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Impacts of Information and Communication Technologies on Country Development: Accounting for Area Interrelationships

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ABSTRACT: Single-item composite indices gauge ICT readiness at the country level but do not represent the direct impact of ICTs on a country's development. This paper describes a new approach to measuring the macrolevel impacts of ICTs across a range of development areas. The indirect effects of one area on others is taken into consideration by a simultaneous equation model that permits the inclusion of multiple development areas. The model is applied to data pertaining to four development areas in 64 countries: trade flows, agricultural productivity, R&D, and quality of life. ICT readiness is found to have a positive association with trade flows and R&D, but the impact depends on the country's development level. The strengths and limitations of this modeling approach, and the implications of the results, are assessed.

KEY WORDS AND PHRASES: Country assessment, development, economic analysis, e-readiness, ICTs, index measures, measurement, policy-making, simultaneous equation model, three-stage least squares.

As we move toward an increasingly global information society, countries the world over are devoting greater resources to the development of information and communication technologies (ICTs) to encourage the emergence of electronic commerce activities and increase their scope [160]. The World Bank's Comprehensive Development Framework defines ICTs as all hardware, software, networks, and media for collection, storage, processing, transmission, and presentation of information (including voice, data, text, and images) [151].[1] ICT investments—especially those that build technological infrastructure, enable interpersonal communication, and support products and structures for e-commerce and digital mercantile exchange—can significantly contribute to a country's digital economy as well as its overall development process [159]. Information on the economic impact of ICTs is essential for effective investment and business decisions so that governments can formulate sound policies. However, there is a need for suitable performance and evaluation measures, similar to those used in any business, to assess the impact of ICTs at the country level.

Assessing the impact of ICTs at the country level is critical but ridden with complexity. In fact, assessing the impact of ICTs is challenging, not only at the aggregate level, but even at the lower levels of firms, processes, products, and individuals. For example, at the economy level, the question of whether ICT investments lead to improvements in the productivity of firms has long vexed researchers [26]. ICTs may have strategic impacts that are not easy to measure. At the process level, Alpar, Porembski, and Pickerodt have analyzed the complications of efficiency measurement posed by Web site traffic [5]. Complexities in assessing the impacts of ICTs may also arise due to perception differences [19]. Intangible impacts also pose assessment difficulties. Customer satisfaction and improvements in quality and customer service are examples of intangible impacts of ICTs that are not easy to measure [16, 27]. The difficulty in assessing intangible impacts of ICTs at the individual or firm-level scales up at aggregate-level analysis. For example, improvements in the quality of goods and services lead to improvements in overall quality of life.

Recognizing the need for effective measurement capabilities for ICT impacts, the United Nations (UN) and the International Telecommunications Unions World Summit on the Information Society have called for the creation of an "ICT Development (Digital Opportunity) Index" [156].[2] A significant amount of research has sought to assess the impact of ICT investments on a country's economy [40, 44, 45, 83]. There are also studies on ICT impacts in other development areas, including health, gender equality, and employment [30, 31, 62, 99]. Most of the earlier studies tried to measure the impacts of ICTs on a specific parameter. However, ICT impacts are often felt on several parameters simultaneously. For example, greater penetration of the Internet results in more e-commerce opportunities, but can also be a powerful source of information for spreading democracy or health awareness. To date, no empirical study has tried to assess the impacts of ICTs at the country level in this holistic manner. Moreover, most existing measures of ICTs at the country level relate to measurement of *ICT readiness* (also called *e-readiness*), which refers to the preparedness of a country to exploit the capabilities of ICTs [82]. In contrast, the assessment of ICT impacts involves estimating the relationship between their use and their effects on the outputs of different development areas.

Measurement of ICT impacts at the country level is essential for policymaking. Optimal allocation of limited resources is a major concern of policymakers. It requires good estimates of the returns on ICT investments. The declaration of the UN World Summit on the Information Society in December 2003 emphasized the need to measure ICT impacts and set out the goal of tracking global progress in the use of ICTs to achieve internationally agreed upon development goals, including those of the Millennium Declaration. The UN General Assembly's eight Millennium Development Goals to be achieved by 2015 are: eradicate extreme poverty and hunger; achieve universal primary education; promote gender equality and empower women; reduce child mortality; improve maternal health; combat HIV/AIDS, malaria, and other diseases; ensure environmental sustainability; and develop global partnership for development [141]. The existing measures of ICT readiness are not very helpful in assessing how far ICTs go toward achieving these goals.

The present study develops a new approach and model for the measurement of ICT impact on development area outputs. It addresses the following key research questions:

- What theoretical perspectives are useful in the development of a measurement approach for ICT impacts at the macro level? How do measures of ICT readiness at the country level relate to measurements of ICT impacts?

- What kind of empirical model can reveal the extent of ICT impact on development area outputs at the macro level? Specifically, how do the interrelationships between different development areas and ICTs motivate a simultaneous equations model? How can the complications of endogeneity be addressed in this context?
- How do the impacts of ICTs vary across countries at different stages of development and different stages of ICT readiness? To what extent does the assessment of impacts reveal a new understanding of the role of ICTs in the development of countries?

Measurement Approaches

The study of ICT impacts has attracted researchers for several decades. A possible basis for impact assessment is provided by the sustainability impact assessment studies carried out in the context of trade liberalization and World Trade Organization (WTO) negotiations [1, 58, 89, 117]. Impact assessment studies typically involve identifying inputs, processes, and outputs. The present article provides a quantitative assessment of the impacts of ICTs. As will be explained, it is assumed that the outputs of the development area of interest can be expressed via a parametric relationship between inputs that use related technologies to generate the development area output.

