials it is not less than 15% (of the maximal observed value of materials). Thus the shift with respect to the second variable was much more restrictive. Note also that the frontier production function  $f(x)$  following from DE+RA is convex, while that with shifted input vari-

ables  $f(z)$ , estimated by the DE+RAs method, and is concave as required. Comparing both methods we can notice that the proposed one provides efficiencies compatible with that following from the non-parametric DEA (VRS) approach.

The estimated efficiencies from the second data set related to the USA agriculture are contained in Table 2. This table is organized in the same way as the previous one, with the exception that now we have three inputs: land ( $x_1$ ), labour ( $x_2$ ) and materials ( $x_3$ ).

Table 1. Estimates of technical efficiencies of agricultural production in 34 regions of EU

Regions	DEA		Parametric methods				Elasticity's		
	CRS	VRS	COLS	MOLS	DE+RA	DE+RA <sub>s</sub>	labour	materials	scale
1 Belgium (BEL)	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.139	0.898	1.037
2 Hamburg (DEU)	1.000	<b>1.000</b>	0.951	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.131	0.955	1.086
3 Bayern (DEU)	0.945	<b>1.000</b>	0.899	0.982	<b>1.000</b>	<b>1.000</b>	0.163	1.121	1.284
4 Saarland (DEU)	<b>1.000</b>	<b>1.000</b>	0.941	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.316	0.930	1.246
5 Languedoc-Roussillon (FRA)	0.911	<b>1.000</b>	0.871	0.952	<b>1.000</b>	<b>1.000</b>	0.132	1.396	1.528
6 Provence-Apes-Côte (FRA)	<b>1.000</b>	<b>1.000</b>	0.950	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.129	1.108	1.238
7 The Netherlands (NED)	0.950	<b>1.000</b>	0.895	0.977	0.928	<b>1.000</b>	0.130	0.749	0.879
8 Champagne-Ardenne (FRA)	0.987	<b>1.000</b>	0.940	<b>1.000</b>	<b>1.000</b>	0.997	0.132	0.858	0.989
9 Corse (FRA)	0.825	<b>1.000</b>	0.795	0.869	0.930	0.996	0.133	1.589	1.722
10 Franche-Comté (FRA)	0.948	0.962	0.887	0.968	<b>1.000</b>	0.960	0.158	0.961	1.118
11 Auvergne (FRA)	0.844	<b>1.000</b>	0.809	0.884	0.963	0.956	0.169	1.289	1.458
12 Alsace (FRA)	0.918	0.967	0.886	0.968	<b>1.000</b>	0.953	0.134	1.037	1.171
13 Limousine (FRA)	0.770	<b>1.000</b>	0.761	0.832	0.912	0.949	0.163	1.490	1.653
14 Rheinland-Pfalz (DEU)	0.903	0.968	0.869	0.949	0.989	0.946	0.134	1.093	1.227
15 Bretagne (FRA)	0.906	0.946	0.883	0.965	0.960	0.946	0.134	0.825	0.959
16 Rhône-Alpes (FRA)	0.887	0.959	0.854	0.933	0.974	0.933	0.134	1.108	1.243
17 Niedersachsen (DEU)	0.872	0.924	0.865	0.945	0.953	0.922	0.137	0.852	0.989
18 Hessen (DEU)	0.876	0.906	0.835	0.912	0.966	0.912	0.155	1.028	1.183
19 Schleswig-Holstein (DEU)	0.870	0.899	0.852	0.930	0.931	0.909	0.135	0.838	0.973
20 Baden-Württemberg (DEU)	0.864	0.901	0.838	0.915	0.947	0.896	0.135	0.999	1.134
21 Nordrhein-Westfalen (DEU)	0.858	0.865	0.839	0.917	0.926	0.891	0.135	0.872	1.008
22 Nord-Pas-de-Calais (FRA)	0.845	0.906	0.835	0.912	0.921	0.891	0.138	0.852	0.990
23 Basse-Normandie (FRA)	0.869	0.875	0.834	0.911	0.938	0.890	0.144	0.901	1.045
24 Pays de la Loire (FRA)	0.837	0.837	0.832	0.909	0.928	0.884	0.138	0.898	1.036
25 Lorraine (FRA)	0.871	<b>1.000</b>	0.797	0.871	0.885	0.865	0.151	0.828	0.979
26 Luxembourg (LUX)	0.819	0.836	0.804	0.879	0.897	0.857	0.140	0.884	1.025
27 Aquitaine (FRA)	0.852	0.858	0.807	0.882	0.891	0.854	0.131	0.941	1.071
28 Picardie (FRA)	0.805	0.909	0.787	0.860	0.847	0.852	0.134	0.798	0.932
29 Midi-Pyrénées (FRA)	0.762	0.876	0.752	0.822	0.870	0.837	0.140	1.159	1.299
30 Bourgogne (FRA)	0.809	0.809	0.786	0.859	0.874	0.833	0.135	0.909	1.043
31 Poitou-Charentes (FRA)	0.775	0.817	0.776	0.848	0.881	0.831	0.141	0.977	1.118
32 Haute-Normandie (FRA)	0.760	0.813	0.751	0.820	0.829	0.801	0.138	0.853	0.991
33 Île de France (FRA)	0.727	0.741	0.689	0.753	0.747	0.732	0.131	0.845	0.976
34 Centre (FRA)	0.710	0.715	0.681	0.743	0.749	0.720	0.133	0.884	1.017
Pearson's correlations	1.000	0.759	0.974	0.965	0.870	0.851			
		1.000	0.728	0.744	0.813	0.925			

