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Financial Centre Productivity and Innovation prior to and during the Financial Crisis

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Abstract

This paper assesses and tests the response of banks operating in the financial centres to the financial crisis in terms of the actual productivity change and its main components: the pure efficiency change, scale efficiency change and technological change (innovation). The heterogeneity in the organizational form and the size that exists among banks have been accounted for with the Aggregated Malmquist Productivity Index and the bootstrap techniques extended to this index. Our findings indicate that both the branch and subsidiary banks respond to the financial crisis with productivity improvements, and in both cases, this improvement is driven mostly by the positive technical change. However, the branch banks outperform the subsidiary banks. In addition, for the three categories of big, medium and small banks, we find a positive productivity reaction to the crisis, driven by the technical change. However, as small banks not only respond to the financial crisis with improvements in the technical change but also in the scale-efficiency change, they seem to reach a higher productivity growth, compared with larger banks, as a response to the financial crisis.

JEL classification: C14; D24; G01; G21; F23.
Keywords: Financial Centre; Bank Productivity; Data Envelopment Analysis; Aggregated Malmquist Productivity Index; Sensitivity Analysis; Financial crisis.

1. Introduction

Analysis of the performance of foreign banks is gaining increasing attention of policy makers, financial institution managers and academics in the banking literature. This interest has gained high priority in light of the financial crisis because foreign banks are a crucial component of the entire interconnected banking industry. Understanding how foreign banks behave and how they have responded to the financial crisis have become urgent issues for policy makers; they must explore these issues more deeply to be able to take action in the definition of new regulations in the international banking framework. In particular, realizing how the banks that decide to operate in the financial centre perform became an interesting assignment, particularly during the financial crisis, because the financial centres, which host mainly foreign banks among few domestic banks, have been called upon to demonstrate their constructive contribution to the world economy (*The Economist*, 2013).

In this paper, we empirically test the general view that states that financial centres are highly productive banking systems that are shaped by innovation over a long period, including the financial crisis. In particular, we test whether financial centres were productive places before the financial crisis and their performance response to the financial crisis. We then test three possible sources (i.e., pure efficiency, scale efficiency and technical change) of the performance to explain the changes in productivity and to highlight certain insights regarding which of these components contributes more to the productivity growth of banks in the financial centre and which of them constitutes an answer to the financial crisis.

The empirical literature on the performance of foreign banks in the "normal" banking sector is widespread; nevertheless, the research on foreign banks operating in the financial centre remains slight, although financial centres account for particular peculiarities. It is well documented in the international banking literature that multinational banks decide to establish their presence in financial centres because they can exploit the benefits of doing business through "face-to-face" interactions with other multinational banks; the benefits are derived from the usage of the capital market; they are capable of behaving strategically with different and quickly adaptable business models and, importantly, can benefit from the agglomeration economies. The net result is a banking sector in which diversification and innovation in intermediation production shapes the financial centre by on-going centrifugal and centripetal forces with the effect of high innovation (Tschoegl, 2000). All of these peculiarities constitute the main engine of the financial centre for speeding innovation, making the financial centre a special case in the banking sector for which the analysis of its performance constitutes a relevant issue.

Few empirical works have been performed for the banks located in the financial centre. Fisher and Molyneux (1996) focus on the determinants of the foreign bank activity in the London

financial centre. Recently, the paper by Clare et al. (2012) extends the previous paper's analysis by looking closer at the factors that cause the foreign banks to stay in the financial centre, using London as a specific case. Other papers focus on testing the aspects that constitute the specific features of the financial centre. These aspects include the factors that lead the multinational banks to expand abroad according to the "following the customers" hypothesis (e.g., Seth et al., 1998); to gain access to the largest economy and financial markets in the world (e.g., Damanpour, 1991); to take advantage of the opportunity for profitable investment of excess funds in a low-risk and stable economy (Damanpour, 1991); favourable tax laws and regulatory and political climate; and the factors that determine the withdrawal of the foreign banks (e.g., Hryckiewicz and Kowalewski, 2011). Moreover, the measurement problems of the performance of the financial centre have been noted by Brealey and Kaplanis (1996). However, a scarce number of papers have analysed the efficiency of the foreign banks in the financial centre. Rime and Stiroh (2003) analysed the data from Switzerland, Kwan (2006) studied the banks in Hong Kong, and Sufian and Majid (2007) worked with the banks in Singapore. Curi et al. (2013a,b) analysed the determinants of foreign bank efficiency in Luxembourg. Guarda and Rouabah (2006, 2007) and Curi and Lozano-Vivas (2013) instead focused on the analysis of the productivity growth and constitute the first stand of the literature aimed at the productivity evolution of banks in the financial centre, making an effort to analyse not only the bank efficiency but also the impact of the innovation on the performance of banks in the financial centre.

This paper attempts to contribute to the scarce literature on the performance of banks operating in financial centres. The target of this paper is to analyse the productivity growth of banks in a financial centre, disentangling the heterogeneity across the bank groups and the effects of possible innovation, and attempts to realize how the banks behave in the financial centres and how they responded to the recent financial crisis. In particular, we test the performance of the banks in terms of the *total factor productivity change*, along with its mutually exclusive and exhaustive components: *pure efficiency change* (catching-up or falling behind), *scale efficiency change* and *technological change* (innovation or shock). Because the productivity assessment based on the entire industry as a whole might be driven by the specific bank characteristics that can define a group of banks, we implement the Aggregated Malmquist Productivity Index following the method of aggregation developed by Zelenyuk (2006). Our analysis is based on the idea of estimating the productivity of the banks at the aggregated level rather than the bank level. This approach accounts for the relative importance of each observation, and the score of each observation is entered into the average to accurately estimate the aggregate or group results. Moreover, we adapt the firm-level Simar and Wilson (1999) bootstrap estimation procedure to the

case of the group-level estimation for obtaining the confidence intervals and bias correction of the Aggregated Malmquist Productivity Index and the relative components.

Based on this methodological approach, we estimate the main productivity sources that consider the two specific bank characteristics that originate with the group of banks: the organizational form and size. While the bank size is found in the banking literature to constitute a relevant characteristic for the differences in productivity (Wheelock and Wilson, 1999), the organizational form is presumed to be one of important relevance for the case of the banks in the financial centre. Because foreign banks can operate in terms of the different organizational forms (branches or subsidiaries), the recent empirical literature found that the organizational form has an impact on the operating behaviour of foreign banks along several dimensions, including the performance and business model (Curi, Guarda and Zelenyuk, 2011; Curi et al. 2013a,b). Using our empirical estimates, we shed light on the productivity behaviour during the financial crisis; thus, we contrast our productivity estimates for the bank performance in the financial centre prior to and during the financial crisis. We use the Luxembourg case, as it is a unique banking sector where banks are mainly from abroad and it has a number of features for investigating the issues regarding the performance of foreign banks surviving in the financial centre. For instance, the long time span elapsed allows for observing the failure and survival of banks before and after the financial crisis.

The remainder of this paper is organized as follows: Section 2 presents the literature overview, Section 3 the methodology, and Section 4 the sample set and the variables used to estimate the model. In Section 5, we present and discuss our results. Finally, in Section 6, we summarize the main conclusions of our study.

2. Literature overview

The empirical literature related to the analysis of the production process performance of the financial centres is minimal and focuses on international financial centres located in Europe (Switzerland, Liechtenstein and Luxembourg) and in Asia (Hong Kong and Singapore). Most of the studies focused on the operational, cost and profit efficiency, while a portion of them focus on productivity.

