JAE Journal of Agricultural Economics

Journal of Agricultural Economics, Vol. 68, No. 2, 2017, 579–599
doi: 10.1111/1477-9552.12188

Input-Specific Dynamic Productivity Change: Measurement and Application to European Dairy Manufacturing Firms

Magdalena Kapelko, Alfons Oude Lansink and Spiro E. Stefanou[1]

(Original submitted September 2015, revision received March 2016, accepted June 2016.)

Abstract

We propose a new method for measuring and decomposing input-specific productivity change in a dynamic context. The resulting input-specific dynamic Luenberger productivity change indicator is decomposed to identify the contributions of input-specific dynamic technical, technical inefficiency and scale inefficiency changes. The empirical application of the paper focuses on panel data of large firms in the European dairy processing industry over the period 2005–2012. The results show similar patterns for dynamic input-specific productivity change and its components for labour across European regions (Eastern, Western and Southern), while differences between regions are found regarding materials and investments.

Keywords: *Dairy processing industry*; *data envelopment analysis*; *dynamics of production decisions*; *input-specific productivity change*.

JEL classifications: *D24, D92, L66*.

1. Introduction

Productivity growth is a reflection of changes in the firm's use of the existing production potential and can reflect how investments enhance production potential through

---

[1]Magdalena Kapelko is with the Institute of Applied Mathematics, Department of Logistics, Wroclaw University of Economics, Poland. E-mail: magdalena.kapelko@ue.wroc.pl for correspondence. Alfons Oude Lansink is with the Business Economics Group, Wageningen University, the Netherlands. Spiro Stefanou is in the Food and Resource Economics Department, University of Florida, USA, and also a member of the Business Economics Group, Wageningen University, the Netherlands. This research has been funded by the National Science Centre in Poland, decision number DEC-2013/11/D/HS4/00252. Part of the calculations for this article was made at the Wroclaw Centre for Networking and Supercomputing (http://www.wcss.wroc.pl). The authors are also grateful for comments of participants at the 2015 EWEPA conference in Helsinki.

innovation resulting in new technologies. From a policy perspective, the notion of productivity of a sector is a long-run concept that serves as a benchmark for how well firms and the sector perform. While partial productivity measures have long given way to total factor productivity measures, guidance on input-specific contributions to economic performance are of value from a decision-making perspective. Disaggregating the sources of productivity change can be a useful approach to explore which input factor contributes to productivity and efficiency change. The recent literature has addressed input-specific productivity change measurement. Malmquist-motivated measures are presented by Oude Lansink and Ondersteijn (2006) and Mahlberg *et al.* (2011). More recently, the directional distance approaches using the Luenberger-based indicators have been addressed by Mahlberg and Sahoo (2011), Chang *et al.* (2012), Skevas and Oude Lansink (2014), Mahlberg and Luptacik (2014) and Kapelko *et al.* (2015a). Yet another approach to measuring an input-specific Luenberger indicator is based on the Principle of Least Action that is related to the notion of least distance and the determination of closest strongly efficient targets (Aparicio *et al.*, 2015).

These studies are all conceived in the static framework where current decisions are not necessarily linked to the future.[2] When addressing input allocation, it is important to distinguish between the variable and the quasi-fixed (typically, capital) inputs when addressing inefficiency or productivity growth. For example, when variable input use is not meeting its potential, remedies include improved monitoring of resource use; when asset use is not meeting potential, remedies can include training programmes to enhance performance. The shortcomings of the static framework in explaining the gradual adjustment of some inputs has led to the development of dynamic models of production where current production decisions constrain or enhance future production possibilities. Silva and Stefanou (2003) advance a non-parametric approach to dynamic production analysis that distinguishes between the variable and the dynamic factors, and serves as a foundation for the measurement of dynamic productivity and efficiency measurement.[3] Luenberger-based approaches that have followed can decompose productivity change to identify the contributions of technical inefficiency change, scale inefficiency change and technical change (Kapelko *et al.*, 2015b,c, 2016; Oude Lansink *et al.*, 2015). However, the existing dynamic approaches do not consider input-specific contributions to dynamic productivity growth, which is demonstrated in this paper.

We address the productivity change measurement within an input-specific framework accounting for dynamic adjustment of quasi-fixed factors of production. Panel data of the European dairy products manufacturing sector are the focus of the empirical application. While investigations into productivity change of dairy farms are numerous, studies of productivity growth of dairy manufacturing (processors) are more scarce. The existing studies on dairy processing consider productivity growth of all inputs simultaneously. Doucouliagos and Hone (2001) find a moderate

[2]The paper by Skevas and Oude Lansink (2014) applies a DEA approach to account for the impact of pesticides use on future periods production environments. Their approach to measuring input-specific productivity growth does not account for adjustment costs induced by investments.

[3]This approach is based on the adjustment costs hypothesis that is related to the notion that changes in quasi fixed factors induced by investments are associated with adjustment costs. Other approaches to dynamic production analysis, such as for example dynamic network data envelopment analysis, are reviewed in Fallah-Fini *et al.* (2014).

productivity growth of 2% a year for the Australian dairy processing industry in the period 1969–1996, which is mainly driven by technical progress. Geylani and Stefanou (2011) investigate the productivity patterns of US dairy manufacturing using Census Bureau's plant-level data and find considerable cross-sectional dispersion in productivity growth. Productivity growth is on average negative −0.3%, and both the scale effect and technical change effect contribute negatively. Bontemps *et al*. (2012) investigate French cheese production and find a negative productivity growth over the period 1996–2006; the main reason for productivity decline is technical regress experienced by most firms. Ohlan (2013) assesses productivity growth in the Indian dairy processing industry over the period 1980–2008 and finds that productivity has grown significantly, with technical efficiency change being the main driver rather than scale efficiency change. Vlontzos and Theodoridis (2013) find a positive productivity growth for Greek dairy manufacturing for all years in the period 2003–2007 (except for the year 2007). In the study of Ali *et al*. (2009) on productivity growth of the Indian food manufacturing industry in the period 1980–2001, the dairy processing industry productivity growth is driven by efficiency increase and technical progress. Kapelko *et al*. (2015b, 2014b) focus on the Spanish food processing industry and for dairy manufacturing firms they find dynamic productivity growth to be very close to zero, with dynamic technical change having a negative contribution to dynamic productivity growth and dynamic technical inefficiency change offering a positive contribution. On balance, productivity growth is marginal, at best, and the contribution of technical change is mixed.