Source: authors computation using FADN data

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Table 2. Estimates of technical efficiencies of agricultural production in the United States

States	DEA		Parametric methods				Elasticities			
	CRS	VRS	COLS	MOLS	DE+RA	DE+RAs	labour	land	materials	scale
1 Rhode Island	0.940	<b>1.000</b>	0.751	0.890	0.982	<b>1.000</b>	0.511	0.163	0.561	1.235
2 Illinois	0.927	<b>1.000</b>	0.853	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.410	0.130	0.450	0.990
3 North Dakota	1.000	<b>1.000</b>	0.957	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.411	0.130	0.459	1.000
4 North Carolina	<b>1.000</b>	<b>1.000</b>	0.917	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.410	0.131	0.454	0.994
5 Florida	<b>1.000</b>	<b>1.000</b>	0.946	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.413	0.131	0.462	1.005
6 Arizona	1.000	1.000	1.000	1.000	1.000	<b>1.000</b>	0.421	0.130	0.477	1.028
7 Washington	0.993	0.994	0.896	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.412	0.131	0.455	0.998
8 California	1.000	<b>1.000</b>	0.958	<b>1.000</b>	<b>1.000</b>	<b>1.000</b>	0.410	0.130	0.451	0.992
9 New Jersey	<b>1.000</b>	<b>1.000</b>	0.800	0.948	<b>1.000</b>	0.982	0.416	0.133	0.456	1.005
10 Iowa	0.895	<b>1.000</b>	0.791	0.938	0.949	0.978	0.410	0.130	0.449	0.990
11 Connecticut	0.999	<b>1.000</b>	0.797	0.945	<b>1.000</b>	0.975	0.424	0.134	0.463	1.020
12 Massachusetts	0.979	0.983	0.779	0.923	0.991	0.950	0.420	0.133	0.461	1.015
13 Maine	0.944	0.950	0.797	0.944	0.983	0.945	0.418	0.132	0.464	1.014
14 Indiana	0.875	0.877	0.785	0.931	0.936	0.943	0.410	0.130	0.451	0.992
15 Delaware	<b>1.000</b>	<b>1.000</b>	0.741	0.878	0.964	0.925	0.437	0.135	0.463	1.034
16 Louisiana	0.896	0.942	0.796	0.943	0.920	0.907	0.411	0.131	0.463	1.004
17 Michigan	0.883	0.905	0.772	0.915	0.908	0.906	0.410	0.131	0.453	0.994
18 Nevada	0.850	<b>1.000</b>	0.733	0.869	0.872	0.897	0.468	0.131	0.548	1.147
19 Oregon	0.866	0.867	0.774	0.918	0.914	0.893	0.413	0.131	0.456	1.000
20 Montana	0.809	0.943	0.782	0.927	0.895	0.875	0.413	0.130	0.459	1.003
21 South Carolina	0.983	1.000	0.766	0.908	0.882	0.872	0.410	0.131	0.464	1.005
22 Minnesota	0.820	0.911	0.729	0.864	0.857	0.871	0.410	0.130	0.451	0.991
23 Kansas	0.807	0.866	0.721	0.854	0.845	0.855	0.410	0.130	0.451	0.991