Based on the empirical literature that is focused on the operational, cost and profit efficiency, Rime and Stiroh (2003), by using the distribution-free approach and defining a broad range of bank output, estimate the production efficiency of the Swiss banks during the period 1996-1999. The Swiss banks are found to operate at relatively large inefficiencies both in terms of cost and profit across all types of banks (the specialized and universal banks). The small and mid-size banks are found to experience

cost scale economies, while the largest universal banks are not. Larger banks do not substantially benefit from continued size gains and product diversity. The paper by Burgstaller and Cocca (2011) performs a cross-financial centre analysis in which the private banks and wealth management from Switzerland and Liechtenstein are compared in terms of technical efficiency for the period 2003-2007 by means of the Data Envelopment Analysis (DEA). The private banks operating in Liechtenstein are found to perform better than their Swiss counterparts. In both financial centres, the degree of specialization and investment performance are found to explain the relatively large technical and scale inefficiency, while size does not. Curi et al. (2013a) investigate whether specific bank characteristics such as size, organizational form, and business diversification, as well as the home- and host-country characteristics, might drive the technical efficiency in a financial centre. Using the two-step analysis based on bootstrap techniques, they analyse the banks operating in Luxembourg during the period 1999-2009. The results suggest that diversification boosts technical efficiency. However, the organizational form also plays a crucial role: the branches appear to perform better than the subsidiaries if they are specialized, and the subsidiaries perform better when following the diversified business model. Moreover, when the parent banks are located in the euro area, the banks in the financial centre have higher technical efficiency on average. Kwan (2006), using the stochastic cost frontier approach, analyses the cost efficiency of the banks from Hong-Kong for 1992-1999 and discovers that the cost inefficiency of these country banks is quite large but declines over time. Moreover, the large banks seem to be less efficient than the small banks, although the former tend to converge with the latter over time in terms of cost efficiency. Finally, Sufian and Majid (2007), by means of the variable returns and the scale DEA model, estimate the pure and scale efficiency of Singapore banks during the period 1998-2004. The results indicate that the scale inefficiency outperforms the pure inefficiency, although they found a high efficiency level for the banks in Singapore. Of interest is their finding related to bank size. It seems that the rise in size has become the greatest factor resulting in the inefficiency of the Singapore banking system.

The last group of papers analyses the productivity of the banking system in the financial centre. The analysis of bank productivity in the financial centre has been undertaken only for the case of banks in Luxembourg. The productivity analysis is a more complex aspect of the banking performance, and mixed results are found, due to the different econometric approaches used as well as the time span. Guarda and Rouabah (2007, 2009) analysed the quarterly productivity growth of Luxembourg banks prior to the financial crisis (1994-2007) and, by using the Malmquist productivity indices and the Tornquist indices on the quarterly data, found the productivity growth in Luxembourg to be positive since the mid-1990s, with persistent and pro-cyclical dynamics. Moreover, the productivity has been found to vary across all banks, and larger banks are found to be more

productive. Lastly, the Malmquist index analysis suggested that the efficiency change dominated the technical change. Curi and Lozano-Vivas (2013) examine the productivity of Luxembourg banks, accounting for the organizational form, size and nationality with the bias-corrected DEA estimates. The results indicate that independently of the organizational form, size and nationality, foreign banks operating in the financial centre responded to the financial crisis with technological improvements. In general, it seems that in a normal time (without crisis), both types of organizational form exhibit barely equal paths in productivity mainly due to the similarity in the technological path. Of interest are the findings that led to the conclusion that the technical change seems to be the main driver of the improvement in productivity, to which attends the foreign banks in Luxembourg during the financial crisis. Finally, it is found that the large banks exhibit higher productivity growth than the medium and small banks.

From the review of the literature on the performance of the banking system in the financial centre, it can be concluded that in general, the big banks account for less efficiency than the small or mid-size banks in the financial centre. However, in the only paper that analyses productivity, big banks account for the higher productivity in the financial centre of Luxembourg. The analysis of productivity is scarce in the financial centre; Luxembourg has been the only financial centre where bank productivity has been analysed. Moreover, although the organizational form chosen by foreign banks to operate in the financial centre is an important issue, few papers pay attention to it. Finally, although the Curi and Lozano-Vivas (2013) paper is a first attempt to measure the productivity and the relative components of foreign banks by asking how the different bank-specific and socioeconomic aspects impact the productivity before and during the financial crisis, the approach used for measuring productivity does not allow for an appropriate aggregated (weighted) Malmquist Index (and relative components) due to the inappropriate choice of weights used by means of the individual Malmquist Index. In addition, that paper does not allow for making a statistical inference from the aggregated productivity change (and its components) among the distinct groups of banks within the financial centre.

The present paper attempts to reassess the productivity of a financial centre using Luxembourg as a special case with the aim to uncover additional information on the statistically significant changes of the Aggregated (weighted) Malmquist Index (and relative components) in terms of the bank groups and on the equality of the Aggregated (weighted) Malmquist Index (and relative components) between the two bank groups. Lastly, the paper aims to uncover how the productivity of the Luxembourg banks is affected by the scale efficiency and which bank group productivity is affected to a greater extent. Because this more resilient methodology allows disentangling the heterogeneity

across bank groups, it should be effective for clarifying the actual effect of innovation on productivity and how banks responded to the recent financial crisis in the financial centre.

3. Methodology

We use the economic approach of the Malmquist Productivity Index (M) (Caves et al. 1982; Nishimizu and Page 1982; Färe et al. 1994) to assess the productivity growth in the Luxembourg financial centre for an extended time span that includes the recent financial crisis. Contrary to other indexes, such as the Fisher index, the Malmquist Productivity Index exhibits two clear advantages: first, it does not require price data for the inputs and outputs; second, it makes available the economically meaningful decompositions that shed light on the underlying sources of productivity growth.

Because our aim is to compare the performance of groups of banks (subsidiary vs. branch banks and big vs. medium vs. small banks), we use the Aggregated (or Weighted) Malmquist Productivity Index proposed by Zelenyuk (2006). The Aggregated Malmquist Productivity Index, extends the simple version of the Malmquist Productivity Index by offering the advantage of higher accuracy in a group-based productivity assessment. More specifically, this type of assessment provides the group-based estimates where the productivity of each bank is accounted for according to the weight of the bank relative to the peer banks in the same group. To draw inference from these aggregated indexes, we extend the bootstrap algorithm developed for the case of the single firm M (Simar and Wilson, 1999) to the case of the aggregated M, designated the AM.

Among the several Malmquist Productivity Index decompositions proposed in literature thus far (Zofio, 2007 and Johnson and Ruggiero, forthcoming), we use the "Enhanced Decomposition of MPI" (Färe et al. 1994), which identifies along the pure efficiency change (PEC) and the technological change (TEC), in addition to the role played by the change in scale (SEC). This allows disentangling the productivity differentials among the banks accounting also for the suboptimal scale.

The M (as the AM) estimation requires the definition of the distances of each bank to the frontiers at different points in time. To formalize these concepts, we briefly introduce some notation. Let each bank k ($k=1,2,\ldots, n$) employ N inputs to produce M outputs in period τ (for our case, $\tau=s, t$). Let $x \in R_+^N$ and $y \in \Re_+^M$ denote a nonnegative vector of N inputs and a nonnegative vector of M outputs, respectively. We assume that the technology of bank k in any period τ satisfies the usual regulatory axioms of production theory (see Färe and Primont, 1995 for details), and it is characterized by the outputs set:

$$P_\tau^k(x^k) \equiv \{y: y \in R_+^M \; is \; producible \; from \; x^k \in R_+^N\} \quad (1)$$

Given this characterization, the output-oriented Farrell (1957) distance function of bank *k* in the input/output space at time *s* to technology at time τ is defined as:

$$D_t^k(x_s^k, y_s^k) = \sup\left\{\lambda \geq 0 \middle| \left(x_s^k, \lambda y_s^k\right) \in P_t^k\left(x^k\right)\right\} \quad (2)$$

However, allowing the banks to operate at their suboptimal scale requires the definition of the convex cone V_τ (analogous to (2) and with the vertex at the origin) spanned by P_τ to compute the distance against the constant returns to scale (CRS) technology. Thus, the CRS output-oriented Farrell (1957) distance function of bank *k* in the input/output space at time *s* to the boundary of V_t in the hyperplane where the inputs remain constant is defined as:

$$\Delta_t^k(x_s^k, y_s^k) = \sup\left\{\lambda \geq 0 \middle| \left(x_s^k, \lambda y_s^k\right) \in V_t^k\left(x^k\right)\right\} \quad (3)$$

