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ABSTRACT

High-quality information and communication technology (ICT) infrastructure is essential for developing countries to achieve rapid economic growth. International trade and the structure of the global economy require a level of integration that is achievable only with sophisticated infrastructure. Since the early 1990s, international institutions have been pushing developing nations to deregulate and heavily invest in ICT infrastructure as a strategy for accelerating socioeconomic development. After more than a decade of continued investments, some countries have still not achieved expected outcomes. Recently, the International Telecommunications Union (ITU) has called for empirical research to assess the performance and impact of ICT expansion in developing countries. In this article, we respond to this call by investigating factors affecting the efficiency of ICT expansion in five emerging economies in Latin America. Our findings demonstrate that deregulation is not enough to effect efficient ICT expansion, and we argue that existing conditions (economic factors, human capital, geography, and civil infrastructure factors) must also be considered. We conclude by asserting that policy makers can more easily realize socioeconomic development via ICTs if they consider these conditions while cultivating their technology strategies. © 2009 Wiley Periodicals, Inc.

Keywords: IT4D; emerging economies; Latin America; ICT expansion; social and economic development

1. INTRODUCTION

Many researchers argue that information and communication technology (ICT) infrastructure is essential to the rapid development of emerging economies (Cronin et al., 1993; Dholakia & Harlam, 1994; Jukka & Pohjola, 2002; Madon, 2000; Pohjola, 2001; Röller & Waverman, 2001). Others have argued that too much stock is given to ICT expansion as an engine of growth, while not enough attention is given to human capital, health, and civil infrastructure (roads, clean water, electricity, etc.) (Bollou, 2006; Fielding, 2002; Kneller, 2005; Lamberton, 2001; Nwagwu, 2005; Von Lubitz & Wickramasinghe, 2006). However,

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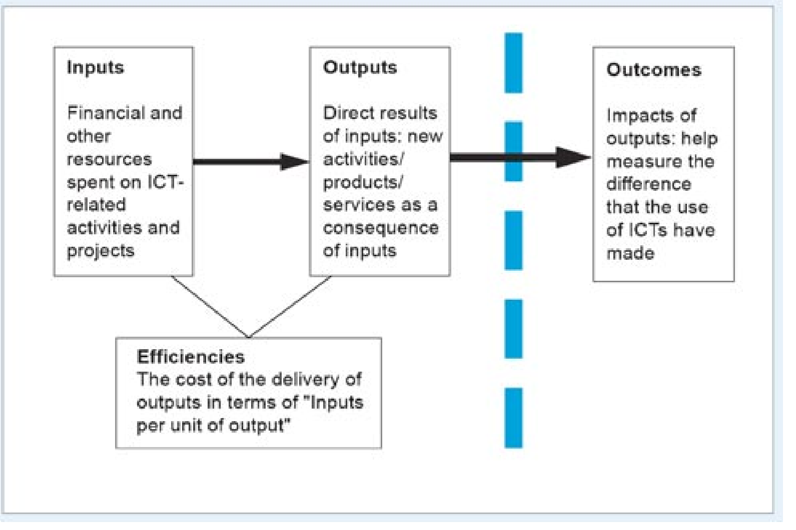
proponents of ICT infrastructure expansion argue that it facilitates the movement of capital and the coordination of global production and transportation, as well as allows for new methods of cross-border investments and the expansion of services (Antonelli, 2003; Carayannis & Sagi, 2002; Henderson et al., 2002; Kumar, 2005; Werthner & Klein, 1999; Zaheer & Manrakhan, 2001). These activities are now viewed as vital to the new global economy, in which connectivity and seamless communication are revolutionizing the structures of economic exchange. Furthermore, some researchers have also argued that the impact of ICTs extends well beyond the economic domain, having positive spillover effects on numerous dimensions of social life. For example, these technologies have been harnessed to enhance learning (Aduwa-Ogiegbaen & Iyamu, 2005; Kankaanranta, 2005), improve health care (Branko, Lovell, & Basilakis, 2003; Von Lubitz & Wickramasinghe, 2006), empower marginalized women (Gurumurthy, 2003; Huyer, 2005), promote indigenous knowledge (Jain, 2006), and maintain good governance (Meso, Datta, & Mbarika, 2005). Under the assumption that ICTs are essential to rapid socioeconomic progress, institutions such as the World Bank, International Telecommunications Union (ITU), and International Monetary Fund (IMF) have been pushing emerging economies to invest heavily in ICT infrastructure expansion.

The idea that all emerging economies can achieve high rates of economic growth by expanding their ICT infrastructures has come under intense scrutiny (Estache, Perelman, & Trujillo, 2005; Gasmi, Laffont, & Sharkey, 2000; Gutierrez & Berg, 2000). Although some emerging economies have managed to achieve significant outcomes in ICT expansion and economic growth, others still face significant difficulties. In a 2002 report on a study of 60 countries, *The Economist* cautioned that developing countries may not see the same returns on their ICT investments as developed countries. According to this study, ICT begins to deliver gross domestic product (GDP) per capita growth only after a certain threshold of ICT development is attained. Others have argued that unlike developed countries, developing countries have little of the supporting infrastructure necessary for the expansion and utilization of the productive capacity of ICTs (UNCSTD, 1997). As such, development via ICTs is difficult. For development via ICTs to occur in developing countries, national governments must first cultivate an environment that is conducive to ICT expansion and recognize the factors that may hinder this process. Most research investigating ICT expansion has focused on the impact of privatization on network expansion and efficiency (Baliamoune-Lutz, 2003; Birdsall & Nellis, 2003; Evarsito, 1998; Gutierrez & Berg, 2000; Ros, 1999) or discussed the institutional and socioeconomic barriers to technology adoption and development (Parente & Prescott, 1994; Strang & Meyer, 1993). Bollou (2006) suggests that factors such as landscape or GDP per capita may also affect ICT expansion rates. He notes, however, that more research is needed to identify these factors and to measure the effect that they have on ICT expansion. A key limitation of current research is the decoupling of ICT infrastructure from other civil infrastructure (Henderson et al., 2002; Kessides, 2004). Unless the focus is on the production and marketing of digital goods and services, other civil infrastructures are essential components of the global trade network. In this article, we investigate factors other than deregulation that affect the efficiency of ICT expansion in the context of emerging Latin American economies.