ICT impacts are felt at the individual, business process, firm, market, or regional level. They are also felt on several variables, including economic growth, productivity, trade, health, education, freedom of speech, and access to information. ICT impacts have been studied from several theoretical perspectives, mainly the economic perspective, the sociological-anthropological perspective, and the knowledge-management perspective.

The economic perspective is extensively used in studies relating to ICT impact. The impact of ICTs on productivity has been an important subject of research since Solow's famous statement of the "productivity paradox" in 1987: "You can see the computer age everywhere but in the productivity statistics." The findings have been mixed. Studies in the early 1980s found no productivity improvements resulting from investments in information technology (IT). Studies in the 1990s and later, though, showed that the use of ICTs leads to higher productivity (e.g., [26, 46, 75]). Jorgenson and Stiroh earlier posited that use of IT is fundamentally changing the U.S. economy even though it does not lead to faster growth and increased productivity [74]. Kraemer and Dedrick found a positive correlation between IT investments and GDP growth as well as productivity growth for 12 Asia–Pacific nations during the period 1984 to 1990 [83]. Dewan and Kraemer reported that investments in ITs affect developing and developed countries differently [45]. Jorgenson found differences in the economic impact of IT investments in G-7 member countries [73]. The returns from IT investments are substantial in developed countries but less so in developing countries. Waverman, Meschi, and Fuss studied the impact of ICTs on labor productivity and found positive impacts that vary from country to country [147].

Apart from the impact on productivity, other economic impacts of ICTs have also been studied. Kauffman and Kumar reported significant impacts of the Internet on market linkages and agglomeration of IT manufacturing and service industries [78]. Gaspar and Glaeser explored the impact of communication technologies on cities and posited that they are likely to be complements and not substitutes for face-to-face interactions [57]. Venables argued that use of IT will lead to some activities becoming entrenched in higher-income countries [144]. Information that can be codified and digitized may relocate to lower-income countries. Thus, not all low-income countries will benefit from the use of ICTs. Feenstra and Hanson examined the impact of computers and outsourcing on wages [53]. They found that computers explain 35 percent of the increase in the relative wages of nonproduction workers and outsourcing explains 15 percent.

A number of scholars have studied ICT impacts from a sociological perspective. Rosenberg provided a comprehensive discussion of the social impact of the use of computers, including impacts on education, health, free speech, governance, and privacy [122]. Chandrasekhar and Ghosh considered the difficulty of achieving the benefits of ICTs in the health sectors of developing countries [31]. Nidumolu et al. studied the experience of IT in the implementation of local administration in Egypt and showed that symbolic/political and social information-processing perspectives have considerable power in explaining outcomes during implementation [111]. Straub, Loch, and Hill argued that cultural beliefs in the Arab countries are a very strong predictor of resistance to IT [133]. Hedley suggested that (at least for now) the Internet is overwhelmingly United States–based, English-speaking, and Western-focused [66]. In his view the use of ICTs and the Internet may support cultural imperialism by the West.

Yet another perspective in the study of ICT impacts emphasizes knowledge management. The "Knowledge Assessment Methodology" of the World Bank is representative of this approach and highlights the impact of ICTs in developing a knowledge-based society [152]. Arunachalam argued that the digital divide in access to ICTs will make it even more difficult for developing countries to contribute to or take advantage of knowledge in the sciences and thereby further marginalizes these countries [11]. Salazar, Hackney, and Howells adopted a knowledge-management perspective to study the impact of Internet on the biotechnology and pharmaceutical sector [126].

What are the requirements for a measurement approach to quantify ICT impacts? For the purposes of this study, ICTs are thought of as tools to achieve something. In their meta-categorization of ICT artifacts, Orlikowski and Iacono referred to such use of ICT artifacts as the *tool view* (they use the term IT instead of ICT, but include communication and network technologies as part of IT) [114]. The tool view suggests that ICTs can substitute for labor, increase productivity, process information, and support social relations. The tool view is most appropriate in studying what is affected, altered, or transformed by the tool. Since the focus of the present study is on the impact of ICTs, the tool view conceptualization of ICTs is appropriate. Based on the tool view of ICTs, it is possible to express the transformation of inputs to outputs using technology, of which ICTs form an important part.

Development Area as Unit of Analysis, Interrelationships, and Lag Effects

The impacts of ICTs are felt across different development areas. The term *development area* is used here to describe the sphere of development activities that share the same or related products or services. This flexible definition enables the assessment of ICT impacts across a wide range of development attributes that can be aggregated at different levels of analysis. To illustrate, a department of the U.S. federal government (e.g., the Department of Agriculture, Department of Commerce, Department of Health and Human Services, or Department of Education) can be treated as a development area. Alternatively, commerce may be further disaggregated into industry development, international trade development, and so on, and each of these could be considered a development area. Thus, a development area can be defined at the *appropriate* level of aggregation at which the analysis examines the impacts of ICTs.

Different development areas are sometimes interrelated. Consider an illustration involving three development areas: industry growth, R&D, and physical quality of life. The relationship among these areas is shown in Figure 1, adapted from the UN Development Program report [139].

