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delivery networks**

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Cost Efficiency Measurement in Postal Delivery Networks*

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ABSTRACT

The purpose of this study is to analyze the level of cost efficiency of Swiss Post's postal delivery units to enable policy makers' as well as Swiss Post to decide on the reactions to market changes. In particular, we use different panel data models to assess cost efficiency in these units to account for unobserved heterogeneity. The results from applying Mundlak's formulation to the Pooled stochastic frontier model provides evidence that this model is not affected by a heterogeneity bias and that the cost efficiency values lie within a lower and upper bound of the other recent and standard econometric frontier models. Overall, the analysis shows that assumptions on unobserved heterogeneity are crucial and that results of econometric cost efficiency measurement models have to be interpreted with corresponding caution.

Keywords: cost efficiency, stochastic frontier models, unobserved heterogeneity, Mundlak, postal delivery network

JEL classification: C33, D24, H42, L87

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1 INTRODUCTION

During the last two decades, several countries around the world have been gradually liberalizing their postal markets. The key objectives of these reforms are improved efficiency within the sector, an increase in product innovation, higher quality levels, and affordable postal products while maintaining the provision of a minimum universal postal service (see e.g. for Europe the 3rd European Postal Directive (2008)). One of the most challenging tasks of the universal service providers in this process is to improve efficiency given the universal service obligations they face.

In Switzerland, the postal market is also affected by such regulatory changes. The largest and most important provider of postal services in the country is the incumbent Swiss Post, a publicly owned company. Besides the operation of a nationwide network of postal outlets, Swiss Post is obliged to deliver letters and parcels in every year-round occupied residential area in the entire country every working day (PG (1997)). These universal services traditionally were subject to the legal monopoly of Swiss Post. Today, some services are still reserved for Swiss Post, whereas in respect of other services, Swiss Post is competing on the open market. In the course of market liberalization, the reserved services were first limited to letters below 100 grams and then below 50 grams as a compromise in order to secure its financing (PV (2004)). However, today, physical letters are also in competition with electronic mail, and the decline in letter volumes is ascribed mainly to electronic substitution (see e.g. Nikali (2008) or Dietl et al. (2011)). In this context of increasing competition, it is important for Swiss Post to increase the level of productive efficiency.

In order to increase efficiency, the internal organization of Swiss Post has also undergone extensive restructuring. One of these changes was the organizational and in most of the cases geographical separation of the collection and delivery processes. The commissioning of new, more centralized sorting centers came along with this disentanglement. The intention of these measures was to benefit from considerable scale effects through merger of delivery bases and centralized sorting centers while losing some economies through vertical disintegration.

Inefficiencies in the delivery process are of particular importance, as about half of total costs of letters and more than one third of total costs of parcels accrue in this process (NERA (2004)). For the improvement of competitiveness as well as for future discussions on the extent of the universal service and its financing, it is important to gain information on cost efficiency through the implemen-

tation of an internal benchmarking system in the delivery process of Swiss Post.⁴ Until now, the delivery units were benchmarked based on simple indicators including some quality aspects and operating ratios. Therefore, this paper addresses the formulation of suitable econometric cost efficiency measurement models in the postal sector. From a methodological point of view, this requires the estimation of a cost frontier and comparing different model specifications that adequately reflect the supply of the postal delivery. Thereby, special attention is paid to the consideration of unobserved time-invariant factors attributed to unobserved heterogeneity⁵, as the delivery bases are subject to many different factors such as landscape, weather, traffic, output-mix, culture, etc., which cannot all be controlled perfectly in the models. Therefore, we apply different panel data models and some extensions that are suitable to control unobserved heterogeneity.

The paper is organized as follows. Section 2 outlines the main contribution of this paper with regard to the relevant literature available on the subject. Section 3 presents the model specifications and Section 4 introduces the data. Section 5 provides the estimation results and measures of cost efficiency for different model specifications. We draw the conclusions in Section 6.

2 PREVIOUS STUDIES ON COST EFFICIENCY MEASUREMENT

During the last decades, various studies have investigated cost efficiency measurement in network industries such as the energy and transport sector, healthcare, the banking industry, or even in the education sector.⁶ As far as postal services are concerned, only few studies exist on empirical cost efficiency measurement. Therefore, we also include studies on production efficiency due to the similar nature of production and cost efficiency. The first three of the reviewed studies analyze the collection and delivery process in the postal sector jointly, and the second three uniquely the delivery process.

⁴ In other industries, benchmarking systems are used for incentive regulation schemes such as price- or revenue cap (Littlechild (1983)) or yardstick regulation (Shleifer (1985)). However, these regulation schemes are not suited in the postal market, as the monopoly situation no longer exists with liberalization (except for light letters below 50 grams). Moreover, there was only one monopoly and not several regional monopoly companies that could be benchmarked against each other. In liberalized markets without monopoly situations, price setting and market allocation are a function of competition.

⁵ The general term “unobserved heterogeneity” refers to unobserved, time-invariant and time-varying factors that affect the dependent variable. Other names can be found in the literature as well, such as unobserved effect, individual heterogeneity, or unobserved individual-specific effect. In the present study, the term unobserved heterogeneity refers mainly to time-invariant factors.

⁶ For recent studies on cost efficiency measurement using stochastic models in non-postal industries, see e.g. Farsi and Filippini (2009a) (energy sector), Cullmann et al. (2012) (transport sector), Filippini et al. (2008) (water distribution), Greene (2004) (health care sector), and Johnes and Johnes (2009) (education).

In this paper, we raise the question of econometric cost efficiency measurement in Swiss Post's delivery network. Unlike in earlier studies, the separate inspection of the delivery process is unproblematic, as these days, this process is organizationally and geographically separated from other main processes of the postal value chain. The delivery process includes manual sequencing of all items according to the planned delivery route as well as their delivery to the mailboxes, post office boxes and to the doorsteps.

An early but remarkable study was conducted by Perelman and Pestieau (1994) and aimed at comparing productive performance of national postal services in 16 OECD industrial countries, using a panel data set containing 15 years. In the first step, they estimated technical efficiency applying a translog production function to the Pooled model proposed by Aigner et al. (1977). Number of items plus that of transactions were used as output, and labor, number of post offices and vehicles as inputs. The average efficiency ranged from about 39% to 90%. As remarked by the authors, this wide spread was the result of the very simple model neglecting any geographical and institutional differences and thus excluding a good portion of heterogeneity among countries. Therefore, in the second step, the estimated efficiency scores were regressed on mailbox density, on inhabitants per letter drop, on indexes of private franchisees and regulatory constraints to explain the inefficiency at least partly by heterogeneity. The question remains, why these geographical and institutional variables were not included in the frontier equation in order to reduce unobserved heterogeneity *ab initio*. Such an approach would have been more appropriate to obtain accurate efficiency estimates.

The study of Borenstein et al. (2004) analyzed tree groups of totally 113 post offices operating in the year 2000 in Brazil concerning their specific postal services provided: collection, delivery, or both. Using five input and six output variables and applying it to a DEA model, they found about 44% of the offices located on the frontier, thus be fully efficient. However, applying cross-sectional, obviously highly heterogeneous data on this model might result in a heterogeneity bias that should not be neglected. Further, the integrated stores appear to be relatively inefficient, a fact the authors trace back to the 'hybrid nature' of these offices. This result is not intuitively clear at first sight, as one could expect economies of scope resulting from the spreading of fixed costs on more activities.