Hence, following Färe *et al.* (1994) for each bank *k*, the Malmquist Productivity Index (M) is decomposed as followed:

$$M^k\left(x_s^k, y_s^k, x_t^k, y_t^k\right) = PEC^k\left(x_s^k, y_s^k, x_t^k, y_t^k\right) \times SEC^k\left(x_s^k, y_s^k, x_t^k, y_t^k\right) \times TEC^k\left(x_s^k, y_s^k, x_t^k, y_t^k\right) \quad (4)$$

where $PEC^k\left(x_s^k y_s^k x_t^k y_t^k\right) = \frac{D_t^k(x_t^k y_t^k)}{D_s^k(x_s^k y_s^k)}$, (5)

$$SEC^k\left(x_s^k y_s^k x_t^k y_t^k\right) = \frac{\Delta_t^k(x_t^k y_t^k)/D_t^k(x_t^k y_t^k)}{\Delta_s^k(x_s^k y_s^k)/D_s^k(x_s^k y_s^k)}, \quad (6)$$

and

$$TEC^k = \left[\frac{\Delta_s^k(x_t^k, y_t^k)}{\Delta_s^k(x_t^k, y_t^k)} \times \frac{\Delta_s^k(x_s^k, y_s^k)}{\Delta_t^k(x_s^k, y_s^k)}\right]^{1/2} \quad (7)$$

To estimate the distance functions, we use Data Envelopment Analysis (DEA). The banks are grouped according to specific characteristics (i.e., size and organizational form), and for each group, we define the *within* weights. The within weights ($S_t^{k,l}$) represent the weights associated with each bank k within its group l in period τ when entering the group average estimate. By assuming the additive structure of the aggregation of the outputs set (Färe and Zelenyuk, 2003) and the output orientation measurement, we denote as the aggregate technology of all banks within the same group the sum of the corresponding output vector, $\overline{Y}_\tau$.

For each group *l*, the aggregated (or group) analogues of (5), (6), and (7) become:

$$\widehat{APEC^l}(\overline{Y}_s, \overline{Y}_t, X_s, X_t) = \frac{\left(\sum_{k=1}^n [D_t^k(x_t^k, y_t^k)] \cdot s_t^{k,l}\right)}{\left(\sum_{k=1}^n [D_s^k(x_s^k, y_s^k)] \cdot s_s^{k,l}\right)} \quad (8)$$

$$\widehat{ASEC^l}(\overline{Y}_s, \overline{Y}_t, X_s, X_t) = \frac{\left(\sum_{k=1}^{n}[\Delta_t^k(x_t^k, y_t^k)] \cdot s_t^{k,l}\right) / \left(\sum_{k=1}^{n}[D_t^k(x_t^k, y_t^k)] \cdot s_t^{k,l}\right)}{\left(\sum_{k=1}^{n}[\Delta_s^k(x_s^k, y_s^k)] \cdot s_s^{k,l}\right) / \left(\sum_{k=1}^{n}[D_s^k(x_s^k, y_s^k)] \cdot s_s^{k,l}\right)} \quad (9)$$

$$\widehat{ATEC^l}(\overline{Y}_s, \overline{Y}_t, X_s, X_t) = \left[\frac{\left(\sum_{k=1}^{n}[\Delta_s^k(x_t^k, y_t^k)] \cdot s_t^{k,l}\right)}{\left(\sum_{k=1}^{n}[\Delta(x_t^k, y_t^k)] \cdot s_t^{k,l}\right)} \times \frac{\left(\sum_{k=1}^{n}[\Delta_s^k(x_s^k, y_s^k)] \cdot s_s^{k,l}\right)}{\left(\sum_{k=1}^{n}[\Delta_t^k(x_s^k, y_s^k)] \cdot s_s^{k,l}\right)}\right]^{1/2} \quad (10)$$

Having estimated the DEA distances defined in (2) and (3), we compute the aggregated productivity set of measures, defined in expressions (8), (9) and (10). Then, we perform the bootstrap loops to derive the inference on each estimate. Because we handle the group-level estimations, we adapt the firm-level Simar and Wilson (1999) bootstrap estimation procedure to the case of the group-level estimation. In particular, we generate a sequence of pseudo datasets for each group *l* to form the corresponding reference bootstrap technology using the bivariate kernel density estimation – where the bandwidth is selected following the normal rule of thumb – and the adaptation of the reflection method. We compute the bootstrapped distances (the analogues of expressions (2) and (3)) and the bootstrapped output-based within weights to derive the bootstrapped aggregated productivity set of measures (the analogues of the measures defined in expressions (8-10) and the Aggregated Malmquist Productivity Index). From the bootstrap sample associated with each group *l*, we compute the bias-correction terms and confidence intervals for the productivity set of estimates by selecting the appropriate percentiles.

In addition to bias-corrected estimation and the estimation of confidence intervals, we use the bootstrap to test hypotheses of the statistically significant differences between the groups of banks. We follow the idea proposed by Simar and Wilson (2008) and used in different contexts by Simar and Zelenyuk (2007) and Curi et al. (2013b), among others. Thus, after having estimated the AM and relative components, we perform a pairwise-test comparison of the group estimates assuming under the null hypothesis that the estimates related to the two groups, defined as group *a* and group *b*, are equal. For the case of the AM, we postulate that $H_0 := \widehat{AM}^a = \widehat{AM}^b$ against $H_1 := \widehat{AM}^a \neq \widehat{AM}^b$. The statistic is given by the ratio statistic as follows:

$$RD_{a,b} = \widehat{AM}^a / \widehat{AM}^b \quad (11)$$

The null hypothesis is rejected (at a certain level of confidence) if $RD_{a,b} < 1$ or $RD_{a,b} > 1$. The rejection of the null hypothesis will mean that a difference exists between the average performance behaviour of the two groups under comparison, thus supporting that the group classification achieved is relevant to analyse the banking industry under investigation.

4. Sample

We use the individual bank data taken from the nonconsolidated banks' financial statements, provided by the Central Bank of Luxembourg (BCL). The initial sample consists of 2,354 observations for the period 1995-2010. However, several banks are excluded including cooperative banks, a central securities depository with bank status, and those banks that reported non-positive values for any of the inputs or outputs; thus, the values are frequently indicative of reporting error. Our final sample consists of 2,025 observations, including both domestic and foreign banks, and varies between 167 observations in 1995 to 90 observations in 2010. It is well representative of the Luxembourg banking sector, as it constitutes (on average) 96% of the total assets and 86% of the total number of banks in the financial centre.

Table 1 presents the information about the final sample used. In terms of the full sample (column 2, Table 1), it can be observed that the banks steadily disappear during the sample period. As a peculiarity of the financial centre, banks could be under domestic or foreign ownership. Among the foreign banks, banks can take the form of a subsidiary bank or a branch bank (columns 3-5, Table 1). The number of domestic banks is far smaller than the number of foreign banks[1], confirming the peculiarity of the banking sector associated with a financial centre, and the number of subsidiary banks is far larger than the number of branch banks. Because the domestic banks follow the same legislation of the subsidiary banks, throughout the paper, we have conducted all of the descriptive statistics and productivity analyses considering the domestic banks and foreign subsidiary banks as a category, which we refer to as the subsidiary banks[2]. Table 1 includes, in the last three columns, information about the number of banks in terms of size. According to the BCL classification, the Luxembourg banks fall into three size-categories: big banks, which hold total assets greater than 10 billion euro; medium banks, which hold total assets between 10 billion and 1 billion; and small banks, which hold less than 1 billion in total assets. In terms of size, the small banks constitute the largest category through the year 2007, and subsequent to 2007, the category of medium banks constitutes the largest category. Moreover, although the number of big and medium banks is quite stable over time, the number of small banks is decreasing over time.