1.1 Measuring the Impact of ICT

Researchers have acknowledged that it is quite challenging to measure the impact of ICT on socioeconomic development (Lamberton, 2001; Lishan & Wood, 1999; Pohjola, 2002).



Source: International Telecommunications Union (ITU) (2006).

Figure 1 Measuring the impact of ICT on social development.

In their 2006 ICT Development Report, the ITU states that to understand whether real progress is being made toward socioeconomic development via ICTs, it is necessary to measure progress at the national level. The ITU proposes a two-phase measuring process: Phase 1 is concerned with the measurement of efficiencies of ICT investments with regard to infrastructure expansion and the cost of providing ICT services, whereas Phase 2 is concerned with measuring the impact of ICT on specific social indicators (Figure 1). According to the ITU, "one of the key arguments for using ICTs is that if they work well, they are capable of delivering social services both more effectively and at a lower cost. Therefore it is important to measure the cost of delivery, in terms of input per unit of output [. . . .] Without the ability to make these kinds of comparisons, it becomes significantly harder, if not impossible, to track the impact of ICTs." We agree with the ITU that there is a need to develop approaches to measuring the impact of ICT on economic development. However, the problem is not simply that of determining efficiency of ICT infrastructure, its utilization, and determining the impacts on social indicators. If we are to reap the benefits of ICTs, we must first note the factors that might impede ICT infrastructure expansion and utilization in developing countries. Only with such information can we design appropriate strategies to manage these factors and to avoid the misallocation of valuable resources.

In this article, we contribute to Phase 1 of the discourse by measuring efficiencies of ICT investments in relation to infrastructure expansion, as well as the cost of the ICT services. We do this by (1) proposing a process for measuring the efficiency of ICT infrastructure expansion, (2) investigating factors other than privatization that impact the efficiency of ICT expansion, and (3) providing a cross-country analysis of such efficiency measures. Our research follows a two-step approach and uses two methods, data envelopment analysis (DEA) and Tobit regression (Bowlin et al., 1985). First, we use DEA and archival data to investigate the efficiency of ICT expansion in five emerging Latin American economies—Argentina, Brazil, Colombia, Chile, and Peru—for the years 1994–2001. We then use Tobit regression analysis to investigate the impact of existing conditions (civil infrastructure, human capital, and economic factors) on ICT expansion. Such an analysis will allow us to gauge how national governments are using their financial and human resources for the expansion of ICT infrastructure. It will further allow us to make inferences regarding the numerous other factors that may hinder expansion rates.

2. SETTING THE CONTEXT FOR ANALYSIS

Before we move on to examine the technical efficiency of ICT expansion, we briefly set the context for this investigation. As mentioned previously, we have chosen to incorporate five Latin American countries into this study. Although these countries differ in their level of social and economic development, they have all been considered emerging economies in the literature (Arnold & Quelch, 1998; Hoskisson et al., 2000). According to Hoskisson et al. (2000), an emerging economy satisfies two criteria: (1) the nation is undergoing a rapid pace of economic development, and (2) the national government is focusing on economic liberalization along with the adoption of a free market system. Within the countries used in our sample, it was the 1980s debt crises that instigated this move toward economic liberalization (Gutierrez & Berg, 2000; Ros & Banerjee, 2000). During this period, the national governments of these countries faced instances of high foreign debt, rising inflation and unemployment rates, and perceived risks of political instability. In reaction to such threat, they moved toward market liberalization as a strategy for stimulating economic growth. The debt crises also had profound implications for the ICT environment in these Latin American countries (Gutierrez & Berg, 2000). Because Latin American governments were no longer able to maintain, expand, or modernize their national telecommunication infrastructures, there was a move toward privatization. It has been estimated that between 1984 and 1997, 14 of 24 Latin American nations undertook a process of full or partial privatization (Gutierrez & Berg, 2000). Chile was the first to privatize in 1987, followed by Argentina in 1990, Colombia and Peru in 1994, and finally Brazil in 1998 (Gutierrez & Berg, 2000). This trend toward privatization was coupled with new types of regulatory regimes that were meant to stimulate competition and thereafter improve effiency. The nature of the regulatory landscape continues to differ between countries as national governments have divergent strategies to ensure the sustainable growth of their ICT sectors.

A few studies have investigated ICT expansion in Latin America. For example, Gutierrez and Berg (2000) examine the impact of privatization on ICT expansion in 19 Latin American countries between 1985 and 1995. They conclude that privatization, together with the effective regulation of the telecommunications environment, is an important determinant of telecommunications density. Ros (1999) found that privatization was positively correlated with network expansion; Ros and Banjeree (2000), who studied telecommunications in 23 Latin American countries from 1986 to 1995, conclude that privatization resulted in higher-quality networks. More recently, Gutierrez (2003) argues that privatization with a sound regulatory environment is crucial to network deployment and efficiency. What is missing from these studies, however, is how factors such as civil infrastructure development, knowledge, and economic status impact ICT expansion efficiency.

3. RESEARCH APPROACH AND METHOD

It is vital to note the importance of ICT infrastructure to the permeation and utilization of communication technologies. To illustrate this point, we introduce a three-stage model of ICT expansion: Stage 1 includes the deployment or expansion of ICT infrastructure in order to develop the capacity for extensive utilization; Stage 2 includes the adoption and utilization of ICT by individuals and enterprises in society; and Stage 3 involves the intensification/informatization of business, public, and government services. We are not suggesting these stages do not overlap. Rather, they have a recursive relationship. For example, infrastructure expansion will often increase utilization. Similarly, when a critical mass of utilization has been achieved, it will trigger demand for more infrastructure expansion; subsequently, Stage 3 begins when intensification of services appears. We believe that it is necessary to examine efficiencies at each stage and to investigate the numerous factors that may impede this process of ICT expansion. Such an examination can help policy makers develop policies and incentive structures for each stage of this process (ICT infrastructure expansion, ICT adoption, and ICT intensification). It can also help them understand how various contextual factors can impact ICT infrastructure expansion. In the next section, we illustrate our approach to conducting efficiency analysis at Stage 1. It must be noted that this approach is general and can be adopted to analyze any stage of the evolutionary process.