Filippini and Zola (2005) estimated a Cobb-Douglas stochastic cost frontier function for a small sample of post offices operating in the year 2001 in Switzerland and combined collection and delivery processes. Explaining total costs by collected and delivered mail and the factor prices for labor and physical capital as well as by the population density, they found more than 50% of the sam-

pled offices having mean inefficiency scores lower than twelve percent. The fact that the majority of the postal offices are operating relatively close to the fully efficient cost frontier can be explained, notwithstanding the very simple model and small sample, by the relatively similar environmental conditions, as all offices are small and located in the same region of Switzerland. Hence, unobserved heterogeneity in this sample can be expected as relatively low. Nevertheless, the authors suggest using panel data for future research.

The paper of Moriarty et al. (2006) is the first in the field of cost efficiency measurement in the postal sector which distinguishes between processes. Using cross-sectional data of more than 1100 delivery offices of Royal Mail and a Cobb-Douglas total cost function, the authors estimated the stochastic frontier model of Aigner et al. (1977) and a type of corrected OLS that shifts the frontier not to the lowest observation, but to the lowest decile, allowing at least for some unobserved effects. Nine different explanatory variables were employed, including volumes, density, local wages, and business penetration in the region as well as five additional dummy variables indicating the degree of the region's urbanization. Unfortunately, the authors did only report the estimation results, but not the efficiency scores. However, they indicated that the initial results of the stochastic and the deterministic model were within five percent of each other and that they remained close after some model adjustments. As a policy implication for the regulator authority, they overtaxed the scope of interpretation of the results and valued the savings potential of more than one quarter billion pounds simply by applying best practices within the delivery network. This implication neglects the fact that on the one hand the unobserved heterogeneity is only insufficiently respected in these simple, cross-sectional models and on the other that the adaption rate on new practices is limited.

Cost efficiency of Royal Mail's delivery offices was also under investigation in the paper of Horncastle et al. (2006). Based on the same cross-sectional data as the paper of Moriarty et al. (2006), the authors removed about one fourth of the observations due to limitations of accuracy. Presumably, this process also removed a considerable amount of unobserved heterogeneity out of the data. Applying Cobb-Douglas and translog functional form and specifying different distributions of the inefficiency term of the stochastic frontier model suggested by Aigner et al. (1977), they compared the results with results from a variable returns to scale model in the context of a data envelopment analysis. For the DEA model, different stratifications of the data were conducted, because dummy variables cannot be included. In general, the average inefficiency was higher in the DEA models than in the SFA models, especially for the Cobb-Douglas specification. This is because the latter two

models allow for random noise in the data, whereas the former assess the whole distance to the frontier as inefficiency. The inefficiency in the DEA models monotonically decreased as the number of data sets from the stratification of the data increased due to decreasing heterogeneity in every single data set.

The motive of calculating cost efficiency of Visco Commandini et al. (2010) was the state aid regulation in the European antitrust law. The cornerstone of the analysis is the European Justice's *Altmark* decision, which defined four conditions so that compensation for public services (e.g. in the context of universal service obligations) is not considered to be state aid. The fourth condition says that the level of compensation is determined on the basis of an analysis of the cost of a typical, well-run company to discharge such public services. Hence, costs stemming from inefficient performance are not to be compensated. In their study, the authors estimated a ten year panel data set with 13 European countries that includes data on operating cost, mail volume, labor costs, and number of households and percentage of population living in urban areas. Unfortunately, they pooled the data to shape it for their models and neglected the panel dimension; hence they abstained from an obvious possibility to control unobserved heterogeneity. They specified a translog functional form and estimated a corrected OLS, a corrected GLS, and DEA model and found considerable differences between countries and models.

Generally, as already mentioned, the issue of unobserved heterogeneity remains mainly undiscussed in the reviewed studies. Perelman and Pestieau (1994) circumvent this problem rudimentarily regressing the inefficiency scores on some environmental variables in a second stage. Horncastle et al. (2006) excluded a good deal of the observations in order to reduce heterogeneity. Filippini and Zola (2005) refer to the problem and suggest using panel data in addition to environmental characteristics in order to capture the unobserved heterogeneity. However, they use regional data where the unobserved heterogeneity can be expected to be relatively low. Even though in some of the other studies panel data was available, none of the authors made use of sophisticated panel data models in order to separate unobserved heterogeneity from inefficiency. As hardly any attention has been paid to the unobserved heterogeneity, the identification problem of inefficiency and unobserved heterogeneity has, to the best of our knowledge, not been discussed in the postal context. Furthermore, none of the studies focused on the choice of methods that are suitable for an internal benchmarking.

One of the main contributions of this paper is to discuss and consider the observed heterogeneity problem within the context of cost efficiency measurement in postal delivery networks. The unob-

served heterogeneity problem is considered in two ways. First, by introducing a selective set of variables in the model specification and distinguishing sharply from different ancillary production processes that are carried out additionally in a small number of delivery units (e.g. interoffice mail delivery). Second, by applying econometric models for panel data that takes the unobserved heterogeneity into account. For this purpose, we apply the panel data on different elaborated cost model specifications. Most importantly and following the idea of Farsi et al. (2005), we extend the Pooled model of Aigner et al. (1977) and the True Random Effects model of Greene (2005) by the formulation of Mundlak (1978). The estimators of this auxiliary equation should absorb the correlated components of the unobserved heterogeneity and therefore avoid a heterogeneity bias. For comparability reasons, we also estimate a True Fixed Effects model and the familiar Random Effects model of Pitt and Lee (1981).

3 COST MODEL SPECIFICATION AND METHODOLOGY

We specify a cost model that explains total costs of Swiss Post's delivery network with three aggregated output variables, two input variables and five environmental characteristics. Under the assumption of cost-minimizing behavior of postal delivery units and convex production technology, we write this model as follows:

$$C = f(Q_1, Q_2, Q_3, P_L, P_C, D, dA, dH, dS_S, T) \quad (1),$$

where the dependent variable C represents total costs of a delivery unit. The three outputs ($Q_1 - Q_3$) are measured by the following parameters: letters, parcels, and post office box delivery. The model incorporates two different inputs: P_L is the price of labor and P_C the price of capital, respectively.

Furthermore, in order to capture the heterogeneity of Swiss Post's delivery units, additional variables have been included to the model. D represents the mailbox density in the delivery area by the ratio of street time and number of mailboxes. The dummy variable dA accounts for geographical disadvantages in alpine regions originating from atmospheric exposure such as snowfall or low temperatures. It is approximated by the height above sea level, averaged and weighted by the total output on zip code level. The dummy variable dH measures the share of addresses with 'doorstep service', where postmen provide households with postal services at the doorstep upon request. This service is offered in remote regions with few post offices or third-party owned agencies. The variables dS_S are

dummies denoting the seasons, as the data is on quarterly basis (see Section 4) and subject to strong seasonal fluctuation, especially concerning output volumes. Finally, a time trend T has been introduced to capture the neutral technical progress. For a complete description of the variables with the corresponding data see Section 4.