The prospects for dairy manufacturing (the processing of fluid (fresh) milk) are closely linked to dairy policies. The European dairy policy has been dominated by the production quota system, in place since 1983 until its elimination in 2015. The European and other major country milk sectors experienced a period of high volatility of prices from 2007 to 2009 (see Figure 1). After the spike in 2007 of European Union and world dairy market prices, the dairy prices and producers' incomes substantially decreased in 2008 and 2009 (European Commission, 2010). This process was further influenced by the economic crisis in 2008 and 2009, which caused a drop in household consumption. The volatility persisted until the end of 2010, but to smaller extent than during the period 2007–2009. The dairy market stabilised in 2011 and 2012 leading to

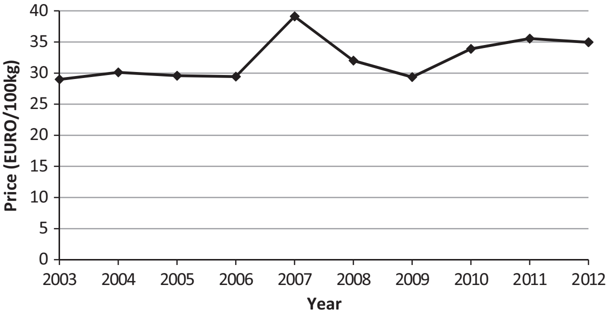

Figure 1. The evolution of milk prices, in EURO per 100 kg, 2003–2012 (average prices for the end of each year for EU-25 countries without Malta)
Source: Elaborated based on the data from Eurostat (2015b) database on agricultural statistics and European Commission (2015).

increased production and higher prices (European Commission, 2012).[4] The rapidly changing environment in which the European dairy manufacturing sector has operated in the last decade is associated with changes in the long-run optimal capital stock, which makes this sector appropriate for analysing productivity growth in a dynamic framework.

Given a major deregulation of the milk production sector with the elimination of quotas, we investigate the dynamic performance of the European dairy processing sector, allowing for the nature of capital adjustment, as we track growth and efficiency over the period 2005–2012 for 2,796 observations for large firms for 23 nations. We decompose the production factors' growth contributions and identify the relative importance of labour, materials (largely the raw milk commodity input) and capital to the prospects of this sector. For this purpose a new method of input-specific dynamic productivity growth indicator is developed which is operationalised using Data Envelopment Analysis as an input-specific dynamic Luenberger indicator. Hence, our major contribution is to identify dynamic input specific contributions to productivity change, which has not been done before, to our knowledge.

The next section presents the construction of input-specific productivity change under dynamic adjustment of quasi-fixed factors of production using an input-oriented dynamic directional distance function within the DEA framework. The empirical application and the results of the DEA analysis follow, and the paper concludes with comments and suggestions for future research.

2. Input-specific Productivity Change in a Dynamic Setting

Suppose we have a data series in time t representing (vectors of) observed quantities of M outputs (y^t), N variable inputs (x^t), F gross investments (I^t), and F quasi-fixed factors (k^t), of $j = 1,\ldots, J$ firms at time t.

The dynamic (or adjustment-cost) production technology in time t is denoted by P_t. The dynamic production technology in time t that transforms variable inputs and gross investments into outputs at a given level of quasi-fixed inputs is defined as (see Silva *et al.*, 2015):

$$P_t = \{(x^t, I^t, y^t, k^t) : x^t, I^t \text{ can produce } y^t, \text{ given } k^t\}. \tag{1}$$

The dynamic input requirement set is assumed to have the following properties: P_t is a closed and non-empty set, has a lower bound, is positive monotonic in variable inputs, negative monotonic in gross investments, is a strictly convex set, output levels increase with the stock of capital and quasi-fixed inputs and are freely disposable (Silva and Stefanou, 2003).

The dynamic directional input distance function ($\bar{D}^t$) at time t seeks to reduce the use of inputs x^t and to expand gross investments I^t:

$$\overline{D}^t(x^t, I^t, y^t, k^t; g_x^t, g_I^t) = \sup\left\{\sum_{n=1}^{N}\beta_n + \sum_{f=1}^{F}\gamma_f : (x_n^t - \beta_n g_{xn}^t, I_f^t + \gamma_f g_{If}^t, y_m^t, k_f^t) \in P_t\right\} \tag{2}$$

[4]More recent developments of milk prices in the EU-25 countries show an increase in prices in 2013 similar to the increase of 2007, and then a decrease in prices in 2014 and 2015 to the levels similar to those of 2011 and 2012.

where g_x^t and g_I^t represent the directional vectors determining the direction in which each input vector x^t and each investment vector I^t can be scaled, β_n and γ_f measures the degree of input n – and investment f-specific inefficiency at time t.

The Russell type of model represented by (2) sums the input and investment-specific inefficiencies. The Russell representation (2) measures inefficiency taking into account all sources of inefficiency (including slacks).[5] Moreover, this measure provides an estimate of the inefficiency of each variable input and each investment separately. Therefore, this measure is more informative about the sources of inefficiency in production than the dynamic directional distance function that has been used in the literature (for example, Kapelko *et al.*, 2014a). In fact, the measure of technical inefficiency provided by Kapelko *et al.* (2014a) is a special case of the model presented in (2). That is, the measure is obtained by incorporating the following restriction: $\beta_1 = \beta_2 = \ldots = \beta_N = \gamma_1 = \gamma_2 = \ldots = \gamma_F$.

The dynamic input-specific productivity is computed using Data Envelopment Analysis (DEA), which entails solving four linear programming (LP) models for two consecutive years; two single period LP models (one for time t and the second for time $t + 1$) and two cross-period LP models (one for a firm at time $t + 1$ in relation to the technology at time t, and the second for a firm at time t in relation to the technology at time $t + 1$):

$$\begin{aligned}
\overline{D}^t(x^t, I^t, y^t, k^t; g_x^t, g_I^t) = \max_{\beta_n^1, \gamma_f^1, \lambda_j^1} & \left(\sum_{n=1}^{N} \beta_i^1 + \sum_{f=1}^{F} \gamma_f^1 \right) \\
\text{s.t.} & \\
& \sum_{j=1}^{J} \lambda_j^1 y_{mj}^t \geq y_{m0}^t, \qquad m = 1, \ldots, M \\
& \sum_{j=1}^{J} \lambda_j^1 x_{nj}^t \leq x_{n0}^t - \beta_n^1 g_{xn}^t, \qquad n = 1, \ldots, N \\
& \sum_{j=1}^{J} \lambda_j^1 (I_{fj}^t - \delta k_{fj}^t) \geq I_{f0}^t + \gamma_f^1 g_{If}^t - \delta k_{f0}^t, f = 1, \ldots, F
\end{aligned} \tag{3}$$

$$\begin{aligned}
\overline{D}^{t+1}(x^t, I^t, y^t, k^t; g_x^t, g_I^t) = \max_{\beta_n^2, \gamma_f^2, \lambda_j^2} & \left(\sum_{n=1}^{N} \beta_i^2 + \sum_{f=1}^{F} \gamma_f^2 \right) \\
\text{s.t.} & \\
& \sum_{j=1}^{J} \lambda_j^2 y_{mj}^{t+1} \geq y_{m0}^t, \qquad m = 1, \ldots, M \\
& \sum_{j=1}^{J} \lambda_j^2 x_{nj}^{t+1} \leq x_{n0}^t - \beta_n^2 g_{xn}^t, \qquad n = 1, \ldots, N \\
& \sum_{j=1}^{J} \lambda_j^2 (I_{fj}^{t+1} - \delta k_{fj}^{t+1}) \geq I_{f0}^t + \gamma_f^2 g_{If}^t - \delta k_{f0}^t, f = 1, \ldots, F
\end{aligned} \tag{4}$$

[5]This measure is related to Färe and Grosskopf (2010) slacks-based measure of inefficiency and Fukuyama and Weber's (2009) directional slacks-based measure of inefficiency, all conceived in the static framework. Moreover, this measure represents the special case of a weighted additive model of Lovell and Pastor (1995) as it was demonstrated by Pastor and Aparicio (2010).