3.1 Research Methods

In this research, we employ data envelopment analysis[1] (DEA) in conjunction with Tobit regression. Our rationale for using DEA is that it is well known and recognized as an effective method for analyzing the relative efficiency of decision-making units (DMUs), which can be organizations, industries, or countries (Bollou, 2006; Chen & Zhu, 2004; Färe & Grosskopf, 2004; Shafer & Byrd, 2000; Wang, Gopal, & Zionts, 1997). DEA uses a nonparametric linear programming technique for evaluating the relative performance of DMUs (countries, regions, firms in an industry sector, departments, etc.) responsible for converting inputs into outputs. The DEA model[2] generates a relative efficiency score for each DMU with values ranging from 0 to 100, where 100 represents maximum efficiency compared to all other DMUs in the study. The most efficient DMU represents the "best practice" or benchmark unit. All inefficient units are meant to compare their practices to efficient ones and possibly improve their performance. Because DEA does not use statistical dependencies between the variables, as does ordinary production function analysis, it is difficult to make statistical inferences about factors affecting efficiency. For that reason, we use Tobit regression analysis as a complementary method to enable researchers to investigate hypotheses about factors influencing performance (Tobin, 1958). It is common practice to use DEA and Tobit regression analyses as complementary methods for studies such as ours (for a detailed discussion of this approach, see Bogetoft, 1997; Bowlin et al., 1985; McDonald & Moffitt, 1979).

3.2 Evaluating Efficiency

In the DEA approach, efficiency is decomposed into two components: technical and allocative (Deliktas & Kok, 2003). Technical efficiency measures the ability of a DMU to

[1]Our interest here is a brief summary of DEA concepts relevant to our study. For a detailed discussion on the DEA methodology, readers are encouraged to examine Charnes, Cooper and Rhodes (1978, 1979, 1981).

[2]The DEA can be either input or output oriented. An input-oriented model defines the efficiency frontier by indicating the maximum reduction in input usage with output levels held constant for the DMU. The output-oriented model describes the increase in output production with input levels held constant.

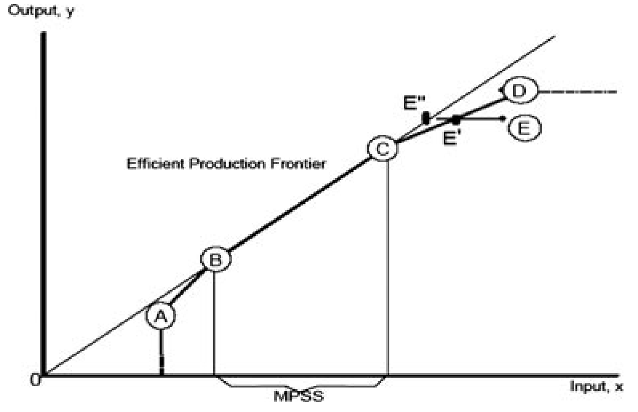


Figure 2 Scale efficiencies and the efficient production frontier.

produce maximum outputs from a given set of inputs for a determined period of time. Allocative efficiency measures the ability of a DMU to optimize the use of its inputs given its existing production technologies. A DMU is fully efficient if it cannot produce any more of an output without decreasing another output or increasing an input (Deliktas & Kok, 2003). A DMU is said to be technically efficient when it operates on the efficient production frontier and technically inefficient when it operates below the efficient production frontier. The efficient production frontier (BC in Figure 2) is the set of all technologically feasible production plans (development policies) with the highest efficiency. A technically efficient DMU may still attain a higher level of productivity by moving upward along the efficient production frontier. Such improvements in productivity can result from improvements in technical efficiency, scale efficiencies, or change in production technology.

Banker, Charnes, and Cooper (1984) provide some DEA models for assessing scale efficiency of DMUs: the constant return to scale (CRS) model, the variable return to scale (VRS) model, and the nonincreasing returns to scale (NIRS) model. The CRS model assesses if a DMU is operating on the production frontier (the line through the origin in Figure 1). It assumes that 1 unit of input will result in 1 unit of output (broadly defined). This assumption is not unusual and is, in fact, implied in both ratio analysis and regression analysis. When a DMU is technically efficient, it will have a CRS (TE_{CRS}) score of 1 (or 100%). When it is not technically efficient, it will have a $TE_{CRS} < 1$ and fall below the production frontier. The VRS model assumes that 1 unit of input can result in output ranging from less than 1 unit to more than 1 unit. This model computes the improvement outputs needed to reach the efficiency frontier based on the slacks of input variables. When a DMU is operating at VRS technical efficiency (TE_{VRS}), it will have a score of 1 (or 100%). This means that no changes in inputs will improve its outputs. When VRS technical efficiency is $TE_{VRS} > 1$ (or 100%), we can infer that the DMU has the potential to achieve higher levels of outputs by rearranging the inputs. Finally, the NIRS model tells the analyst the point beyond which any additional inputs would not achieve an increase in outputs for that DMU. A TE_{NIRS} score of 1 (or 100%) tells the analyst that the DMU is operating at NIRS.

An important aspect of efficiency analysis is the determination of the scale efficiency of a DMU. A DMU is scale efficient (SE) when $TE_{CRS} = TE_{VRS}$, but when $TE_{CRS}/TE_{VRS} < 1$ the DMU is scale inefficient. When a DMU is found to be scale inefficient, we compare the NIRS technical efficiency (TE_{NIRS}) to TE_{CRS} to determine the nature of the scale inefficiency. If a DMU is scale inefficient, that is, $TE_{CRS} < TE_{VRS}$ from an input orientation and $TE_{NIRS} = TE_{CRS}$, then the DMU is operating at an inefficiently small scale (increasing returns to scale, IRTS). In contrast, when $TE_{CRS} < TE_{VRS}$ from an input orientation and $TE_{NIRS} > TE_{CRS}$, the sector is operating at an inefficiently large scale (or decreasing returns to scale [DRTS]). Furthermore, if a DMU scores 100% on both CRS and VRS, we can conclude that the DMU is operating at the most productive scale size (MPSS). Figure 2 shows three different regions of the efficient production frontier that are relevant to this analysis: (1) the segment AB represents increasing returns to scale (IRTS), (2) the segment BC represents scale efficiency SE and MPSS, and (3) the segment CD represents DRTS. These concepts are important to our analysis because they can help us understand where the countries in our study are operating on the efficient production frontier and what kinds of adjustments they can make to improve their performance.

