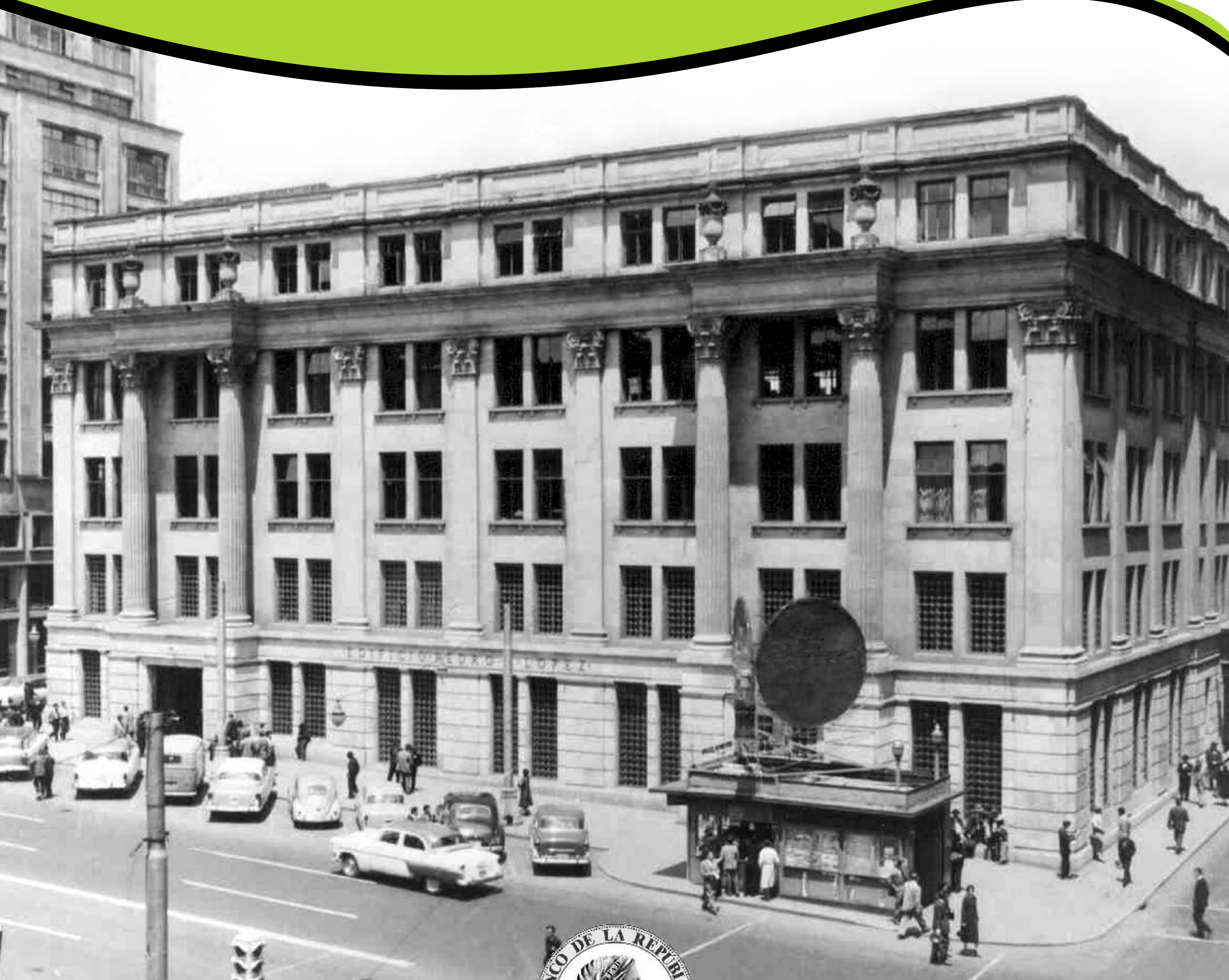
Banknote Printing at Modern Central Banking: Trends, Costs, and Efficiency

Por : Jorge Eduardo Galán Camacho
Miguel Sarmiento Paipilla

Borradores de ECONOMÍA

No. 476
2007



tá - Colombia - Bogotá - Colombia - Bogotá - Colombia - Bogotá - Colombia - Bogotá - Colombia - Bogotá - Colombia - Bogotá - Col

BANKNOTE PRINTING AT MODERN CENTRAL BANKING: TRENDS, COSTS, AND EFFICIENCY*

Jorge Eduardo Galán Camacho
Miguel Sarmiento Paipilla♣

Abstract

This paper examines trends in banknote printing during the period 2000-2005 for a cross-section of 56 central banks. It was identified that central banks have implemented new strategies to increase efficiency in the production of banknotes, primarily due to the increase in the demand for currency in recent years. One of these strategies has been to involve the private sector through different modalities (*e.g.* joint ventures, subsidiaries or purchase of banknotes from specialized companies). With the aim to examine the effect of these strategies and other banknote printing features on production costs, a cost function using a panel data model with random effects was estimated. It was identified that the denomination structure, the size of banknotes, and the production method used by central banks have a significant impact over printing costs. Government printing was found to be the most costly method, while involving companies in the process substantially reduces production costs. Based on these results, a non-parametric efficient frontier model was used to measure technical cost efficiency and changes in productivity of central banks. It was found that most central banks have increased its technical efficiency during the period, especially when the private sector has been involved. The Malmquist index showed a moderate increase in productivity, mainly due to increases in scale efficiency instead of technical change.

Key Words: Central Banks, Banknote Printing, Efficiency Frontier, Cost Function, Panel Data, Malmquist Index.

JEL Classification: E50, C33, C23, C43.

---

* This paper is part of a research program on central banking being developed by the Planning and Budget Department with advice of the Research Unit. An earlier version of this study was presented in the "IV International Course of Cash Management", organized by CEMLA, the Treasurers Committee, and Banco de la República, in Bogotá D.C., September 10 – 14, 2007. We appreciate very much the comments and suggestions received from participants in this event, as well as from Gerardo Hernandez, Nestor Plazas, Javier Sepúlveda and Hernán Rincón. We thank to Martha Misas and Ligia Melo for the technical counseling and Carolina Moreno for her collaboration as a research assistant.

♣ J.E. Galán and M. Sarmiento are economists of Planning and Budget Department of Banco de la República. Comments are welcome at jgalanca@banrep.gov.co and nsarmipa@banrep.gov.co. The opinions expressed herein do not involve the Banco de la República or its Board of Directors; theses are the authors' exclusive responsibility.

La Impresión de Billetes en la Banca Central Moderna: Tendencias, Costos y Eficiencia

Resumen

En este documento se estudian las tendencias en la producción de billetes durante el periodo 2000-2005 a partir de una muestra de 56 bancos centrales. Se encontró que ante el elevado crecimiento de la demanda de efectivo en los últimos años, los bancos centrales han implementado nuevas estrategias para ganar eficiencia en la producción de billetes; entre estas se destacan, la vinculación del sector privado por medio de distintas modalidades (*e.g.* asociaciones de riesgo compartido, creación de subsidiarias o compra de billetes a firmas especializadas). Con el objetivo de examinar los efectos de estas estrategias y de otras características de la impresión de billetes sobre los costos de producción, se estimó una función de costos bajo un modelo de datos panel con efectos aleatorios, donde se encontró que la estructura de denominación, el tamaño de los billetes y la modalidad empleada por los bancos centrales, son variables que afectan los costos de manera significativa. A su vez, se identificó que la impresión a cargo del gobierno es la modalidad más costosa; mientras que la vinculación del sector privado al proceso de producción disminuye los costos de forma importante. Basado en estos resultados, se empleó un modelo no-paramétrico de frontera eficiente con el fin de encontrar medidas de eficiencia técnica en costos y cambios en productividad de los bancos centrales. Se encontró que la mayoría de los bancos centrales han incrementado su nivel de eficiencia técnica durante el periodo, siendo más evidente en los bancos que realizan su producción con participación de terceros. Por su parte, mediante el calculó del índice de Malmquist se identificó un moderado incremento en productividad, el cual obedece principalmente a incrementos en eficiencia de escala y en menor proporción a un cambio técnico.

I. Introduction

Banknote printing has been customarily done by central banks or in some cases by governments. However, with the development of financial markets and the consolidation of specialized companies in banknote production, a number of central banks have invited the private sector to participate in this function.

This change also has been motivated by high increase in the demand for currency in recent years. As a matter of fact, the average growth rate of the value of currency in circulation was 26.5% during the period 2000 – 2005 in the 56 countries studied (See Annex 1). This situation generated, among other effects, an increase in banknote production, and consequently in production costs.[1] In fact, central banks rely on a variety of strategies to enhance efficiency in the production and supply of banknotes to the economy.[2] These include, among others, creating subsidiary companies (*e.g*. Australia and Bulgaria), turning production over to the private sector (*e.g*. United Kingdom and Sweden), and combining currency printing and distribution under one roof, in a single complex (*e.g*. Portugal and Colombia).

In a broad study, the central bank of Colombia examined these methods and strategies for a sample of 133 central banks between 1993 and 2003, finding out a tendency to turn over all or part of banknote production, primarily among central banks of developed countries (Banco de la República, 2005). At the Central Bank of Japan, Nishihara (2006) found that changes in the banknote printing method in central banks of the Executives Meeting of East Asia and Pacific (EMEAP)[3] have depended on the central bank's relationship with the government, the financial sector and private companies, as well as the modernization strategy adopted by each central bank.

Recently, Galán and Sarmiento (2007), using a panel data model for 68 central banks during the period 2000-2004, found that the function of banknote printing is a very

[1] Several studies suggest that the recent increase in monetary aggregates is due to the decline in inflation and interest rates, coupled with the growth in real income (See Hernández et. al., 2005; De Gregorio, 2003).

[2] Baxter et al. (2005) examined how currency is distributed by central banks in Australia, Canada, England, Malaysia and Norway.

[3] The EMEAP is composed of the central banks of Australia, China, Hong Kong S.A.R., Indonesia, Japan, South Korea, Malaysia, New Zealand, Philippines, Singapore and Thailand.

important determinant of the central bank's labor demand. Moreover, they found that a change in the strategy used to perform this function has a relevant effect on staff.[4]

While the aforementioned studies shed light on the modernization strategies adopted recently by central banks to produce banknotes more efficiently, it is important to consider other aspects associated with that function, such as the denomination structure in each country, the features of the banknotes, and the production costs. These aspects are examined in detail on this study, by identifying the banknote printing costs determinants and the effect of changes in strategies and production methods over costs and efficiency.

This paper is divided into four sections, including this introduction. Section two examines the production methods, the denomination structure and the features of banknotes for 56 central banks for the period 2000-2005. Section three builds a set of comparative production costs indicators. A cost function is estimated as well, using a panel data model with random effects in order to identify the main production costs determinants. Additionally, a non-parametric efficiency frontier model is used to identify the technical efficiency of central banks in banknote printing, as well as, changes in productivity through the Malmquist index. Section four presents the main conclusions.

II. Trends in Banknote Printing

1. Modalities

In recent years, central banks have relied on different methods to produce banknotes. The most common include direct printing by the central bank, production through a subsidiary company, purchase from domestic suppliers (private companies and the government), and importation. The relative importance of these methods in 2005 is shown in Table 1. For the sake of comparison, central banks are classified into four groups: Euro Zone, Other Advanced Economies, Latin America and Other Developing Countries.

[4] The case studies by Booth (1989) and Lacker (1993) for the United States are particularly important. Daltung and Ericson (2004) analyzed the banknote printing and currency management strategy adopted recently by the central bank of Sweden.

Table 1. Methods Used by Central Banks to Produce Banknotes (2005)

PRODUCER	EURO ZONE		OTHER ADVANCED ECONOMIES		LATIN AMERICA		OTHER DEVELOPING COUNTRIES	
	Country (12)	%	Country (14)	%	Country (14)	%	Country (16)	%
CENTRAL BANK	Belgium France Greece Ireland Italy	41,7%	Denmark Hong Kong Norway	21,4%	Colombia Mexico Venezuela	21,4%	Albania Armenia Bangladesh Romania Slovenia Thailand Turkey	43,8%
PRIVATE COMPANY	Finland Germany Holland	25,0%	Canada England Sweden	21,4%		0,0%	Poland	6,3%
GOVERNMENT	Spain	8,3%	Japan United States South Korea	21,4%	Argentina Brazil Chile	21,4%	Czech Rep.	6,3%
SIBSIDIARY	Austria Portugal*	16,7%	Australia	7,1%		0,0%	Bulgaria Hungary	12,5%
IMPORTATION	Luxembourg	8,3%	Cyprus Iceland Israel New Zealand	28,6%	Bolivia Costa Rica Dominican Rep. Guatemala Nicaragua Paraguay Peru Uruguay	57,1%	Bosnia Croatia Estonia Malaysia Slovakia	31,3%

* In Portugal, there is a Joint Venture with *De La Rue* since 1999.
Source: Central Banks' Annual Reports (2000 – 2005). Authors' calculations.