$$\overline{D}^{t}(x^{t+1},I^{t+1},y^{t+1},k^{t+1};g_x^{t+1},g_I^{t+1}) = \max_{\beta_n^3,\gamma_f^3,\lambda_j^3}\left(\sum_{n=1}^{N}\beta_i^3+\sum_{f=1}^{F}\gamma_f^3\right)$$

$$\begin{aligned}&\text{s.t.}\\ &\sum_{j=1}^{J}\lambda_j^3 y_{mj}^t \geq y_{m0}^{t+1}, \qquad m=1,\ldots,M\\ &\sum_{j=1}^{J}\lambda_j^3 x_{nj}^t \leq x_{n0}^{t+1}-\beta_n^3 g_{xn}^{t+1}, \qquad n=1,\ldots,N\\ &\sum_{j=1}^{J}\lambda_j^3 (I_{fj}^t-\delta k_{fj}^t) \geq I_{f0}^{t+1}+\gamma_f^3 g_{If}^{t+1}-\delta k_{f0}^{t+1}, f=1,\ldots,F\end{aligned} \tag{5}$$

$$\overline{D}^{t+1}(x^{t+1},I^{t+1},y^{t+1},k^{t+1};g_x^{t+1},g_I^{t+1}) = \max_{\beta_n^4,\gamma_f^4,\lambda_j^4}\left(\sum_{n=1}^{N}\beta_i^4+\sum_{f=1}^{F}\gamma_f^4\right)$$

$$\begin{aligned}&s.t.\\ &\sum_{j=1}^{J}\lambda_j^4 y_{mj}^{t+1} \geq y_{m0}^{t+1}, \qquad m=1,\ldots,M\\ &\sum_{j=1}^{J}\lambda_j^4 x_{nj}^{t+1} \leq x_{n0}^{t+1}-\beta_n^4 g_{xn}^{t+1}, \qquad n=1,\ldots,N\\ &\sum_{j=1}^{J}\lambda_j^4 (I_{fj}^{t+1}-\delta k_{fj}^{t+1}) \geq I_{f0}^{t+1}+\gamma_f^4 g_{If}^{t+1}-\delta k_{f0}^{t+1}, f=1,\ldots,F\end{aligned} \tag{6}$$

The problems in (3–6) assume constant returns to scale (CRS) and the computed values of β_n and γ_f provide the maximum feasible contraction of each input and expansion of each investment given the directional vectors. In this set of problems, λ_j represents the intensity vector of firm weights, and δ indicates the fixed depreciation rate of capital (in percentage), while expression δk reflects the value of depreciation (in monetary units). The last constraint in these models indicates that the production technology not only consists of quantities of outputs and variable and quasi-fixed inputs, but also of gross investments in quasi-fixed inputs.

The Luenberger indicator of input-specific and investment-specific dynamic productivity change for input n (n = 1, …, N) and investment f (f = 1, …, F) are, respectively:

$$\text{LX}_n = \frac{1}{2}\cdot\left(\beta_n^2-\beta_n^4+\beta_n^1-\beta_n^3\right) \tag{7a}$$

$$\text{LI}_f = \frac{1}{2}\cdot\left(\gamma_f^2-\gamma_f^4+\gamma_f^1-\gamma_f^3\right) \tag{7b}$$

This indicator can be decomposed into input-specific dynamic inefficiency change (LECX_n) and input-specific dynamic technical change (LTCX_n), as:

$$\text{LECX}_n = \beta_n^1-\beta_n^4 \tag{8a}$$

$$\text{LTCX}_n = \frac{1}{2}\cdot\left(\beta_n^4-\beta_n^3+\beta_n^2-\beta_n^1\right) \tag{8b}$$

and into investment-specific dynamic inefficiency change ($LECI_f$) and investment-specific dynamic technical change ($LTCI_f$) as:

$$LECI_f = \gamma_f^1 - \gamma_f^4 \tag{9a}$$

$$LTCI_f = \frac{1}{2} \cdot \left(\gamma_f^4 - \gamma_f^3 + \gamma_f^2 - \gamma_f^1\right) \tag{9b}$$

Input- and investment-specific dynamic inefficiency changes ($LECX_n$ and $LECI_f$) can be further decomposed into input- and investment-specific dynamic technical inefficiency changes under variable returns to scale (VRS) and input- and investment-specific dynamic scale inefficiency changes. These measures are estimated by running the two single-period LP models, corresponding to model (3) with the addition of restriction:

$$\sum_{j=1}^{n} \lambda_j^1 = 1 \tag{10}$$

and model (6) with the addition of restriction:

$$\sum_{j=1}^{n} \lambda_j^4 = 1 \tag{11}$$

This yields new solutions under VRS technology that are denoted as $\beta_n^{1\,VRS}$, $\gamma_f^{1\,VRS}$ and $\beta_n^{4\,VRS}$, $\gamma_f^{4\,VRS}$, respectively. The input- and investment-specific dynamic technical inefficiency changes under VRS ($LECX_n^{VRS}$ and $LECI_f^{VRS}$) are then computed as:

$$LECX_n^{VRS} = \beta_n^{1\,VRS} - \beta_n^{4\,VRS} \tag{12a}$$

$$LECI_f^{VRS} = \gamma_f^{1\,VRS} - \gamma_f^{4\,VRS} \tag{12b}$$

Input- and investment-specific dynamic scale inefficiency changes ($LSECX_n$, and $LSECI_f$) are then computed as:

$$LSECX_n = (\beta_n^1 - \beta_n^4) - (\beta_n^{1\,VRS} - \beta_n^{4\,VRS}) \tag{13a}$$

$$LSECI_f = (\gamma_f^1 - \gamma_f^4) - (\gamma_f^{1\,VRS} - \gamma_f^{4\,VRS}) \tag{13b}$$

The sum of $LECX_n^{VRS}$ and $LSECX_n$ is equal to the $LECX_n$; similarly, the sum of $LECI_f^{VRS}$ and $LSECI_f$ is equal to the $LECI_f$.

Hence, the final decomposition of input-specific dynamic productivity change is:

$$LX_n = LTCX_n + LECX_n^{VRS} + LSECX_n \tag{14a}$$

and the final decomposition of investment-specific dynamic productivity change is:

$$LI_f = LTCI_f + LECI_f^{VRS} + LSECI_f \tag{14b}$$

The decomposition of input- and investment-specific dynamic productivity growth indicators in (14a and 14b) show that these indicators provide more information on the sources of productivity growth than dynamic productivity growth measures accounting for all inputs simultaneously that dominate the existing literature (see for example Kapelko *et al.*, 2015b,c, 2016; Oude Lansink *et al.*, 2015).