4. DATA COLLECTION AND ANALYSIS

The data on which this analysis is based were gathered from two different archival sources: the ITU and the World Bank. The ITU provides the research community with complete statistical data collected over the years for the telecommunication sectors for all countries; the World Bank provides general economic data and social indicators such as education index, literacy rates, life expectancy, and so on. The data of this study were drawn from these sources and cover the period 1994 to 2001. This period was chosen for two reasons: (1) the early to mid-1990s marked the period of liberalization in the ICT sectors of these countries; and (2) the 1990s saw the most intensive investment in the ICT sectors of these countries. We would have liked to include data to the present, but there is a considerable lag in reporting to the ITU.

4.1 Data Analysis

The data analysis is presented in three steps. In step 1, we present descriptive statistics of ICT expansion rates, which gives us a sense of the rate of expansion of various ICT technologies in the countries studied. In step 2, we conduct a DEA analysis to assess the relative efficiency of the ICT expansion in the countries. Our DEA analysis comprises three models: CRS, VRS, and NIRS. The first is concerned with assessing the pure technical efficiency (TE_{CRS}) of the ICT expansion. We run the Constant Return to Scale Maximum Average Input-oriented (CRS_MAX_IN) model to investigate the relative technical efficiencies of the ICT sectors with regard to their utilization of investments and manpower to achieve the expansion. Because the CRS analysis alone cannot tell us about the scale efficiencies of the ICT sectors, we complement it with VRS analysis, for which we run the Maximum Average Output-oriented (VRS_MAX_OUT) model. This helps us determine whether, under the prevailing conditions, any of the countries could be more efficient in achieving ICT expansion. We then run the NIRS model to examine the scale efficiencies of each country. Finally, in step 3, we use Tobit regression analysis to test hypotheses concerning factors that affect the efficiency of ICT expansion in these countries.

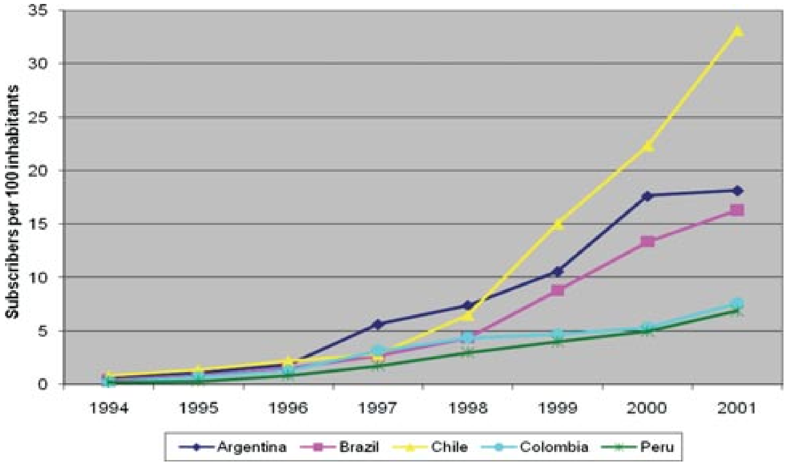


Figure 3 Expansion rate of mobile phone users.

5. FINDINGS FROM EMPIRICAL ANALYSIS

5.1 Descriptive Statistics of ICT Expansion

In Figure 3, we outline ICT expansion rates per 100 residents for each of the countries under investigation. This analysis allows us to map the changing ICT user base for the time period stipulated previously. It also allows us to provide a comparative analysis of ICT expansion in our sample countries. Chile has had one of the highest rates of ICT expansion. In 1987, when Chile started ICT privatization, it had 4.65 main lines per 100 inhabitants. By 1994, it had 15.22, and by 2001, it had 56.81. In its first report in 1989, Chile reported 4,886 mobile telephone subscribers. In 1994, it reported 115,691 subscribers (.83 per 100 inhabitants), and by 2001, this number had grown to 3,478,490 (34.22 per 100 inhabitants; cf. Figure 3). Chile also saw an explosive growth of Internet users, starting in 1992 with an estimated 5,000. By 1994, the number had quadrupled to 20,000; by 2001, it had grown to 3,102,200. Argentina had the second highest rate of ICT expansion. In 1990, Argentina started its privatization process, hosting 9 main lines per 100 inhabitants and 12,000 mobile telephone subscribers. By 1994, the number of main lines in operation had grown to 15.22 per 100 inhabitants, and mobile telephone subscribers had grown to .7 per 100 inhabitants. By 2001, Argentina had 40 main lines and 18.14 mobile subscribers per 100 inhabitants. Argentina also saw explosive growth of Internet users over the period of our study (cf. Figure 4). In 1992, the country reported its first 1,000 Internet users, and by 1994, the number had grown to 15,000 (.04 per 100), which doubled during the following year. In 2001, Argentina reported 9.82 Internet users per 100 inhabitants.

Colombia, like Argentina, also started its privatization process in 1990. At that time, Colombia had 7 main lines per 100 inhabitants; by 1994, it had 9.53 per 100 inhabitants. In 2001, it had 24.85. Colombia also saw rapid growth in mobile telephone subscribers: in 1994, it reported 86,805 mobile subscribers (2.3 per 100 inhabitants), and by 2001, it reported 3,256,261 (7.62 per 100 inhabitants). In our sample, Brazil was the last country to start the privatization process. In 1994, before privatization began, Brazil had 8.35 main lines per 100 inhabitants in operation, with .7 mobile subscribers and .04 Internet users per