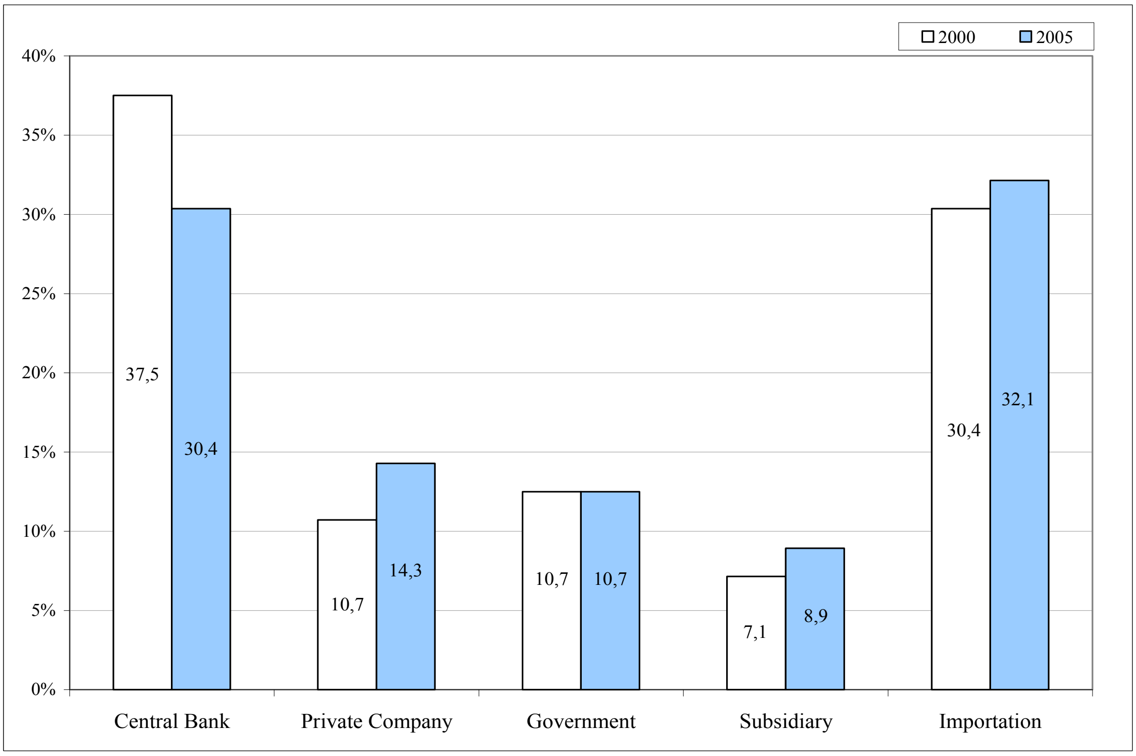
As illustrated, in most of the Euro Zone countries and in the group of Other Developing Countries, banknotes are produced by the central bank. Nonetheless, central banks that perform directly this function account for less than half of the sample analyzed. Table 1 also shows that the purchase of banknotes from private companies is more common among central banks in Advanced Economies and Euro Zone, than in other regions. The establishment of a subsidiary company is not a method used in Latin America, where more than half of the countries studied import their banknotes. As to the importation of banknotes, most central banks rely on more than one supplier.[5]

Figure 1 shows the tendency in these methods during 2000-2005, when the number of central banks printing banknotes decreased, while the participation of private companies

[5] For example, the central bank of Slovakia uses several suppliers depending on the banknote's denomination: The *British Printer De la Rue,* and the Canadian company *Giesecke & Devrient GmbH*. The central bank of Bosnia imports banknotes from two companies: *Oesterreichische Banknoten und Sicherheitsdruck* (OeBS), of Vienna, and the French company *Francois – Charles – Oberthur* (FCO).

and importation increased. This tendency reflects the constant search for strategies to modernize banknote production, largely through active participation by third parties.

Figure 1. Trends in the Banknote Printing Methods (2000 - 2005)



Source: Central Banks' Annual Reports (2000 – 2005). Authors' calculations.

The central banks that changed their method during the period studied were those of Bulgaria and Croatia in the group of Other Developing Countries, and England and Sweden in the group of Other Advanced Economies. The central bank of Bulgaria used the strategy of establishing its currency printing works as an independent legal entity, which operates as a subsidiary of the central bank since January 2002.[6] In year 2002 as well, the central bank of Croatia stopped producing banknotes directly and began to import them, initially from *OeBS*, the subsidiary company of the Austrian central bank since 1998.

[6] The central bank of Bulgaria assumed full control of the company (100% stock ownership), with the authority to direct its financial and operative policies and to profit from its activities. Since 2004, the government owns some shares of the company. While dedicated primary to banknote production, this subsidiary also has been commissioned to produce certain types of paper and documents for the Finance Ministry of Bulgaria and other government agencies. See Bulgarian National Bank, *Annual Report,* 2002.

The strategy implemented by the central banks of Sweden and England was selling their banknote printing works to private companies. In March 2003, the central bank of England sold its banknote printing works to *De la Rue* in order to achieve certain cost and security objectives for the banknotes it offers.[7] Likewise, the central bank of Sweden, with the aim of focusing in the core functions, sold its banknote printing facilities in 2001 to *Crane & Co, Inc.,* a US company.[8] Under a similar approach, the central bank of Norway, decided in 2003 to stop producing banknotes directly in 2007 (Norges Bank, 2003).[9]

The transfer of banknote production from central banks to other agents is not the only strategy being used to make this activity more efficient. In 1995, the central bank of Portugal built the *Carregado* complex to house banknote production and cash distribution activities under one roof. *De la Rue* has been printing banknotes there since 1999, as part of a joint venture. In Colombia, the central bank began operating the *Central de Efectivo* in 2006, a complex that combines banknote production and currency distribution activities.

Central banks in Euro Zone have adopted other strategy consisting of a joint and decentralized banknote production, since 2002. Under this approach, each national central bank is responsible for producing a portion of the banknotes, in a reduced number of denominations. However, each central bank may use a particular production method.[10]

2. Denomination Structure

Central banks must define the structure of denominations in circulation, regardless of the printing method used. This implies estimating the share of each denomination out of the total amount of currency the economy needs, and introducing a new denomination when it is required by the market. Therefore, when drafting a production plan, it is essential to

[7] Initially, the central bank transferred capital and staff for banknote production at its subsidiary, *Debben Security Printing Ltd.,* which was sold eventually to *De la Rue*. The initial agreement called for *De la Rue* to sell notes to the central bank for a seven-year period. See Bank of England (2003).

[8] It was considered that this company would develop additional printing techniques and supply the production volume required for long-term benefits (See Sveriges Riksbank, 2002; Daltung and Ericson, 2004).

[9] On December 2006, the central bank of Norway signed an agreement with *De La Rue* and FCO to purchase banknotes from them during the period 2007 -2012. (See, Norges Bank, 2006).

[10] The European Central Bank plans to institute a single bidding procedure in 2012 to print banknotes for the Euro system. The goal is to have only few suppliers, so as to make the production more efficient (See the ECB Annual Report, 2002). For details on the role of central banks in Euro Zone, see Wellink et al. (2002).

analyze the production needs for each denomination. These are based essentially on three factors: change in the quantity of banknotes demanded by the public; restocking deteriorated banknotes; and the inventory needed to cover unexpected events.

Each of these factors differs from one denomination to another. Restocking deteriorated banknotes is more frequent with lower denominations. Because they are employed in a greater number of transactions, their useful life is shorter than that of other denominations.

Changes in the units required during an average year and in inventory needs depend on the public's preferences for each denomination. The quantity of denominations in circulation each year depends of a combination of economic circumstances that shapes the demand for currency. To illustrate this situation, Table 2 shows that developed countries tend to use fewer denominations than developing countries, although a significant portion of the sample uses a structure that varies from five to seven denominations (See Annex 2).

In economies with highly developed technological means of payment and currency distribution, and with advanced distribution models for goods and services (*e.g*. large department store chains and electronic payment networks integrated into commerce), the dynamics of currency are expected to be more stable, as is the composition of currency in circulation (Misas et. al., 2004). Added to this is the fact that financial institutions can influence significantly the demand for currency.[11]

On the other hand, in developing countries the demand for currency has high variability that alters its composition. At times of high inflation rates, the purchasing power of the denominations in circulation declines, making it necessary to introduce a denomination that adjusts to market conditions. In other words, an increase in the nominal value of daily transactions in the economy, due to inflation or economic growth, is regarded as a signal to introduce a new denomination.[12]

[11] Financial institutions may influence the demand for currency, given their general biased towards high denominations for ATM's, which are one of the primary means of currency distribution.

[12] This result applies to countries where the Metric-D System is used. This method developed by L. C. Payne and H. L. Morgan, it is employed to estimate the quantity of banknotes to be produced for each denomination and the predominant structure. The model relates average daily remuneration in the economy to the denominations of banknotes and coins to be issued. For details on models for currency issue see Mushin (1998).

Table 2. Structure of Denominations of Banknotes in Circulation (2005)

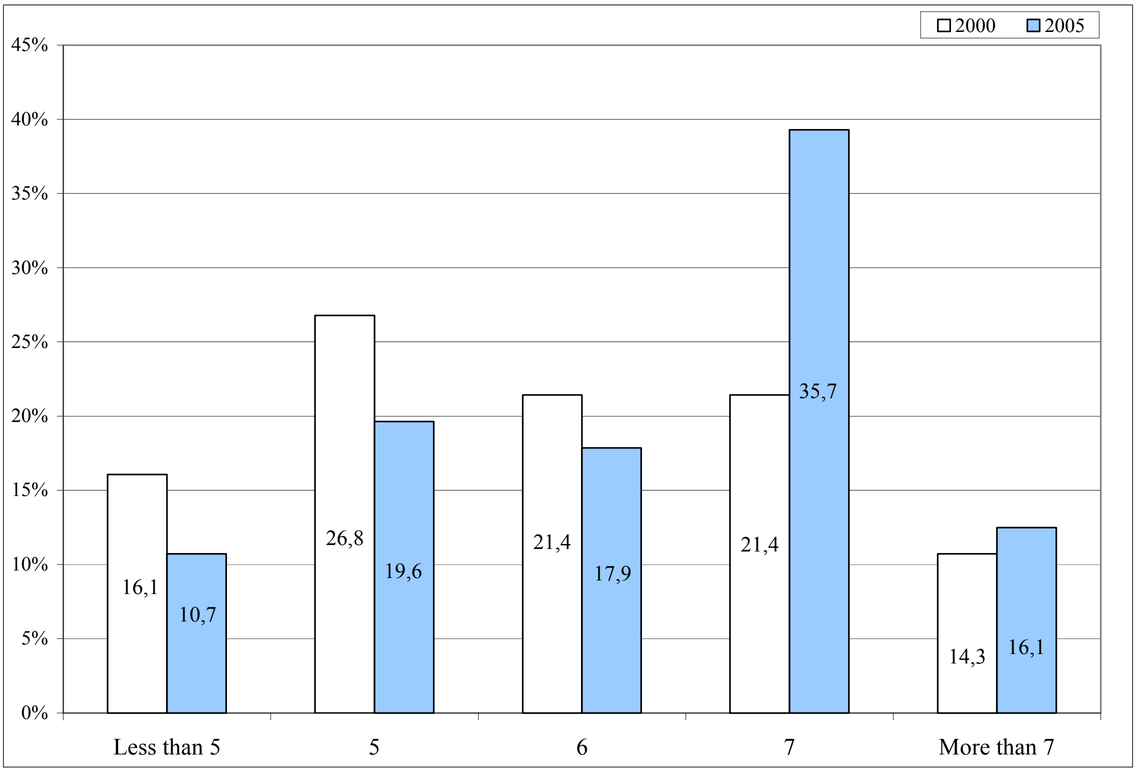
STRUCTURE OF DENOMINATIONS	EURO ZONE		OTHER ADVANCED ECONOMIES		LATIN AMERICA		OTHER DEVELOPING COUNTRIES	
	Country (12)	%	Country (14)	%	Country (14)	%	Country (16)	%
Less than 5 denominations			Cyprus England Israel Japan South Korea	35,71%	Costa Rica	7,14%		
5 denominations			Australia Canada Denmark New Zealand Norway	35,71%	Nicaragua Paraguay Peru	21,43%	Albania Poland Thailand	18,8%
6 denominations			Hong Kong	7,14%	Argentina Chile Colombia Mexico Venezuela	35,71%	Armenia Malaysia Romania Turkey	25,0%
7 denominations	Austria Belgium France Finland Germany Greece Holland Ireland Italy Luxembourg Portugal Spain	100%	Iceland Sweden United States	21,43%	Bolivia Brazil Dominican Rep. Guatemala	28,57%	Bulgaria Hungary Slovakia	18,8%
More than 7 denominations					Uruguay	7,14%	Bangladesh Bosnia Estonia Croatia Czech Rep. Slovenia	37,5%

Source: Central Banks' Annual Reports (2000-2005), CEMLA (2005) and central banks' websites. Authors' calculations.

Figure 2 shows the changes in the denomination structure for the central banks in the sample, and a tendency for the number of denominations to increase. Between 2000 and 2005, the percentage of countries using six denominations or less decreased and the portion of central banks issuing seven or more denominations increased. The most representative changes occurred in the Euro Zone after the adoption of Euro, in Latin America and in the group of Other Developing Countries (See Annex 2).