3. Empirical Application

3.1. Sample and data description

This study analyses input-specific dynamic productivity change for European dairy manufacturing firms (NACE Rev. 2 code 10.5). The data cover the period between 2005 and 2012 and were obtained from AMADEUS which is a comprehensive database prepared by Bureau van Dijk containing financial information of European companies.[6] The study sample was generated following several steps. First, only large firms were considered to create a dataset of firms that are comparable in terms of size. Large firms tend to be diversified and function globally, while small firms tend to be more specialised and act in local markets. The focus on large firms results in a homogenous sample of firms, in terms of inputs used, outputs produced and technologies employed. The large dairy manufacturing firms usually produce a wide variety of different products such as pasteurised milk, yoghurt, butter or cheese, hence the common set of outputs is produced by firms. Also, the firms all use the same main input, i.e. raw milk as the basis for the outputs produced. The selection of large firms in our sample follows the European Union definition of firm size (firms with more than 250 employees and an annual turnover exceeding 50 million euros are large (European Commission, 2003)). In the next step, firms with missing observations were removed from the sample. And finally, outliers were detected and removed following Simar's (2003) proposal, based on the application of the order-m efficiencies of Cazals *et al.* (2002). The final dataset consisted of 344 large dairy manufacturing firms operating in Europe in at least two consecutive years during the period from 2005 to 2012. The panel is unbalanced and consists of 2,796 observations. Taking into account that dynamic Luenberger productivity growth is estimated using pairs of observations from the same firm in two consecutive years, this means that we have 1,398 such pairs. The majority of dairy manufacturing firms are based in Western Europe, followed by the Southern European countries and finally the smallest fraction of the sample is represented by the Eastern European countries.

The DEA model distinguishes two variable inputs, one quasi-fixed input, gross investments in quasi-fixed input and one output. The two variable inputs are material costs and labour costs, which were taken directly from dairy manufacturing firms' profit and loss accounts. Material costs refer to cost of purchasing the materials and includes mainly raw milk. Labour costs consist mainly of workers' salaries. The quasi-fixed input is represented by capital and measured as the opening value of fixed assets from the balance sheet, which shows the value of buildings, machinery and non-physical assets, net of depreciation. Gross investments in fixed assets in year t are computed as the opening value of fixed assets in year $t + 1$ minus the opening value of fixed assets in year t plus the value of depreciation in year t. The firm-specific values of depreciation, directly taken from AMADEUS, are used in the estimation of dynamic directional distance function. The analysed firms produce a number of different products such as liquid milk, butter, yoghurt and cheese and all these outputs are

[6]The financial information in AMADEUS is unified between different European countries, hence it is fully comparable across countries, which guarantees the consistency of our dataset.

Table 1
Descriptive statistics of the data, averages and standard deviations for 2005–2012 (measured in PPP, in thousands of 2004 US dollars)

Variable	Western*	Eastern†	Southern‡	Whole Europe
Fixed assets	56,244.7	46,659.4	100,165.3	66,515.0
	(98,618.3)	(52,289.8)	(248,659.6)	(153,368.6)
Labour cost	25,207.7	8,995.6	28,340.6	21,863.8
	(39,533.1)	(8,559.9)	(66,747.0)	(45,531.2)
Material cost	220,543.8	130,545.0	177,138.2	184,280.9
	(297,139.5)	(166,927.8)	(318,422.5)	(278,482.7)
Investments	10,737.2	8,217.4	13,624.8	10,916.3
	(22,474.3)	(11,940.4)	(34,045.4)	(24,575.5)
Output	301,847.1	173,910.3	298,185.7	267,195.5
	(415,141.6)	(201,194.0)	(606,551.6)	(444,548.2)
No of observations	1,248	734	814	2,796

Note: Standard deviations are in parentheses.
*Austria, Belgium, Finland, France, Germany, Luxembourg, Netherlands, Norway, Switzerland.
†Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Poland, Romania, Serbia, Slovakia, Slovenia.
‡Italy, Portugal, Spain.

proxied by the firms' total revenues from selling all products since the data reported do not distinguish between revenues from different outputs.

All variables are extracted from AMADEUS in local currencies and in current prices. These variables are adjusted by the Purchasing Power Parity (PPP) of the local currency to the US dollar, obtained from the World Bank, to facilitate cross-country comparison, and then the input-output variables are deflated using country-specific price indices to facilitate across-period comparisons. In particular, material costs are deflated by applying the producer price index for non-durable consumer goods, labour costs by the labour cost index in industry, fixed assets by the producer price index for capital goods, and for revenues the producer price index for food manufacturing is used.[7] All price indices are taken from the Eurostat (2015a) database on short-term business statistics, however for some countries also the local statistical offices need to be consulted to obtain information on some of the indices.[8]

Table 1 provides the descriptive statistics for the output and input variables for the whole sample of large dairy manufacturing firms in Europe and separately for different European regions (Western, Eastern and Southern). The table shows that Southern European dairy manufacturing firms have, on average, the largest values for input and output variables, with exception of material costs and revenues which are the largest for Western European firms. In contrast, Eastern European firms have the lowest values for inputs and output, on average. While the sample is restricted to large firms

[7]For some countries, however, because producer price index for food manufacturing is not available, producer price index for general manufacturing is used instead. This is the case of Luxembourg and Serbia.

[8]This is the case of Switzerland, Bosnia and Herzegovina, Croatia, Serbia and Portugal.

only, the table also reports that there are still considerable differences in the values of inputs and output between firms as shown by the large values of standard deviations relative to their respective means.

3.2. Results

The computation of input- and investment-specific dynamic productivity changes and their decomposition was undertaken for each pair of observations of firms that are observed in two consecutive years.[9] The input-specific dynamic measures are estimated for each region separately to account for potential technology differences between European regions (Western, Eastern and Southern). Hence, using a region-specific frontier produces region-specific dynamic productivity measures. The directional vector applied in computations is the actual quantity of variable inputs for variable inputs and actual quantity of capital for investments ($(g_x, g_I) = (x, k)$).

Table 2 shows the averages of region-specific dynamic productivity changes for inputs and investments and their decomposition into input- and investment-specific dynamic technical, technical inefficiency and scale inefficiency changes over the entire study period 2005–2012. The table also shows the results for Europe as a whole, which refer to the computation of average values of indicators for all firms, independent of region. The table also reports the results of the Simar and Zelenyuk (2006) test (S-Z test) that is used to assess the statistical differences between indicators across European regions.[10]

Table 2 suggests that there are similar patterns of region-specific dynamic productivity change and its components for labour input across European regions in the period 2005–2012. In particular, dynamic productivity change of labour is negative for all regions, i.e. it is −2.4% for Western European dairy manufacturing firms, −0.8% for Eastern European firms and −1% for Southern European firms. The drivers of negative dynamic productivity growth for labour for Western and Southern European companies are negative dynamic technical inefficiency change and dynamic technical change. Hence, dairy manufacturing firms in these regions use the existing production technology potential of labour less efficiently over time and experience technical

[9]It is worth noting that in the estimates of input-specific productivity growth, the mixed period distance functions might give infeasible solutions for some observations. This situation appears when an observation from one period is not in the production possibility set of the next time period, and as a result the distance function cannot be estimated. In our case it occurred for <2% of all observations. In addition, Briec and Kerstens (2009) elaborate on the general problem of infeasibilities that depends on the data structure, specification of technology and the choice of directional vector. In particular, the directional distance function may yield infeasibilities when the output direction is non-zero and the number of outputs is larger than or equal to two, or the directional input vector is not of full dimension whenever the output direction is null. This general problem of infeasibilities does not pertain to our case as, although our output direction is null, the directional vector for inputs is of full dimension.