The estimation of the cost model in Equation (1) requires the specification of a functional form. Proposed by Christensen et al. (1973) and applied in numerous empirical studies in production economics, we specify a translog functional form for the purpose of flexibility and the straightforward imposition of the linear homogeneity restriction.^{7,8} In the non-homothetic form,⁹ it can be written as:

$$\begin{aligned}
\ln \frac{C_{it}}{P_{Lit}} = & \alpha_0 + \sum_{m=1}^3 \beta_m \ln Q_{mit} + \frac{1}{2} \sum_{m=1}^3 \beta_{mm} \ln Q_{mit} \ln Q_{mit} + \sum_{m=1}^3 \sum_{n>m}^3 \beta_{mn} \ln Q_{mit} \ln Q_{nit} \\
& + \beta_P \ln \frac{P_{Cit}}{P_{Lit}} + \frac{1}{2} \beta_{PP} \ln \frac{P_{Cit}}{P_{Lit}} \ln \frac{P_{Cit}}{P_{Lit}} + \beta_D \ln D_{it} + \frac{1}{2} \beta_{DD} \ln D_{it} \ln D_{it} \\
& + \beta_{PD} \ln \frac{P_{Cit}}{P_{Lit}} \ln D_{it} + \sum_{m=1}^3 \beta_{Pm} \ln \frac{P_{Cit}}{P_{Lit}} \ln Q_{mit} + \sum_{m=1}^3 \beta_{Dm} \ln D_{it} \ln Q_{mit} \\
& + \beta_A dA_{it} + \beta_H dH_{it} + \beta_S dS_{it} + \beta_T T_{it} + \beta_{TT} T_{it} T_{it} + \alpha_i + \varepsilon_{it}
\end{aligned} \tag{2}$$

where subscript i denotes postal delivery unit $i = 1, 2, \dots, I$, subscript t 16 quarters from 1/2007 – 4/2010, and subscripts m and n outputs $m = 1, 2, 3$ and $n = 2, 3$. α_i stands for the individual effects that should capture the time-invariant unobserved heterogeneity, and ε_{it} is the composite error term, consisting of the inefficiency u_{it} and the random error v_{it} . As the translog functional form is a second order Taylor-approximation, the values of the explanatory variables must be normalized to

⁷ The following restrictions are necessary to guarantee linear homogeneity in inputs: $\sum_r \gamma_{Pr} = 1$, $\sum_{r=1}^3 \sum_{s=1}^3 \gamma_{PCrPCs} = 0$, and $\sum_r \lambda_{rm} = 0$ for all values m . Linear homogeneity implies for any $t > 0$: $C(t\mathbf{P}, \mathbf{Q}) = tC(\mathbf{P}, \mathbf{Q})$. Therefore, to impose linear homogeneity, one of the inputs, say P_C , might be arbitrarily chosen and set $t = 1/P_C$. Then one obtains $C(\mathbf{P}, \mathbf{Q})/P_C = C(\mathbf{P}/P_C, \mathbf{Q})$.

⁸ A proper cost function should exhibit the following characteristics to conform with neoclassical microeconomic theory: (a) non-negative and non-decreasing in input prices and outputs, (b) linearly homogeneous, concave and continuous in input prices.

⁹ A cost function is non-homothetic, if input prices depend on output levels, hence if input prices and output levels are not separable. In contrast, a homothetic cost function is separable in the sense: $C(\mathbf{P}, \mathbf{Q}) = h(\mathbf{Q})c(\mathbf{P})$. Further properties of the translog functional form: symmetry ($\beta_{mm} = \beta_{nm}$) and positivity ($\beta_m \geq 0$). The translog functional form requires every unit to have strictly positive outputs.

the approximation point. For this purpose, we chose the median value of the variables.¹⁰ Finally, a time trend has been introduced in a neutral, non-linear way accounting for technological progresses.

The estimation of the level of cost efficiency and the identification problem of unobserved heterogeneity is studied by a comparative analysis of pooled cross-sections and Random and Fixed Effects models. All models are based on the specification in Equation (2). The differences among the models are related to assumptions on the individual effect α_i and the composite error term ε_i . Table 1 summarizes the econometric specifications of the six models used in this paper.

Table 1: Econometric specifications

	Model I	Model II	Model III	Model IV	Model V	Model VI
	Pooled	RE (ML)	True RE	True RE + Mundlak's equation	True FE	Pooled + Mundlak's equation
Individual effect α_i	none	$iid(0, \sigma_\alpha^2)$	$N(0, \sigma_\alpha^2)$	$\alpha_i = \gamma \bar{x}_i + \delta_i$ $\bar{x}_i = \frac{1}{T} \sum_{t=1}^T x_{it}$ $\delta_i \sim N(0, \sigma_\delta^2)$	fixed	$\alpha_i = \gamma \bar{x}_i$ $\bar{x}_i = \frac{1}{T} \sum_{t=1}^T x_{it}$
Composite error ε_{it}	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+(0, \sigma_u^2)$ $v_{it} \sim N(0, \sigma_v^2)$	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+(0, \sigma_u^2)$ $v_{it} \sim N(0, \sigma_v^2)$	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+(0, \sigma_u^2)$ $v_{it} \sim N(0, \sigma_v^2)$	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+(0, \sigma_u^2)$ $v_{it} \sim N(0, \sigma_v^2)$	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+(0, \sigma_u^2)$ $v_{it} \sim N(0, \sigma_v^2)$	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+(0, \sigma_u^2)$ $v_{it} \sim N(0, \sigma_v^2)$
Inefficiency	$E[u_{it} \varepsilon_{it}]$	$E[u_{it} \varepsilon_{it}]$	$E[u_{it} \alpha_i + \varepsilon_{it}]$	$E[u_{it} \delta_i + \varepsilon_{it}]$	$E[u_{it} \varepsilon_{it}]$	$E[u_{it} \varepsilon_{it}]$

Model I is the conventional Pooled model of Aigner et al. (1977), which does not account for the individual effects, i.e. the time-invariant unobserved heterogeneity. In case of correlation of these effects with the explanatory variables, this model might exhibit biased coefficients.¹¹ Model II is a Random Effects (RE) model as proposed by Pitt and Lee (1981). As in any RE model, the individual effects u_i , that should capture the unobserved heterogeneity, are assumed to be uncorrelated with the explanatory variables. As long as this assumption holds, the estimators are not affected by a heterogeneity bias. Furthermore, this model interprets the individual effects u_i as inefficiency. Model III is based on the True RE model of Greene (2005), which is a successor of the models of Kumbhakar (1991) and Polachek and Yoon (1996). It estimates unit-specific constants that are designed to cap-

¹⁰ The median value is better suited as an approximation point than the mean value, as it is less affected by outliers.