[1] In the Luxembourg financial center, only four banks operated throughout 1995-2010, six banks disappeared over time, and three banks entered between 2006 and 2007.

[2] In the untabulated estimation, we have conducted all of the analyses restricting the sample to include only foreign subsidiary banks and obtained results similar to those with the full sample.

Table 1: Bank frequency by bank ownership, organizational form and size.

Year	Full Sample	Frequency by bank ownership and organizational form			Frequency by bank size		
			Foreign banks				
		Domestic banks	Subsidiary	Branch	Big	Medium	Small
1995	167	8	132	27	11	55	101
1996	162	8	127	27	11	53	98
1997	162	8	128	26	13	56	93
1998	156	8	123	25	16	56	84
1999	150	8	121	21	13	57	80
2000	141	7	116	18	15	57	69
2001	133	5	111	17	20	44	69
2002	120	5	103	12	17	42	61
2003	120	5	102	13	15	44	61
2004	115	3	100	12	16	40	59
2005	107	2	94	11	16	37	54
2006	105	3	93	9	20	39	46
2007	107	4	92	11	18	44	45
2008	97	4	85	8	20	45	32
2009	93	4	82	7	17	42	34
2010	90	4	79	7	14	43	33

In specifying the banking inputs and outputs, we use the intermediation approach (Sealey and Lindley, 1977) and adapt it to the case of the international intermediation activity. Specifically, on the output side, we select interbank loans, customer loans, securities and non-interest income. More specifically, interbank activities include those within the parent banking group as well as with other banks; customer activities include the intermediation activities with households and with non-financial corporations; and securities include government securities, fixed-income securities, shares, participations and other variable-income securities. Due to the lack of off-balance sheet fee services information and acknowledging the importance of the inclusion of a proxy in the frontier estimation (Lozano-Vivas and Pasiouras, 2010), we use the non-interest income as a measure of the off-balance sheet fee services (Clark and Siems, 2002). On the input side, we include (i) labour, measured by total labour expenses; (ii) capital, measured as the sum of the tangible and intangible assets; (iii) interbank deposits; and (iv) customer deposits. Moreover, we follow Fixler and Zieschang (1992) in identifying the additional inputs as the purchased materials and services, including the non-wage administrative costs and commissions paid. It is crucial to include this commission flow, as the net commission income is of the same order of magnitude as the income from the interest rate margin[3]. Because any

[3]As it has been noted by Guarda and Rouabah (2009).

efficiency and productivity analyses involved comparisons across time, the data in nominal values are converted to real terms using the GDP deflator with the base year 2000.

The descriptive statistics of the banking inputs and outputs are presented according to the two specific bank characteristics for which we estimate productivity: the organizational form and size (Tables 2 and 3). Given that the length of the period under investigation allows us to better track the productivity dynamics, thus quantifying the changes in performance across banks over the period prior to the financial crisis (*Pre-crisis,* before 2007) and during the financial crisis (*Crisis*, up to 2010), the information on Tables 2 and 3 is displayed foFr those two sub-periods, as well.

Table 2 indicates that subsidiary banks are larger than branch banks in terms of total assets. On average, subsidiary banks are more labour and capital intensive than branch banks, make larger use of customer deposits, and support larger costs. Interestingly, median branch banks make greater use of interbank deposits throughout the entire period, and even more during the crisis.

Table 2: Descriptive statistics of bank inputs and outputs by organizational forms

	Whole sample €M Mean (Median)		Pre-crisis €M Mean (Median)		Crisis €M Mean (Median)	
Size	Subsidiary	Branch	Subsidiary	Branch	Subsidiary	Branch
Total Assets	4461.38	2277.93	4230.24	2144.93	5819.55	3711.11
	999.18	857.63	902.79	804.88	2180.29	1534.44
Inputs						
Labour	39.16	7.74	25.34	7.48	19.14	8.56
	5.78	1.02	5.47	0.95	8.48	1.62
Capital	24.40	1.25	42.57	1.32	18.89	0.51
	4.93	0.61	5.47	0.65	3.15	0.12
Interbank Deposits	2016.73	1457.38	1922.81	1356.40	2568.58	2529.39
	285.92	343.55	257.71	328.15	399.57	577.88
Customer Deposits	1567.38	472.73	1490.05	445.22	2021.81	771.99
	405.12	221.74	374.73	228.87	773.85	83.66
Other Costs	44.50	11.75	47.30	11.33	28.07	13.21
	6.95	1.43	6.43	1.38	11.42	2.77
Outputs						
Interbank Loans	2090.27	1467.20	2022.81	1432.29	2486.69	1848.90
	573.88	494.16	523.72	494.16	888.49	607.53
Customer Loans	949.50	295.96	872.31	258.89	1403.09	692.31
	139.63	94.25	124.61	86.92	266.96	272.07
Securities	1194.37	454.59	1145.97	404.93	1478.75	989.51
	83.42	65.24	81.91	62.95	90.74	305.10
Non-Interest Income	63.52	14.07	67.04	13.84	42.83	15.13
	11.60	1.29	11.07	1.14	16.13	2.09

On the output side, prior to the financial crisis, subsidiary banks are larger producers of financial services, while during the financial crisis, branch banks are more active in securities and customer loans service.

Concerning the three size categories of banks, Table 3 demonstrates that during the financial crisis, the three size categories experience a contraction in the average of total assets, although the median medium and small banks experience an expansion. The bank size reflects the dimension of the financial intermediation activity: big banks use a larger amount of inputs to produce a larger amount of outputs, followed by medium and small banks. Comparing the inputs used prior to the financial crisis and during the financial crisis, they decrease for all of the size categories, with two exceptions. Customer deposits increase for medium and small banks, while interbank deposits increase for big banks. On the outputs side, intermediation activities contract during the financial crisis, except for a slight increase in customer loans associated with big and medium banks and securities associated with small banks.

Summarizing, regarding the descriptive statistics, it seems that heterogeneity exists in terms of the production process (i.e., banking inputs and outputs) of the banks operating in the financial centre of Luxembourg. Moreover, this heterogeneity is relevant according to two banking characteristics: (i) the organizational form and (ii) size. Thus, given the heterogeneity between the groups that is revealed through the descriptive statistic, it seems that our main goal of the paper, oriented to analyse the productivity evolution of Luxembourg banks taking into account the groups of banks (i.e., organizational form and size), is justified a priori. Consequently, our productivity assessment framework will allow controlling for the possible different effects of the technology and regulatory changes not only on the different sizes of the banks, as emphasized by Wheelock and Wilson (1999) and Berger et al. (2004), but also on the organizational form, as demonstrated for the case of the efficiency analysis by Curi et al. (2013a,b).