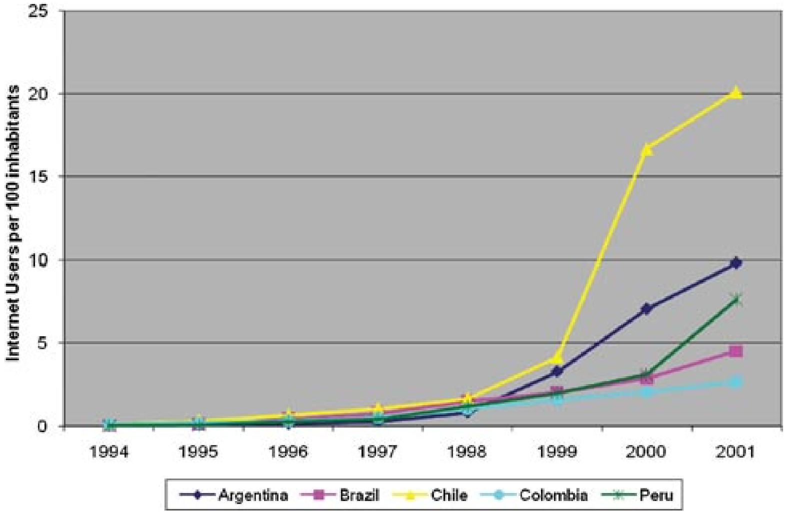


Figure 4 Expansion rate of Internet users.

100 inhabitants. By 1998, when privatization began, Brazil reported 16.49 main lines per 100 inhabitants. By 2001, this number increased to 38.5 main lines per 100 inhabitants, along with 16.73 mobile subscribers and 4.66 Internet users per 100 inhabitants. Although Peru started its privatization process before Brazil, it experienced slower ICT expansion. In 1994, it reported about 3.5 main lines per 100, and by 2001, this coverage had improved to 12.89. However, it is important to note that between 2000 and 2001, Peru reported a reduction of 146,161 main lines. With regard to mobile telephone subscribers, Peru reported 1,650 in 1990, but this number had grown to 52,200 (.22 per 100) by 1994 and to 1,793,284 (6.7 per 100) by 2001. In 1994, Peru reported Internet users for the first time, numbering 2,000; however, in 2001, it reported 2 million Internet users (or 7.66 per 100 inhabitants). Although these statistics give a general idea of progress in ICT expansion, they do not reveal any insights about the cost/efficiencies of expansion that the ITU considers an important measure of progress. In the next section, we examine the efficiency of ICT expansion.

5.2 DEA Efficiency Findings

The input and output variables used in the DEA analysis of the ICT sectors of the five Latin American countries are presented in Appendix A. The results from our DEA analysis placed Colombia as the best practice country among this group (cf. Table 1). It operated at MPSS five times during the period of study (in 1996, 1997, 1998, 1999, and 2001). The next best performance was by Argentina, which operated at MPSS three times (in 1999, 2000, and 2001). Colombia, however, did operate at DRTS for 1 year (2000), but for 2 other years (1994 and 1995) it operated at IRTS. The only other countries to operate at MPSS were Chile and Peru, in 2001. The least efficient country was Brazil, which operated at DRTS for 6 of the 7 years of our study, and at IRTS in 1994. We did not anticipate that Colombia would emerge as the best practice country in our analysis. We had expected that perhaps Argentina or Brazil would have been the best practice country due to scale and the level of development of their other civil infrastructures.

TABLE 1. CRS Technical and Scale Efficiencies of ICT Expansion

	1994		1995		1996		1997		1998		1999		2000		2001	
	CRS	SE	CRS	SE	CRS	SE	CRS	SE	CRS	SE	CRS	SE	CRS	SE	CRS	SE
Argentina	.81	IRTS	.84	IRTS	.86	IRTS	.90	IRTS	.97	IRTS	1	MPSS	1	MPSS	1	MPSS
Brazil	.79	IRTS	.80	DRTS	.80	DRTS	.82	DRTS	.81	DRTS	.84	DRTS	.84	DRTS	.87	DRTS
Chile	.96	IRTS	.93	IRTS	.94	IRTS	.96	IRTS	.95	IRTS	.96	IRTS	.96	IRTS	1	MPSS
Colombia	.87	IRTS	.89	IRTS	1	MPSS	1	MPSS	1	MPSS	1	MPSS	.98	DRTS	1	MPSS
Peru	.84	IRTS	.83	IRTS	.86	IRTS	.88	IRTS	.88	IRTS	.92	IRTS	.93	IRTS	1	MPSS

Now that we have ascertained the relative efficiencies of these countries, the following question might be raised: how efficient are these countries on a global scale? Would comparing these countries to one of the most efficient countries globally provide a more accurate measure of their efficiencies? The answer requires some discussion. Suppose we had selected Finland, one of the most efficient countries with regard to ICT, as a benchmark. Would this have provided more accurate results? We would have to answer "no" for the following reasons. First, Finland is not in Stage 1 of the ICT expansion process—it is in Stage 3, or "Intensification of use of ICT." Comparing these countries would be unfair because Finland has already passed the stage of the countries under study and has already gained from the learning effect. Second, the existing conditions of socioeconomic development, technological capabilities, and other civil infrastructure in Finland are far beyond those of our sample countries and of other Latin American countries. Thus, in determining efficiencies, it is important to select countries that are in similar stages of ICT expansion. However, it is also important to take into account other factors such as the geographic size of the countries and topological features. For example, a mountainous country would offer more obstacles to expansion of land lines than a flat country. It would be more challenging to string land lines in a desert landscape than in a more hospitable temperate climate. In the next section of the article, we take into account some of these features in our investigation of factors that influence the efficiency of ICT expansion.

5.3 Factors Affecting ICT Expansion Efficiencies

To develop some understanding of factors affecting TE_{CRS} in these countries, we introduce potential explanatory variables and test possible hypotheses. This part of our analysis is informed by research from the past four decades, which demonstrated that new technology adoption and expansion in developing countries is path dependent and influenced by a range of factors, such as government policy, human capital, wealth, and existing civil infrastructure. However, much of this research was conducted on agricultural and industrial technology expansion in developing countries. For example, researchers in the agricultural sector discovered that existing infrastructure, level of income in the wider community, and human capital factors (education, technical skills, and social networks) had significant influence on new technology adoption and expansion (Feder & Slade, 1984; Rahm & Huffman, 1984). Others who studied the expansion of new technologies in the industrial sectors of developing countries found similar connections (Besley & Case, 1993; Colombo & Mosconi, 1995; Lall, 1993). The role of educational institutions in establishing the technological competence necessary for the adoption and expansion of new technologies in developing countries has also been discussed (Kneller, 2005; Lall, 1993; Papageorpiou, 2002, 2003; Tamura, 2002; Wozniak, 1984, 1987). With regard to civil infrastructure, other research (Henderson et al., 2002; Kessides, 1993; Ngwenyama et al., 2006; Pohjola, 2003; Röller & Waverman, 2001) has suggested that there is a link between the level of development of civil infrastructure and ICT expansion; however, this work provides no empirical evidence to support the claim. In his study of some developing countries in Latin America, Montealegre (1999) illustrated the importance of knowledge building and the role of educational institutions in the adoption and expansion of ICT infrastructure. Bollou (2006) also found that human capital was linked to ICT infrastructure expansion efficiency in Francophone West Africa.