The central positioning of ICTs shows that they are used in practically all of a country's development areas. The double-ended arrows from the ICTs to the three development areas reflect the *duality* of ICTs. The development areas are affected by the use of ICTs and modify ICTs, depending on how they are adopted and used [113]. The use of ICTs requires investment, and the nature and kind of ICTs invested often depends on profits generated within industries. This is an example of the impact of industry growth on ICTs, in terms of which ICTs are used and how extensively. The rapid innovation in ICTs is an example of the impact of R&D, for example.

The interrelationship between development areas and ICTs is easily demonstrated. For example, the use of ICTs by a country may lead to higher productivity and, thereby, higher industrial growth. But higher industrial growth increases the availability of resources for investment in R&D, and this enables the generation of new intellectual property. Higher industrial growth also leads to an improvement in the quality of life. Better quality of life leads to improved human resources—people who are educated, healthy, and capable of more productive work, and this in turn leads to improved industry productivity and growth. Better-educated human resources are more capable of assimilating new knowledge and adopting and using new technologies that affect the R&D in the country. Adoption of new technologies and products leads to demand for these products, which may then spur industrial growth. To meet the demand for a greater variety of new products, industry will continuously innovate and produce differentiated products, adding to the overall information pool, a further impact on R&D in the country. The relationships mentioned are only illustrative. Development areas may influence each other in ways other than those described. Therefore, what is needed is an *integrated* approach to the measurement of ICT impact that accounts for the described interrelationships across different development areas and ICTs.

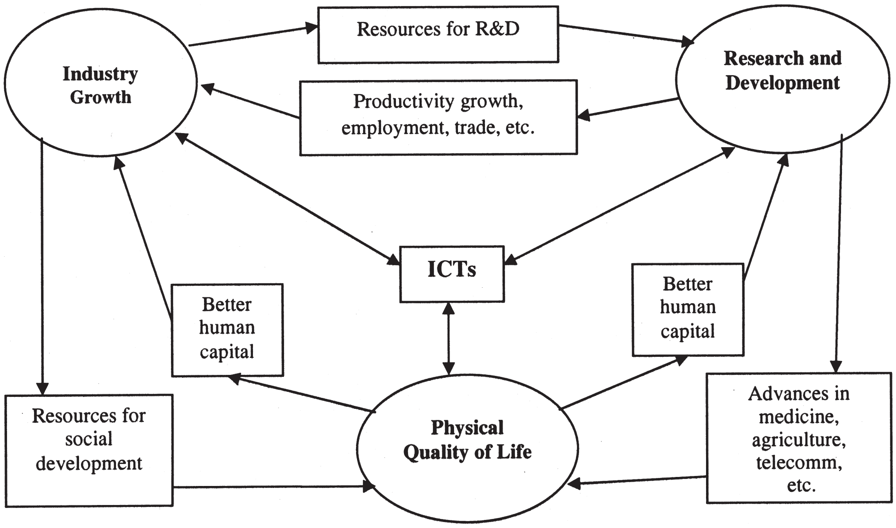

Figure 1. Interrelationships Between the Development Areas

An important factor in assessing ICT impact is the delay in the realization of the value of many ICTs: the so-called *value latency* problem [43]. Prior research at the organizational level has shown that because of the unusual complexity and novelty of ICTs, managers require experience and time before they can become proficient. Curley and Pyburn found evidence of lagged IT impact in organizational productivity, as did Loveman [38, 95]. One would expect to observe the accumulation of these impacts across firms and organizations in a country, resulting in lagged aggregate ICT impacts.

Single-Item Index Measures

Researchers often use single-item index measures to capture the most salient variables pertaining to the use of ICTs at the country level. Single-item index measures have been used to assess composite ICT variables, including ICT readiness, digital divide, and "informatization" at the country level or for other regions. A number of single-item index measures for ICT readiness have been developed, applied, and tested. Table 1 summarizes some illustrative single-item index measures for ICT measurements. These single-item index measures have been constructed from multiple underlying indicators that typically relate to the environment, ICT readiness, and individual usage. The scope of the measurement possibilities offered by these approaches may be conveyed by the fact that there are more than 100 indicators for some measures. (Appendix Table A1 provides additional details on the well-known single-item measures for ICT readiness.) One advantage of using a number of indicators in an index measure, according to the UN Conference on Trade and Development, is that it makes for more robust measurements of qualitative variables of interest (e.g., quality of life, e-readiness) [137, p. 16]. Note that most of these

Index	Agency	High-level constructs used
Network Readiness Index (NRI)	Center for International Development, Harvard University [47, 82]	Environment (market, political, regulatory, infrastructure), readiness (individual, business, government), usage (individual, business, government)
E-Readiness Index (ERI)	Economist Intelligence Unit [48]	Technology infrastructure, business environment, e-business adoption, social/cultural conditions influencing Internet usage, e-business services
Digital Access Index (DAI)	International Telecommunications Union [69]	Infrastructure, affordability, knowledge, quality, usage
Infrastructural Readiness Index (IRI)	Interactive Data Corporation/World Times [149]	Computer infrastructure, Internet infrastructure, social infrastructure, information infrastructure
National Informatization Quotient (NIQ)	People's Republic of China [72]	Development and application of info resources, info network construction, application of ICTs, info industry development, human resources, environment
Information State	Orbicom/UN [129]	Information density (capital, labor), info use (uptake, intensity)
Digital Divide	Husing and Selhofer [68]	Gender, age, income, and education
Composite Digitization	Corrocher and Ordanini [37]	Markets, diffusion, infrastructures, human resources, competitiveness, competition
Global Diffusion of the Internet Framework (GDI)	MOSAIC Group [150]	Pervasiveness, geographic dispersion, sectoral absorption, connectivity infrastructure, organizational infrastructure, sophistication of use

Table 1. Key ICT Single-Item Index Measures.