There are different causes of these changes. In some countries (*e.g.* Uruguay, Armenia and Hungary) the years when new banknote denominations were introduced coincide with periods of high inflation. In Colombia, the changes in denomination structure were associated with the behavior of inflation, as well as the need to tackle in counterfeiting. In Rumania, the adoption of an additional denomination was the result of a redenomination of national currency in 2005.[13]

Figure 2. Trends in the structure of banknotes denomination (2000 - 2005)



Source: Central Banks' Annual Reports (2000-2005), CEMLA (2005) and central banks' websites. Authors' calculations.

3. Banknote Features

3.1. Security

Central banks include security features on banknotes to prevent counterfeiting. They face the challenge of using security features that are on par with the latest printing, copying and engraving technology. There is considerable variation in the security features used on banknotes. Some are implicit in the paper manufacturing process (*e.g.* thickness, texture, inlays, etc.); others, such as the use of special inks, symbols, images, serial numbers and the

[13] During the period, the central bank of Colombia issued a $50,000 peso banknote given the trend in inflation, and a $1,000 peso banknote to discourage counterfeit coins of the same denomination.

like, are developed during the printing process. Likewise, the materials used to manufacture banknotes determine some security features and the circulation life. Usually banknotes are made of cotton paper; however, some countries issue polymer banknotes.[14] Table 3 shows the percentage of countries using the most common security features and issuing polymer banknotes.[15]

Table 3. Security Features Most Commonly Used on Banknotes and Polymer (2005)

FEATURES	EURO ZONE	OTHER ADVANCED ECONOMIES	LATIN AMERICA	OTHER DEVELOPING COUNTRIES
	Countries (12)	Countries (14)	Countries (10)	Countries (13)
Watermark	100%	85,7%	100%	92,3%
Security threads	100%	78,6%	100%	92,3%
Intaglio printing	100%	78,6%	100%	84,6%
Micro-inscription	100%	85,7%	90,0%	100%
Hidden image	100%	71,4%	90,0%	92,3%
Perfectly matched drawing	100%	57,1%	90,0%	92,3%
Color changing ink	100%	78,6%	60,0%	100%
Observation under ultra violent light	100%	85,7%	50,0%	69,2%
Hologram (contrasting elements)	100%	64,3%	50,0%	53,6%
Average Number of Features	**9,0**	**6,7**	**7,1**	**7,4**
Polymer Banknotes	**0%**	**21,4%**	**21,4%**	**18,8%**

Note: Security features may vary among denominations. Definitions of each security feature and countries using them are showed in Annex 3.
Source: Central Banks' Annual Reports (2000-2005) and central banks' websites. Authors' calculations.

In general, watermarks and security thread are the most used security features, because they come already printed in cotton paper and polymer, even though it is more common in paper notes. The security thread has some characteristics; it can be used complete,

[14] Some combinations have been used, for example, Bulgaria issued a hybrid polymer-paper banknote in 2005 and it is currently under a test period. See Annex 3 for details about the use of polymer banknotes.

[15] There are many other complimentary features used in some countries: Holographic bands (Brazil, Bulgaria, Canada, Hungary, Nicaragua and Norway); holographic patches (Denmark, England and Japan); multiple redundant hologram (Cyprus and Paraguay); holographic security thread (Bangladesh, Honk Kong and Peru); windowed security thread (Argentina, Canada, Costa Rica, Korea and Paraguay); iridescent band (Costa Rica, Mexico and Peru); multicolor planchettes (Canada and Colombia); micro-perforations (Euro Zone and Rumania); among others.

windowed or holographic. Other widely used security features are intaglio printing, micro-inscriptions and hidden image. While perfect register is a security feature less common in the Other Advanced Economies group and color-changing ink is less used in Latin America.

On the other side, observation under ultra violet light and holograms are not frequently features except in developed countries.[16] As to holograms, there are some differences. For example, Bulgaria, Canada and Hungary use holographic bands; Denmark, England and Japan use holographic patches; and Euro notes use both, bands for low denominations and patches for high denominations.

With respect to the total number of security features used, most of the countries use between 7 and 8 characteristics, although there are variations among denominations.[17] Only five central banks use less than 6 security features; while a significant group of countries, including those using the Euro, present more than 10 features. However, in both groups less common elements are used, such as micro-perforations (Euro Zone and Rumania), security background (Guatemala), *Kinegram* (Slovak Republic), invisible security fibers, intra-red ink and seals printing (Albania), and accentuated three-dimensional watermarks (Uruguay).[18] To summarize, not every central bank uses the features exposed in this section, they combine the security features in different ways depending on denominations.

A trend to the adoption of polymer banknotes was identified, mainly in low denomination notes which are those with the shortest circulation life. Some of the new countries that issued polymer notes during the period were Brazil in 2000, Mexico in 2002 and Chile in 2004.

---

[16] Most of the central banks that use observation under ultra violet light print their notes on non-fluorescent paper, so it darkens when exposed to this light. Serial numbers, security threads, special characters, and fibrils are some of the devices observed most often under ultraviolet light. United States is distinguished for not using florescent ink; however, the background colors on its banknotes are regarded as essential in the fight against counterfeiting.

[17] Usually, the highest denominations present more features. In fact, for example in Rumania, the highest denomination has 10 security features; however, the lowest denomination has only three.

[18] The security background consists of a plane printing in the note background with fine designs that form complex figures. Micro-perforations are very small perforations through paper that form figures when they are observed under light. *Kinegram* is a half-moon-shaped metallic slip that allows the formation of images that change with the angle of the light.

3.2. Size

Unlike security features, which are more the result of a decision to discourage counterfeiting, the size of banknotes is an aspect of the production process that central banks can control to reduce production resources (*e.g.* paper and ink). In many cases, the size of banknotes varies from one denomination to another. For example, the central bank of Denmark decided that all banknotes would be equal in height, but with a difference of 10 mm between each denomination. This is done to facilitate classification and counting, and to help visually impaired persons to distinguish the different denominations. This last objective served as justification for the Euro banknotes being designed in sizes that vary with the increase in denomination. The same is true for the British pound sterling and the Mexican peso since 2006.[19]

Table 4. Size of Banknotes in Circulation (2005)

EURO ZONE		OTHER ADVANCED ECONOMIES		LATIN AMERICA		OTHER DEVELOPING COUNTRIES	
Country (12)	**(cm2)**	**Country (14)**	**(cm2)**	**Country (14)**	**(cm2)**	**Country (16)**	**(cm2)**
Austria	105,58	Australia	93,6	Brazil	91,0	Poland	87,5
Belgium		New Zealand	93,6	Peru	91,0	Bulgaria	89,2
France		Israel	98,0	Mexico	96,6	Malaysia	91,9
Finland		Iceland	100,5	Colombia	98,0	Croatia	92,1
Germany		Norway	101,6	Venezuela	98,5	Bosnia	94,6
Greece		United States	103,4	Dominican Rep.	99,2	Estonia	96,6
Holland		Denmark	104,4	Nicaragua	100,5	Albania	100,7
Ireland		Canada	106,5	Argentina	100,8	Romania	101,5
Italy		Sweden	106,5	Guatemala	101,3	Slovenia	101,7
Luxembourg		Cyprus	112,9	Chile	101,5	Hungary	103,5
Portugal		England	113,2	Bolivia	102,2	Czech Rep.	104,2
Spain		Hong Kong	117,3	Uruguay	102,3	Bangladesh	104,5
		Japan	117,8	Costa Rica	102,3	Armenia	106,1
		South Korea	118,6	Paraguay	105,2	Thailand	108,0
						Slovakia	108,5
						Turkey	123,2
Average	**105,58**	**Average**	**106,3**	**Average**	**99,3**	**Average**	**100,9**

Source: Central Banks' Annual Reports (2000-2005) and central banks' websites. Authors' calculations.

Nevertheless, cost considerations also influence the size of banknotes. Larger banknotes are more expensive, because additional materials are used to produce them. For example, more sheets of paper are needed, and it translates into more time spent to manufacture and verify the same quantity of banknotes.

[19] Mexico plans to put in circulation a complete new family of banknotes with size differences before 2010.

In Table 4 the average size of circulating notes in each country is compared. It is observed that developed countries have the largest banknotes while Latin America has the smallest, followed closely by the group of Other Developing Countries. However, this last group is more dispersed, as it includes countries with the smallest and largest banknotes in the entire sample (Poland with 87.48 cm^2 and Turkey with 123.17 cm^2).

One strategy to reduce printing costs is to produce smaller banknotes for the lower denominations, because their circulation life is shorter. For example, the central bank of Colombia decided in 2006 to reduce the cost of banknote production by reducing the size of the two lowest denomination notes.[20]

III. Printing Costs, Cost Function, and Efficiency

1. Comparative Cost Analysis

A comparative analysis of banknote printing costs is only provided for the 28 central banks with detailed information about their costs. Printing costs are those of producing banknotes directly or of being supplied with new banknotes, depending on the method used.[21]

There are two aspects to consider when comparing the central banks' costs. First, cost data for the same central bank can vary considerably due to the different factors that alter the production during the year. For example, there are periods when banknote production is low, since available inventory is enough to supply production needs; and there are periods when a large quantity of banknotes must be produced because of deterioration or counterfeiting. This is why the cost figures are analyzed as an average for the years 2000 - 2005.

Secondly, costs vary widely among central banks, as the quantities of banknotes produced are very different, depending on the characteristics of the country and its

[20] The size of the banknotes of $1.000 and $2.000 pesos was reduced in 14% (from 140mm x 70mm to 130mm x 65mm). As a result, the production costs of these notes will decline by 15% and 20%, respectively.

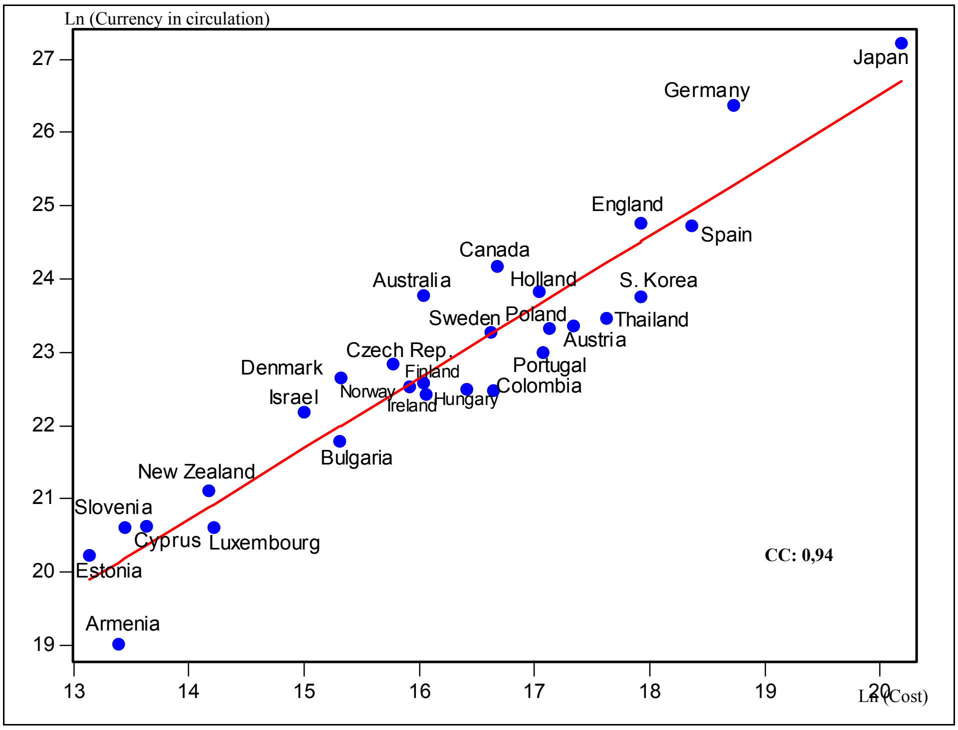
[21] When a central bank purchases banknotes from a private company, the amount it pays includes the company's profit margin. When the government takes responsibility for production, the central bank usually recognizes only production costs, or a part of them. When banknotes are produced by the central bank, the cost includes production materials, depreciation of machinery, and the cost of staff involved directly in production. For the central banks in the Euro Zone, data from 2002 to 2005, refer to the production costs of the denominations assigned by the European Central Bank.

economy. For example, while the central bank of Slovenia presents average printing costs of USD$0.5 millions a year, in Japan those costs are about USD$586 millions (See Annex 4). This explains the need for comparisons linked to variables such as the country's population and the currency in circulation.[22]

1.1. Printing Costs and Currency in Circulation

The level of currency in circulation is a good measurement of the quantity of banknotes a central bank must produce to satisfy the economy's currency needs. In fact, more currency in circulation implies more production and, consequently, higher costs. This is verified by the high correlation coefficient of the series in Figure 3. The central banks above the regression line have fewer costs in relation to the currency in circulation (*e.g.* Germany, Canada and Australia). Those below the line and furthest from it are the central banks of Armenia, South Korea, Colombia and Thailand.