Although several researchers point to the need for understanding these issues in order to develop policy for efficient ICT expansion, we can find no published literature that

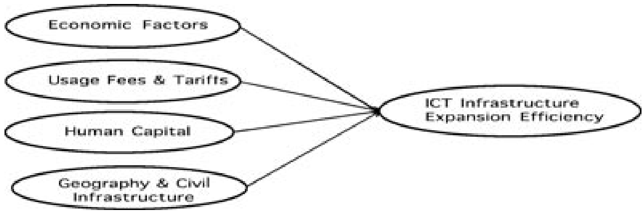


Figure 5 Factors influencing ICT infrastructure expansion.

has systematically examined relationships between (1) economic, (2) usage and tariffs, (3) human capital, and (4) infrastructural factors and ICT expansion. In this regard, we postulate a theoretical model for the investigation of these issues (cf. Figure 5). To examine the relationships suggested in our theoretical model, we formulate the following set of hypotheses:

- H_1 Economic factors (as measured by GDP per capita) positively impact TE_{CRS}; as GDP per capita increases, TE_{CRS} will increase.
- H_2 Usage fees and tariff factors (as measured by residential and business connection charges) negatively impact TE_{CRS}; as usage fees and tariffs increase, TE_{CRS} will decrease.
- H_3 Human capital (as measured by literacy rate, education attainment, and tertiary institutions) positively impacts TE_{CRS}; as the level of human capital increases, TE_{CRS} will increase.
- H_4 Geography and civil infrastructure (as measured by land area, airports, and highway and railway networks) negatively impacts TE_{CRS}; as geography and civil infrastructure increases, TE_{CRS} will decrease.

To investigate this model, we selected a set of candidate explanatory variables for this analysis from the same ITU and UN databases from which we drew the rest of our data. In the Economic Factors category, we use GDP per capita; for the Usage Fees and Tariffs category, we use residential connection charges and business connection charges. In the Human Capital category, we consider three proxy variables: (1) the number of universities in the country, (2) literacy rate of adults age 15 years and older, and (3) the education index as reported in the UN Human Development Report. Instead of the number of universities, we wanted to use annual university graduation rates, but we could not obtain these data for all countries. For the Geography and Infrastructure category, we consider (1) land area, (2) kilometers of highway, (3) kilometers of railway, and (4) the number of airports as candidate explanatory variables. We are not suggesting that these are the complete set of factors that affect ICT expansion. There are clearly other factors, such as social capital, but we do not have any measures of these. However, the categories of factors we are investigating are considered important in ICT infrastructure expansion (cf. Bollou, 2006; Kneller, 2005; Lall, 1993; Papageorgiou, 2002; Tamura, 2002; Wozniak, 1984, 1987).

Before performing the regression analysis, we first conducted a correlation analysis on the candidate explanatory variables to identify which of these are highly correlated. The correlation test helps us carefully select appropriate explanatory variables for our regression analysis and avoid problems of autocorrelation. Specifically, we conducted a two-tailed Pearson correlation test at the .01 level of significance. Table 2 presents the

TABLE 2. Pearson Correlation Matrix

	GDPP	EDUI	LITRATE	UNI	RCONCHG	BCONCHG	RWAYS	HWAYS	APORTS	AREAKM
GDPP	1									
EDUI	.690*	1								
LITRATE	.738*	.858*	1							
UNI	−.168	−.669*	−.702*	1						
RCONCHG	−.134	−.471*	−.368	.247	1					
BCONCHG	−.156	−.369	−.294	.096	.915*	1				
RWAYS	.692*	.189	.065	.422*	.164	.078	1			
HWAYS	−.052	−.520*	−.668*	.887*	.246	.065	.589*	1		
APORTS	.064	−.477*	−.589*	.924*	.250	.078	−.190	.932*	1	
AREAKM	.044	−.446*	−.613*	.864*	.264	.096	.694*	.988*	.985*	1

Note: 40 total observations. *Denotes significant at .01 level, two-tailed test.

results of our correlation analysis of the explanatory data set variables. From our results, the reader can observe that some of our variables are highly correlated. For example, there is a high degree of correlation, .988, between AREAKM (land area in square kilometers) and HWAYS (kilometers of highways). There is a .932 correlation between APORTS (number of airports) and HWAYS and a .985 correlation between APORTS and AREAKM. The variables BCONCHG (business connection charges) and RCONCHG (residential connection charges) are also highly correlated (at .915), which again suggests that these two variables are providing the same information and that both need not be included in the regression. Likewise, the variables LITRATE (literacy rate) and EDUI (education index) appear to be providing most of the same information given that they show a .858 correlation. Given these correlation findings, we moved ahead with our regression analysis using only the variables GDPP as a proxy for Economic factors; EDUI and UNIS (number of universities) as proxies for Human Capital factors; BCONCHG for Usage Fees and Tariffs factors; and, finally, RWAYS and APORTS for Geography and Civil Infrastructure factors.