Note: Additional information on single-item index measures is available from Bridges.org (www.bridges.org).

single-item index measures only measure ICT readiness and not ICT impacts at the country level. ICT readiness relates to ICT use and preparedness for its use, while ICT impacts are a post-use issue.

Three main strengths of single-item index measures are relevant in the context of measuring ICT impacts. First, although ICTs are used in different development areas, single-item index measures provide a simple measure representative of the overall usage across all development areas. Second, a single-item index provides a scale on which to measure intangible qualitative variables like e-readiness, which convey more than the mere physical presence of ICTs in a country. Third, index measures provide a cumulative assessment at each point of time that takes account of all the previous inputs. Compare this with estimates of annual ICT investment, which convey information about the incremental change during the year but do not include information regarding contributions in past years. The cumulative nature of assessment is relevant in the context of lag effects in ICT value.

The use of single-item index measures also has some limitations. The first relates to the indicators used in constructing them. There does not as yet seem to be a unanimous approach in this regard. For example, the E-Readiness Index (ERI) has more than 100 indicators, while the Digital Access Index (DAI) uses just eight [48, 69]. Another issue relates to finding suitable weights for combining indicators. For example, one might argue that a user connected via a broadband connection has access to many applications and services that are not possible via lower-capacity phone lines, and this should have more weight in an ICT readiness index measure (e.g., [85, 88]). But how much more? And who decides? Different and sometimes *ad hoc* methods of aggregation have been adopted in different single-item index measures of ICT readiness. The National Informatization Quotient (NIQ), for example, uses a subjective expert evaluation to weight the different factors, which are then summed to give the final index value [72]. The Network Readiness Index (NRI), in contrast, sums up just three subindices, each given equal weight [47]. Each indicator within a subindex is also given equal weight. However, since the number of indicators differs for different subindices, the effective weight of an indicator on an index will vary.

Several ICT products, services, and applications exhibit network externalities that affect the value of ICT impacts. By *value* is meant the utility rendered by a good or service. For example, the value of adoption of the Internet by 10 percent of a population is likely to be more than twice the value of adoption by 5 percent. This is because *network goods* of this sort have a value derived from both the technology-specific valuation and the network-related valuation [130]. However, the number of people adopting the technology accounts only for their technology-specific valuations and not their network-related valuations. ICT readiness indices do not account for network-related valuations.

To summarize the preceding discussion, ICT index measures have not been developed to assess ICT impacts at the country level. However, a number of agencies have developed single-item index measures for ICT readiness at the country level. This coincides with the findings of Bridges.org, an international charitable organization that promotes the effective use of ICTs in the developing world. (See various articles at www.bridges.org.)

Measurement of Country-Level ICT Impacts

Development areas (e.g., agriculture, industry, tourism, R&D, healthcare) are not measurable as a whole, but every development area will have measurable outputs. For example, the outputs for an industry might be the amount of industrial production or productivity per unit of labor. The use of ICTs in a given development area is expected to have some direct impact on the area. In addition, there may be indirect impacts on other development areas that are linked to it in some way. Measurement of the impacts of ICTs in a development area should account for both direct and indirect effects. The level of the ICTs used in a country depends on the level of development of the development area, with more developed areas using more advanced ICTs.

An *input-output model* to measure ICT impacts on a development area is explained below (*see Figure 2*).

A standard input-output relationship can be written as:

$$OUTPUT_i = f_i(\ INPUTS_i) \qquad (1)$$

where $OUTPUT_i$ represents the output of development area i, and $INPUTS_i$ represents all the inputs used by development area i. The function f_i represents the technology used in transforming the inputs to outputs in the given development area. Note that f_i corresponds to the aggregate state of technology employed by the development area across the country, even though there may be disparities in the technologies used by individual firms. Note, too, that the use of ICTs in a development area changes the state of technology in that area. For example, paper financial instruments are slowly becoming extinct due to the increasing use of electronic financial instruments, such as ATMs, on-line payments, and Paypal. Better connectivity signifies improved access to information, which should enable a user to make better choices. The use of ICTs also enables faster, cheaper, and easier communication between stakeholders in a development area, whether customers and suppliers, doctors and patients, or governments and citizens. This is consistent with the tool view of ICTs.

Barro and Sala-i-Martin posited that advanced countries discover new ideas that other countries imitate, but that the use of ICTs can help developing countries grow faster without having to innovate on their own [20, 138]. ICTs influence the state of technology a country uses. This thinking is reflected in the Technology Achievement Index (TAI) of the UN Development Program [41, 139]. TAI represents the state of the technology created and used in a country. Several of the indicators used by the Development Program in constructing TAI relate to ICTs. For example, *diffusion of recent innovations* is measured by the number of Internet hosts per capita, while *diffusion of older innovations* is measured by per capita telephones (including both landlines and cellular phones). A change in these indicators will modify the TAI, validating the assertion that ICTs influence the overall technology. Thus Equation (1) can be rewritten as:

$$OUTPUT_i = f'_i(ICT,\ INPUTS_i) \qquad (2)$$

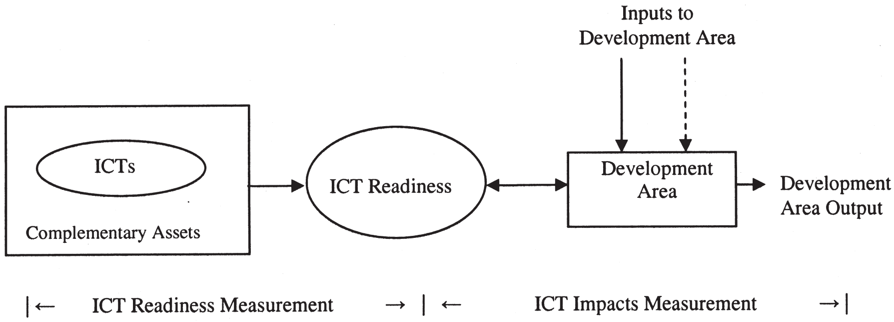

Figure 2. Country-Level Input-Output Model for Assessment of ICT Impacts

Notes: (1) For simplicity, the figure above represents the input-output model for only one development area. In the real world, there are several development areas, each of which can be represented by similar diagrams. (2) The inputs are shown as solid lines and dashed lines. The solid line represents an exogenous input to the specified development area. The dashed line represents an output from another development area that acts as input to the specified development area (also called an intermediate). Thus, an output in a given development area is the result of the inputs and the technology as determined by ICT readiness and development area-specific technology. However, it is possible that the outputs of other development areas will impact the output of a given development area, though this may not always be the case. We represent this with the dashed lines from other development area outputs to the input-output process for a given development area.

where f'_i represents the transformation of inputs and ICTs into the outputs for a given development area *i*. This conceptualization of ICTs is different from considering ICT investments in hardware and software as one of the inputs to the input-output transformation process—an approach adopted in several previous studies that looked into the impacts of ICTs (e.g., [44, 45, 83]). In the proposed formulation, the variable *ICTs* signifies the role ICTs play in influencing the state of technology in the specified development area. This conceptualization includes both positive and negative influences of ICTs. The *valence* of the relationship between $OUTPUT_i$ and *ICT* shows whether the impact is positive or negative. For an $OUTPUT_i$ that is desirable, a negative relationship between *ICT* and $OUTPUT_i$ signifies a negative impact of ICTs. On the other hand, for an undesirable output (say pollution), a negative relationship between *ICT* and $OUTPUT_i$ indicates a positive impact.

Complementary assets also have an important role in the impacts of ICTs on a development area. At the firm level, ICT impacts depend on ICT investments and other complementary investments [28, 46]. For example, the success of a new enterprise resource planning (ERP) system will depend on the ability of the firm's employees to adapt to the capabilities of its systems, which may necessitate changes in managerial and operating procedures, employee training, and so on. Investments in non-ICT areas in an organization and its employees, for example, to equip them to use the ERP system, are complementary investments. Country-level complementary investments are slightly different. For example, the education of people in engineering and technology-related courses is essential for industry to take advantage of ICT applications to improve productivity. Education investments will complement the ICT investments made by an industry. Several ICT readiness index measures include indicators that represent complementary assets. For example, the Network Readiness Index (NRI) has indicators for the efficiency of the tax system, the overall quality of the infrastructure, and foreign ownership restrictions. Based on the above, Equation (2) is rewritten as:

$$OUTPUT_i = f''_i(ICT, COMPLEMENTARY\ ASSETS, INPUTS_i) \quad (3)$$

where f''_i represents the transformation of inputs, ICTs and complementary assets into the outputs for a given development area *i.*

The ICT readiness index measures also can be viewed as a composite representation of the use of ICTs in a country and the e-readiness of the complementary assets to exploit these ICTs. Equation (3) is rewritten as:

$$OUTPUT_i = f_i(ICT\_READINESS, INPUTS_i) \quad (4)$$

The wide disparity among countries in respect to development and use leads to systemic differences in their ability to exploit ICTs. For example, there is less than one PC per thousand people in Niger, as against 750 in the United States or 826 in Switzerland. The disparity is starker for Internet servers. Bangladesh and Myanmar have fewer than 0.002 Internet servers per million people, whereas the corresponding figure in the United States is 783 and in Iceland it is 1,010. The differences in the development of countries prompt different processes in the usage of ICTs. For example, e-commerce is in an embryonic stage in most developing countries, whereas it is becoming increasingly significant in developed countries [105, 135]. Developing countries tend to make greater use of community-based ICT applications [29, 84]. Developing countries also face greater institutional, political, and cultural obstacles to the adoption and exploitation of ICTs [108, 120, 131, 143]. Starting from a low base of initial development, ICTs face issues of *scaling* and *sustainability* that are quite different from those in developed countries [81, 125]. Avgerou argued that developing countries that hope to take advantages of ICTs for economic growth should try to develop organizational practices that are locally appropriate [14]. Also, ICTs enable developing countries to leapfrog the development divide. Some developing countries have been implementing state-of-the-art ICT applications—e-banking is a good example [77, 97]. To summarize, the differences between the ICTs in developed and less-developed countries necessitate examination of whether the impacts of ICTs also vary for countries at different levels of ICT readiness or development.

Based on the considerations discussed above, an approach is proposed for assessing ICT impacts at the country level. The approach can be described in two stages. The first stage instantiates the details of the framework under discussion (*see Figure 2*). The second stage specifies a representative econometric model that supports the estimation of the impacts.