[10]This test consists in the adaptation of the Li (1996) test to the context of comparing the distributions of DEA efficiency scores. In this study Simar and Zelenyuk's (2006) test is further adapted to the context of DEA productivity measures. In particular, Simar and Zelenyuk's (2006) test is based on bootstrapping the Li (1996) statistic using DEA efficiency measures with truncated values equal to unity smoothed. In our implementation of this test the smoothing of productivity measures is not undertaken since they are not truncated.

Table 2
Input- and investment-specific dynamic productivity change indicators and their decomposition, 2005–2012

Dynamic indicator	Western	Eastern	Southern	S-Z test	Europe
Materials					
Productivity change	−0.002	−0.010	0.003	a, b	−0.002
Technical change	−0.005	−0.019	0.021	a, b, c	−0.001
Technical inefficiency change	0.009	0.026	−0.019	a, c	0.005
Scale inefficiency change	−0.006	−0.016	0.001	a, b, c	−0.006
Labour					
Productivity change	−0.024	−0.008	−0.010	a, b, c	−0.016
Technical change	−0.002	−0.066	−0.002	a, c	−0.019
Technical inefficiency change	−0.025	0.007	−0.013	b, c	−0.013
Scale inefficiency change	0.003	0.051	0.006	a, b, c	0.016
Investments					
Productivity change	0.003	0.013	−0.002	b, c	0.005
Technical change	−0.010	−0.069	−0.012	a, b, c	−0.026
Technical inefficiency change	0.005	0.072	−0.018	a, b, c	0.016
Scale inefficiency change	0.008	0.010	0.028	b, c	0.014

Note: a, denotes significant differences between Western and Eastern European countries at the critical 5% level; b, denotes significant differences between Western and Southern European countries at the critical 5% level; c, denotes significant differences between Eastern and Southern European countries at the critical 5% level.

regress for this input. Eastern European firms' decline in dynamic productivity growth of labour is driven by negative dynamic technical change only as dynamic technical inefficiency change for this input slightly improves over time. Dynamic scale inefficiency change of labour contributes positively to dynamic productivity growth of this input for all European regions analysed. Hence, the firms in the sample improve the scale of operation of labour over time. This enhancement is especially large for Eastern European firms.

The results in Table 2 also suggest that region-specific dynamic productivity growth and its components for material input and capital investments show similar patterns for Western and Eastern European countries, while a different pattern is observed for firms from Southern Europe. In particular, for dairy manufacturing firms in Western and Eastern Europe, dynamic productivity change of materials is negative (−0.2% and −1%, on average, respectively) due to the negative contributions of dynamic technical change and scale inefficiency change (of −0.5% and −0.6%, and −1.9% and −1.6%, on average, respectively), which dominates the positive contribution of dynamic technical inefficiency change for materials (on average of 0.9% and 2.6%, respectively). On the other hand, firms in Southern Europe experience positive dynamic productivity change of materials (of 0.3%, on average), which is mainly driven by a positive dynamic technical change and dynamic scale inefficiency change (on average equal to 2.1% and 0.1%, respectively). Dynamic technical inefficiency change negatively contributes to productivity change for this input (−1.9%, on average). The differences across regions are not always statistically significant as shown by the result of the S-Z test. In particular, dynamic productivity growth for materials does not differ between Eastern and Southern European regions, also the distribution of dynamic technical inefficiency change for materials does not differ significantly between Western and Southern European countries.

The results in Table 2 also show that investment-specific dynamic productivity change is positive for Western and Eastern European countries (0.3% and 1.3%, on average, respectively) due to the positive technical and scale inefficiency changes (0.5% and 0.8%, and 7.2% and 1%, on average, respectively). Dynamic technical change for investments in these regions contributes negatively to dynamic productivity change, on average (−1% and −6.9, respectively). Investments in Southern European countries negatively contribute to productivity change, on average, with the exception of dynamic scale inefficiency change which contributes positively. Again, the differences between distributions of these indicators are not always statistically significant. The results of the S-Z test indicate that the distributions of dynamic productivity change and dynamic scale inefficiency change of investments do not significantly differ between dairy manufacturing firms in Western and Eastern European countries.

Overall, the results in Table 2 suggest that the magnitude of change in region-specific dynamic productivity growth of the two inputs and investments is very small. The components of input- and investment-specific dynamic productivity change show, in general, slightly larger values. The largest changes are found for dynamic technical change, dynamic technical change and scale inefficiency change for investments.

Region-specific dynamic productivity changes for variable inputs and investments and their decomposition for different periods are further analysed to depict if and how dynamic productivity change in dairy manufacturing has been impacted by the increasing price volatility of milk in recent years. Tables 3–6 present the results of input- and investment-specific dynamic productivity change indicators and their components for consecutive years, different time periods, and each region. The entire period is partitioned into three sub-periods to reflect the effect of volatility of prices in more detail. The first period encompasses the years 2005–2007 (periods 2005/2006 and 2006/2007) and concerns the period of relatively stable dairy prices. The second period consists of the years 2007/2008–2009/2010 and relates to the period of high volatility of prices in dairy markets. The third period is 2010/2011 and 2011/2012 and covers the period of stabilisation of dairy prices.

Table 3 shows, first, some remarkably large changes in region-specific dynamic productivity growth regarding all inputs in all European regions in the years of high volatility in milk prices (2007/2008 and 2008/2009) and also in the year preceding this period change (2006/2007, the peak in prices). This suggests that input-specific dynamic productivity change of dairy firms' is susceptible to the volatility of prices in dairy markets. Second, there is a tendency towards an overall decrease in input-specific dynamic productivity change for dairy firms in all European regions between the first two sub-periods. This drop of input-specific dynamic productivity change might be associated with the sudden change in dairy market prices in the second sub-period. The only exception is investment-specific dynamic productivity change in Western and Southern European countries, which improves in the period that was characterised by high volatility in dairy prices.

The results in Table 4 indicate that, on average, region-specific dynamic technical change for variable inputs and investments improves for all European regions in the period of decrease in milk prices (2007–2010) as compared to the period preceding this decrease (2005–2007). That is, either firms change from technical regress to technical progress, or the technical regress of their inputs and investments becomes smaller in the period when milk prices decreased. Hence, firms improved their dynamic

Table 3

Evolution of input- and investment-specific dynamic productivity change for consecutive years in the period from 2005 to 2012

Dynamic indicator	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012	2005–2007	2007–2010	2010–2012	S-Z test
Materials											
Western	0.023	–0.006	–0.008	–0.013	0.021	–0.019	–0.002	0.006	–0.001	–0.011	a, b, c
Eastern	–0.002	0.001	–0.029	0.000	–0.021	–0.005	–0.003	–0.001	–0.016	–0.004	b, c
Southern	0.020	0.007	0.028	0.013	–0.017	–0.006	–0.017	0.013	0.007	–0.012	a, b, c
Europe	0.016	–0.001	–0.005	–0.002	–0.003	–0.011	–0.007	0.007	–0.003	–0.009	a, b, c
Labour											
Western	–0.039	–0.027	–0.006	–0.010	0.011	–0.046	–0.061	–0.032	–0.002	–0.054	a, b, c
Eastern	0.054	–0.003	–0.018	–0.045	0.000	–0.032	0.011	0.024	–0.020	–0.010	a, b, c
Southern	–0.014	0.030	–0.008	0.027	–0.029	–0.010	–0.060	0.009	–0.003	–0.035	c
Europe	–0.011	–0.005	–0.009	–0.010	–0.003	–0.031	–0.042	–0.007	–0.008	–0.037	a, b
Investments											
Western	0.016	–0.035	0.033	0.000	–0.002	0.019	–0.007	–0.012	0.011	0.006	b, c
Eastern	0.112	0.021	0.050	0.017	–0.057	0.004	0.002	0.065	–0.001	0.003	a, b, c
Southern	0.005	–0.042	0.021	0.023	0.001	–0.002	–0.013	–0.020	0.015	–0.008	a, b
Europe	0.034	–0.026	0.034	0.011	–0.019	0.009	–0.006	0.002	0.009	0.001	a, b, c

Note: a, denotes significant differences between 2005–2007 and 2007–2010 at the critical 5% level; b, denotes significant differences between 2005–2007 and 2010–2012 at the critical 5% level; c, denotes significant differences between 2007–2010 and 2010–2012 at the critical 5% level.