Table 3: Descriptive statistics of the bank inputs and outputs by size

	Whole Sample €M Mean (Median)				Pre-Crisis €M Mean (Median)				Crisis €M Mean (Median)			
	All	Big	Medium	Small	All	Big	Medium	Small	All	Big	Medium	Small
Size												
Total Assets	4190.74	20689.32	3785.78	410.26	3955.97	20751.45	3792.18	405.13	5653.88	20580.21	3755.09	457.94
	994.51	16784.85	2871.11	367.10	893.96	17124.38	2869.25	359.38	2167.36	16161.11	2910.04	411.24
Inputs												
Labour	35.27	128.56	35.93	11.71	37.99	149.99	39.84	12.42	18.31	46.86	17.16	5.10
	4.98	33.86	8.75	2.61	4.62	34.05	7.86	2.54	6.95	33.00	11.63	3.33
Capital	21.53	108.24	16.56	3.77	22.19	122.00	17.19	3.89	17.45	56.21	13.54	2.62
	3.95	50.37	8.02	2.17	4.19	62.48	9.08	2.28	2.70	14.94	3.50	1.17
Interbank Deposits	1947.40	9807.42	1782.05	125.95	1848.22	9711.45	1855.92	127.60	2565.50	10231.69	1427.45	110.67
	291.60	8075.42	986.59	57.77	266.31	8108.87	1107.28	61.13	411.95	7921.57	686.80	42.78
Customer Deposits	1431.70	6623.92	1350.87	207.47	1352.77	6766.36	1304.90	203.76	1923.61	6085.55	1571.54	241.89
	367.46	5249.24	943.63	161.35	342.74	5210.58	892.37	152.90	655.57	5331.71	1280.09	227.88
Other Costs	40.44	116.07	49.39	15.12	42.61	130.63	54.41	15.51	26.90	60.92	25.29	11.49
	6.15	43.57	10.77	2.76	5.61	35.99	9.74	2.69	10.48	57.86	15.16	4.42
Outputs												
Interbank Loans	2013.04	9050.91	2031.45	258.95	1945.08	9358.46	2052.87	257.37	2436.58	7929.86	1928.62	273.72
	561.90	7765.49	1452.60	212.16	518.81	8003.24	1477.18	211.82	882.19	5080.42	1215.86	212.26
Customer Loans	868.49	4689.63	661.76	76.49	791.68	4456.88	668.87	76.82	1347.24	5654.09	627.64	73.50
	133.95	3847.99	374.94	43.60	118.92	3717.26	366.71	44.20	269.77	4296.93	404.61	34.40
Securities	1102.67	5910.82	911.52	55.05	1048.49	5986.75	921.92	54.53	1440.31	5595.16	861.59	59.86
	79.52	4762.11	370.69	19.80	78.09	4607.56	384.15	21.53	97.16	5010.09	263.67	8.77
Non-Interest Income	57.39	170.10	69.69	20.41	60.07	192.56	75.48	20.86	40.66	84.93	41.89	16.23
	9.81	79.35	16.21	4.45	9.24	79.35	15.34	4.29	15.31	79.59	23.10	7.27

5. Empirical Results

Following the main research issue of the paper, in this section, we examine the evolution of the aggregated year-on-year productivity and relative components over the period 1995-2010. Regarding the peculiarities and heterogeneity between the groups of the banking system of the Luxembourg financial centre, presented in the previous section, we define the aggregated productivity and its components in terms of the different groups according to two specific bank characteristics: the organizational form and size. Thus, we report the weighted average annual levels of the pure efficiency change, the scale efficiency change, the technical change and the Malmquist Productivity Index, within the two organizational form classes and the three bank size classes.

Following our productivity assessment framework, which is an extension of the Aggregated Malmquist Productivity Index to its relative statistical inference, we achieve not only the bias-corrected aggregated Malmquist Productivity Index (information displayed in the tables) but also the relative confidence intervals. The computation of the confidence interval for each aggregated estimate allows us to test their statistical significance, adding economic meaning to the productivity change and its components. In this sense, given that the "realized" changes (i.e., the changes computed from the sample observations) are the estimates of true, though unobserved, quantities, we test which of these estimates are "actual" changes (i.e., to what extent changes really occur), that is, which of the realized changes are statistically significant. The actual changes can be distinguished from the realized change estimates in the reported information by the presence of an asterisk indicating that they are significantly different from unity.

In addition to analysing the evolution of the productivity growth of banks in the financial centre, the aim of the paper is to understand how they responded to the recent financial crisis; the average productivity estimates and its components prior to the financial crisis (1995-2007) and during the financial crisis (2007-2010) are reported at the bottom of Tables 4 and 6. The first two rows correspond to the average of the realized value of each performance measure before and during the crisis, while the last two rows correspond to the average of the actual value, i.e., accounting for computing the average of only the estimated values that are significant in a statistical sense.

In the presentation of the results, we first present the total productivity change (and its components) in terms of the realized values (i.e., without paying attention to statistical significance) and then the actual estimates (i.e., given the estimated confidence interval of those that are statistically significant). Thus, we focus on those that indeed give information about the real changes, i.e., that have economic means, from which we will draw inference about the actual evolution of the bank

productivity changes in the financial sector of Luxembourg and how they have certainly responded to the financial crisis in terms of each performance measure.

Table 4 shows the evolution of the bias-corrected aggregated estimates of the Malmquist Productivity Index and the relative components for Luxembourg banks. The estimates are aggregated according to the bank organizational form, namely the subsidiary and branch. Overall, the results based on the average realized estimates obtained from the bias-corrected pure efficiency ($\widehat{APEC}$) corresponding with the period prior to the financial crisis (1995-2007), the first two rows at the bottom of Table 4, indicate that subsidiary and branch banks seem to account for an almost stable pure efficiency. However, during the financial crisis (2007-2010), the realized average estimates of the $\widehat{APEC}$ suggest that both bank categories become less efficient: the realized inefficiency level peaks during the first year of the financial crisis for subsidiary banks, while it is delayed one year for branch banks. These results are somewhat in accordance with the results obtained in Curi and Lozano-Vivas (2013).

Turning to the results for the bias-corrected realized values of the scale efficiency change ($\widehat{ASEC}$), we find that subsidiary banks, on average, seem to be more scale efficient prior to the financial crisis (0.9%), while branch banks appear to be less scale efficient (-0.7%). During the financial crisis, subsidiary banks appear to become less scale efficient (-1%); in particular, the realized $\widehat{ASEC}$ indicates that the largest loss is in the first year of the financial crisis. Branch banks, although on average continuing to be scale inefficient (-0.5%), seem to gain marginal efficiency scale from 2008 to 2010.

Regarding the bias-corrected realized value of technological change ($\widehat{ATEC}$), prior to the financial crisis, subsidiary banks experience a slight decrease in technology (-0.6%), while branch banks experience, on average, improvements over time (1.6%). During the financial crisis, both bank categories experience large positive technological progress. However, apparently, branch banks outperform subsidiary banks with a rate of growth equal to 14.5% against the 11% registered by subsidiary banks. Again, the results corresponding to technical change are in agreement with those of Curi and Lozano-Vivas (2013).

Combining these components, both categories of banks seem to reach small increases in the realized productivity prior to the financial crisis (0.4% for subsidiary banks and 0.1% for branch banks). During the financial crisis, they apparently respond with significantly larger realized productivity growth: 6.5% and 14.6% for subsidiary and branch banks, respectively. Similar results were obtained by Curi and Lozano-Vivas (2013).

Although these results consider the bias-corrected performance measures, they should not report the real performance changes of banks in Luxembourg. Thus, we will turn our attention to the results obtained once the statistical significance of each realized value is ascertained, thus making it possible

to know to what extent the changes actually exist and to draw true inferences from them. The bootstrap technique allows us to test whether the realized changes estimated are significant or not, thus obtaining the real path and behaviour of the productivity change and its components. Table 4 presents this information, assigning the statistical significance to each realized change with an asterisk.

The results indicate that for both subsidiary and branch banks, the year-on year realized changes in pure efficiency are not statistically significant. This implies that in reality, i.e., in terms of the actual changes, banks experience neither an improvement nor a loss in efficiency over time because they are equal to one, warning of the fact that banks operating in the financial centre do not aim to converge towards best practices. This situation holds for the period before and during the crisis. Thus, by using the confidence intervals, the previous finding whereby both the subsidiaries and branches seemed to attend to a deterioration of pure efficiency during the crisis period is not apparent because the realized pure efficiency change is not significantly different from unity. Furthermore, for the case of the changes in scale efficiency, the year-on-year realized changes are not statistically significant prior to the financial crisis, except for a significant positive gain between 1999 and 2000 for the subsidiary and a negative one for the branches between the years 1996 and 1997. Thus, it seems that while before the financial crisis, subsidiary banks accounted for a slight average per year improvement in the actual scale (0.06%), branches had a minor average yearly loss (-0.04%). However, in terms of the actual scale change, the financial crisis affected those organizational forms differently: branch banks experienced an important average per year loss in scale (-2.4%), while subsidiaries were not affected (the last two rows at the bottom of Table 4).