Stage One. Figure 2 shows ICT readiness as a variable affecting the output of a development area. A development area's output is dependent on several inputs and, in some cases, on the output of other development areas—often called *intermediates* in production economics. This is depicted by dashed lines. The development areas in the framework can be specified at a level of aggregation for which the ICT impacts are assessed. For example, a development area may be defined to include the overall industrial growth of a country or industrial growth in several different industries (e.g., the mining, electronics, and IT industries). The basis for an econometric model that represents this framework so that country-level ICT impacts can be assessed using real-world data is outlined below.

Stage Two. For the development areas under study, the relationship between the dependent variable *OUTPUT* for a given development area *i*, and ICT readiness and the other inputs, is given by Equation (4). There will be one equation for each development area for which ICT impacts are to be estimated. The equations can be instantiated with different dependent and independent variables, as appropriate, for each of the different development areas, but the same functions can be used for all the countries in the analysis. Thus, the function *f* may be different for different development areas *i*. The selected *INPUTS* and f_i will also be different, depending on the theoretical relationship that underlies output production in a development area. Some of the inputs to a development area may be the outputs of other development areas. (In Figure 2 this is represented by the dashed line in the input-output process of the development area.) Note the duality of ICT readiness: It influences the development area but is influenced by the level of development. The demand for ICT products like PCs and Internet connectivity is determined by different development factors, including per capita income, trade, and education [17]. The duality of ICT is represented by a double-ended arrow, one side pointing from ICT readiness to the development area, and the other pointing from the development area to ICT readiness.

Since countries at different levels of ICT readiness or development may experience ICT impacts differently, dummy variables are introduced in Equation (4). The World Bank classifies countries in four income categories (high-income, upper-middle-income, lower-middle income, and low-income) based on per capita gross national income (GNI) [155]. (See Appendix Tables A2 and A3 for a listing of the countries and a breakdown of their income levels.) A parallel specification is defined here for different levels of ICT readiness: Countries with e-readiness values of more than 8 are classified as high ICT readiness, between 6 and 8 as upper-middle ICT readiness, between 4 and 6 as lower-middle ICT readiness, and less than 4 as low ICT readiness. Dummies are used for three of the four categories, with the fourth as the base case. Significant values of the dummies in an empirical estimation indicate the differences that countries demonstrate at different levels of development. Accordingly, the relationship in Equation (4) that accounts for differences between a country's level of development and ICT readiness can be expressed as:

$$OUTPUT_i = f_i(ICT\_READINESS,\ INPUTS_i,\ DEVP\_Dummies) \tag{5}$$

$$OUTPUT_i = f_i(ICT\_READINESS,\ INPUTS_i,\ READINESS\_Dummies) \tag{6}$$

Empirical Model and Data Collection

The application of the framework and general estimation model will now be demonstrated for selected development areas and output in a set of 64 countries over four years. The development areas are related to: (1) the *volume of international trade* of a country; (2) domestic agricultural development, as represented by *cereal productivity;* (3) domestic R&D development, as represented by the number of *patent applications filed;* and (4) social development, as represented by a measure of the *quality of life.*

Empirical Model Development

Expanding on the observations about the framework and its translation into a testable empirical model, it is appropriate to point out the role of prior theory in guiding the choice of modeling details for each of the development area equations. Whenever possible, *structural equations* should be developed—in essence, theory-based representations of the input-output relationships that will be estimated. This can be done for each of the development area equations by examining the literature and extracting structural models that have a basis in the accumulated theoretical knowledge that has guided prior estimations of the individual relationships.

Trade

Based on his studies of the integration of trade and disintegration of production in an ICT-enabled global economy, Feenstra argues that companies are now finding it profitable to outsource increasing amounts of the production process, an example of the impact of ICTs on trade [52].[3] Anderson and van Wincoop make an interesting argument that trade between two countries "depends on the bilateral [trade] barriers between them relative to average trade barriers that both regions face with all their trading partners" [6, p. 176]. They translate this general argument via a structural model that solves for equilibrium consumer price indices and trade shares between the countries. They state that the bilateral trade between two countries, $TRADE_{ij}$, can be represented as:

$$TRADE_{ij} = [(GDP_i \cdot GDP_j)/GDP_{WORLD}] \\ (BILAT\_RESIST_{ij}/AVG\_RESIST_i \cdot AVG\_RESIST_j)^{1-\sigma} \qquad (7)$$

where *GDP* represents the *gross domestic products* of countries *i* and *j* and the world total (*WORLD*). In addition, the two forms of resistance to trade are the *average trade barriers* for the countries *i* and *j*, as represented by AVG_RESIST_i and AVG_RESIST_j, and the (reflexive) bilateral trade barrier for the two countries is represented by $BILAT\_RESIST_{ij}$. ICTs enable greater information dissemination, increase interfirm interactions across countries, expand markets for sellers, and create new demand by increasing consumer awareness of new products [35, 80, 87, 96]. Therefore, greater use of ICTs should lead to reduced resistance to trade. Thus, ICT use in country *i* has a positive impact on both AVG_RESIST_i and $BILAT\_RESIST_{ij}$, and ICT use in country *j* will also affect $BILAT\_RESIST_{ij}$. Finally, σ represents the *elasticity of substitution* between all traded goods, an important consideration for establishing a supply-and-demand equilibrium relative to the consumer price indices and trade barriers of the countries studied.