¹¹ Moreover, this model might be affected by positive serial correlation, as the individual effects are included in the error term.

ture unobserved heterogeneity by maximum simulated likelihood, so that the remaining elements in the error term, including inefficiency, vary freely over time.¹² Still, correlation between the individual effects and the explanatory variables might cause a heterogeneity bias. Model *IV*, therefore, extends Model *III* using the auxiliary equation proposed by Mundlak (1978) and first applied to stochastic frontier models by Farsi et al. (2005b) and subsequently by Farsi et al. (2005a). This equation considers possible correlation between the unobserved heterogeneity and the explanatory variables with the group-means of the explanatory variables:

$$\alpha_i = \gamma \bar{\mathbf{x}}_i + \delta_i, \quad \bar{\mathbf{x}}_i = \frac{1}{T_i} \sum_{t=1}^{T_i} \mathbf{x}_{it}, \quad \delta_i \sim N(0, \sigma_\delta^2) \quad (3).$$

This auxiliary equation can directly be incorporated into the cost model specification in Equation (2) above, which divides the unobserved heterogeneity term into two components. The first component with the estimators γ absorbs that part of the unobserved heterogeneity that is correlated with the explanatory variables. The second component (δ_i) is assumed to be orthogonal to the explanatory variables and accounts for the unit-specific constants. If this formulation is applied to a normal RE or an OLS model, it results in estimators equivalent to the Fixed Effects (FE) estimator, thus it is unbiased even when unobserved heterogeneity is correlated with explanatory variables.^{13,14} Model *V* is a variant of the True FE model of Greene (2005),¹⁵ in that it estimates the unit-specific constants α_i by including dummy variables.¹⁶ As any model with FE estimators, this model should not be affected

¹² This model is a special case of the random parameter model of Greene (2005), where only the intercept is random. It is therefore also known as the random constant model.

¹³ This argument holds for RE models, which are based on normality, but does not strictly apply to stochastic frontier models estimated by ML, as these models possess an asymmetric composite error term ε_i . As the model captures the correlation between the individual effects and the explanatory variables at least partly, the resulting heterogeneity bias is expected to be minimal.

¹⁴ This can be seen easily by extending the equation $y_{it} = \mathbf{x}_{it}\beta + \bar{\mathbf{x}}_i\alpha + \varepsilon_{it}$ with $\pm \bar{\mathbf{x}}_i\beta$ on the right hand side of the equation. It leads to $y_{it} = (\mathbf{x}_{it} - \bar{\mathbf{x}}_i)\beta + \bar{\mathbf{x}}_i(\alpha + \beta) + \varepsilon_{it}$. Therefore, β is the within and $(\alpha + \beta)$ the between estimator. For more details on Mundlak's approach and a comparison with other estimators, see Wooldridge (2010).

¹⁵ This model is not to be confused with an LSDV model in the stochastic frontier context, as it is estimated by maximum likelihood and as it is not based on normality.

¹⁶ The primary True FE model is estimated by Simulated ML, our variant with dummy variables by ML. Greene (2005) mentions two problems likely to arise using the variant with dummies, especially if N and hence the number of parameters becomes large. First, the number of parameters might cause estimation problems, which, though, did not arise in this study. Second, a bias could result from the incidental parameter problem.

by a heterogeneity bias. As mentioned, the coefficients and hence also the inefficiencies should be equal to that of Model *IV* (True RE with Mundlak’s auxiliary equation).

Models *I*–*V* presented above exhibit an important limitation identifying and separating inefficiency and unobserved heterogeneity, irrespective of the possible heterogeneity bias in some of the models. In Model *I*, the composite error term contains the time-invariant unobserved heterogeneity component. Therefore, part of this component is captured as inefficiency. Model *II*, the one-sided disturbance term u_i , which is interpreted as inefficiency, contains also the time-invariant unobserved heterogeneity. It has been shown in several papers (e.g. in Bagdadioglu and Weyman-Jones (2007) or in Farsi and Filippini (2009)), that this model tends to overstate inefficiency or at least forms an upper bound. By contrast, the composite errors of Models *III*–*V* are exempt from the time-invariant unobserved heterogeneity component, as it is captured by the individual effects. This results in relatively low inefficiencies that can therefore be interpreted as a lower bound. Comparing these models, Greene (2008) states explicitly that the ‘truth’ doubtless lies somewhere between the two extremes of Model *II* and Models *III*–*V*. He also remarks that this identification problem only can be resolved by non-sample information, i.e. by additional assumptions.

Model *VI* therefore extends the Pooled model of Aigner et al. (1977) (Model *I*) with Mundlak’s auxiliary equation also used in Model *IV*. With this specification, the correlated components of the unobserved heterogeneity are absorbed by the group-means of the explanatory variables, whereas the uncorrelated components are stuck in the composite error. The additional assumption that underlies Model *VI* is that only uncorrelated, i.e. separable components of unobserved heterogeneity are in the composite error and, therefore, can be absorbed by the inefficiency term. The correlated, i.e. non-separable components of unobserved heterogeneity are considered in the coefficients of the auxiliary equation and thus not interpreted as inefficiency. This assumption is in line with Bagdadioglu and Weyman-Jones (2007) and Cullmann et al. (2012) in that time-invariant non-separable factors are assumed to be an integrated part of the production process and therefore not inefficiency. This seems to be reasonable in our cost model, because it takes into account various time-invariant environmental variables and because the data only contains observations that belong to the same superordinate company following the same guidelines and principles and conduct the same processes. Hence, heterogeneity in the production technologies is captured to a high degree in the

However, this possible bias is expected to be negligible, because the panel data set is relatively long ($T = 16$) compared to the limited number of units ($N = 77$).

cost model of Equation (1). As in the Models IV and V, the unobserved heterogeneity bias is avoided in Model VI.^{17,18} To the best of our knowledge, this specification has not yet been used in the context of stochastic frontier models.

Table 2 summarizes these explanations on the identification of inefficiency in the six models.

Table 2: Treatment of unobserved heterogeneity

	Model I	Model II	Model III	Model IV	Model V	Model VI
	Pooled	RE (ML)	True RE	True RE + Mundlak's equation	True FE	Pooled + Mundlak's equation
Unobs. heterogeneity bias	possible	possible	possible	no	no	no
Time-variant unobs. heterogeneity	in ε_{it}	in ε_{it}	in ε_{it}	in ε_{it}	in ε_{it}	in ε_{it}
Time-inv. uncorrelated unobs. heterogeneity	in ε_{it}	in ε_{it}	in α_i	in α_i	in α_i	in ε_{it}
Time-inv. correlated unobs. heterogeneity	in β	in β	in β	in γ	in α_i	in γ
Inefficiency	$E[u_{it} \varepsilon_{it}]$	$E[u_i \varepsilon_{it}]$	$E[u_{it} \alpha_i + \varepsilon_{it}]$	$E[u_{it} \delta_i + \varepsilon_{it}]$	$E[u_{it} \varepsilon_{it}]$	$E[u_{it} \varepsilon_{it}]$
The individual effect (α_i) in Model V is estimated using dummy variables						

4 DATA

This study is based on an unbalanced panel dataset from 2007 – 2010 with quarterly observations on 77 postal delivery units operating in Switzerland at the beginning of the observation period and 73 at the end.¹⁹ These units cover the whole delivery area of Swiss Post's mail division; the difference in numbers is due mainly to consolidation of units. Each of these units belongs to one of the nine superordinate delivery zones and includes about one and a half dozen subordinate delivery areas on average, where postmen start their delivery routes.²⁰

¹⁷ Of course, we are aware that this model specification could suffer from a serial correlation problem.

¹⁸ Another interesting approach recently applied by Farsi et al. (2005b) is to estimate the model of Pitt and Lee (1981) (Model II) with Mundlak's auxiliary equation. Applied to our study, the coefficients are similar to those of the True FE model (Model V).