Finally, the results indicate that the only productivity component that is significantly different from unity over a relatively long period is the technical change for both types of organizational form. The fact that both the branch and the subsidiary react to the crisis by pushing upwards the technology is interesting, although they depart from very different situations. While subsidiaries accounted on average for an actual negative technical change of -1.2% before the crisis, branches had, on average, actual technical progress of 2.2% per year. However, both types of institutions improve their actual average technical change during the crisis period. Subsidiary (branch) banks reach an actual average technical change of 7.3% (16.4%). The important improvement in technical change undertaken by the two types of institutions could be explained by the fact that the "face-to-face" competition and the repeated interactions among banks in the financial centre create a widespread presence of tacit production knowledge that, in turn, constitutes dynamic externalities (Henderson et al. 1995). However, between the two organizational forms, branch banks seem to be more affected. This

additional evidence could be explained by the fact that branches are entities characterized by more specialized business models (Curi et al. 2013a), which enable them to innovate.

In terms of productivity change, prior to the financial crisis, both subsidiary and branch banks experience a significant change in productivity during the period 2000-2002, which corresponds with the time of the stock market crisis. Branch banks experience additional significant changes before and after this period. Interestingly, during the financial crisis, both subsidiary and branch banks experience positive and significant changes in productivity. In average terms, the actual productivity changes before the crisis for subsidiaries were -0.3% per year and an increase to 6.5% during the financial crisis. While branches accounted for a positive average actual productivity change before the crisis of 0.8%, this organizational form enlarged the productivity rate to 13.6% during the financial crisis. Overall, the actual value indicates that the main force of productivity improvements during the crisis for both types of institutions was technical progress; however, contrary to the results obtained by Curi and Lozano-Vivas (2013), the pure technical efficiency change does not improve nor deteriorate the productivity change for those types of institutions. The scale economy changes contribute somewhat to explain, though only in terms of a negative trend, the changes in productivity, at least for the case of branch banks.

Because our analysis is based on the comparison of the productivity and its components of banks in Luxembourg in terms of different groups, i.e., organizational form and size, and although we corroborate the important heterogeneity between these two groups from the descriptive statistics, we go further and use bootstrapping to test whether (or not) significant differences exist between the weighted average results obtained by the group. Following our methodology for testing this issue, Table 5 suggests that the difference in the aggregated pure and scale efficiency between subsidiary and branch banks is not statistically significant, which means that we cannot identify significant differences in the weighted average efficiencies between the two organizational forms[4]. The test of the possible differences in technological change provides evidence of several significant differences in the aggregated technological change, meaning that they perform differently. These are relevant in specific years before the financial crisis as well as the period of the run-up to the financial crisis. The test of the possible difference in productivity change provides evidence of several significant differences: while prior to the financial crisis, the differences in the productivity changes are notable in four periods, during the financial crisis, the differences are persistent in all three years. This test again upholds that both types of institutions are different in their performance, and thus, it is important to group them to draw inferences about their performance.

[4]The only exception is in the scale efficiency change for the years 1999-2000 (the consolidation boom period).

The above results regarding the actual productivity changes of the Luxembourg banking industry differ somewhat from those obtained by Curi and Lozano-Vivas (2013) because in our present analysis, we add important information in terms of the scale efficiency, statistical significance of the aggregated estimates and lastly statistical significance of the differences of the estimates between the two organizational forms. Specifically, testing the statistical significance of the aggregated estimates allows us to give information about the real path of the productivity changes and its components in the Luxembourg banking system.

Banks operating in the financial centre could experience different patterns of productivity growth depending on their size (Table 6). We therefore explore the results by investigating whether the big banks are more productive than the medium and small banks. As before, we will first present the realized value and then the actual values of the performance measure estimates. What we observe from realized values is that both big and medium banks experience a slight loss of $\widehat{APEC}$ over the period prior to the financial crisis, while small banks become slightly more efficient (0.6%) (the two first rows at the bottom of Table 6). During the financial crisis, small banks experience a steady level of realized pure efficiency, while big and medium banks continue deepening their pure efficiency loss (-1.8% and 2.3%, respectively). These results are in line with those found by Curi and Lozano-Vivas (2013). In terms of the realized value concerning the $\widehat{ASEC}$, big banks seem to experience a scale efficiency gain prior to the financial crisis (0.9%), while medium and small banks seem to suffer from high scale inefficiency (-17.3% and -9.9%, respectively). However, during the financial crisis, it seems that, to a different extent, the three bank sizes account for a loss in scale efficiency, although compared with the previous period, only small banks had obtained a slight improvement in the scale efficiency. Regarding the realized technological change ($\widehat{ATEC}$), prior to the financial crisis, medium banks are the only category that seem to experience technological progress (1.4). However, all of the categories of banks respond to the financial crisis with progress in technology: medium banks were the most innovative, followed by small and big banks, as demonstrated in Curi and Lozano-Vivas (2013).

Thus, prior to the financial crisis, the overall realized productivity growth ($\widehat{AM}$) of the three sizes of bank categories seems to remain quite stable, improving slightly for medium and small banks and decreasing slightly for big banks. However, the realized value computed identifies the different productivity drivers for each category: the positive productivity growths of medium and small banks seem to be driven by technological change and pure efficiency change, respectively. The negative productivity growth of big banks seems to be affected mostly by technological regress. During the financial crisis, all three bank categories seem to improve their productivity, exploiting positive and large technological changes. Thus, it seems that banks in the financial centre respond to the financial

crisis mainly through innovation, the positive effects of which by far compensate for the negative effects of the scale inefficiency of medium and small banks and the pure inefficiency of big banks.

Turning our attention again to the actual changes to draw real inferences, the bootstrap technique, which allows us to obtain the actual changes, again excludes the pure efficiency change as the possible productivity driver, as its results are not statistically significant in any bank size category at any time. These results would appear to support the findings on large US banks by Wheelock and Wilson (1999). Moreover, they imply that independently of the organizational form as well as of the size, banks in Luxembourg do not obtain any productivity advantages (or disadvantages) through the pure efficiency change. Second, we can confirm that, although Luxembourg banks are not purely inefficient, medium and small banks are scale inefficient over time. These findings are in line with the results by Sufian and Majid (2007) for the case of Singapore banks. Third, in line with previous literature, we find that technological change estimates are significant for all bank categories: medium banks indicate the highest frequency of significant changes, followed by small and big banks. Additionally, during the financial crisis, all categories experience at least one significant technological change.

On average, before and during the crisis, big banks do not improve or deteriorate their pure efficiency nor their scale efficiency because they are not significantly different from 1 (the last two rows at the bottom of Table 6); however, while big banks account for a slight actual technical regress before the crisis (-0.08%), they respond with important technical progress during the crisis (5.2%). Conversely, medium and small banks account for an actual loss of scale efficiency before and during the crisis, although as the big banks did, they do not attend to any significant change in terms of the pure efficiency. While small banks respond to the crisis by slightly improving their loss in scale efficiency (from 9.9% to 8.6%), medium banks deteriorate it to an even greater extent (from 17.3% to 24.7%). Finally, medium and small banks also improve the actual technical change during the crisis. Compared with the period before the crisis, medium banks increase on average their actual technical change by 11.2%, while small banks do so by 6.1%.

Overall, these findings allow portraying additional conclusions on the actual productivity of banks in the financial centre. Prior to the financial crisis, they indicate a lack of important changes in productivity for big banks (-0.04%), while they are somewhat more substantial among medium and small banks, 1.4% and 0.9%, respectively. During the financial crisis, all three categories experience an increase in actual productivity. The highest rate was reached by small banks (7%) followed by big and medium banks that increased at the rates of 6.8% and 5.5%, respectively. For the three size categories, the driver of the productivity improvement has been technical change. As opposed to the

results obtained by Curi and Lozano-Vivas (2013), we find that the efficiency change neither improves nor deteriorates productivity.