5.3.1 Tobit Regression Results. To investigate the impact of the four categories of factors of ICT expansion efficiency—(1) Economic, (2) Usage and Tariffs, (3) Human Capital, and (4) Geography and Infrastructure—we use a Tobit regression model (Tobin, 1958). The Tobit regression model is appropriate for two reasons: (1) we have archival panel time series data, and (2) our dependent variable TE_{CRS} is limited between 0 and 100 (Tobin, 1958). Our initial Tobit model can be written as follows:

$$TE_{CRS} = \beta GDPP + \beta Edui + \beta Unis + \beta BConChg + \beta Rways + \beta Aports + \varepsilon,$$
$$\text{where } (0 \leq TE_{CRS} \leq 100)$$

Interpreting the Tobit regression results is fairly straightforward. The fundamental assumption of our analysis is that if $H = P > |t|$ when the value of α is .05 (obtained from 95% confidence level), the hypothesis is supported. Given this assumption, the decision rule for interpreting the Tobit results is as follows: if $(P > |t|) \leq .05$, the independent variable concerned has an impact on the dependent variable, TE_{CRS}. The sign of the coefficient of the independent variable determines whether the impact is positive or negative. Table 3 presents a summary of the Tobit regression results.

In examining the results from the regression analysis, the reader will notice that for the variables RWAYS and EDUI $(P > |t|) > .05$. This tells us that, given the present model, the two variables RWAYS and EDUI are not significant and do not impact the dependent variable TE_{CRS}. However, the other variables GDPP, UNIS, BCONCHG, and APORTS are significant at the 95% confidence level. The model fit statistic, R^2, is .756814, and the log likelihood is −106.85211. It is important to note that our data set is small, consisting of 40 observations. Ideally, a larger number of observations would significantly improve the stability of our data analysis. However, it is clear from these regression results that our model is well supported, and we have managed to explain 75.68% of the variance in the dependent variable TE_{CRS}. Furthermore, our error distribution and validation statistics (see bottom of Table 3) are within acceptable ranges. In Appendix B, we also present the distribution validation statistics that illustrate the robustness of our model. However, future investigations with larger data sets could improve the scientific validity of our model.

TABLE 3. Parameters from Tobit Regression Analysis

		R-squared		.756814
		Adjusted R-squared		.703617
		Uncensored observations		40
		Right censored observations		0
Dependent Variable: TECRS		..... Total observations		40
Independent Variables	Coefficient	SE	t Statistic	Prob. |t|
UNIS	.142748	.036288	3.933799	.0001
GDPP	.001260	.000535	2.353429	.0186
RWAYS	−.000131	.000158	−.831109	.4059
EDUI	39.72833	41.83940	.949543	.3423
BCONCHG	−.008376	.002316	−3.617513	.0003
APORTS	−.007175	.002059	−3.485174	.0005
C	44.77942	36.81711	1.216267	.2239
	Error Distribution			
SCALE:C(8)	3.498605	.391153	8.944331	.0000
Regression Validation Statistics				
S.E. of regression	3.911559	Akaike info criterion		5.742606
Sum squared resid	489.6094	Schwarz criterion		6.080381
Log likelihood	−106.8521	Hannan-Quinn criterion		5.864735
Avg. log likelihood	−2.671303			

5.3.2 Discussion of Findings. Our regression analysis confirms Hypotheses H_1, and H_2. Consequently, we can state with a 95% level of confidence that Economic Factors (as measured by GDPP) positively impact the technical efficiency of ICT expansion. As GDP per capita for these countries increases, the technical efficiency of ICT expansion will increase. We can also state with 95% confidence that ICT Usage Fees and Tariffs (as measured by business connection charges) negatively impact TE_{CRS}; as business connection charges increase, TE_{CRS} will decrease. ICT services in developing countries are quite price sensitive, and small increases in the price of services can push individuals out of the market and inhibit access for newcomers. This is not surprising as the GDP per capita in these countries is relatively low (compared to more developed countries like Canada, the United States, etc.); therefore, ICT Usage Fees and Tariffs can be a burden to large segments of the populations of developing countries.

Although the impact of EDUI on TE_{CRS} is insignificant in our model, our regression analysis does confirm Hypothesis H_3. Human Capital (as measured by the number of universities) positively impacts ICT expansion. The variable UNI has a positive impact on TE_{CRS}. We can state with 95% confidence that as the number of universities increase, TE_{CRS} will increase. Furthermore, in our model, UNI has the largest impact on TE_{CRS}. There are some possible explanations for this: (1) graduates of universities would have a higher than average annual income that could lead to increased demand for ICT services, thus increasing the need for ICT expansion; (2) the institutions themselves are often net users of ICT services; and (3) some tertiary institutions will produce engineers and technicians that will enter the workforce and further contribute to the development of ICT productive capacity.

Finally, our hypothesis concerning the impact of Geographic and Civil Infrastructure on ICT expansion efficiency has also been confirmed. From our analysis we can state, with 95% confidence, that APORTS (number of airports) negatively impact technical efficiency of ICT expansion. Initially, we hypothesized that land area would have a negative impact on efficiency of ICT expansion, and because land area (AREAKM) is almost perfectly correlated (.985) with APORTS, that conjecture is borne out. However, our findings are inconsistent with some of the theoretical arguments (Munnell, 1992; Rauch, 1995), which hold that that civil infrastructure would have a positive impact on efficiency of ICT expansion. The theoretical arguments of Rauch (1995) and Munnell (1992) are understandable because the expansion of ICT infrastructure depends on existing roads for moving heavy equipment for the construction of microwave towers, and telephone lines are usually strung along existing roads and highways. But given that other civil infrastructure and ICT infrastructure are competing for the same investment resources, investments in one sector impact investments in another. Furthermore, developing countries have more challenging geographic and infrastructure issues to contend with because they are at an earlier stage of development (relative to developed countries). This finding also offers one explanation for why Brazil, the largest of the countries in our analysis, has the highest investments in ICT over the period of our study but ranks the lowest in ICT expansion efficiency.