24 Texas	0.807	<b>1.000</b>	0.709	0.841	0.809	0.833	0.410	0.130	0.450	0.990
25 Idaho	0.792	0.796	0.715	0.848	0.850	0.829	0.413	0.131	0.457	1.000
26 Wisconsin	0.798	0.828	0.691	0.819	0.815	0.824	0.410	0.130	0.451	0.992
27 Ohio	0.783	0.793	0.686	0.814	0.814	0.822	0.410	0.130	0.451	0.992
28 Mississippi	0.949	0.953	0.721	0.855	0.820	0.822	0.410	0.131	0.457	0.997
29 Nebraska	0.780	0.801	0.676	0.802	0.797	0.806	0.410	0.130	0.450	0.991
30 Arkansas	0.756	0.787	0.677	0.802	0.784	0.783	0.410	0.131	0.455	0.995
31 New York	0.755	0.813	0.640	0.759	0.773	0.774	0.411	0.131	0.451	0.992
32 Colorado	0.845	0.851	0.663	0.786	0.784	0.773	0.413	0.130	0.453	0.996
33 Maryland	0.786	0.788	0.624	0.740	0.771	0.746	0.415	0.131	0.458	1.003
34 Pennsylvania	0.741	0.858	0.607	0.719	0.736	0.737	0.411	0.131	0.451	0.992
35 Virginia	0.726	0.729	0.619	0.733	0.733	0.727	0.410	0.131	0.454	0.995
36 Missouri	0.679	0.763	0.605	0.718	0.711	0.724	0.410	0.130	0.450	0.991
37 South Dakota	0.707	0.743	0.626	0.741	0.726	0.722	0.411	0.130	0.453	0.994
38 Georgia	0.685	0.716	0.612	0.725	0.707	0.709	0.410	0.131	0.454	0.995
39 Alabama	0.729	0.732	0.616	0.731	0.706	0.705	0.410	0.131	0.457	0.997
40 Oklahoma	0.669	0.723	0.601	0.712	0.696	0.697	0.410	0.130	0.452	0.993
41 New Mexico	0.664	0.717	0.623	0.738	0.716	0.696	0.416	0.130	0.463	1.009
42 New Hampshire	0.661	0.672	0.556	0.659	0.703	0.674	0.432	0.133	0.472	1.037
43 Tennessee	0.634	0.653	0.565	0.670	0.655	0.656	0.410	0.131	0.454	0.995
44 Kentucky	0.644	0.662	0.559	0.662	0.650	0.654	0.410	0.131	0.453	0.993
45 Vermont	0.584	0.596	0.543	0.644	0.668	0.641	0.420	0.131	0.465	1.017
46 Utah	0.622	0.629	0.540	0.641	0.648	0.626	0.417	0.131	0.459	1.007
47 Wyoming	0.732	0.734	0.527	0.625	0.617	0.596	0.422	0.130	0.464	1.016
48 West Virginia	0.529	0.534	0.470	0.557	0.558	0.543	0.413	0.131	0.462	1.005
Pearson's correlations	1.000	0.943	0.903	0.928	0.945	0.935				
		1.000	0.870	0.920	0.919	0.932				

Source: authors' computation using data of Ferrell (1957)

First of all, it needs to be noted that the averaged elasticity of scale, 1.010, corresponds perfectly to that assumed by Farrell, who used the constant returns to scale Cobb–Douglas function. The averaged elasticities of inputs,

$$\varepsilon(\text{labour}) = 0.417, \varepsilon(\text{land}) = 0.132, \varepsilon(\text{materials}) = 0.461$$

also correspond to those calculated by Farrell.