¹⁹ This dataset might be interpreted as a pseudo panel, as the obvious temporal delimitation would be one year. However, working with quarters allows for absorbing systematic seasonal variation caused by weather influences or quantity changes.

²⁰ For a small share of these delivery routes in urban areas, parcels are delivered separately by Swiss Post's logistics division. However, the aggregated number of delivered parcels is high enough for robust conclusions on delivery unit level.

The delivery units cover a wide range of outputs and geographical characteristics. Total costs (C) are measured in Swiss Francs and vary only by a factor of approximately four among delivery units. All of these units deliver letters and parcels in post- and post office boxes and offer payment services. The outputs are weighted sums of different subproducts of the corresponding output. As all delivery units must comply with the same internal quality guidelines and principles, we assume comparable quality levels for all units.²¹

Letter output (Q_1) is a generic term for all categories of addressed and direct mail including catalogues that can be readily dropped into the mailbox at the street or at the doorway. In contrast, parcel output (Q_2) includes all categories of registered mail, parcels and express items that entail more and costlier processes than Q_1 , for example dismounting from the motorcycle or getting out of the car, knocking at the door to submit for signature and ensuring traceability of the items. If the consignee is out, a pickup notice has to be filled in and the item brought to the closest postal outlet. Both Q_1 and Q_2 are calculated as the weighted sum of the number of delivered letters and parcel, respectively.²² The output of payment services is measured and to be understood analogously. The weighted number of outpayments is added to the weighted number of incoming payments. Except for cash on delivery and doorstep service (see below), payment transactions have been decreasing steadily in the last years. Due to very similar production processes and quantitative negligibility, these services are subsumed under Q_2 . The last output, post office box delivery (Q_3), includes all items delivered in a post office box, again measured as a weighted sum. Compared to Q_1 and Q_2 , most of the process steps fall away with post office box delivery.

Two different inputs prices, defined as factor expenditures per factor unit, are included in the model. As postal delivery is still labor intensive to a high degree, the most important input is the price of labor (P_L).²³ It is measured by average full-time equivalents per-capita expenses and varies by attributes such as age, type of contract, experience and special qualification of the postman. The second input is a residual price that has been considered for the approximation of the price of capital (P_C), following the idea of Friedlaender and Wang Chiang (1983). It is measured as the ratio of non-

²¹ In fact, customer satisfaction varies sparsely and on a high quality level. It is indeed surveyed for every delivery unit, but it is to some extent affected by public perception of the umbrella brand *Swiss Post*, which includes the mail, logistics, finance, bus transport, international and the technical solutions divisions. Furthermore, the survey is published only once a year and on a retrospective view.

²² For weighting factors, we use the internal standards of performance.

²³ More than 80% of total costs originate from labor expenses. In the forthcoming years, this rate is likely to decline due to a substitution by capital, as automated sorting and sequencing processes will be established.

labor expenses to a measure of real estate capital. The measure of real estate capital is approximated by the rented surface of the postal delivery unit in square meters. We did not include the price of movables such as motorcycles or cars, as the vehicle service is provided by a central division; hence all delivery units face the same prices for movable capital.

As indicated in Section 3, Swiss Post's delivery units are heterogeneous, in terms of geographical preconditions such as density, urbanity and alpine exposure as well as in terms of organizational differences such as doorstep service in remote parts of the delivery area. The most important geographical characteristic is density (D) of the delivery area, which depends on time on the road on the one hand and on the number of stops at the other. Delivery costs are clearly higher in dispersed settlements than in densely populated areas with a high share of multiple-family dwellings having several mailboxes located at the same place. Therefore, the variable D is calculated by the ratio of time spent on the road and the number of mailboxes served. It varies by a factor of more than ten among delivery units.²⁴

The second variable accounting for geographical influences is alpine exposure (dA). In general and both in summer and in winter, topographic conditions are more challenging in alpine regions than in the remaining parts of Switzerland. In particular, snowfall and low temperatures have an effect on the delivery process as they cause traffic jams, scarcely passable streets or limitedly accessible mailboxes. Furthermore, the use of motorcycles is more dangerous and sometimes impossible, and mounting snow chains time consuming. These influences are therefore approximated by the height above sea level, weighted by the total output on zip code grade.²⁵ Weighting the height by output is important, because height and output vary considerably between delivery units and subordinate delivery areas. Altogether, the weighted height of the lowest delivery unit lies about 200, the highest almost 1'700 meters above sea level. However, as the distribution of heights shows a discontinuous pattern at 700 meter, dA is defined as a dummy variable taking the value 1 in about 13 percent of all observations lying above this threshold.

²⁴ In addition to D , one could also think of a variable accounting for urbanity of the delivery area, representing characteristics such as personnel turnover, traffic lights and jams and different customer behavior. The idea behind is that also rural villages may be dense with respect to the definition of D , depending on the landscape and on the housing settlement structure. However, a pretest with such a variable has shown that it is highly correlated with D on the aggregation level of delivery units used in this analysis.

²⁵ Data on height above sea level on zip code grade was provided by the Federal Office of Statistics (2008). The other data was provided by Swiss Post.

The dummy variable dH accounts for organizational differences and indicates if there are addresses with ‘doorstep service’ in the delivery unit. Households with doorstep service are provided by the postmen with postal services and products at the doorstep upon request, indicated by a sign at the mailbox. This service is offered in remote regions with few post offices or third-party owned agencies.²⁶ The highest share of routes with doorstep service is 42%, the lowest zero.

The variables dS_s are dummies denoting the season, as the data is on quarterly basis and subject to strong seasonal fluctuation, especially concerning output volumes. The reference season includes the last three months in the year, hence the time before Christmas, where outputs achieve their maximum. The first six months in the year are represented in the first two seasons. July, August and September build the third season including summer vacations, where outputs achieve their minimum. The variables T and TT , finally, form a neutral, non-linear time trend it that it does not interact with the other explanatory variables. Hence, it captures only technical progress, but not labor or capital savings.

Table 3 provides summary statistics for these variables.

Table 3: Summary statistics

Variable	Unit	Mean	Std. dev.	Median
Total costs (C)	CHF	3'732'603	1'516'322	3'459'533
Letter output (Q_1)	10 ³ items	10'300	4'429	10'100
Parcel output (Q_2)	10 ³ items	228	113	209
P.O. box output (Q_3)	10 ³ items	2'564	2'286	1'951
Price of labor (P_L)	CHF / FTE	20'742	1'043	20'735
Price of capital (P_C)	CHF / m ²	179	71	173
Density (D)	mailboxes / s	0.058	0.024	0.052
Alpine exposure (dA)	1	0.126	0.332	0
Doorstep service (dH)	1	0.743	0.437	1

n = 1'177

5 RESULTS

Table 4 and 5 list the regression results of the six stochastic frontier models as specified in Equation (2) and listed in Table 1. Generally, the estimated coefficients of the first-order terms have the expected signs and are statistically significant. Since the dependent and independent variables are

²⁶ For more background information and especially on the political implications of doorstep service, see Buser et al. (2008), Filippini et al. (2010) or Filippini and Koller (2012).

in natural logarithms, the estimated coefficients can be interpreted as cost elasticities at the approximation point.²⁷ For example, a volume rise of one percent of items delivered in post office boxes (Q_3) increases total costs by about 0.04 to 0.05 percent in most of the models.