As before, we also test whether (or not) the differences between the three categories are statistically significant to prove that the decision to group by size makes sense in our study. The comparison of big banks to medium banks in Table 7 suggests that the differences in the aggregated pure efficiency scores (both prior to and during the financial crisis) are not statistically significant, while they are significantly different for the scale efficiency change. When we compare big banks to small banks, the picture is similar. For some years prior to the financial crisis, big and medium banks differ in their technological change. The same occurs in the case of the Malmquist Productivity Index. Medium and small banks also differ in the scale efficiency change, technological change and productivity change.

Table 4: Aggregated Malmquist Productivity Index and Components, by organizational form

	Subsidiary					Branch				
Period	No.	$\widehat{APEC}$	$\widehat{ASEC}$	$\widehat{ATEC}$	$\widehat{AM}$	No.	$\widehat{APEC}$	$\widehat{ASEC}$	$\widehat{ATEC}$	$\widehat{AM}$
1995-96	130	1.002	1.037	0.925	0.962	23	0.983	0.983	1.035	1.002
1996-97	128	1.003	1.003	0.997	1.005	24	0.92	1.044*	1.097*	1.069*
1997-98	128	1.011	0.966	0.999	0.976	22	0.98	0.997	1.02	0.998
1998-99	126	0.996	0.978	1.023	0.998	19	1.028	1.014	0.966	1.009
1999-00	119	0.964	0.926*	1.132*	1.014	16	1.036	1.02	0.93	0.984
2000-01	112	1.025	1.004	0.940*	0.969*	16	1.017	1.001	0.890*	0.909*
2001-02	104	1.001	1.007	1.054	1.064*	11	1.026	0.995	0.859*	0.879*
2002-03	105	0.971	1.008	1.022	1.001	12	0.933	0.988	1.054	0.98
2003-04	101	1.011	0.996	0.954	0.963	12	1.026	1.002	0.886*	0.915*
2004-05	93	0.981	0.953	1.069*	1.001	11	1.02	0.998	0.922	0.94
2005-06	92	1.012	1.004	0.98	0.996	8	0.97	1.051	1.047	1.071
2006-07	92	1.021	1.006	0.974	1.002	9	1.018	0.997	1.108	1.128*
2007-08	88	1.046	1.041	0.840*	0.919*	7	0.971	1.072*	0.755*	0.791*
2008-09	84	1.009	0.986	0.946	0.944*	6	1.026	0.953	0.753*	0.741*
2009-10	78	1.001	1.001	0.940*	0.942*	7	1.021	0.992	1.01	1.031
Realized Estimates										
1995-07	1330	1.000	0.991	1.006	0.996	183	0.997	1.007	0.984	0.990
2007-10	250	1.019	1.01	0.909	0.935	20	1.006	1.005	0.839	0.854
Actual Estimates										
1995-07	1330	1.000	0.994	1.012	1.003	180	1.000	1.004	0.978	0.992
2007-10	250	1.000	1.000	0.927	0.935	20	1.000	1.024	0.836	0.844

Note: $\widehat{APEC}$ =(Bias-Corrected) Aggregated Pure Efficiency Change, $\widehat{ASEC}$ = (Bias- Corrected) Scale Efficiency Change, $\widehat{ATEC}$= (Bias-Corrected) Aggregated Technical Efficiency Change, $\widehat{AM}$ = (Bias-corrected) Aggregated Malmquist Productivity Index. * Significance at the 5% level.

Table 5: RD statistics for comparing subsidiary vs. branch banks in terms of the aggregated Malmquist Productivity Index and its components

Period	$\widetilde{APEC}$	$\widetilde{ASEC}$	$\widetilde{ATEC}$	$\widetilde{AM}$
1995-96	1.017	1.054	0.891*	0.958
1996-97	1.075	0.96	0.896*	0.938*
1997-98	1.03	0.968	0.978	0.978
1998-99	0.967	0.964	1.055	0.985
1999-00	0.928	0.908*	1.215*	1.029
2000-01	1.006	1.003	1.054	1.066*
2001-02	0.973	1.012	1.222*	1.207*
2002-03	1.033	1.02	0.961	1.019
2003-04	0.982	0.995	1.072	1.052
2004-05	0.96	0.954	1.155*	1.06
2005-06	1.036	0.955	0.93	0.923
2006-07	1.002	1.008	0.876*	0.887*
2007-08	1.067	0.971	1.109	1.161*
2008-09	0.977	1.033	1.250*	1.268*
2009-10	0.97	1.009	0.924	0.911*

Note: $\widetilde{APEC}$ =(Bias-Corrected) Aggregated Pure Efficiency Change, $\widetilde{ASEC}$ = (Bias- Corrected) Scale Efficiency Change, $\widetilde{ATEC}$= (Bias-Corrected) Aggregated Technical Efficiency Change, $\widetilde{AM}$ = (Bias-corrected) Aggregated Malmquist Productivity Index. * Significance at the 5% level.

Table 6: Aggregated Malmquist Productivity Index and its components, by size

Period	Big Banks					Medium Banks					Small Banks			
	No.	$\widehat{APEC}$	$\widehat{ASEC}$	$\widehat{ATEC}$	$\widehat{AM}$	No.	$\widehat{APEC}$	$\widehat{ASEC}$	$\widehat{ATEC}$	$\widehat{AM}$	No.	$\widehat{APEC}$	$\widehat{ASEC}$	$\widehat{ATEC}$
1995-96	11	1.069	1.071	0.851*	0.993	51	1.016	1.184*	0.981	0.979*	91	0.988	1.086*	0.997
1996-97	11	1.004	0.994	1.014	1.015	51	1.015	1.250*	0.961*	0.983*	90	0.978	1.177*	0.995
1997-98	12	0.968	0.954	1.036	0.962	55	0.998	1.188*	0.974	0.971*	83	1.034	1.161*	0.995
1998-99	16	0.99	0.98	1.074	1.044*	52	1.009	1.157*	0.956*	0.962*	77	0.958	1.080*	1.015
1999-00	13	0.919	0.922	1.160*	0.999	53	0.989	1.041*	1.084*	1.012	69	0.971	1.021*	1.082*
2000-01	15	1.054	0.971	0.956	0.985	50	1.028	1.165*	0.893*	0.937*	63	1.029	1.038*	0.996
2001-02	20	1.003	0.981	1.055	1.041	38	1.043	1.260*	0.994	1.092*	57	0.975	1.090*	1.021
2002-03	17	0.999	1.045	0.999	1.044	42	0.932	1.137*	1.055	0.943*	58	0.959	1.104*	1.022
2003-04	15	1.02	0.994	0.947	0.968	43	0.982	1.200*	0.96	0.961*	55	1.022	1.137*	0.984
2004-05	15	0.97	0.946	1.080*	0.997	38	0.984	1.079*	1.065*	1.026	51	0.98	1.024*	1.016
2005-06	16	1.002	1.002	1.005	1.01	35	1.021	1.204*	0.949*	0.997	49	1.009	1.139*	0.888*
2006-07	20	1.012	1.027	0.982	1.023	37	1.025	1.215*	0.969	0.971	44	1.026	1.137*	0.992
2007-08	18	1.063	1.022	0.845*	0.924*	41	1.057	1.268*	0.793*	0.878*	36	1.012	1.063*	0.920*
2008-09	19	0.988	0.991	0.959	0.942*	39	1.012	1.240*	0.915*	0.916*	32	0.99	1.160*	0.891*
2009-10	16	1.002	0.99	0.947	0.942*	37	0.999	1.235*	0.933*	0.951	32	0.995	1.034*	0.942
Realized Estimates														
1995-07	181	1.001	0.991	1.013	1.007	545	1.004	1.173	0.987	0.986	787	0.994	1.099	1.000
2007-10	53	1.018	1.001	0.917	0.936	117	1.023	1.247	0.88	0.915	100	0.999	1.086	0.917
Actual Estimates														
1995-07	181	1.000	1.000	1.008	1.004	545	1.000	1.173	0.992	0.986	787	1.000	1.099	0.998
2007-10	53	1.000	1.000	0.948	0.936	117	1.000	1.247	0.880	0.931	100	1.000	1.086	0.937

Note: $\widehat{APEC}$ =(Bias-Corrected) Aggregated Pure Efficiency Change, $\widehat{ASEC}$ = (Bias- Corrected) Scale Efficiency Change, $\widehat{ATEC}$= (Bias-Corrected) Aggregated Technical Efficiency Change, $\widehat{AM}$ = (Bias-corrected) Aggregated Malmquist Productivity Index. * Significance at the 5% level.