Table 4
Evolution of input- and investment-specific dynamic technical change for consecutive years in the period from 2005 to 2012

Dynamic indicator	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012	2005–2007	2007–2010	2010–2012	S-Z test
Materials											
Western	−0.030	0.041	0.034	−0.011	−0.040	−0.029	−0.016	0.010	−0.004	−0.022	a, b, c
Eastern	−0.152	−0.202	0.131	−0.028	0.008	−0.027	0.021	−0.178	0.033	−0.003	a, b, c
Southern	0.073	0.061	−0.036	0.056	−0.062	−0.006	0.061	0.067	−0.014	0.028	a, b, c
Europe	−0.024	−0.002	0.042	0.002	−0.031	−0.021	0.018	−0.012	0.004	−0.001	a, b, c
Labour											
Western	0.003	−0.064	0.038	−0.091	0.069	0.058	−0.022	−0.035	0.005	0.017	a, b, c
Eastern	−0.009	−0.194	−0.318	−0.148	0.165	−0.116	0.091	−0.105	−0.083	−0.011	b, c
Southern	−0.060	0.007	0.105	0.007	−0.017	−0.083	0.029	−0.024	0.029	−0.025	a, b, c
Europe	−0.020	−0.069	−0.040	−0.081	0.076	−0.033	0.024	−0.046	−0.014	−0.004	a, b, c
Investments											
Western	−0.210	−0.219	−0.231	0.264	0.096	−0.107	−0.019	−0.030	0.034	−0.062	b, c
Eastern	−0.140	0.079	−0.223	0.228	−0.225	0.004	−0.171	−0.026	−0.076	−0.085	a, b, c
Southern	−0.024	−0.189	0.143	0.038	0.257	0.106	−0.364	−0.111	0.147	−0.136	a, b, c
Europe	0.058	−0.150	−0.135	0.193	0.037	−0.011	−0.168	−0.054	0.032	−0.092	a, b, c

Note: a, denotes significant differences between 2005–2007 and 2007–2010 at the critical 5% level; b, denotes significant differences between 2005–2007 and 2010–2012 at the critical 5% level; c, denotes significant differences between 2007–2010 and 2010–2012 at the critical 5% level.

Table 5

Evolution of input- and investment-specific dynamic technical inefficiency change for consecutive years in the period from 2005 to 2012

Dynamic indicator	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012	2005–2007	2007–2010	2010–2012	S-Z test
Materials											
Western	0.037	–0.017	–0.013	0.001	0.042	0.023	0.004	0.007	0.009	0.013	c
Eastern	0.192	0.060	–0.072	0.057	–0.006	0.057	–0.031	0.124	–0.005	0.012	a, b, c
Southern	–0.038	–0.067	0.018	–0.040	0.044	–0.001	–0.049	–0.053	0.008	–0.026	a, b
Europe	0.047	–0.016	–0.021	0.006	0.027	0.025	–0.022	0.013	0.004	0.001	a, c
Labour											
Western	–0.050	0.020	–0.006	0.001	–0.025	–0.072	–0.056	–0.011	–0.010	–0.064	a, c
Eastern	0.035	0.081	0.094	–0.033	–0.067	0.052	–0.058	0.059	–0.007	–0.004	c
Southern	–0.037	0.033	–0.104	0.007	–0.006	0.022	–0.021	–0.001	–0.032	0.000	
Europe	–0.027	0.036	–0.004	–0.007	–0.033	–0.010	–0.045	0.007	–0.015	–0.028	a
Investments											
Western	–0.122	0.051	0.159	–0.064	–0.109	0.055	0.025	–0.025	0.002	0.039	a, b, c
Eastern	0.136	–0.214	0.226	0.088	0.070	0.000	0.126	–0.046	0.123	0.064	b, c
Southern	0.012	0.044	–0.082	–0.058	–0.213	–0.098	0.239	0.029	–0.120	0.076	a, b, c
Europe	–0.022	–0.005	0.116	–0.019	–0.080	–0.008	0.119	–0.013	0.005	0.057	b, c

Note: a, denotes significant differences between 2005–2007 and 2007–2010 at the critical 5% level; b, denotes significant differences between 2005–2007 and 2010–2012 at the critical 5% level; c, denotes significant differences between 2007–2010 and 2010–2012 at the critical 5% level.

Table 6

Evolution of input- and investment-specific dynamic scale inefficiency change for consecutive years in the period from 2005 to 2012

Dynamic indicator	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012	2005–2007	2007–2010	2010–2012	S-Z test
Materials											
Western	0.016	−0.030	−0.029	−0.003	0.019	−0.014	0.010	−0.010	−0.006	−0.001	a, c
Eastern	−0.042	0.142	−0.089	−0.029	−0.023	−0.036	0.007	0.054	−0.045	−0.014	a, b, c
Southern	−0.015	0.013	0.046	−0.003	0.000	0.001	−0.029	−0.001	0.013	−0.014	a, b, c
Europe	−0.007	0.018	−0.026	−0.010	0.000	−0.015	−0.003	0.006	−0.012	−0.009	a, b, c
Labour											
Western	0.008	0.018	−0.038	0.081	−0.033	−0.032	0.017	0.014	0.003	−0.007	c
Eastern	0.028	0.110	0.207	0.135	−0.097	0.033	−0.022	0.071	0.071	0.005	a, b, c
Southern	0.083	−0.010	−0.008	0.013	−0.006	0.052	−0.068	0.034	−0.001	−0.010	
Europe	0.036	0.028	0.035	0.078	−0.046	0.011	−0.020	0.032	0.022	−0.005	b, c
Investments											
Western	−0.072	0.134	0.105	−0.201	0.012	0.072	−0.013	0.043	−0.025	0.028	b, c
Eastern	0.116	0.155	0.046	−0.299	0.098	0.000	0.048	0.136	−0.048	0.025	a, b, c
Southern	0.017	0.102	−0.040	0.043	−0.043	−0.010	0.112	0.062	−0.013	0.053	a, b, c
Europe	−0.002	0.128	0.053	−0.164	0.024	0.027	0.043	0.069	−0.028	0.035	a, b, c

Note: a, denotes significant differences between 2005–2007 and 2007–2010 at the critical 5% level; b, denotes significant differences between 2005–2007 and 2010–2012 at the critical 5% level; c, denotes significant differences between 2007–2010 and 2010–2012 at the critical 5% level.

technology regarding variable inputs and investments in the period of increased volatility of prices in dairy markets.