Figure 3. Banknote Production Costs and Currency in Circulation (2000 – 2005)



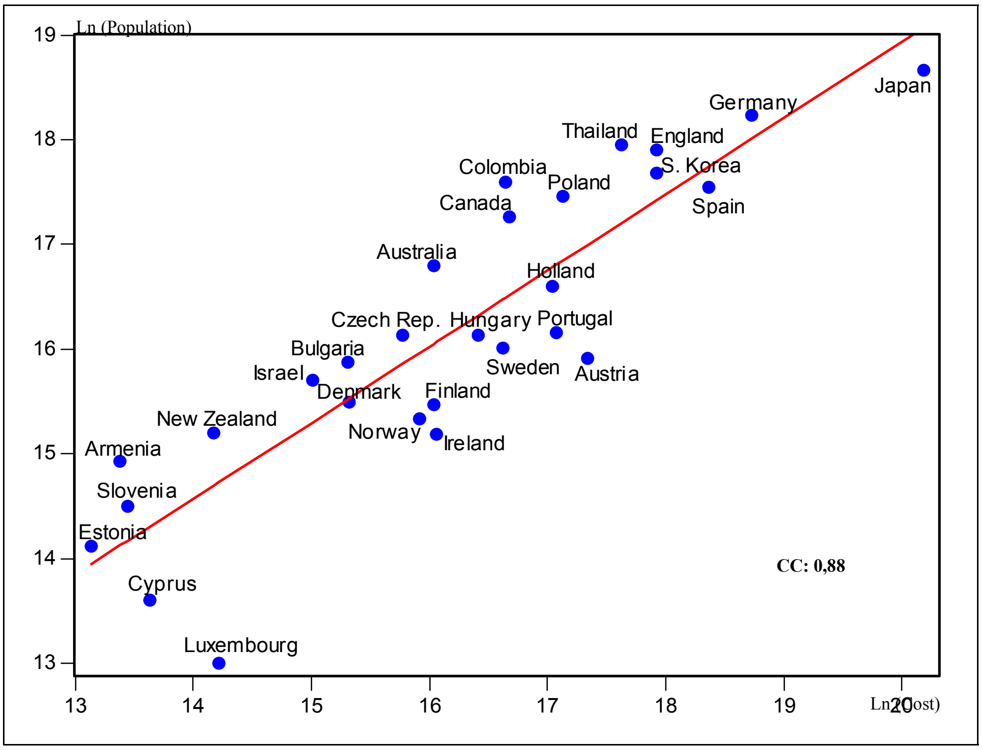
CC: Correlation Coefficient. Data in Logarithms.
Source: Central Banks' Annual Reports (2000-2005). Authors' calculations.

[22] The most precise index is the cost per produced banknote; however, only 11 central banks reported detailed information. This index and two other comparing costs with GDP and operational costs are shown in Annex 4

1.2. Printing Costs and Population

The country's population also is considered as measure of the quantity of banknotes required for the economy. Under this index, printing costs are compared to the population the central bank must supply with banknotes. The central banks situated above the regression line in Figure 4 have comparatively low costs, considering their population. Central banks with the best results are those of Colombia, Australia, Canada and Armenia. In contrast, the central banks of Japan, Luxembourg and Austria are situated below the regression line. In the case of Japan, the central bank has costs four times higher than those of Germany, but with a population that is only 1.5 times larger.

Figure 4. Banknote Production Costs and Population (2000 – 2005)



CC: Correlation Coefficient. Data in Logarithms.
Source: Central Banks' Annual Reports (2000-2005). Authors' calculations.

2. A Cost Function for Banknotes Printing

In order to suggest strategies to reduce printing costs and to enhance efficiency in the performance of this function, it is necessary to identify the variables that determine printing costs. For this purpose, a cost function is estimated with a panel data model with random effects for 28 central banks during the years 2000-2005.

2.1. The Model

The printing cost function for central banks is assumed as a traditional Cobb-Douglas cost function, which is expressed as follows:

$$\ln C(y,w) = \beta_0 + \beta_1 \cdot \ln(Y) + \sum_{i=1}^{n} \beta_i \cdot \ln(w_i) \qquad (1)$$

In the previous equation, (*Y*) represents the quantity of the final service or good produced and (*w*) the prices of i production factors. Using a Cobb-Douglas cost function is appropriated for this exercise as it allows inferring directly about elasticities of the independent variables. For the econometric estimation, this function can be expressed as a log-lineal equation, where a set of variables (*Z*) affecting production costs and out of the control of the bank, can be included (Battese and Coelli, 1995). Due to efficiency measures are not directly estimated and unavailable data about input prices, the variable (*w*) is omitted. Therefore, the following short term cost function is used:

$$\ln(C_{it}) = \beta_0 + \beta_1 \cdot \ln(Y_{it}) + \sum_{j=1}^{m} \beta_j \cdot \ln(Zj_{it}) + u_{it} \qquad (2)$$

Based on equation (2), variables that reflect the output level, the characteristics of the banknote production, and the production methods used by central banks are introduced in the model. The econometric model is:

$$Ln(C_{it}) = B_0 + B_1.Ln(N_{it}) + B_2.Ln(Circ_{it}) + B_3.Ln(Y_{it}) + B_4.Ln(Den_{it}) + B_5.Ln(Sec_{it})$$
$$B_6.Ln(Size_{it}) + B_7.\Pr iv_{it} + B_8.Gov_{it} + u_{it} \qquad (3)$$

In equation (3), the banknote printing costs (*C*) are function of: population of the country (*N*), currency in circulation (*Circ*), per capita income (*Y*), number of denominations produced and circulating in the economy (*Den*), average number of security features (*Sec*), average size of the banknotes (*Size*), and the method used by a central bank to produce banknotes (*Priv* and *Gov*).

The variable (*Priv)* refers to the method whereby private third parties participate in the printing process. This includes joint venture agreements, the various subsidiary methods, or full delegation of the process to private companies, with the central bank purchasing their output. This is a dummy variable that takes the value of 1 in either of the aforementioned cases and 0 in the other. Likewise, (*Gov)* is a dummy variable that specifically identifies the method in which the government is in charge of banknote printing; accordingly, it takes the value of 1 in that case and 0 in the other.[23]

The relation between the first two explicative variables (*N* and *Circ*) and costs was identified in the previous indicators. In the model these variables are introduced as *proxies* of the output level the central bank must supply to economy and are expected to have a positive sign over them, in as much as the larger the country's population, the larger the quantity of banknotes required and, therefore, the higher the costs. By the same token, if there is a large amount of currency circulating in the economy, the country's need for currency will be greater and, consequently, so will production costs.

Per capita income (*Y*) is a variable used to identify the extent to which the financial development level of an economy affects the printing costs. Usually, in more developed economies, the use of non-cash means of payment (*e.g.* electronic transfers and cards) is more prevalent; so, a negative sign is expected for this variable.[24] The number of denominations (*Den*) is also, to some extent, a measure of output, as the central bank has the obligation to supply banknotes of every existing denomination in circulation. A positive sign is expected due to, the more denominations, the higher the need for different types of plates, paper, ink combinations and time.

The security features (*Sec*) and the size of the banknotes (*Size*) are particular aspects of the product and are defined by the central bank. However, the central bank exercises only

[23] The method whereby the central bank is in charge of printing all banknotes is the base case model. In other words, it is identified because, the (*Priv*) and (*Gov*) variables assume the 0 value simultaneously.

[24] Evidence of this situation has been observed during recent years (See, ECB, 2007; BIS, 2007)

indirect control over security features, which depend on factors such as counterfeiting. So, the bank is required to prevent it through the introduction of security features. Positive signs are expected for both variables, because more security features and a larger size of banknotes imply the use of more materials and production factors, which increase costs.

Lastly, the variables (*Priv* and *Gov*) are intended to find out if the methods used to produce banknotes determine their cost, and which of those methods can represent greater benefits in terms of cost.

2.2. Methodology and Results

A random effects panel data model was used to estimate equation (3), which is given as follows:

$$y_{it} = X_{it}\beta + u_{it} \qquad \text{Where: } i = 1, ...,28 \text{ y } t = 2000,...,2005. \qquad (4)$$

Equation (4) represents a traditional panel data model where Y_{it} is the dependent variable that changes for each central bank *i* during each time period *t*; X_{it} is the set of explicative variables, and u_{it} is the error term, which, at its turn, is composed as follows:

$$u_{it} = \mu_i + \varepsilon_{it} \qquad (5)$$

In equation (5), μ_i represents the individual effect (either fixed or random) and ε_{it} is the observation error.[25] An estimator with dynamic effects allows admitting differences in the minimal printing costs between central banks, by allocating different values to each observation.[26]

Equation (3) above was estimated through the generalized least squares method (GLS) using random effects which results from applying the Hausman's test. The results in Table

[25] The difference between a model with fixed effects and one with random effects resides in that the latter adduces a random variable that changes for each individual, whereas in the former the effect is a fixed number. The selection of the model depends on the correlation between the individual effect and the explanatory variables, which are reviewed through Hausman's test (See, Hsiao, 2003).

[26] An interesting exercise would be to obtain different coefficients for all variables at each central bank by using a Swamy-type model. However, the number of years for which data were obtained is very short and prevents the use of this type of models (See Amemiya, 1978).

5 show a well model specification and a high joint significance of variables. The population and circulation coefficients were positive and significant with a 99% confidence level. This indicates they are good approximations to output and have a positive impact on costs.

As to the per capita income variable, its coefficient is significant and its sign is negative, as it was expected. This may suggest that more developed economies make more use of payment means other than currency, which is related to fewer needs for currency and lower costs. The denomination structure used by central banks was significant with a 90% confidence level and positive sign. This suggests that a central bank with fewer denominations could obtain lower printing costs.

Table 5. Results of the Panel Data Model

Dependent variable: Ln(*C*) Observations: 168, Random Effects – GLS Regression	
Intercept	10.3371 (1.50)
Ln (*N*)	0.5894 (4.35)***
Ln (*Circ*)	0.7395 (5.21)***
Ln (*Y*)	-0.1085 (-2.03)**
Ln (*Den*)	0.6740 (1.87)*
Ln (*Sec*)	w.s. (-0.71)
Ln (*Size*)	1.9855 (3.09)***
Priv	-0.0895 (-2.17)**
Gov	0.3402 (2.11)**
Wald (*p-value)*	293.59 (0.00)
Hausman (*p-value)*	2.7103 (0.93)

Symbols (*,**,***) indicate that the statistics are significantly different from zero at 1%, 5% and 10%, respectively.
w.s.: Wrong sign
Wald's test: Joint significance of the variables (Prob. > Chi 2)
Hausman's test: Differences in coefficients are not systematic (Prob. > Chi 2)
Source: Authors' calculations

Contrary to expectations, the coefficient of the variable including the number of security features (*Sec*) is negative and no significant. So, the variable is not a relevant determinant of costs. However, it is possible that what determines printing costs is the kind of security features used instead of the number. Unfortunately, this detailed information is hard to introduce in the model.[27]

Banknote size, as a variable pretending to detect an important feature of the product was proved to be highly significant and with the expected sign. In other words, a central bank's decision about the size of banknotes has a major impact on production costs. Therefore, adopting a smaller size of banknotes is a valid strategy to reduce those costs. This largely supports the decisions taken recently by a number of central banks in this respect (*e.g.* Colombia and Mexico).

One of the model's most relevant results concerns the coefficients of the variables related to production methods. These variables proved to be significant, confirming that the type of method a central bank selects to produce its banknotes does much to determine the cost of production. The coefficients obtained and their signs allow for some important conclusions, considering that the base method used in the model is the case where production is the responsibility of the central bank. To begin with, the costs are higher when governments are responsible for banknote production than when production is done by the central bank. In fact, the difference is substantial. The coefficient suggests that, in countries where the government is responsible for production, the cost is 34% higher, on average, than when the central bank is in charge of the production.

Secondly, the costs are less when a degree of private participation in banknote production is allowed, than when production is the exclusive responsibility of the central bank. These results confirm the decisions taken by some central banks to include private agents or companies who specialize in banknote production, be it through management agreements, the establishment of subsidiaries, the sale of their entire printing works, etc. The elasticity calculated on the basis of the coefficient points to the conclusion that a central bank may obtains annual costs reductions close to 9%, by involving the private sector in the production process.

[27] Other characteristics such as the use of polymer could affect printing costs. However, this variable couldn't be included in the model because only 3 central banks in the sample issue polymer banknotes (Australia, New Zealand and Thailand), and only Thailand presented changes over the period. This avoids a correct statistical inference over the variable.

3. Efficiency and Productivity Change in Banknote Printing

The estimation of a cost function let us to identify the determinants of the banknote printing costs, as well as the different strategies that central banks may use to reduce their printing costs. As a complement of this analysis, measures of technical efficiency on banknote printing and changes in productivity during the period are identified. These measures are obtained by estimating an efficient production frontier and by constructing the Malmquist index. The latter measure allows decomposing changes in productivity into changes in efficiency and technology through the years under study.