6. INSIGHTS FOR POLICY FORMULATION

Our motivation for this research was to develop some understanding of factors impacting ICT expansion in developing countries. Some researchers have argued that understanding the dynamics of ICT expansion is essential for policy reform and development progress (Bollou, 2006; Estache, Perelman, & Trujillo, 2005; Ros & Banerjee, 2000). However, although other studies examine ICT expansion in developing contexts, there are no integrated models for investigating factors impacting efficient expansion of ICT infrastructure. More recently, various researchers have suggested that human capital and other civil infrastructure impacts the expansion of ICT (Bollou, 2006; Henderson et al., 2002; Papageorgiou, 2003; Pohjola, 2003); yet, systematic empirical studies have yet to appear in this area. The challenges faced by developing countries as they attempt to speed up ICT expansion to achieve social and economic development are still not well understood (Baliamoune-Lutz, 2003; Bollou, 2006; Colle, 2005; Lamberton, 2001). The study we report here is an attempt to further the discourse on ICT and development by contributing to two important problems: (1) how to measure the performance of ICT expansion programs in developing economies, and (2) providing policy makers with better models for analyzing and developing policy options for their infrastructure expansion and economic growth strategies. This research offers a method for measuring the relative efficiencies of ICT performance at the macro level and an integrated model for studying the impact of a range of factors impacting the efficiency of ICT expansion. Also, it illustrates that simple measures of efficiency cannot answer the question of how well emerging economies are using their resources for the purposes of ICT sector expansion. Simple efficiency measures do not take into account exogenous factors, which may affect efficiency. Finally, the approach to measurement needs to consider that there are different stages to ICT expansion. It must also consider the contingency of these stages because present developments are built on those of the past, and specific natural endowments within countries also play a role. It is no accident that developed countries (Finland, Denmark, Norway, Sweden, Singapore, Japan, Canada, Germany, the United States) can benefit from the conditions created by their prior levels of development. These countries share a common set of characteristics: (1) high levels of per capita income, (2) high levels of education and technological capabilities, (3) excellent civil infrastructures, and (4) functional and stable national governmental structures. All were achieved before the rapid expansion of their ICT infrastructures to support global economic activity.

An examination of the efficiency of ICT infrastructure expansion thus demands a consideration of the numerous factors that may impede or enhance this process. For example, ICT infrastructure is unworkable in the absence of infrastructure for the reliable generation and distribution of electricity. Trade and commerce (electronic or brick-and-mortar) depend on efficient transportation systems, including ports (air and sea), highways, and railways, to get products from suppliers to retailers and consumers. Furthermore, educational institutions play a significant role in producing knowledgeable, skilled workers and consumers who will implement, maintain, use, and exploit ICT infrastructure for trade, commerce, and entertainment. Investments in ICT infrastructure cannot be made in isolation from other infrastructure development programs. Policy makers and researchers can benefit by viewing ICT infrastructure expansion as a complex evolutionary process in which ICTs complement other basic infrastructures and are dependent on socioeconomic and human capital attainments. The findings of this study suggest that policy makers consider some important issues when planning for ICT infrastructure expansion: (1) careful assessment of existing conditions and the level of technical capability, the ability to produce local engineers and technicians, and the level of development of basic civil infrastructure. These factors could hinder the expansion of the ICT infrastructure, and a lack of understanding of these conditions could lead to unrealistic goals and wasted investment; (2) complementarity of investment strategies to achieve improvements in those factors that may impede expansion. For example, more synergistic planning will be needed to achieve adequate levels of development of civil infrastructure and the technical capability necessary to expand and maintain ICT infrastructure.

With regard to future research, this study raises many questions about current approaches to thinking about the policies and frameworks that guide emerging economies toward ICT infrastructure expansion. The approach to using ICT policy and regulatory frameworks to induce economic growth is too limited. More comprehensive models for understanding the importance of infrastructures to global trade and economic growth are needed. Although we have presented an approach that policy makers can use to evaluate the progress of their ICT development programs, future research is needed to expand our understanding of factors that affect ICT expansion. Such research could help us build better models for predicting outcomes and guiding policy.

APPENDIX A

Description of Input–Output Variables of the DEA Empirical Analysis

Input Variables

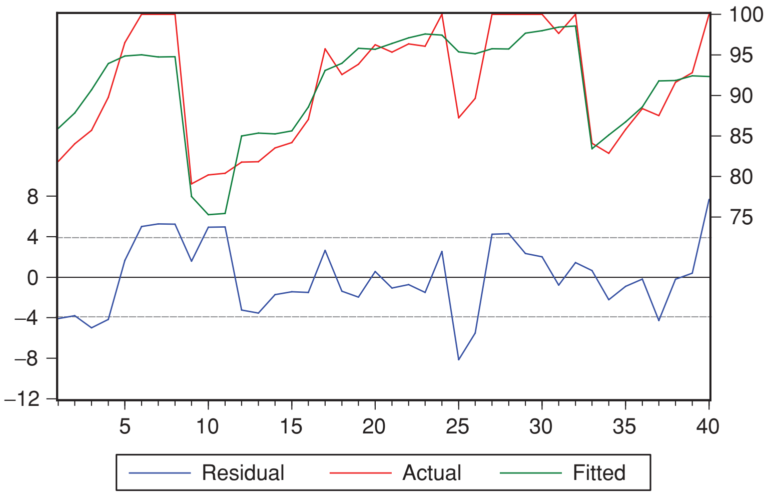
- Total annual telecommunications investments
- Number of full-time staff working in the telecommunications sector

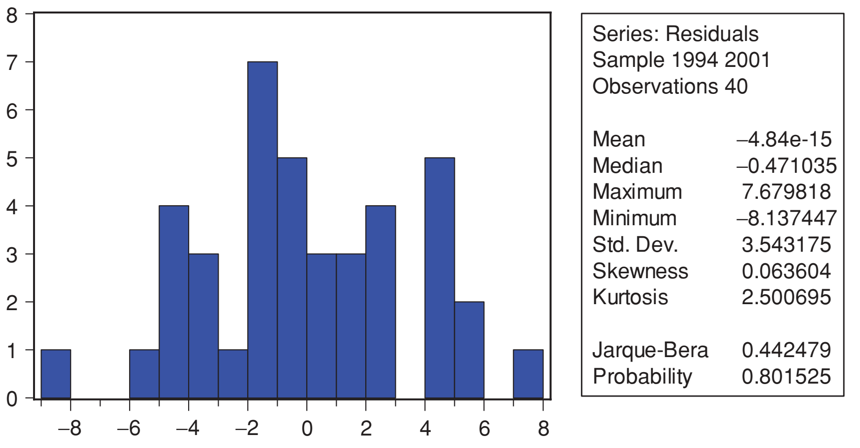
Output Variables

- Annual telecommunications revenue
- Number of main telephone lines
- Number of Internet users
- Number of public payphones
- Number of mobile phone subscribers

APPENDIX B

Validation of the final regression model and regression analysis





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