The first order coefficients of the three output variables (letter (Q_1), parcel (Q_2), and post office box delivery (Q_3)) are of similar magnitude, except for Q_3 in Model *I*. The cost elasticity of Q_1 is much higher than of Q_2 and Q_3 reflecting the relative importance in terms of volumes. The coefficients for the input price ratio (P) show that parts of the differences in total costs among delivery units can be explained by higher input prices, either capital or labor. An exception with this variable is again Model *I* that exhibits an insignificant value. The negative signs of the coefficients for D confirm that in densely populated areas costs are lower. An exception with this variable is Model *III* that exhibits an insignificant value. As argued above, the effects of the urbanity of the area should be captured by the coefficient of D . The coefficients for the dummy variable dA accounting for alpine exposure are positively significant throughout all models, hence alpine exposure increase costs for the delivery. The coefficients for the dummy variable dH denoting doorstep services is not significant for the Models *IV*, *V* and *VI*, hence in the models with Mundlak's auxiliary equation and in the True FE model that avoid the unobserved heterogeneity bias. The coefficients for the seasonal dummy variables (dS_S) do not vary considerably among models, but among seasons: all of them are significantly positive and of similar magnitude. This implies that the costs in the reference season including the months before Christmas can be explained by high outputs. Also and not unexpected, the third season, with the months July until September including summer vacation, exhibits the highest coefficient. The coefficients for the variables T and TT , finally, confirm a neutral, non-linear time trend that is positive but decreasing for all models except for Model *I*. This means that the technical progress was highest negative at the beginning of the observation period and became positive by the end, when all automated sorting centers have overcome their initial technical problems. The unit-specific constants of Model *V* are not reported due to space restrictions. They are mainly significant and positive. Lambda is significant, indicating skewness of the composite error term and hence existence of inefficiency.

Finally, only three of the six cost functions (Models *I*, *II*, and *VI*) are concave in input prices (labor and capital) at the approximation point.²⁸ This means that the management's strategies are not

²⁷ Cost elasticities with respect to the dummy variables d (dA , dH and dS_S) are calculated as $[\exp(d)-1]$. Thus, a shift from conventional postal delivery to doorstep service raises costs about 5.52 (4.23) percent in Model *I* (*II*).

strictly responsive to changes in input prices, i.e. they do not show completely unconstrained cost-minimizing behavior as theory might predict. According to Farsi and Filippini (2009), the reason could lie in constraints in input choices by regulations, e.g. labor contracts or quality restrictions. Furthermore, substitution of capital and labor is in many cases not feasible in the postal delivery sector.

²⁸ With a translog cost function, the concavity condition is satisfied if the Hessian matrix of the second derivatives of total costs with respect to the input prices, $\frac{\partial^2 \ln TC}{\partial \ln P_j \partial \ln P_i}$, is negatively semi-definite, i.e. if the eigenvalues of the matrix are non-positive. In the actual analysis with two input prices and imposed linear homogeneity, the Hessian matrix reduces to $H = \begin{pmatrix} \beta_{PP} & -\beta_{PP} \\ -\beta_{PP} & \beta_{PP} \end{pmatrix}$. However, one could also argue that the concavity condition is fulfilled since none of the second derivatives are significantly different from zero, i.e. the eigenvalues are zero.

Table 4: Regression results (Models I, II and VI)

Variable	Model II	Model I	Model VI	
	RE (ML)	Pooled	Pooled + Mundlak's equation	
	Coefficient (SE)	Coefficient (SE)	Main equation Coefficient (SE)	Auxiliary equation Coefficient (SE)
Letter output (Q_1)	0.5787 *** (0.019)	0.6605 *** (0.013)	0.5502 *** (0.027)	0.1162 *** (0.032)
Parcel output (Q_2)	0.1672 *** (0.016)	0.1358 *** (0.010)	0.1578 *** (0.022)	-0.0198 (0.025)
P.O. box output (Q_3)	0.0394 *** (0.011)	0.1155 *** (0.007)	0.0471 *** (0.015)	0.0863 *** (0.018)
Input price ratio (P)	0.0609 *** (0.009)	0.0069 (0.010)	0.0641 *** (0.013)	-0.1042 *** (0.021)
Density (D)	-0.0879 *** (0.024)	-0.1217 *** (0.012)	-0.0874 ** (0.036)	-0.0881 ** (0.038)
$(Q_1 Q_1)$	0.1276 *** (0.045)	0.0895 * (0.050)	0.0340 (0.063)	0.0206 (0.099)
$(Q_2 Q_2)$	0.0720 * (0.040)	0.1102 *** (0.040)	0.0352 (0.059)	0.1424 * (0.081)
$(Q_3 Q_3)$	0.0387 *** (0.015)	0.0168 (0.019)	0.0563 *** (0.020)	-0.1867 *** (0.036)
(PP)	-0.0155 (0.029)	-0.0073 (0.039)	-0.0053 (0.041)	-0.0145 (0.092)
(DD)	-0.1600 *** (0.056)	0.0701 (0.047)	-0.1418 * (0.077)	-0.0059 (0.101)
$(Q_1 Q_2)$	-0.0267 (0.036)	-0.1203 *** (0.039)	0.0586 (0.049)	-0.2770 *** (0.076)
$(Q_1 Q_3)$	-0.0827 *** (0.021)	-0.0339 (0.022)	-0.0981 *** (0.028)	0.1355 *** (0.041)
$(Q_1 P)$	0.0027 (0.025)	0.0257 (0.029)	0.0085 (0.035)	0.0041 (0.065)
$(Q_1 D)$	-0.1860 *** (0.040)	-0.0654 * (0.037)	-0.1334 ** (0.059)	0.0516 (0.073)
$(Q_2 Q_3)$	0.0278 (0.018)	0.0551 *** (0.017)	0.0246 (0.025)	0.0679 ** (0.033)
$(Q_2 P)$	-0.0655 *** (0.022)	-0.0917 *** (0.027)	-0.0854 *** (0.029)	-0.2025 *** (0.066)
$(Q_2 D)$	0.1355 *** (0.040)	0.0981 *** (0.029)	0.0545 (0.056)	-0.0105 (0.065)
$(Q_3 P)$	0.0264 * (0.015)	0.0364 * (0.019)	0.0271 (0.020)	0.2512 *** (0.047)
$(Q_3 D)$	0.0148 (0.025)	0.0290 (0.028)	0.0047 (0.035)	0.2080 *** (0.055)
(PD)	-0.1208 *** (0.028)	-0.0713 ** (0.032)	-0.1202 *** (0.039)	-0.2540 *** (0.072)
Alpine exposure (dA)	0.0642 *** (0.021)	0.0408 *** (0.010)	0.0269 *** (0.009)	-
Doorstep service (dH)	0.0537 *** (0.013)	0.0273 *** (0.010)	0.0107 (0.010)	-
Season 1 (dS_1)	0.0442 *** (0.005)	0.0433 *** (0.007)	0.0471 *** (0.007)	-
Season 2 (dS_2)	0.0656 *** (0.005)	0.0739 *** (0.007)	0.0670 *** (0.007)	-
Season 3 (dS_3)	0.1053 *** (0.005)	0.1206 *** (0.007)	0.1027 *** (0.007)	-
Time trend (T)	0.0067 ** (0.003)	-0.0068 ** (0.003)	0.0097 *** (0.003)	-
(TT)	-0.0003 ** (0.000)	0.0005 *** (0.000)	-0.0004 ** (0.000)	-
Constant	4.8026 *** (0.023)	4.9612 *** (0.019)	4.9400 *** (0.021)	-
$\sigma^2 = \sigma_u^2 + \sigma_v^2$	0.0511 *** (0.011)	0.0133 *** (0.001)	0.0110 *** (0.001)	-
$\lambda = \sigma_u / \sigma_v$	4.0514 *** (0.116)	1.5887 *** (0.011)	1.7277 *** (0.011)	-