An efficiency frontier can be estimated through, whether the non-parametric approach Data Envelopment Analysis (DEA), or the parametric methodology Stochastic Frontier Approach (SFA).[28] Among the most recent applications to central banking is the study by Wheelock and Wilson (2004), which used a DEA model to gauge checks processing efficiency at the offices of the US Federal Reserve Bank (Fed). Under the SFA, Bohn et. al. (2001) assessed the efficiency of currency processing at the Fed's 37 branch offices. The same function was assessed by Sarmiento (2005), using a DEA model for 15 branch offices of central bank of Colombia during the years 2000-2004. An international comparison was developed by McKinley and Banaian (2005) using the SFA to evaluate the efficiency of monetary policy and financials supervision of 32 central banks from OECD and developing countries.[29]

As to productivity change, it can be estimated through either production/cost functions or the construction of index numbers using non-parametric methods. Under the latter approach, the Malmquist index was initially presented by Caves et. al. (1982) and widely

[28] The SFA presented by Aigner et. al. (1977) is based on the estimation of a cost or a production function (*e.g.*, Cobb Douglas or Trans-log), where the parameters make it possible to characterize the efficiency frontier. Under this approach, the error term is divided into two components: random error and technical inefficiency (See details in Kumbhakar and Lovell, 2000). On the other hand, the DEA methodology proposed by Charnes et. al. (1978), models a set of variables (input and outputs) and the type of returns to scale, through a linear programming model, which is optimized to obtain a technical efficiency index for each assessed unit (Cooper et. al., 2000).

[29] For more detailed analysis on efficient frontier models and their application on central banking, see Mester (2003) and Sarmiento (2007).

developed by Färe et. al. (1989), who decomposed variations in productivity, into efficiency and technology changes through time.[30]

A DEA input oriented model is used to evaluate technical efficiency on banknote printing for 28 central banks for the years 2000-2005. The same approach is used to calculate the Malmquist index and estimate changes in productivity and its components during the period under study.

Using the non-parametric approach to estimate efficiency and productivity measures doesn't impose a specific functional form for the production or technology structure (unknown in this case), contrary to the parametric approach. In addition, the Malmquist index doesn't require information about quantity and prices of inputs and outputs, as well as assumptions about profit maximization or cost minimization. These conditions are required to calculate Törnqvist and Ficher indexes, which are also used to measure changes in productivity. These two features make the Malmquist index a great instrument to identify productivity changes in public sector and central banking, where prices usually are not available (Coelli, 1998; Sarmiento, 2007)

3.1. Technical, Global and Scale Efficiency

Under the DEA approach, a production possibilities set (PPS) enveloped, convex and with strong availability of inputs and outputs is assumed. The PPS or technology, which is referred as *Z*, is composed by a vector *M* of inputs $x = (x_1,...,x_M)' \in R_+^M$, which is used to produce a vector *S* of outputs $y = (y_1,...,y_S)' \in R_+^S$.

After the production technology is defined, we have *N* central banks which consume *M* inputs to produce *S* outputs.[31] The central bank *j* consumes X_{ji} of input *i* and produces Y_{jr} of

[30] The Malmquist index has been widely applied to financial system, mainly for analyzing productivity changes after financial liberalization processes (See, Humphrey, 1993; Wheelock and Wilson, 1999; Park and Weber, 2006). A detailed review of the application of this methodology on financial system is presented by Berger and Mester (1997).

[31] Färe (1988) defines that inside the PPS of outputs $P(x)$ and the one of inputs $L(y)$, it is true that $(x, y) \in Z \Leftrightarrow y \in P(x) \Leftrightarrow x \in L(y)$. Given this relation, Z has strong inputs and outputs availability if for a productive process $(x, y) \in Z, \forall x' \geq x \Rightarrow (x', y) \in Z$ and $\forall y' \leq y \Rightarrow (x, y') \in Z$ or, alternatively if $x \in L(y), x' \in L(y), \forall x' \geq x$ and $y \in P(x), y' \in P(x), \forall 0 \leq y' \geq y$.

output r, assuming that $X_{ji} \geq 0$ and $Y_{jr} \geq 0$. In fact, X and Y are both matrixes MxN and SxN which contain all inputs and outputs corresponding to the N evaluated central banks. So, the model which allows measuring inputs technical efficiency for each central bank during the period t is (Charnes et. al., 1978):

$$\begin{aligned} &\underset{\theta,\lambda}{Min\theta} \\ &\quad r.t.\lambda X^t - \theta x_0^t \leq 0 \\ &\quad \lambda Y^t \geq y_0^t \\ &\quad \lambda \geq 0 \end{aligned} \tag{6}$$

The model stated in equation (6) pretends to minimize the inputs quantity used by the assessed central bank, where θ is a scalar accompanying each input, and λ an intensity vector (Nx1) weighting the input and output level of every central bank evaluated. The process is the same for each central bank j, by introducing in the model $(x_o, y_o) = (x_j, y_j)$. Therefore, a central bank is technically efficient if $\theta^* = 1$ and $\lambda^* = 0$; on the other hand, it is inefficient if $\theta^* < 1$ and $\lambda^* > 0$.[32]

The model assumes constant returns to scale (CRS), which implies that every central bank operates under an optimal production scale. Nevertheless, market failures and variables not controlled by central banks (*e.g.* demand for currency), may cause banks not producing at optimal scales. In fact, Banker *et. al.* (1984) study variable returns to scale (VRS) by incorporating to the equation (6) the restriction $e^T \lambda = 1$ (where e is a ones' vector of Nx1). This generates an additional convexity requirement where the production possibilities efficient frontier must have segments joining the extreme points. Then, with a CRS model a measurement of global technical efficiency (GTE), without scale efficiencies, is obtained; while using a VRS model a technical efficiency is found, and if a central bank is producing on an increasing or decreasing returns to scale zone is identified. The ratio of

[32] Nevertheless, a central bank may present $\theta^* = 1$ and $\lambda^* > 0$. This is a frontier point located in the weak zone of the efficiency frontier. In order to distinguish between a frontier point and an efficient frontier point, Seiford and Thrall (1990) state that the radial projection $(x_o, y_o) \rightarrow (\theta^* x_o, y_o)$ always takes to a frontier point, but the technical efficiency only is reached if $\theta^* x_o = X\lambda^*$ and $y_o = Y\lambda^*$, for every λ^*. Therefore, to reach technical efficiency, restrictions must be fulfilled with equalities.

both models allows finding out a scale efficiency (SE) measurement for every central bank as follows: $SE = \theta^{CRS} / \theta^{VRS}$.

3.2. Productivity Change: A Malmquist Index Approach

To estimate changes in productivity, the Malmquist index approach presented by Färe *et. al.* (1989) is used, where changes in productivity are determined by efficiency and technology changes through time. The Malmquist index is expressed as follows (See Appendix):

$$M_I(X^{t+1}, Y^{t+1}, X^t, Y^t) = \frac{D_I^{t+1}(X^{t+1}, Y^{t+1})}{D_I^t(X^t, Y^t)} \left[\left(\frac{D_I^t(X^{t+1}, Y^{t+1})}{D_I^{t+1}(X^{t+1}, Y^{t+1})} \right) \left(\frac{D_I^t(X^t, Y^t)}{D_I^{t+1}(X^t, Y^t)} \right) \right]^{1/2} \quad (7)$$

The first component in (7) calculates changes in technical efficiency (catch-up) by comparing the distance from a central bank to the efficiency frontier each year. If this ratio has a value higher than 1, the central bank is more efficient in period *t+1* than in period *t* (it is closer to frontier in period *t+1*). The opposite is interpreted if the ratio value is lower than 1. The second component in (7) calculates technical change or boundary shift of industry (in this case all central banks as a set) by comparing the distance between the efficiency frontiers in *t* and the one in *t+1*. Therefore, if the result of this component is higher than 1, the industry presented a positive technological shift, improving the central bank relative efficiency.

The result of multiplying both components is the Malmquist index. If it is higher than 1, the central bank increased its productivity during the period evaluated. This increase may be consequence of an increase in technical efficiency and/or a positive technological shift. When there are variables returns to scale (VRS), the change in efficiency may be divided into two other components: pure technical efficiency and scale efficiency (Färe et. al., 1994):

$$CE = \frac{D_I^{t+1}(X^{t+1}, Y^{t+1})}{D_I^t(X^t, Y^t)} = \frac{D_{VRS}^{t+1}(X^{t+1}, Y^{t+1})}{D_{VRS}^t(X^t, Y^t)} \times \frac{\dfrac{D_{CRS}^{t+1}(X^{t+1}, Y^{t+1})}{D_{VRS}^{t+1}(X^{t+1}, Y^{t+1})}}{\dfrac{D_{CRS}^t(X^t, Y^t)}{D_{VRS}^t(X^t, Y^t)}} \quad (8)$$

For the Malmquist index calculation, the non-parametric method (DEA) is used, assuming distance functions reciprocal to the input oriented technical efficiency measure defined above in equation (6) (Seiford and Thrall, 1990).

3.3. Results on Efficiency and Productivity Change

To measure technical efficiency and changes in productivity, printing costs and the size of banknotes were introduced as inputs in the model, for considering them as variables under the control of the central bank. On the other side, the number of denominations and the currency in circulation per inhabitant were introduced as output variables in the model. All of these variables showed high statistic significance as determinants of printing costs (Section 2). Estimations were calculated for the same 28 central banks used in the econometric model (see Annex 5).

Table 6 shows results of the three efficiency measures (technical, global and scale) calculated with model in equation (6). Results of the variable returns to scale model (VRS) show that during the period under study, 75% of central banks increased technical efficiency (TE) in banknote printing, and that the average technical efficiency index for central banks in the sample was 0.93. It is remarkable that the central banks of Bulgaria, Estonia and Slovenia are located at the efficiency frontier every evaluated period. These central banks produce banknotes under three different methods: subsidiary company, central bank and importation, respectively.

After examining the global technical efficiency (GTE), which results of calculating the model with CRS, a relevant decreasing of the efficiency index is observed, going down to 0.79 in average. This is a consequence of the CRS approach, where central banks are compared assuming that they operate at an optimal production scale. However, this is not a real situation for central banks due to market failures, particularly, differences in the currency demand behavior. This result is proved empirically through the scale efficiency index (SE), where it is observed that 68% of central banks are located in the decreasing returns to scale zone (drs), while 28% of central banks are located in the increasing returns to scale zone (irs). Only the central bank of Slovenia is in the constant returns to scale (crs) or optimal zone with an index equal to 1.

Table 6. Technical, Global and Scale Efficiency at Central Banks (2000-2005)

Central Bank	Method 1/	Technical Efficiency (TE-VRS)						Average (2000-2005)		
		2000	2001	2002	2003	2004	2005	TE (vrs)	GTE (crs)	SE
Germany	P.C	0,946	1,000	1,000	1,000	1,000	0,933	0,980	0,973	0,994 (drs)
Armenia	C.B	0,993	0,928	0,966	0,932	1,000	0,946	0,961	0,717	0,746 (irs)
Australia	S	0,940	0,961	0,972	0,990	0,996	0,995	0,976	0,790	0,810 (drs)
Austria	S	0,971	0,918	0,891	0,910	0,922	0,941	0,925	0,866	0,935 (drs)
Bulgaria	S	1,000	1,000	1,000	1,000	1,000	1,000	1,000	0,879	0,8792 (irs)
Canada	P.C	0,912	0,878	0,874	0,880	0,878	0,881	0,884	0,689	0,780 (drs)
Cyprus	I	1,000	0,876	0,999	0,958	0,915	0,895	0,940	0,591	0,628 (drs)
Colombia	C.B	0,878	0,867	0,888	0,913	0,921	0,927	0,899	0,714	0,794 (irs)
South Korea	G	0,776	0,757	0,773	0,782	0,782	0,778	0,775	0,553	0,714 (drs)
Denmark	C.B	0,938	0,937	0,918	0,925	0,930	0,931	0,930	0,732	0,788 (drs)
Slovenia	C.B	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000 (crs)
Spain	G	0,904	0,887	0,871	0,871	0,886	0,903	0,887	0,832	0,938 (drs)
Estonia	I	1,000	1,000	1,000	1,000	1,000	1,000	1,000	0,949	0,949 (drs)
Finland	P.C	0,896	0,891	0,968	0,958	0,966	0,949	0,938	0,841	0,897 (drs)
Holland	P.C	0,899	0,854	0,897	0,892	0,915	0,938	0,899	0,844	0,938 (drs)
Hungary	S	0,872	0,880	0,893	0,891	0,897	0,894	0,888	0,821	0,925 (irs)
England	P.C	0,797	0,806	0,814	0,828	0,833	0,829	0,818	0,633	0,774 (drs)
Ireland	C.B	0,984	0,947	0,893	0,908	0,935	0,937	0,934	0,845	0,904 (irs)
Israel	I	0,996	0,937	0,922	0,969	0,959	0,953	0,956	0,623	0,651 (drs)
Japan	G	1,000	1,000	0,898	1,000	1,000	1,000	0,983	0,969	0,985 (drs)
Luxembourg	I	1,000	0,986	0,975	1,000	1,000	1,000	0,994	0,905	0,911 (drs)
Norway	C.B	0,939	0,931	0,922	0,939	0,940	0,946	0,936	0,770	0,823 (drs)
New Zealand	I	0,954	0,967	1,000	0,993	1,000	0,986	0,983	0,726	0,738 (irs)
Poland	P.C	0,955	0,961	0,970	1,000	1,000	1,000	0,981	0,740	0,754 (drs)
Portugal	S	0,875	0,889	0,873	0,900	0,923	0,906	0,894	0,804	0,899 (irs)
Czech Rep.	G	0,927	0,926	0,925	0,928	0,932	0,941	0,930	0,906	0,975 (drs)
Sweden	P.C	0,905	0,879	0,877	0,902	0,911	0,904	0,896	0,725	0,809 (irs)
Thailand	C.B	0,815	0,794	0,816	0,838	0,846	0,845	0,826	0,663	0,803 (drs)
Average	..	0,931	0,916	0,921	0,932	0,939	0,934	0,929	0,789	0,848

1/ Method used for the banknote production in 2005. P.C: Private Company; C.B: Central Bank; S: Subsidiary; I: Importation; G: Government. T.E: Technical Efficiency (VRS model); ETG: Global technical efficiency (CRS model); S.E: Scale Efficiency (S.E = GTE/TE); drs: decreasing returns to scale; irs: increasing returns to scale; crs: constant returns to scale.
Source: Authors' calculations.