The main advantage of parametric approaches, however, is a possibility of establishing the form of the frontier production function. The estimated logs of this function, obtained in the frames of models under considerations, are as follows:

COLS:

$$\log f(\mathbf{x}) = -2.180 + 0.406 \log x_1 + 0.112 \log x_2 + 0.492 \log x_3$$

$$(0.581) \quad (0.040) \quad (0.025) \quad (0.045)$$

$$\varepsilon(\text{scale}) = 1.010 \quad (0.026) \quad R^2 = 0.974$$

MOLS:

$$\log f(\mathbf{x}) = -2.174 + 0.406 \log x_1 + 0.112 \log x_2 + 0.492 \log x_3$$

$$(0.581) \quad (0.040) \quad (0.025) \quad (0.045)$$

$$\varepsilon(\text{scale}) = 1.010 \quad (0.026) \quad R^2 = 0.974$$

DE+RA:

$$\log f(\mathbf{x}) = 1.113 + 0.426 \log x_1 + 0.134 \log x_2 + 0.463 \log x_3$$

$$(0.477) \quad (0.056) \quad (0.031) \quad (0.052)$$

$$\varepsilon(\text{scale}) = 1.023 \quad (0.028) \quad R^2 = 0.985$$

DE+RAs:

$$\log f(\mathbf{z}) = -1.842 + 0.409 \log z_1 + 0.130 \log z_2 + 0.449 \log z_3$$

$$(0.460) \quad (0.054) \quad (0.030) \quad (0.051)$$

$$\varepsilon(\text{scale}) = 1.009 \quad (0.006) \quad R^2 = 0.985$$

where  $z_1 = x_1 - 0.39$ ,  $z_2 = x_2 - 11.87$ ,  $z_3 = x_3 - 859.94$ .

In the DE+RAs method the translation vector was equal to 20% of the vector (1.97, 59.36, 4299.72) composed from the minimal values of all the three inputs. This time the translation was rather small. In consequence, the differences between the coefficients of functions following from the combined methods are almost indistinguishable. Moreover, they are also very similar to those following from the COLS and MOLS approaches. This agreement is a consequence of the constant return to scale assumption, which is strongly supported by the data. It is confirmed by a very high correlation coefficient between results obtained from DEA(CRS) and DEA(VRS). In consequence, we have also very high correlations between efficiencies following from the other methods. Nevertheless, technical efficiencies produced by the proposed DA+RAs method are most similar to those following from the non-parametric DEA(VRS).

## CONCLUSIONS

In the paper various techniques of evaluating technical efficiency are discussed. Among them we considered the non-parametric approaches related with data envelopment analysis (DEA), parametric ones based on regression analysis (RA) and using the concept of frontier production function, and the combined method linking both parametric and non-parametric approaches. Unfortunately, different methods, as it was observed by some authors, can produce very different estimates of efficiencies, which is unexpected when analysing the same data set. Therefore, in the presentation of various methods we paid special attention to their differences and weak points in the context of technical efficiency estimation.

In this respect we noted that in the case of stochastic frontier functions and deterministic frontier functions there is an important difference in the definitions of technical efficiency. This justifies even large differences between estimated efficiencies, since the crucial assumptions of these models are different. In turn, we have observed that the DEA approach can deliver similar estimates as the RA approach with a deterministic production function, but only if the basic assumptions of the methods applied are consistent and simultaneously these assumptions are supported by the data under investigation. As a result of this discussion we have proposed a shift of the production function, which modification may improve the estimation process in a case when the assumption of constant returns to scale is not valid. The usefulness of this modified method is illustrated by analyses of two data sets concerning agricultural production.

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