Table 5 indicates that Western European dairy manufacturing firms in the sample improved their region-specific dynamic technical inefficiency change for both inputs and investments in the time period 2007–2010 as compared to the period 2005–2007. However, as the S-Z test shows, this improvement was not statistically significant at the critical 5% level for materials. Dairy processing firms in Eastern European countries improved their dynamic technical inefficiency change for investments, but find their dynamic technical inefficiency change with regard to materials and labour worsening in the period of high volatility in milk prices. However, the changes between periods for investments and labour are not statistically significant at the critical 5% level. In the same period Southern European dairy manufacturing firms in the sample experienced a decrease in the contribution of dynamic technical inefficiency change of labour input and investments to dynamic productivity growth; an improvement was found for the material-specific dynamic technical inefficiency change. However, the changes for labour are not statistically significant at the critical 5% level.

Finally, the results for region-specific dynamic scale inefficiency change for variable inputs and investments in Table 6 show that dairy manufacturing firms in all European regions experience more problems in defining the optimal scale of operations regarding all inputs employed and investments in the time period related with decrease in milk prices as compared to the period before this decrease. However, some of the differences in dynamic scale inefficiency change for labour input are not statistically significant at the critical 5% level as indicated by the S-Z test.

4. Conclusions

We introduce a method for the measurement of dynamic input and investment-specific productivity change. The method controls for the dependence of firms' production decisions over time through investments in the firms' capital stock. The method is operationalised as an input-specific dynamic Luenberger indicator and applied to a sample of large European dairy manufacturing firms over the period 2005–2012.

Our results suggest that over the entire study period, Western, Southern and Eastern European large dairy manufacturing firms in the sample experienced a decline in dynamic productivity change for labour input that is mainly driven by technical regress. However, the dynamic scale inefficiency change for labour is positive across all regions suggesting that firms succeeded, on average, in moving the scale of the labour towards constant returns to scale. Additionally, the paper finds regional differences between dynamic indicators for materials and investments. In particular, dairy manufacturing firms in Western and Eastern Europe have enhanced contributions of investments to dynamic productivity growth, while Southern European firms have enhanced contributions emanating from materials. Finally, we find evidence of the impact of volatility in milk market prices on dynamic productivity growth of inputs and investments in dairy manufacturing firms. The sudden decrease in milk prices in the period 2007–2010 is accompanied, on average, by a decrease in input- and investment-specific dynamic productivity change and scale inefficiency changes; input- and investment-specific dynamic technical change improved.

Policy-makers and dairy manufacturers may use the findings of this study to improve the productivity and efficiency of inputs and investments. The results of this paper clearly indicate that the worst performance in productivity and technological and scale inefficiency dimensions is associated with materials in Western and Eastern European dairy manufacturing firms. Materials (mainly raw milk) is the major cost component of dairy manufacturers and should be the main focus of business interventions in these regions. The results suggest that dairy processing companies may have to improve the sourcing of milk (e.g. sourcing for better quality milk, or lower prices), or enhance the utilisation of this input. It should be noted though that, changing raw material sourcing may come with an increase in search costs and transaction costs, which can discourage firms from doing so. Also, the flexibility in the sourcing of milk may be limited for cooperatives, which have the obligation to process all their members' milk. Future research could investigate this issue more precisely by analysing the impact of sourcing of milk. Such research would require more granular data on input sourcing, information that is typically not available in databases such as AMADEUS (the database that was used in this study).

Southern European firms' performance is mainly constrained by investments in fixed assets. Southern European firms in the sample on average had the largest investments; also, however, the coefficient of variation (the ratio of the mean and standard deviation) of investments for these firms was the largest on average for these firms. The relatively large variation in the size of investments in Southern European firms could be the underlying cause of the negative contribution of dynamic technical inefficiency change to the investment-specific dynamic productivity growth for these firms. Policy interventions in this region could encourage investments in capital, especially for firms that made small investments. Policy and business interventions could focus on improving the access of dairy processing firms to the capital market, e.g. by enabling new capital suppliers in the market, or by facilitating new sources of funding such as crowd funding or credit unions. Enhancing investments that can introduce newly developed technologies inducing technical progress for this input could also be a focus of policy-makers.

The results of this study are also important in the light of the elimination of the dairy quota system, which will impact the future performance of the dairy manufacturing sector. European policy-makers and dairy processors should be aware of the need to enhance the performance of investments for Southern European firms and of materials' input for Western and Eastern European firms. Western and Eastern European dairy manufacturers can encounter even more problems with attaining the performance level for materials after the elimination of dairy quota.

This research could be extended in several ways. Our method is based on the dynamic directional distance function, and a promising line of future research would be to extend it to multi-directional efficiency and productivity analysis, extending the proposal of Bogetoft and Hougaard (1999). Furthermore, from the application side, the method developed in this study can be used to analyse investments in different types of capital (for example, buildings and equipment) or different types of workers (for example, low- medium- and high-skilled). We shed some light on the impact of volatility in milk prices and attribute the changes in input- and investment-specific dynamic productivity change in the period of volatility in milk prices to this change in market conditions. Other forces may also have contributed to these changes. Therefore, future research could analyse more precisely and in more detail the impact of volatility in milk prices on input- and investment-specific dynamic productivity growth and its components, for example by applying the method of impulse responses (Jordà, 2005; Teulings and Zubanov, 2014). Such a study could provide more precise guidance to policy-makers about the impact of volatility and other environmental factors on input and investment-specific productivity growth. Also, future research could address the organisational form of dairy manufacturing firms and, in particular, whether cooperatives and other organisational forms have different patterns of input-specific dynamic productivity change. Finally, the present study focuses on large firms only and it would be useful to estimate input- and investment-specific dynamic productivity change measures for dairy manufacturing firms of other sizes.

References

Ali, J., Singh, S. P. and Ekanem, E. 'Efficiency and productivity changes in the Indian food processing industry: Determinants and policy implications', *International Food and Agribusiness Management Review*, Vol. 12, (2009) pp. 43–66.

Aparicio, J., Kapelko, M., Mahlberg, B. and Sainz-Pardo, J. L. *Measuring Input-Specific Productivity Change Based on the Principle of Least Action*, Paper presented at XIV EWEPA in Helsinki and OR2015 in Vienna, 2015. Available at SSRN: http://ssrn.com/abstract=2817874

Bogetoft, P. and Hougaard, J. L. 'Efficiency evaluations based on potential (non-proportional) improvements', *Journal of Productivity Analysis*, Vol. 12, (1999) pp. 233–247.

Bontemps, C., Nauges, C., Réquillart, V. and Simioni, N. *Food Safety Regulation and Firm Productivity: Evidence from the French Food Industry*, IDEI Working Papers, 2012. Available at: http://www.idei.fr/doc/by/requillart/foodsafety.pdf (last accessed September 2015).

Briec, W. and Kerstens, K. 'Infeasibility and directional distance functions with application to the determinateness of the Luenberger productivity indicator', *Journal of Optimization Theory and Applications*, Vol. 141, (2009) pp. 55–73.

Cazals, C., Florens, J. and Simar, L. 'Nonparametric frontier estimation: A robust approach', *Journal of Econometrics*, Vol. 106, (2002) pp. 1–25.