It is very useful to know the kind of scale returns because it allows identifying key aspects for the central banks performance. In fact, for central banks located in the increasing returns to scale zone (irs), an increase in the inputs level will result in more than proportional increases in the output level. For example, in the case of the central bank of Colombia, this means that a larger producing scale would generate a more than proportional increase in the production level. This confirms, in this case the construction of the *Central de Efectivo*, the Colombian complex for banknote printing and cash processing, that began operations in 2006.

Results of the Malmquist index and its components are shown in Table 7, where it is observed that central banks increased moderately their productivity, especially during the period 2004-2005 where they showed an increase of 1.7%. The larger productivity increasing was exhibited by the central banks of Portugal, Bulgaria, Austria, Australia, Colombia and Sweden with increases higher than 10%. The average productivity increase for the sample was 0.2%. It is worthy of notice that the 5 central banks producing banknotes through a subsidiary company are part of the 13 central banks with average productivity increases (38.5%). By producing methods, they are followed by central banks producing through private companies and by those producing banknotes with their own resources, with 3 central banks each.

Table 7. Malmquist Index, Technical and Efficiency Changes (2000-2005)

Central Bank	Method 1/	Malmquist Index					Average (2000-2005)				
		00 - 01	01 - 02	02 - 03	03 - 04	04 - 05	Malmquist Index	Technical Change	Efficiency Change	Pure Efficiency	Scale Efficiency
Germany	P.C	0,996	1,000	1,000	1,000	0,960	0,991	1,002	0,992	0,998	0,993
Armenia	C.B	0,974	1,018	1,033	0,997	0,966	0,998	0,961	1,037	0,992	1,048
Australia	S	0,994	0,986	1,023	1,018	1,051	1,014	1,039	0,975	1,011	0,965
Austria	S	0,986	1,002	1,000	1,047	1,031	1,013	1,015	0,999	0,994	1,003
Bulgaria	S	0,995	1,033	1,024	0,997	1,019	1,014	1,013	1,001	1,000	1,001
Canada	P.C	0,975	0,935	1,010	0,994	1,039	0,991	0,999	0,990	1,007	0,996
Cyprus	I	0,994	1,031	1,033	0,997	0,971	1,005	1,015	0,991	0,982	1,011
Colombia	C.B	0,995	1,002	1,003	1,056	1,005	1,012	0,937	1,069	1,011	1,057
South Korea	G	0,985	0,976	1,000	1,036	1,013	1,002	1,033	0,994	1,001	0,993
Denmark	C.B	0,966	0,950	1,015	1,003	1,046	0,996	0,988	0,993	0,998	0,994
Slovenia	C.B	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Spain	G	0,961	0,971	0,999	0,995	1,029	0,991	0,950	1,048	1,000	1,048
Estonia	I	0,976	1,009	1,004	0,999	1,003	0,998	0,984	1,010	1,000	1,010
Finland	P.C	0,977	0,994	1,022	1,010	1,007	1,002	0,934	1,072	1,012	1,056
Holland	P.C	0,972	0,988	0,992	1,014	1,049	1,003	0,977	1,026	1,009	1,015
Hungary	S	0,985	1,013	0,999	0,996	1,010	1,001	0,970	1,032	1,005	1,027
England	P.C	0,971	0,987	1,000	0,995	1,042	0,999	0,998	0,994	1,008	0,986
Ireland	C.B	0,963	1,005	0,999	1,023	1,029	1,004	0,983	1,021	0,991	1,032
Israel	I	0,973	0,955	1,000	0,995	1,025	0,990	1,001	0,989	0,992	0,998
Japan	G	1,000	0,988	1,009	0,977	1,006	0,996	0,990	1,002	1,002	1,001
Luxembourg	I	0,976	1,007	1,024	0,995	1,005	1,001	0,959	1,049	1,000	1,049
Norway	C.B	0,974	0,986	1,000	1,031	1,055	1,009	1,015	0,994	1,007	0,989
New Zealand	I	0,998	0,995	1,003	0,996	1,005	1,000	0,998	1,002	1,007	0,996
Poland	P.C	0,988	0,994	0,998	0,996	1,010	0,997	0,996	1,002	1,009	0,993
Portugal	S	0,986	1,057	1,005	1,016	1,027	1,018	0,968	1,051	1,007	1,044
Czech Rep.	G	0,981	1,004	0,999	0,995	1,018	0,999	0,990	1,006	1,003	1,003
Sweden	P.C	0,987	1,003	1,017	0,990	1,060	1,011	1,024	0,988	1,000	0,988
Thailand	C.B	0,994	1,002	1,001	0,999	0,997	0,998	0,999	0,999	1,007	0,992
Average	..	0,983	0,996	1,008	1,006	1,017	1,002	0,991	1,012	1,002	1,010

1/ Method used for the banknote production in 2005. P.C: Private Company; C.B: Central Bank; S: Subsidiary; I: Importation; G: Government.
Source: Authors' calculations.

In general, productivity increases are primarily a consequence of increases in efficiency and, in a lower proportion of technical change. In most of the cases, a positive change in efficiency is mainly the result of higher scale efficiency, while in a minor proportion of the closer location of central banks to the reference frontier efficiency (pure efficiency). This could obey to high increase in demand for currency; it has generated an important increase of the banknote production for most central banks. In Colombia, for example, banknote production has increased around 45% between 2000 and 2005, due to high demand for currency motivated for the financial transactions tax, which has reduced the use of checks and electronic payment methods.[33]

IV. Conclusions

The main modernization strategies implemented recently by central banks to deal with the growing demand for currency in the last few years are identified in this paper. The period under study witnessed a decline in the number of central banks producing banknotes and an increase in partial or total private involvement in the banknote production process (*e.g.*, Croatia, England, Sweden and Bulgaria). Another strategy is applied by central banks of Portugal and Colombia, where currency production, processing and distribution activities are combined under one roof, in a single complex.

It was identified that most of the Latin American central banks import their banknotes, which becomes a marketing opportunity for printing central banks in the region. Concerning to the denomination structure, central banks of developed countries were found to have fewer denominations than those of developing countries, which have issued new denominations in recent years (*e.g.* Bulgaria and Uruguay).

There are important differences in the use of security features on banknotes, which vary among countries and denominations, and are related with the material used to print banknotes (cotton paper or polymer). In fact, a tendency to the production of polymer banknotes was identified, especially in low denomination banknotes, which are those with the shortest circulation life (*e.g.* Brazil, Mexico and Chile). Regarding the size of banknotes, it was identified that the average size of banknotes is smaller in Latin America and in other developing countries than in advanced economies. In addition, a trend to reduce the size of banknotes was identified, usually making differences between denominations (*e.g.*, Colombia and Mexico).

[33] Arango *et. al*. (2006) showed that hidden economy also has been an important effect on the demand for currency in Colombia.

On the other hand, the comparative analysis of banknote printing costs showed major differences among central banks, primarily due to the size of the country's population and the amount of currency in circulation. The estimation of the cost function showed that the number of denominations and the size of banknotes are relevant factors determining printing costs. Consequently, reductions in these characteristics lead to major cost savings. Likewise, the method a central bank uses to produce banknotes also was found to be a determinant of printing costs. In fact, it was identified that government printing is the most costly method, while involving the private sector in the production process (*e.g.* joint ventures, subsidiaries, specialized companies) substantially reduces costs.

The efficient frontier model, found that most central banks have increased its technical efficiency during the period, especially in where the private-sector has involved. Likewise, the calculate of Malmquist index identified that central banks have showed a moderate increase in its productivity, primarily due to increases in efficiency and, in a lower proportion to technical change. In most of the cases, a positive change in efficiency is mainly the result of higher scale efficiency. This could obey to high increase in demand for currency.

This study identifies possible strategies to reduce banknote printing costs and to perform this function more efficiently. Among the most important strategies are decreasing the number of denominations circulating in the economy, reducing the size of banknotes, and involving the private sector to some extent in the production process. However, in some countries, there are economic and institutional conditions (*e.g.* counterfeiting level or hidden economy) that should be carefully assessed before the adoption of any of these strategies.

References

Aigner, D.J., Lovell, C.A.K and P.J. Schmidt. (1977). "Formulation and Estimation of Stochastic Frontier Production Function Models", *Journal of Econometrics*, No.6, pp.21-37

Amemiya, T. (1978) "A Note on a Random Coefficients Model" *International Economic Review*, Vol. 19, No. 3, October.

Arango, C., Misas, M, and E. López. (2006) "Economía subterránea en Colombia 1976-2003: Una medición a partir de la demanda de efectivo, *Ensayos sobre Política Económica*, No. 50. pp. 155-211, Banco de la República.

Banco de la República (2005). *Tendencias en Funciones y Planta de Personal de Bancos Centrales,* Department of Planning and Budget, Banco de la República, Bogotá, D.C., June. Available at: http://www.banrep.gov.co/banco/pdf/Bancos-centrales- tendencias.pdf

Banker, R.D., Charnes, A., and W. Cooper (1984). "Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis", *Management Science*, No. 30, Vol. 9, pp. 1078-1092.

Bank of England. (2003) "Sale of Bank Note Printing Operations", March. Available at: http://www.bankofengland.co.uk/publications/news/2003/041.htm

Battese, G.E. and Coelli T.I. (1995) "A Model for Technical Inefficiency Effects in a Stochastic Frontier Production Function for Panel Data", *Empirical Economics*, No. 20, pp. 325-32.

Baxter, A., Gerard, A. Melbourn, B. and B. Noble (2005) "Alternative Models for Outsourcing Banknote Services" in *Central Bank Modernisation* (eds.) Courtis, N. and Peter N., Central Banking Publications, London.

Berger, A.N. and L.J. Mester. (1997) "Inside the Black Box: What Explains Differences in the Efficiencies of Financial Institutions?", *Journal of Banking and Finance*, No. 21, pp. 895-947.

BIS. (2007) "Statistics on payment and settlement systems in selected countries" Prepared by the Committee on Payment and Settlement Systems of the Group of Ten Countries, Bank for International Settlements, March.

Bohn, J., Hancock, D. and P. Bauer (2001) "Estimates of Scale and Cost Efficiency for Federal Reserve Currency Operations", Research Department, Federal Reserve Bank of Cleveland, *Economic Review*, Q. IV, pp. 2-26.

Booth, G. (1989) *Currency and coin responsibilities of the Federal Reserve: A historical perspective,* Federal Reserve Bank of Cleveland, Cleveland.

Caves, D.W., Christensen, L.R. and W.E. Diewert. (1982) "The Economic Theory of Index Numbers and the Measurement of Input, Output, and Productivity", *Econométrica*, Vol. 50 No.6, pp. 1393-1414.

CEMLA. (2005) “Estadísticas Comparativas de Sistemas de Pago de América Latina y el Caribe 2000-2004”, Working Group on Payment Systems Issues of Latin America and the Caribbean. (GTSP-ALC), Centre for Latin American Monetary Studies CEMLA, December.

Charnes, A., W. Cooper. and E. Rhodes. (1978) “Measuring the Efficiency on Decision Making Units”, *European Journal of Operational Research*, Vol. 2, pp. 429-444.

Coelli, T.J., Prasada, D. and G. Battese (1998) *An Introduction to Efficiency and Productivity Analysis*, Kluwer Academic Publisher, Boston.

Cooper W., L. Seiford and K. Tone (2000) Data *Envelopment Analysis: A Comprehensive text with models, applications, references and DEA-solver software*, Kluwer Academic Publishers.

Daltung, S and M. Ericson (2004) “Cash-supply efficiency”, Sveriges Riksbank, *Economic Review*, No. 3, pp. 27-42, Stockholm.

De Gregorio, J. (2003) “Mucho dinero y poca inflación: Chile y la evidencia internacional”, *Documento de política económica,* Banco Central de Chile, September.

ECB. (2007) “Payment and securities settlement systems in the European Union”, European Central Bank, August.

Färe, R., S. Grosskopf, S., Lindgren, B and P. Roos. (1989) “Productivity Developments in Swedish Hospitals: A Malmquist Output Index Approach”, *Discussion Paper* No. 89-3, Southern Illinois University, Illinois.

Färe, R., S. Grosskopf, S. Norris. and Z. Zhang. (1994). “Productivity Growth, Technical Progress, and Efficiency Changes in Industrialised Countries”, *American Economic Review,* No. 84, pp. 66-83.