Table 7: RD for Aggregated Malmquist Productivity Index and its components, by size

Period	Big Banks vs. Medium Banks				Big Banks vs. Small Banks				Medium Banks vs. Small Banks			
	$\widehat{APEC}$	$\widehat{ASEC}$	$\widehat{ATEC}$	$\widehat{AM}$	$\widehat{APEC}$	$\widehat{ASEC}$	$\widehat{ATEC}$	$\widehat{AM}$	$\widehat{APEC}$	$\widehat{ASEC}$	$\widehat{ATEC}$	$\widehat{AM}$
1995-96	1.052	0.755*	0.867*	1.015	1.075	0.924	0.852*	1.027	1.026	1.109*	0.983	1.011
1996-97	0.988	0.695*	1.055	1.033	1.025	0.806*	1.018	1.008	1.036	1.084*	0.965	0.976
1997-98	0.97	0.739*	1.063	0.991	0.935	0.786*	1.041	0.932*	0.964	1.036*	0.979	0.941*
1998-99	0.981	0.787*	1.123*	1.085*	1.032	0.887*	1.058	1.108*	1.052	1.088*	0.942*	1.021
1999-00	0.931	0.884*	1.069	0.987	0.948	0.907*	1.07	0.968	1.018	1.024*	1.002	0.978
2000-01	1.026	0.785*	1.070*	1.051*	1.023	0.926	0.959	0.97	0.998	1.131*	0.896*	0.922*
2001-02	0.958	0.638*	1.06	0.953	1.027	0.874*	1.032	1.052	1.069	1.191*	0.972	1.104
2002-03	1.07	0.822*	0.945	1.106*	1.04	0.909	0.976	1.076	0.97	1.048	1.032	0.973
2003-04	1.038	0.740*	0.987	1.006	0.998	0.840*	0.963	0.957	0.961	1.069*	0.975	0.949*
2004-05	0.986	0.860*	1.014	0.971	0.99	0.922	1.063	1.009	1.004	1.060*	1.047	1.039*
2005-06	0.978	0.799*	1.058*	1.013	0.992	0.865*	1.130*	1.094*	1.012	1.065*	1.067*	1.080*
2006-07	0.987	0.752*	1.013	1.051*	0.986	0.877*	0.989	0.996	0.998	1.090*	0.976	0.946*
2007-08	1.005	0.744*	1.063	1.041	1.049	0.954	0.919*	0.977*	1.043	1.209*	0.863*	0.930*
2008-09	0.974	0.744*	1.047	1.023	0.997	0.833*	1.076	1.028	1.022	1.082*	1.027	1.002
2009-10	1.002	0.680*	1.014	0.987	1.006	0.95	1.005	1.043	1.003	1.215*	0.99	1.054

Note: $\widehat{APEC}$ =(Bias-Corrected) Aggregated Pure Efficiency Change, $\widehat{ASEC}$ = (Bias- Corrected) Scale Efficiency Change, $\widehat{ATEC}$= (Bias-Corrected) Aggregated Technical Efficiency Change, $\widehat{AM}$ = (Bias-corrected) Aggregated Malmquist Productivity Index. * Significance at the 5% level.

6. Conclusions

This paper is intended to provide empirical evidence that permits the outline of the real evolution of productivity growth (and its components) of financial centres over a long time span, particularly focusing on the productivity reaction of banks to the financial crisis. We estimate the productivity change along with the pure efficiency change, scale efficiency change and technological change. Given that the financial centre accounts for the heterogeneity among banks, the productivity growth and its three main sources have been estimated with respect to two specific bank characteristics, namely the organizational form and size, which originate in the five groups of banks. We analyse a unique banking sector, that is, the Luxembourg financial centre, as it is the European financial centre with the highest number of banks from abroad. To address the above issue requires us to resort to a methodology that permits us to accurately measure the productivity changes (and its components) at the group-level and to make inferences on them based on their actual changes. To this affair, the Aggregated Malmquist Productivity Index, following the method of aggregation developed by Zelenyuk (2006), is used to estimate the productivity of banks (and the components) at the aggregated level by organizational form and size. However, we extend this approach by merging the group-level productivity estimation with the idea of the Simar and Wilson (1999) bootstrap estimation, applied to the case of the firm-level productivity estimation, for obtaining confidence intervals and bias correction of the Aggregated Malmquist Productivity Index (and the relative components).

This approach allows distinguishing between the "realized" and "actual" changes, whereby the "actual" ones indicate those changes that actually occur, while the "realized" ones are those merely induced by the estimation problem. Lastly, we use the bootstrap idea to test the hypotheses for the statistically significant differences between the groups of banks following Simar and Wilson (2008), enabling us to test whether the group classification achieved is relevant to the analysis of the banking industry under investigation.

Two pieces of empirical evidence confirm that the classification is relevant to answering our research question purpose and corroborate the use of our methodological approach. The first evidence is the descriptive statistics that indicate the existence of heterogeneity between the production mix among the bank groups. The second evidence of heterogeneity among the banks is supported statistically by the pairwise-test comparison of the group estimates using the bootstrap procedure. Overall, the results provide different pictures of how the financial centre responded to the financial crisis in terms of organizational form and size. While the average realized results indicate both positive and negative changes in productivity (and its components) for both organizational forms, the actual results reveal a certain number of these estimates to not be statistically significant. The actual

changes indicate that the productivity change (and its components) path is such that branch and subsidiary banks in Luxembourg experience neither an improvement nor a loss in pure efficiency over time. On the other hand, in terms of the actual scale change, the financial crisis affects those organizational forms differently: While the branch banks experience an important loss in scale, the subsidiary banks are not affected. Lastly, both types of organizational form improve their technical change during the crisis period, although branch banks outperform subsidiary banks. As a result, branch and subsidiary banks respond to the financial crisis with significant productivity growth, whereby the main force of the productivity improvements was technical progress for both types of institutions.

In terms of size, the actual estimates reveal that no size group experiences improvements or a loss in pure efficiency over time. In terms of the actual scale change, the financial crisis positively affects only small banks because medium banks lose scale efficiency and big banks are not affected. Lastly, the three bank-size groups respond to the financial crisis with large improvements in technical change, the medium banks being those with the higher improvements. However, as a consequence of the actual changes in the three components of productivity, small banks respond to the financial crisis with the higher productivity growth, followed by big and medium banks. Overall, it can be inferred that although branch and subsidiary banks respond to the financial crisis with productivity improvement, the former ones react better than the latter. Moreover, it seems that while both types of institutions neither aim to converge towards best practices nor adjust correctly their output mix, they significantly improve their technical change. In terms of size, the actual results indicate that the three bank sizes respond to the crisis with productivity growth, a result of the technical change that drives the productivity growth for all of the bank sizes. However, given that small banks not only respond to the financial crisis with improvements in technical change but also in scale efficiency change, small banks are those that reach a higher productivity growth as a response to the financial crisis.

To conclude, the paper has attempted to contribute to the appraisal of productivity changes of banks operating in the financial centre; it offers evidence on the possible effects of the organizational form and size on productivity and provides a statistical test that reveals to what extent the productivity changes actually occur, thus allowing inferences to be drawn about the best response of banks to the financial crisis in terms of organizational form and size. Our exercise, however, can be considered as a first step to investigate the main sources of productivity. The subjects that would be a natural extension of this work would be to explore the determinants of the productivity growth and the technical progress response to the financial crisis on the part of banks in financial centres and to adapt the new developments in the methodology to the issue, as, for instance, the approach of Johnson and Ruggiero (2011).

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