The trade of country *i* is the sum of all $TRADE_{ij}$ over all of its trading partners:

$$TRADE_i = GDP_i / [GDP_{WORLD} \cdot (AVG\_RESIST_i)^{1-\sigma}] \\ \sum_{j=1 \text{ to } n-1\ (j \neq i)} [GDP_j \cdot BILAT\_RESIST_{ij} / AVG\_RESIST_j^{1-\sigma}] \tag{8}$$

The summation term applies to the ratio of bilateral trade and average trade barrier multiplied by the GDP for each country except the country for which the trade volume is being calculated. When the logarithms of both sides are taken, the log summation for the $n - 1$ countries is approximately the same irrespective of which country is excluded. In essence, the trade of any one country is relatively small in comparison to all international trade, so this relationship can be approximated (and the country subscript *i* eliminated) with:

$$\ln TRADE = \ln CONSTANT + \ln GDP - \ln GDP_{WORLD} \\ - (1 - \sigma) \ln AVG\_RESIST \tag{9}$$

GDP_{WORLD} is constant across the different countries. Therefore, it is proposed, the average resistance to trade AVG_RESIST_i is a function of the ICT readiness of the country. The relationship for the trade of a country *i* with all the other countries in the world can be represented in its estimation form:[4]

$$\ln TRADE_i = f_{TRADE}(\ln GDP_i, \ln AVG\_RESIST_i) \\ = f(\ln GDPi, g(ICT\_READINESS_i)) = \ln CONSTANT_{TRADE} \\ + \beta_1 \ln GDP_i + \beta_2 \ln ICT\_READINESS_i + \varphi \tag{10}$$

The estimation form in Equation (10) represents the functional relationship between *ICT_READINESS* with volume of *TRADE* in the economy with the regression parameters β, with an appropriate regression constant and error term included.[5] The subscripts for country and time are suppressed.

Agricultural Productivity

Hayami and Ruttan's seminal study of agricultural productivity differences between countries found that these could be explained by such variables as labor, land, livestock, fertilizer consumption, machinery, education and technical manpower [64]. Antle's examination of agricultural productivity across countries found that it is related to education, research, and infrastructure in the country [10]. The well-established models developed in prior research are used for the present model. The object is to look into the effect of ICT use on the agricultural productivity of a country in terms of its *cereal production*. Pingali and Heisey studied cereal productivity in developing countries for more than 30 years and found that growth in productivity results from increased and more efficient use of inputs [115]. This is in tune with the findings of Hayami and Ruttan.[6]

The use of fertilizers is, in particular, an important input for cereal productivity (*CEREAL_PROD*). The machinery commonly used for cereal production includes tractors, harvesters, threshers, and tillers, but tractors are the basic machinery to which many other kinds of equipment, including harvesters and tillers, can be attached. Thus, the number of tractors per unit land (*TRAC*) is included as a factor explaining cereal productivity.

Following these authors, percentage enrollment in primary school (*PRIM_EDUC*) and percentage enrollment in secondary school (*SEC_EDUC*) are also included as variables to represent education of human resources in agriculture. Further, since efficient use of agricultural inputs depends on timely and proper administration of inputs, awareness of better managerial practices should be positively associated with the use of ICTs in the country [33, 112].

Information is as crucial as any of the other inputs used in agriculture production. The reduced costs of information dissemination, ease and speed of information access, and greater assimilation through the use of multimedia all help in better crop management and cereal productivity. The *e-choupal* initiative in rural India is an example of an ICT application that provides knowledge to the agri-producer for productivity improvement [23, 142]. The Food and Agriculture Organization (FAO) of the United Nations carried out a development-support communication program in Bangladesh using a multimedia approach, with extremely successful results. "The proportion of farmers controlling rats rose from 10 percent to 40 percent in one year. A media campaign costing $17,500 and rat baits costing $23,400 resulted in wheat harvest saving of $850,000" [158, p. 6]. The extension services in rural areas have traditionally been cornered by the more progressive and powerful farmers [136]. In rural Costa Rica, small coffee growers are able to use ICTs to send shipping notices and receive national and international coffee prices [9].

The benefits of modern technology often do not reach poor and smaller farmers. ICTs enable more extensive dissemination of all extension services, including distribution of agricultural inputs, warning and protection against flood and drought damage for natural resource management, access to and awareness of new and appropriate technologies, market prices, impending insect infestations, and credit opportunities. One program, for example, put a huge amount of information on crop protection and pest management on a CD-ROM and made it available to farmers at a low price.

Based on the reasoning presented so far, the drivers of cereal productivity are defined as:

$$\begin{aligned} \ln CEREAL\_PROD = F_{CEREAL\_PROD}(&\ln ICT\_READINESS, TRAC, \\ &\ln FERT\_CONS, PRIM\_EDUC, SEC\_EDUC) \end{aligned} \tag{11}$$

where *FERT_CONS* refers to fertilizer consumption in cereal production, and *PRIM_EDUC* and *SEC_EDUC* refer to education in primary and secondary levels, respectively. *TRAC* refers to the use of tractors in agriculture production. Since these variables show large variations across countries, the logarithms of all the variables in the equation were used, and the estimation model is stated as follows:

$$\begin{aligned} ln\ CEREAL\_PROD = CONSTANT_{CEREAL\_PROD} + \beta_3 \ln ICT\_READINESS \\ + \beta_4\ ln\ FERT\_CONS + \beta_5\ ln\ TRAC + \beta_6\ ln\ FERT\_CONS \\ + \beta_7\ ln\ PRIM\_EDUC + \beta_8\ ln\ SEC\_EDUC + \phi \end{aligned} \quad (12)$$