***, **, *: significant at 1%, 5% and 10%, respectively; standard errors are given in brackets.

n = 1'177

In GLS models, the coefficients of Mundlak's main equation result in the Fixed Effects (within) estimators. The coefficients of the auxiliary equation cannot be interpreted directly, but adding to the coefficients of the main equation, they result in the between estimator (Mundlak (1978)). Hence, it gives cross-sectional information reflected in the changes between units. As argued above, we ap-

ply Mundlak's extension to stochastic frontier models, where these arguments do not strictly hold. However, we expect the thereby emerging error to be minimal.

Table 5: Regression results (Models III – V)

Variable	Model III		Model IV		Model V		
	True RE		True RE + Mundlak's equation		True FE		
	Coefficient	(SE)	Main equation Coefficient	Auxiliary equation (SE)	Coefficient (SE)		
Letter output (Q_1)	0.6257 ***	(0.007)	0.5654 ***	(0.015)	0.0752 *** (0.019)	0.5656 *** (0.019)	
Parcel output (Q_2)	0.1408 ***	(0.006)	0.1688 ***	(0.014)	-0.0343 ** (0.017)	0.1687 *** (0.015)	
P.O. box output (Q_3)	0.0410 ***	(0.005)	0.0357 ***	(0.010)	0.1212 *** (0.012)	0.0358 *** (0.010)	
Input price ratio (P)	0.0502 ***	(0.006)	0.0628 ***	(0.008)	-0.1007 *** (0.014)	0.0632 *** (0.009)	
Density (D)	-0.0109	(0.008)	-0.0717 ***	(0.015)	-0.1146 *** (0.017)	-0.0701 *** (0.025)	
(Q_1Q_1)	0.0918 ***	(0.034)	0.0963 **	(0.045)	-0.2853 *** (0.071)	0.0946 ** (0.043)	
(Q_2Q_2)	0.0347	(0.025)	0.0531	(0.040)	0.0283	(0.056)	0.0528 (0.040)
(Q_3Q_3)	0.0256 **	(0.012)	0.0367 **	(0.016)	-0.1747 *** (0.027)	0.0365 ** (0.014)	
(PP)	0.0146	(0.019)	0.0032	(0.021)	-0.0765	(0.063)	0.0037 (0.028)
(DD)	0.0837 ***	(0.025)	-0.1157 ***	(0.045)	0.0022 *** (0.067)	-0.1122 ** (0.055)	
(Q_1Q_2)	0.0172	(0.025)	0.0287	(0.033)	-0.0571	(0.053)	0.0295 (0.034)
(Q_1Q_3)	-0.0932 ***	(0.015)	-0.0979 ***	(0.026)	0.1661 *** (0.035)	-0.0985 *** (0.020)	
(Q_1P)	0.0204	(0.019)	0.0008	(0.025)	0.0137	(0.047)	0.0020 (0.024)
(Q_1D)	-0.1461 ***	(0.023)	-0.1684 ***	(0.033)	0.1940 *** (0.048)	-0.1682 *** (0.040)	
(Q_2Q_3)	0.0609 ***	(0.012)	0.0364	(0.028)	0.0063	(0.032)	0.0370 ** (0.017)
(Q_2P)	-0.0949 ***	(0.016)	-0.0752 ***	(0.021)	-0.1905 *** (0.047)	-0.0757 *** (0.021)	
(Q_2D)	0.0763 ***	(0.020)	0.0630	(0.039)	-0.0035	(0.048)	0.0634 (0.039)
(Q_3P)	0.0104	(0.010)	0.0234 *	(0.014)	0.2450 * (0.035)	0.0233 * (0.014)	
(Q_3D)	0.0304 **	(0.015)	0.0211	(0.025)	0.1423	(0.039)	0.0221 (0.024)
(PD)	-0.0647 ***	(0.019)	-0.1130 ***	(0.024)	-0.2669 *** (0.050)	-0.1114 *** (0.027)	
Alpine exposure (dA)	0.0805 ***	(0.006)	0.0363 ***	(0.006)	-	0.0409 * (0.022)	
Doorstep service (dH)	0.0414 ***	(0.006)	0.0107	(0.007)	-	0.0111 (0.014)	
Season 1 (dS_1)	0.0473 ***	(0.008)	0.0460 ***	(0.009)	-	0.0461 *** (0.005)	
Season 2 (dS_2)	0.0688 ***	(0.012)	0.0662 ***	(0.012)	-	0.0663 *** (0.005)	
Season 3 (dS_3)	0.1120 ***	(0.009)	0.1041 ***	(0.011)	-	0.1043 *** (0.005)	
Time trend (T)	0.0092 ***	(0.002)	0.0095 ***	(0.003)	-	0.0096 *** (0.002)	
(TT)	-0.0004 ***	(0.000)	-0.0005 ***	(0.000)	-	-0.0005 *** (0.000)	
Constant	4.8712 ***	(0.014)	4.9846 ***	(0.016)	-	4.8745 *** (0.026)	
Unit-specific constant	0.7860 ***	(0.019)	0.0579 ***	(0.002)	-	†	
$\sigma^2 = \sigma_u^2 + \sigma_v^2$	0.0052 ***	(0.000)	0.0046 ***	(0.000)	-	0.0044 *** (0.000)	
$\lambda = \sigma_u / \sigma_v$	1.4607 ***	(0.203)	1.2601 ***	(0.197)	-	1.3281 *** (0.095)	

***, **, *: significant at 1%, 5% and 10%, respectively; standard errors are given in brackets.

n = 1'177

†: unit-specific constants are estimated as dummies. ***+(-): 43(4) units, **+(-): 5(1) units, *+(-): 2(2) units, insignificant: 19 units

A descriptive summary of the inefficiency scores obtained from the Models *I* – *VI* is given in Table 6. As found by several previous authors, the RE model produces the lowest and the True RE and the True FE models the highest mean and minimum efficiency scores. According to the latter models, the postal delivery units exhibit on average about four percent of excess costs compared to a fully efficient unit. The efficiency scores of the Pooled model lie clearly below the ones of the True RE and True FE models. As already mentioned, the reason is that the True RE and True FE models do not account for persistent (time-invariant) inefficiencies. Therefore, Farsi and Filippini (2009) argue that these models should provide a reasonable upper bound for the efficiency to the extent that there are certain sources of time-invariant inefficiencies. The same argument applies for the Model *II* in that it can be considered to produce a reasonable lower bound for the inefficiency. The median efficiency score is higher than mean in all models suggesting a right-skewed distribution of the scores.²⁹ The maximum score tends to one in all models, which is a known characteristic of the JLMS estimator of Jondrow et al. (1982). As expected, the efficiency scores of Model *VI* are higher than in Model *I* indicating that the coefficients in Mundlak’s extension absorb the factors of the unobserved heterogeneity that are correlated with the explanatory variables.