Chang, T.-P., Hu, J.-L., Chou, R. Y. and Sun, L. 'The sources of bank productivity growth in China during 2002–2009: A disaggregation view', *Journal of Banking and Finance*, Vol. 36, (2012) pp. 1997–2006.

Doucouliagos, H. and Hone, P. 'The efficiency of the Australian dairy processing industry'', *Australian Journal of Agricultural and Resource Economics*, Vol. 44, (2001) pp. 423–438.

European Commission. 'Recommendation concerning the definition of micro, small and medium-sized enterprises', *Official Journal of the European Union*, Vol. 46, (2003), pp. 36–41. Available online at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:124:0036:0041:EN:PDF

European Commission. *Evolution of the Market Situation and the Consequent Conditions for Smoothly Phasing Out the Milk Quota System* Report from the European Commission to the European Parliament and the Council, COM(2010) 727, 8 December 2010 (EC, Brussels, 2010).

European Commission. *Evolution of the Market Situation and the Consequent Conditions for Smoothly Phasing Out the Milk Quota System – Second "Soft Landing" Report*, Report from the European Commission to the European Parliament and the Council, COM(2012) 741, 10 December 2012 (EC, Brussels, 2012).

European Commission. *European Milk Market Observatory* (EC, Brussels, 2015). Available at: http://ec.europa.eu/agriculture/milk-market-observatory/index_en.htm (last accessed September 2015).

Eurostat. *Short-Term Business Statistics* (EC, Brussels, 2015a). Available online at: http://ec.europa.eu/eurostat/web/short-term-business-statistics (last accessed September 2015).

Eurostat. *Agricultural Statistics* (EC, Brussels, 2015b). Available at: http://ec.europa.eu/eurostat/web/agriculture (last accessed September 2015).

Fallah-Fini, S., Triantis, K. and Johnson, A. L. 'Reviewing the literature on non-parametric dynamic efficiency measurement: State-of-the-art', *Journal of Productivity Analysis*, Vol. 41, (2014) pp. 51–67.

Färe, R. and Grosskopf, S. 'Directional distance functions and slacks-based measures of efficiency', *European Journal of Operational Research*, Vol. 200, (2010) pp. 320–322.

Fukuyama, H. and Weber, W. L. 'A directional slacks-based measure of technical inefficiency', *Socio-Economic Planning Sciences*, Vol. 43, (2009) pp. 274–287.

Geylani, P. C. and Stefanou, S. E. 'Productivity growth patterns in U.S. dairy products manufacturing', *Applied Economics*, Vol. 43, (2011) pp. 3415–3432.

Jordà, Ò. 'Estimation and inference of impulse responses by local projections', *American Economic Review*, Vol. 95, (2005) pp. 161–182.

Kapelko, M., Oude Lansink, A. and Stefanou, S. 'Assessing dynamic inefficiency of the Spanish construction sector pre- and post-financial crisis', *European Journal of Operational Research*, Vol. 237, (2014a) pp. 349–357.

Kapelko, M., Oude Lansink, A. and Stefanou, S. *The impact of 2008 financial crisis on dynamic productivity growth of the Spanish food manufacturing industry* (Ljubljana, Slovenia: European Association of Agricultural Economists Congress, 2014b).

Kapelko, M., Horta, I. M., Camanho, A. S. and Oude Lansink, A. 'Measurement of input-specific productivity growth with an application to the construction industry in Spain and Portugal', *International Journal of Production Economics*, Vol. 166, (2015a) pp. 64–71.

Kapelko, M., OudeLansink, A. and Stefanou, S. 'Effect of food regulation on the Spanish food processing industry', *PLoS ONE*, Vol. 10, (2015b) p. e0128217.

Kapelko, M., Oude Lansink, A. and Stefanou, S. 'Analyzing the impact of investment spikes on dynamic productivity growth', *OMEGA – The International Journal of Management Science*, Vol. 54, (2015c) pp. 116–124.

Kapelko, M., Oude Lansink, A. and Stefanou, S. 'Investment age and dynamic productivity growth in the Spanish food processing industry', *American Journal of Agricultural Economics*, Vol. 98, (2016) pp. 946–961.

Li, Q. 'Nonparametric testing of closeness between two unknown distribution functions', *Econometric Reviews*, Vol. 15, (1996) pp. 261–274.

Lovell, C. A. K. and Pastor, J. T. 'Units invariant and translation invariant DEA models', *Operations Research Letters*, Vol. 18, (1995) pp. 147–151.

Mahlberg, B. and Luptacik, M. 'Eco-efficiency and eco-productivity change over time in a multisectoral economic system', *European Journal of Operational Research*, Vol. 234, (2014) pp. 885–897.

Mahlberg, B. and Sahoo, B. K. 'Radial and non-radial decomposition of Luenberger productivity indicator with an illustrative application', *International Journal of Production Economics*, Vol. 131, (2011) pp. 721–726.

Mahlberg, B., Luptacik, M. and Sahoo, B. K. 'Examining the drivers of total factor productivity change with a illustrative example of 14 EU countries', *Ecological Economics*, Vol. 72, (2011) pp. 60–69.

Ohlan, R. 'Efficiency and total factor productivity growth in Indian dairy sector', *Quarterly Journal of International Agriculture*, Vol. 52, (2013) pp. 51–77.

Oude Lansink, A. and Ondersteijn, C. H. 'Energy productivity growth in the Dutch greenhouse industry', *American Journal of Agricultural Economics*, Vol. 88, (2006) pp. 124–132.

Oude Lansink, A., Stefanou, S. E. and Serra, S. 'Primal and dual dynamic Luenberger productivity indicators', *European Journal of Operational Research*, Vol. 241, (2015) pp. 555–563.

Pastor, J. T. and Aparicio, J. 'A note on "A directional slacks-based measure of technical inefficiency"', *Socio-Economic Planning Sciences*, Vol. 44, (2010) pp. 174–175.

Silva, E. and Stefanou, S. E. 'Nonparametric dynamic production analysis and the theory of cost', *Journal of Productivity Analysis*, Vol. 19, (2003) pp. 5–32.

Silva, E., Oude Lansink, A. and Stefanou, S. E. 'The adjustment-cost model of the firm: Duality and productive efficiency', *International Journal of Production Economics*, Vol. 168, (2015) pp. 245–256.

Simar, L. 'Detecting outliers in frontier models: A simple approach', *Journal of Productivity Analysis*, Vol. 20, (2003) pp. 391–424.

Simar, L. and Zelenyuk, V. 'On testing equality of distributions of technical efficiency scores', *Econometric Reviews*, Vol. 25, (2006) pp. 497–522.

Skevas, T. and Oude Lansink, A 'Reducing pesticide use and pesticide impact by productivity growth: The case of Dutch arable farming', *Journal of Agricultural Economics*, Vol. 65, (2014) pp. 191–211.

Teulings, C. N. and Zubanov, N. 'Is economic recovery a myth? Robust estimation of impulse responses', *Journal of Applied Econometrics*, Vol. 29, (2014) pp. 497–514.

Vlontzos, G. and Theodoridis, A. 'Efficiency and productivity change in the Greek dairy industry', *Agricultural Economics Review*, Vol. 14, (2013) pp. 14–28.