Galán, J. and M. Sarmiento. (2007) “Staff, Functions, and Staff Costs at Central Banks: An International Comparison with a Labor-demand Model”, *Money Affairs*, Vol. XX, No. 2, pp. 131-180, July-December, CEMLA.

Hernández, M., Jalil, M. and C. Posada (2006). “¿Por qué ha crecido tanto la cantidad de dinero?: Teoría y Evidencia Internacional (1975-2002)”, *Borradores de Economía*, Banco de la República, No. 402, August.

Hsiao, C. (2003) *Analysis of Panel Data*. Cambridge University Press, Cambridge.

Humphrey, D.B. (1993). “Cost and Technical Change: Effects from Bank Deregulation”, *Journal of Productivity Analysis*, No. 4, pp. 5-34.

Kumbhakar, S.C. and C.A.K. Lovell. (2000) *Stochastic Frontier Analysis*, Cambridge University Press.

Lacker, J. (1993) “Should we subsidize the use of currency?”, *Economic Quarterly*, Winter, pp. 47-73.

McKinley, V. and K. Banaian. (2005) "Central Bank Operational Efficiency: Meaning and Measurement" en *Central Bank Modernisation*, (eds.) Neil Courtis & Peter Nicholl, Central Banking Publications Ltd, London.

Mester, L. (2003) "Applying Efficiency Measurement Techniques to Central Banks", Federal Reserve Bank of Philadelphia and Finance Department, the Wharton School, University of Pennsylvania, *Working Paper,* No. 03-13.

Misas, M., Arango, C. and J. Hernández. (2004) "La Demanda de Especies Monetarias en Colombia: Estructura y Pronóstico", *Borradores de Economía*, Banco de la República, No. 309, October.

Mushin, J. (1998) "Modeling the currency issue", *Atlantic Economic Journal*, Vol. 26, No. 3, September.

Nishihara, R. (2006) "Central Bank Services-Focusing on Core Banking Operations: Cash, Account, and Settlement Services", Report for the 9th BOJ-EMEAP High-Level Workshop, Bank of Japan, May.

Park, K.H., and Weber, W.L. (2006) "A note on efficient productivity growth in the Korean Banking Industry, 1992-2002", *Journal of Banking and Industry*, No. 30, pp. 2371-2386.

Sarmiento, M. (2005) "Eficiencia técnica en el procesamiento de efectivo a cargo de las sucursales del Banco de la República", *mimeo*, Planning and Budget Department, Banco de la República, August.

Sarmiento, M. (2007) "Eficiencia en la Banca Central Moderna: Teoría, Evidencia y Lecciones para América Latina", *mimeo*, Work presented at the "Conferences Cycle on Central Banking", organized by the Central Bank of Ecuador, Quito, June 4-7

Seiford, L.M. and R.M. Thrall. (1990) "Recent Developments in DEA: The Mathematical Approach to Frontier Analysis", *Journal of Econometrics*, No. 46, pp. 7-38.

Symes, P. (1993). "Security features in world banknotes". Available at: www.pjsymes.com.au/articles/security.htm

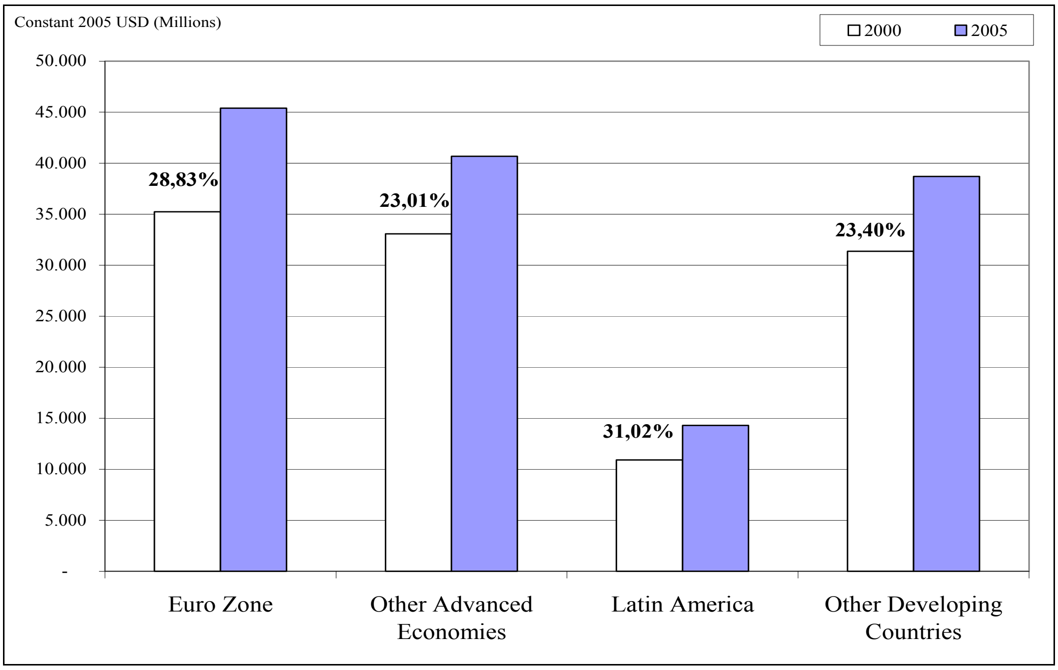
Wheelock, D. and P. Wilson. (1999) "Technical Progress, Inefficiency, and Productivity Change in U.S. Banking, 1984-1993", *Journal of Money, Credit, and Banking* Vol. 31, No.2, pp. 212-234.

Wheelook, D. and P. Wilson. (2004) "Trends in the Efficiency of Federal Reserve Check Processing Operations", *Federal Reserve Bank of St. Louis Review*, September/October 2004, Vol. 86, No. 5, pp.7-19.

Wellink, N. Chapple B. and P. Maier.(2002). "The Role of National Central Banks within the European System of Central Banks: The example of the Nederlandsche Bank", *MEB Series*, 2002-13, Netherlands' Central Bank, Monetary and Economic Policy Department.

Annex 1.

Figure A1. Currency in circulation (2000, 2005)



Source: Central Banks' Annual Reports (2000-2005). Authors' calculations.

Annex 2.

Table A1. Countries changing their denomination structure (2000, 2005)

Country	Denominations	
	2000	2005
Armenia	5	6
Austria	6	7
Belgium	6	7
Bosnia	7	8
Bulgaria	6	7
Colombia	4	6
Costa Rica	7	4
Finland	5	7
France	5	7
Germany	8	7
Greece	6	7
Holland	6	7
Hungary	6	7
Ireland	5	7
Luxembourg	3	7
Mexico	5	6
Portugal	5	7
Romania	5	6
Spain	4	7
Uruguay	8	9

Source: Central Banks' Annual Reports (2000-2005) and central bank's websites. Authors' calculations

Annex 3

Box A1 - Polymer Banknotes

Polymer substrate is a transparent film that darkens with the use of a special coating. The substrate transparency changes with the coating thickness. Polymer notes use traditional print processes similar to that of producing paper banknotes such as the offset process, intaglio, and letterpress printing; although they present some exclusive features like transparent window and diffractive elements. Nevertheless, since 2006, De La Rue and G&D have developed different technologies that allow introducing transparent windows in paper notes.

The circulation life of a polymer banknote is around three or four times that of paper. In addition, polymer notes can be recycled, are cleaner and more difficult to counterfeit. Although, the production costs of polymer notes are higher, their durability and circulation life is longer, so, they represent savings in the long term.

Australia is the leader in polymer notes production and it was pioneer issuing the first circulating polymer note in 1992. In 1996, it was the first country abandoning paper banknotes and issuing all the denominations in polymer. Additionally, Australia is the biggest exporter of these kinds of notes through *Note Printing Australia*, a subsidiary company of the central bank.

By 2005, 23 countries had issued at least one denomination in polymer and, there were more than 3.500 million of polymer banknotes circulating in the world. Only two countries have returned to paper notes. They did it in 2004 due to high production costs: Indonesia had issued the 100.000 Rupees note in 1999 and Thailand the 50 Baht note in 1997.

Source: Central Banks' Annual Reports (2000-2005) and central bank's websites.

Table A2. Countries that have issued polymer banknotes

Country	Introducing year of polymer banknotes	Number of denominations of polymer notes in circulation (2005)
Banknotes for General Circulation		
Australia[1]	1992	5
Brunei[2]	1996	3
Thailand[3]	1997	0
Sri Lanka	1998	1
Indonesia[4]	1999	0
New Zealand[5]	1999	5
Romania[6]	1999	7
Brazil[7]	2000	1
Bangladesh	2001	1
Salomon Island[8]	2001	1
Mexico[9]	2002	1
Papua - New Guinea[10]	2003	6
Vietnam[11]	2003	6
Zambia[12]	2003	2
Chile[13]	2004	1
Malaysia	2004	1
Singapore	2004	1
Nepal	2005	1
Nigeria[14]	2007	0
Hong Kong[15]	2007	0
Guatemala[16]	2007	0
Only Commemorative Banknotes		
Samoa	1990	0
Kuwait	1993	0
Northern Ireland	1999	0
Taiwan	1999	0
China	2000	0

[1] In 1988 Australia introduced the commemorative note of $10 AUD and in 1996 it was the first country issuing all denominations in polymer.
[2] The banknotes of 1, 5 y 10 Ringgit were the first no-commemorative notes alter Australia.
[3] In 1996 Commemorative notes were issued and in 1997 it was issued the 50 Baht note for circulation. Nevertheless, Thailand came back to paper notes in 2004.
[4] In 1999 it was issued for general circulation the 100.000 Rupees note. In 2004 Indonesia came back to paper notes.
[5] Banknotes are imported from Australia. In 1999 they issued all denominations in polymer.
[6] In 1999 it was the first European country issuing all denomination in polymer.
[7] Brazil was the first Latin American country issuing a polymer note for circulation. In 2000 the 10 Reais note was issued.
[8] In 2001 it was issued the $2 polymer note; however, in 2006 it was issued again in paper.
[9] In 2002 Mexico issued the $20 pesos polymer note and in 2006 issued in polymer a new $20 note and a $50 note.
[10] In 1991 the 2 Kina commemorative note was introduced. In 2003 the 20 Kina polymer note was issued and they started a process to issue all denominations in polymer. By 2007, they have issued in polymer 6 of 7 denominations circulating.
[11] In 2001 the commemorative 50 Dong note was issued. Between 2003 and 2006 they issued all denominations in polymer.
[12] It was the first African country issuing a polymer note. In 2003 the 500 and 1000 Kwacha notes were issued.
[13] In 2004 the $2000 pesos note was issued for general circulation.
[14] In 2008, Nigeria will be the first African country issuing all denomination in polymer.
[15] In 2007 the 10 Dollars polymer note was issued for a 2 years testing period.
[16] Ending 2007, Guatemala will issue the 1 Quetzal note in polymer.
Note: Bulgaria issued in 2005 a hybrid paper – polymer note. It is under a test period.
Source: Central Banks' Annual Reports (2000-2005) and central bank's websites.

Box A2 - Security Features Most Commonly Used in the Production of Banknotes

Watermark
A security feature that has come to be regarded as standard in the production of paper money. The watermark process consists of providing various layers of thickness to the paper for different levels of humidity in the drying process. It gives the note a variety of shades when held against the light.

Security Thread
A security feature embedded into the cotton-fiber paper when it is made. A security thread can be synthetic or metallic. It can be windowed (showing the appearance of a weave through the paper) and can contain micro-inscriptions, holograms, florescent ink, color changing ink, etc.

Intaglio Printing or Chalcographic Engraving
A special technique that adds layers to the ink used to print certain elements of the banknote, such as characters, graphics, signatures, serial numbers, portraits, the value for each denomination, etc.

Perfectly Matched Drawing and Matching Image
A security feature made by printing two pictures simultaneously on the sides of the banknote to form a perfectly matched whole or symbol. Some banknotes include a reverse matching image printed on the obverse side, which complements the image printed on the reverse side, forming a new image when the banknote is held against the light.

Hidden or Latent Image
A security feature that is hidden from normal view and visible only under certain conditions, for example, when the banknote is placed at a certain angle or held against the light.

Observation Under Ultraviolet Rays
The use of florescent ink or florescent inlays in the paper, such as fibers, threads or bands, provides for certain effects when the banknote is observed under ultraviolet rays, making it possible to distinguish elements not visible before, visible elements that change color, or elements that glow brighter under ultraviolet rays.

Special Inks
Colored ink: Ink prepared with special mixtures to obtain colors that are difficult to reproduce with conventional equipment.
Color changing ink: Ink that changes the color of a feature. The color changes when the banknote is held at different angles.
Magnetic ink: Used mainly for serial numbers. It allows them to be read by equipment with a magnetic field.

Micro-inscription
A technique for printing characters or a special message that appears as a fine line on the banknote when seen with the naked eye, but is visible under a magnifying glass.

Contrasting Elements: Hologram
A security feature that allows various elements of the banknote, such as images, symbols or values, to be seen in three-dimensional form or to alternate with other elements when the banknote is viewed from different angles.