Table 6: Efficiency scores

	Model <i>II</i> RE (ML)	Model <i>III</i> True RE	Model <i>IV</i> True RE + Mundlak's equation	Model <i>V</i> True FE	Model <i>I</i> Pooled	Model <i>VI</i> Pooled + Mundlak's equation
Mean	0.829	0.954	0.959	0.959	0.926	0.931
Standard deviation	0.088	0.023	0.019	0.020	0.038	0.037
Minimum	0.610	0.812	0.835	0.829	0.731	0.759
10 th Percentile	0.711	0.924	0.935	0.933	0.877	0.880
1 st Quantile	0.770	0.944	0.951	0.951	0.909	0.914
Median	0.840	0.960	0.963	0.964	0.935	0.941
3 rd Quantile	0.888	0.970	0.972	0.972	0.954	0.958
90 th Percentile	0.928	0.977	0.977	0.978	0.966	0.969
Maximum	0.995	0.992	0.993	0.993	0.986	0.988

n = 1'177

²⁹ If the skewness of the error term is in the wrong direction, the results are not those of a frontier, but OLS for the slope and for σ_v^2 and zero for σ_u^2 (Waldman (1982), cited in Greene (2007)).

The pair-wise correlations between the efficiency scores of the six models and the corresponding Spearman rank correlations are listed in Table 7 in the lower and upper triangle of the matrix, respectively. Models *IV* and *V* exhibit almost perfect correlation, consistent with theory; it is generally high among the Models *III* – *V* and among the two Pooled models due to similar model assumptions, at least in the latter case. More surprisingly, the correlations between the models of these two groups are also remarkable. The weakest correlation with all other models shows Model *II*, especially with the True RE models; it is even not significantly different from zero with Model *V*. The reason for this island position is obvious: Model *II* assumes the time-invariant individual effects to be inefficiency, whereas it freely varies over time in all other models. The only moderate correlation is with the Pooled model, which neglects unobserved heterogeneity. The Spearman rank correlations in the upper triangle of the matrix present a similar pattern.

Table 7: Correlations of efficiency scores and Spearman rank correlations

	Model <i>II</i> RE (ML)	Model <i>III</i> True RE	Model <i>IV</i> True RE + Mundlak's equation	Model <i>V</i> True FE	Model <i>I</i> Pooled	Model <i>VI</i> Pooled + Mundlak's equation
Model <i>II</i>	1	0.035	0.012	-0.018	0.459 ***	0.371 ***
Model <i>III</i>	0.078 ***	1	0.959 ***	0.966 ***	0.649 ***	0.664 ***
Model <i>IV</i>	0.065 **	0.966 ***	1	0.998 ***	0.641 ***	0.698 ***
Model <i>V</i>	0.037	0.959 ***	0.997 ***	1	0.603 ***	0.657 ***
Model <i>I</i>	0.489 ***	0.594 ***	0.589 ***	0.543 ***	1	0.886 ***
Model <i>VI</i>	0.374 ***	0.633 ***	0.670 ***	0.620 ***	0.898 ***	1

Note: correlations of efficiency scores are listed in the lower, Spearman rank correlations in the upper triangle of the matrix.
 ***, **, *: significantly different from 0 at 1%, 5% and 10%, respectively. n = 1'177

In Table 4 and Table 5 above we presented the estimation results obtained using several models. Unfortunately, there are no standard statistical tests for frontier models with panel data to identify the best suitable model, as the composite error terms of frontier models are not normally distributed. Models *IV*, *V* and *VI* considered the unobserved heterogeneity bias, the other three did not. As Models *IV* and *V* tend to overestimate the level of cost efficiency or at least form an upper bound, Model *VI* might be a promising alternative.

6 SUMMARY AND CONCLUSIONS

The purpose of this study was to analyze the cost structure of Swiss Post's postal delivery units, and in particular to assess cost efficiency among these units. Information on cost efficiency is important from a policy makers' as well as from Swiss Post's view, as the postal market is facing increasing competition due further steps of liberalization, a market upheaval due to electronic substitution and process changes due to progressive automation of letter sorting.

One contribution of this study is the consideration of the unobserved heterogeneity problem of cost efficiency measurement in the postal sector. In this context, we have proposed to extend the conventional Pooled model of Aigner et al. (1977) by the formulation of Mundlak (1978) and compared it to several recent models suggested by Greene (2005) and to the well-established model of Pitt and Lee (1981). The intention of this model extension was first to avoid the unobserved heterogeneity bias and second to separate parts of unobserved heterogeneity from efficiency. The underlying assumption for the latter was that time-invariant, non-separable unobserved heterogeneity should be interpreted as part of the production process, whereas time-invariant, separable unobserved heterogeneity should be ascribed to inefficiency.

A translog total cost function was estimated using an unbalanced panel data set consisting of 1'177 observations consisting of 77 postal delivery units in 16 quarters of the years 2007 until 2010. The estimation results of the six models support the hypothesis of unobserved heterogeneity in the data and the corresponding bias in the three models that do not avoid it. The coefficients of the other three models that avoid the unobserved heterogeneity bias are – under some assumptions on the testing procedure for stochastic frontier models – statistically indifferent from each other and are thus in line with econometric theory. This is in particular a remarkable result as these three models consist of one Random Effects, one Fixed Effects and one Pooled model.

The empirical results for the cost efficiency confirm, as shown in several papers, that the values of the model of Pitt and Lee form a lower and the values of the three True Effects models of Greene an upper bound (range of average cost efficiency values: 82.9% – 95.9%). The reason for this high range is the completely different treatment of unobserved heterogeneity in the two model groups. Correspondingly, the pair-wise deviation measures between the two model groups are high. Furthermore, there is also almost no correlation either of the cost efficiency and the Spearman ranks. However, there is hardly any difference among the tree True Effects models, in particular not among the two unbiased models: their cost efficiencies as well as the Spearman ranks are highly correlated

and the pair-wise deviations measures tend towards zero. The cost efficiency values of the Pooled models (92.6% and 93.1% on average) lie well within the range. Thereby, especially the results of the latter model with the Pooled model and Mundlak's extension are interesting, as these results should be unbiased and allow for a differentiated treatment of unobserved heterogeneity. Not surprising, the correlation of this model to the model of Pitt and Lee is extremely weak, whereas these values with respect to the True Effects models are remarkably good.

The implications of this study are twofold. First, the treatment of unobserved heterogeneity is of crucial importance, even when relatively homogeneous data is applied. Thereby, considerable industry knowledge is required to make realistic and adequate assumptions on unobserved heterogeneity. Second, the results of a benchmarking process should be interpreted and used with corresponding caution. We do not recommend using them to mechanically reward or punish, e.g. in an internal compensation scheme or in a financing system for the universal service.

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