Source: Symes (1993) and central banks' websites.

Table A3. Most common security features of banknotes (2005)

Country	Polymer	WM	ST	IP	PMD	Hol	HI	UV	MI	CCI	Total
Euro Zone		x	x	x	x	x	x	x	x	x	9
Other Adv. Econ.											
Australia	x			x	x		x	x	x	x	6
Canada		x	x	x	x	x	x	x	x	x	9
Cyprus		x	x	x	x	x	x	x		x	8
Denmark		x	x	x		x	x	x	x	x	8
England		x	x	x		x		x	x		6
Hong Kong	x	x	x	x	x	x	x	x		x	8
Iceland		x	x	x				x	x		5
Israel		x	x	x	x	x		x	x	x	8
Japan		x		x		x	x	x	x	x	7
New Zealand	x			x	x		x	x	x		5
Norway		x	x		x	x	x	x	x	x	8
South Korea		x	x				x		x	x	5
Sweden		x	x	x	x	x	x	x	x	x	9
United States		x	x						x	x	4
Latin America											
Argentina		x	x	x	x		x		x	x	7
Bolivia		x	x	x	x		x	x	x		7
Brazil	x	x	x	x	x		x		x		6
Chile	x	x	x	x	x		x			x	6
Colombia		x	x	x	x		x	x	x	x	8
Costa Rica		x	x	x	x		x		x		6
Dominican Rep.		x	x	x				x	x	x	6
Guatemala[1]		x	x	x	x	x		x	x		7
Mexico	x	x	x	x	x			x	x	x	7
Nicaragua		x	x	x	x	x		x	x	x	8
Paraguay		x	x	x	x	x	x	x	x		8
Peru		x	x	x			x		x	x	6
Uruguay		x	x	x	x	x	x	x	x		8
Venezuela		x	x	x	x	x	x	x	x	x	9
Other Develop. C.											
Albania		x	x	x	x	x	x	x	x	x	9
Armenia		x	x	x	x				x		5
Bangladesh	x	x	x	x	x	x	x		x	x	8
Bosnia		x	x	x	x		x		x		6
Bulgaria		x	x	x	x	x		x	x	x	8
Croatia		x	x	x	x		x	x	x	x	8
Czech Rep.		x	x		x			x	x	x	6
Estonia		x	x	x		x	x	x	x	x	8
Hungary		x	x	x	x	x	x	x	x	x	9
Malaysia	x	x	x	x	x		x		x		6
Poland		x	x		x	x	x	x	x	x	8
Romania	x		x	x	x			x	x	x	6
Slovakia		x	x	x	x		x	x	x	x	8
Slovenia		x	x	x	x			x	x	x	7
Thailand[2]		x	x	x	x	x	x	x	x	x	9
Turkey		x	x	x	x		x	x	x	x	8
Total	**10**	**41**	**41**	**39**	**35**	**21**	**30**	**33**	**40**	**32**	

Note: WM: Watermark; ST: Security thread; IP: Intaglio printing; PMD: Perfect matching drawing; Hol: Holograms; HI: Hidden image; UV: Observation under ultraviolet rays; MI: Micro-inscriptions; CCI: Color changing ink.

[1] Guatemala will issue a polymer note soon. [2] In 2004, Thailand returned to paper alter using polymer.

Source: Central Banks' Annual Reports (2000-2005) and central bank's websites. Authors' calculations.

Annex 4

Table A4. Banknote printing costs (average 2000 – 2005)

Central Bank	Average printing costs per year[1]	Printing costs vs. GDP[2]	Printing costs as a percentage of operational costs[3]	Cost per produced banknote[4]
Estonia	$509.885	$0,5880	3,95%	..
Armenia	$650.835	$2,2071	8,97%	..
Slovenia	$694.686	$0,2672	2,20%	$ 0,039
Cyprus	$834.281	$0,6845	2,86%	..
New Zealand	$1.429.484	$0,1897	6,73%	..
Luxembourg	$1.490.411	$0,5827	4,10%	..
Israel	$3.292.655	$0,2887	1,71%	..
Bulgaria	$4.462.928	$2,3769	14,22%	$ 0,055
Denmark	$4.491.171	$0,2254	4,78%	..
Czech Rep.	$7.090.582	$0,8325	1,82%	$ 0,079
Norway	$8.182.138	$0,3830	3,67%	$ 0,113
Finland	$9.221.025	$0,6053	8,64%	..
Australia	$9.232.025	$0,1825	7,49%	..
Ireland	$9.436.190	$0,6669	12,95%	$ 0,055
Hungary	$13.376.340	$1,7526	15,95%	..
Sweden	$16.649.807	$0,5866	12,09%	..
Colombia	$16.884.348	$1,8570	10,61%	$ 0,027
Canada	$17.508.515	$0,2061	12,73%	..
Holland	$25.281.483	$0,5303	8,13%	..
Portugal	$26.148.199	$1,9014	9,20%	..
Poland	$27.361.343	$1,2364	9,40%	$ 0,100
Austria	$33.828.479	$1,4028	12,58%	..
Thailand	$45.002.927	$3,1903	44,01%	$ 0,023
England	$60.551.726	$0,3443	18,73%	$ 0,070
South Korea	$61.136.159	$1,0144	19,62%	$ 0,052
Spain	$95.034.242	$1,1590	22,90%	..
Germany	$135.992.422	$0,5921	7,28%	..
Japan	$586.364.623	$1,3377	27,09%	$ 0,166

[1] Annual average cost in 2005 constant dollars.
[2] Cost per each USD$10.000 of GDP, in 2005 constant dollars.
[3] Printing cost as a percentage of all the central bank's operational costs.
[4] Average cost per each banknote produced, in 2005 constant dollars.
Source: Central Banks' Annual Reports (2000-2005). Authors' calculations.

Annex 5

Table A5. Variables used in the panel data model (Sample: 28 countries; Years: 2000 – 2005; Observations: 168)

Variable	Average	Maximum	Minimum	Standard Dev.
*C**	43,72	665,14	0,18	118,10
*N**	24.269,8	127.956,0	438,0	29.401,5
*Circ**	45.286	722.159	138,38	131.596
Y	22.482	75.189	571,21	15.844
*Den**	5,7	9,0	3,0	1,5
Seg.	7,0	11,9	3,0	2,1
*Tam**	103,6	119,1	84,8	7,7

*/ Variables used in the estimations of the efficient frontier model and the Malmquist index
C: Printing costs in millions of 2005 constant dollars.
N: Population in thousands of inhabitants.
Circ: Currency in circulation in millions of 2005 constant dollars.
Y: GDP per. capita in 2005 constant dollars..
Den.: Number of denomination in circulation
Sec: Number of average security features of circulating banknotes.
Size: Average size of circulating banknotes in cm^2.
Source: Central Banks' Annual Reports (2000-2005). Authors' calculations.

Table A6. Methods used by central banks to produce banknotes (Panel data 2000-2005)

Country	Central Bank		Private Company		Government		Subsidiary[a]		Importation	
	2000	2005	2000	2005	2000	2005	2000	2005	2000	2005
Germany	..	..	X	X	..	..	..	..	..	..
Armenia	X	X	..	..	..	..	..	..	..	..
Australia	..	..	..	..	..	..	X	X	..	..
Austria	..	..	..	..	..	..	X	X	..	..
Bulgaria	X	..	..	..	..	..	..	X	..	..
Canada	..	..	X	X	..	..	..	..	..	..
Cyprus	..	..	..	..	..	..	..	..	X	X
Colombia	X	X	..	..	..	..	..	..	..	..
South Korea	..	..	..	..	X	X	..	..	..	..
Denmark	X	X	..	..	..	..	..	..	..	..
Slovenia	X	X	..	..	..	..	..	..	..	..
Spain	..	..	..	..	X	X	..	..	..	..
Estonia	..	..	..	..	..	..	..	..	X	X
Finland	..	..	X	X	..	..	..	..	..	..
Holland	..	..	X	X	..	..	..	..	..	..
Hungary	..	..	..	..	..	..	X	X	..	..
England	X	..	..	X	..	..	..	..	..	..
Ireland	X	X	..	..	..	..	..	..	..	..
Israel	..	..	..	..	..	..	..	..	X	X
Japan	..	..	..	..	X	X	..	..	..	..
Luxembourg	..	..	..	..	..	..	..	..	X	X
Norway	X	X	..	..	..	..	..	..	..	..
New Zealand	..	..	..	..	..	..	..	..	X	X
Poland	..	..	X	X	..	..	..	..	..	..
Portugal	..	..	..	..	..	..	X	X	..	..
Czech Rep.	..	..	..	..	X	X	..	..	..	..
Sweden	X	..	..	X	..	..	..	..	..	..
Thailand	X	X	..	..	..	..	..	..	..	..

[a] Including joint ventures.
Source: Central Banks' Annual Reports (2000-2005). Authors' calculations.

Appendix

The Malmquist Index Approach

The starting point on this approach is the definition of a set Z^t (production technology), inside which the transformation of inputs $X^t \in R_+^M$ into outputs $Y^t \in R_+^S$ is produced. This process takes place for each time period $t = 1,...,T$, where it is valid that $Z^t = [(X^t, Y^t): X^t$ can produce $Y^t]$. The Malmquist index is founded on the distance functions introduced by Shephard, which in the case of input orientation is represented as follows:

$$D_I^t(X^t, Y^t) = \max\left[\theta \geq 1 : (X^t/\theta, Y^t) \in Z^t\right] \tag{9}$$

Equation (9) seeks is to maximize the radial input contraction to reach a given output level on period *t*. By the same way, on period *t+1* the distance function is determined by $D_I^{t+1}(X^{t+1}, Y^{t+1})$. For intra period comparison, it is necessary to define a distance function $D_I^t(X^{t+1}, Y^{t+1})$, where the (X^{t+1}, Y^{t+1}) combination is viable in relation with technology in *t*. In addition, it is necessary a distance function $D_I^{t+1}(X^t, Y^t)$, where the (X^t, Y^t) combination is possible under technology in period *t*+1. After the definition of the distance functions, it is possible to define the Malmquist index as:

$$M_I(X^{t+1}, Y^{t+1}, X^t, Y^t) = \left[\frac{D_I^t(X^{t+1}, Y^{t+1})}{D_I^t(X^t, Y^t)} \times \frac{D_I^{t+1}(X^{t+1}, Y^{t+1})}{D_I^{t+1}(X^t, Y^t)}\right]^{1/2} \tag{10}$$

Equation (10) shows that Malmquist index is the geometric mean of two indexes, which use technology in *t* and *t+1* as a reference. This equation can be formulated to obtain changes in productivity, which are determined by changes in efficiency and technological changes through time, as it is expressed in chapter III equation (7).

Measuring changes in productivity for central banks between *t* and *t+1* requires solving four linear programming problems using the non-parametric method (DEA): $D_I^t(X^t, Y^t)$, $D_I^{t+1}(X^t, Y^t)$, $D_I^t(X^{t+1}, Y^{t+1})$, $D_I^{t+1}(X^{t+1}, Y^{t+1})$. To solve this, it is assumed that each central bank $j = 1,2,\ldots, N$, employs $m = 1,2,\ldots,M$ inputs $x_m^{t,j}$ to produce $s = 1, 2,\ldots,S$ outputs $y_s^{t,j}$. Solving the first problem, including technology and observations in period *t*, implies that the following problem for the *j´* central bank must be solved:

$$D_I^t(X^{t,j'}, Y^{t,j'}) = \min \theta^{j'} \tag{11}$$

$$r.t. \quad \sum_{j=1}^{N} \lambda^{t,j} x_m^{t,j} = \theta^{j'} x_m^{t,j'}$$

$$\sum_{j=1}^{N} \lambda^{t,j} y_s^{t,j} = y_s^{t,j'}, \quad \lambda^{t,j} \geq 0$$

Likewise, the distance function $D_I^{t+1}(X^{t+1}, Y^{t+1})$ is calculated by replacing *t* for *t+1* in equation (11). When distance functions require information from both periods simultaneously, the problem is:

$$D_I^t(X^{t+1,j'}, Y^{t+1,j'}) = \min \theta^{j'} \qquad (12)$$

$$r.t. \quad \sum_{j=1}^{N} \lambda^{t,j} x_m^{t,j} = \theta^{j'} x_m^{t+1,j'}$$

$$\sum_{j=1}^{N} \lambda^{t,j} y_s^{t,j} = y_s^{t+1,j'}, \quad \lambda^{t,j} \geq 0$$

In equation (12) the reference technology for the evaluated central bank $(X^{t+1,j'}, Y^{t+1,j'})$ is that of period *t*. Therefore, $D_I^t(X^{t+1,j'}, Y^{t+1,j'})$ may take values above 1; contrary to the situation in equation (11), where $(X^{t,j'}, Y^{t,j'}) \in Z^t$ and $D_I^t(X^{t,j'}, Y^{t,j'}) \leq 1$. In the case of distance function $D_I^{t+1}(X^t, Y^t)$, the problem to solve is the one in equation (12) but exchanging the time periods. In order to decompose the shift in efficiency into pure and scale efficiency, the distance functions using (VRS) are calculated by including the restriction $\sum_{j=1}^{N} \lambda^{t,j} = 1$ to the previous problems.