R&D Output

Several studies have looked at the impact of IT on R&D output at the firm level. ICTs make for better coordination, leading to greater economies of scale and scope in R&D activities. ICTs enable far more sharing of product knowledge, process expertise, and human expertise across researchers irrespective of their geographic distance from one another. For example, Merck's drug-discovery process has benefited from the firm's ability to share the knowledge among its different laboratories [118]. Further, the use of ICTs makes strategic decision-making easier by enabling the compilation and processing of a huge amount of information, which otherwise would be impossible [94].[7] Since the summation of the R&D output of its firms constitutes the R&D output of a country, these studies suggest that the ICTs should also have an impact on R&D output at the aggregate level.

Knowledge production has been studied in past research at the firm level by Griliches and at the geographic region level by Feldman and Florida [54, 61]. Acs, Ancelin, and Varga use the following specific *knowledge production function* for cities [2]:

$$\begin{aligned} ln\ PATENT\_APPS = f_{PATENT\_APPS}(IND\_R\&D,\ UNIV\_R\&D, \\ INNOV\_BASE) \text{ and } = \lambda\ ln\ (IND\_R\&D) + \gamma\ ln\ (UNIV\_R\&D) \\ + \delta\ ln\ (INNOV\_BASE) + \eta \end{aligned} \quad (13)$$

where *PATENT_APPS* is a proxy for the level of knowledge available in a country, *IND_R&D* is the industry R&D there, *UNIV_R&D* is the university research of the country, and *INNOV_BASE* is the national base of financial, legal, marketing, and technical knowledge at business service firms. At the country level, industry and university R&D can be jointly represented with a proxy, *total R&D expenditures* (*R&D_EXP*) [13] and *total R&D employees* (*R&D_EMP*) [71, 90]. Innovation networks and services available to firms are likely to be affected by ICT use, so it is here proposed that *INNOV_BASE* will be related to *ICT_READINESS*. R&D expenditures in a country are likely to be dependent on the size of the economy; larger countries will be able to devote greater resources to R&D [36, 56]. Thus, *GDP_CAP* is used as a control in the knowledge-production function that specifies and states the estimation form as follows:

$$\begin{aligned} ln\ PATENT\_APPS = ln\ CONSTANT_{PATENT\_APPS} \\ + \beta_9\ ln\ ICT\_READINESS + \beta_{10}\ ln\ R\&D\_EXP + \beta_{11}\ ln\ R\&D\_EMP \\ + \beta_{12}\ ln\ GDP\_CAP + \eta \end{aligned} \quad (14)$$

with the variables defined and measured as described previously.

Quality of Life

The Human Development Index (*HDI*) developed by the UN Development Programme is a globally accepted index of the *quality of life* in a country [140]. The *HDI* integrates the following indicators: life expectancy,[8] adult literacy rate, combined primary, secondary, and tertiary gross enrollment ratio,[9] and per capita GDP based on purchasing price parity. Indicators included in the *HDI* are also affected by ICT use, including health and education [12, 39, 42, 86, 91]. Thus, a country's *HDI* should be related to its ICT readiness:

$$HDI = f_{QUALITY\_LIFE}(ICT\_READINESS;\ GDP\_CAP) \quad (15)$$

Two control variables, *GDP_CAP,* are included to capture the baseline influences of the size of the economy and the wealth of the population [49]. The estimation form is:

$$HDI = CONSTANT_{HDI} + \beta_{13}\ ICT\_READINESS + \beta_{14}\ GDP\_CAP + \mu \quad (16)$$

Duality of ICT Readiness

Finally, the duality of ICT readiness is modeled. As argued earlier, ICT readiness not only influences a country's development, but is determined by its level of development . The demand for ICT products depends on the state of the development areas. This dependence of ICT readiness occurs for all the development area outputs considered in the model:

$$ICT\_READINESS = f_{ICT\_READINESS}(GDP\_CAP,\ TRADE,\ CEREAL\_PROD,\ PATENT\_APPS,\ HDI) \quad (17)$$

Again, taking logarithms of all the variables except the index variables, *ICT_READINESS* and *HDI,* yields:

$$ICT\_READINESS = lnCONSTANT_{ICT\_READINESS} + \beta_{15}lnGDP\_CAP + \beta_{16}lnTRADE + \beta_{17}lnCEREAL\_PROD + \beta_{18}lnPATENT\_APPS + \beta_{19}HDI + \tau \quad (18)$$

Simultaneous Equation Model for Estimation of ICT Impacts

The four outputs for which the impact of ICTs will be assessed are related to one other, and each of them is affected by the country's ICT readiness. The explanatory and dummy variables outlined in the preceding sections are not expected to completely represent all of the forces that explain the development area outputs as modeled above. Time-invariant features related to countries, such as land quality, public infrastructure, and climate, may influence development area outputs. To address these unobserved differences, models are estimated for each of the developmental areas using time-differences between 2001 and 2005 for the data set. Combining the individual models and taking time-differences (Δ) gives the following system:

$$\Delta(ln\ TRADE) = ln\ CONSTANT_{TRADE} + \beta_1\Delta(ICT\_READINESS) + \beta_2\Delta(ln\ GDP) + \varphi \quad (19a)$$

$$\Delta(ln\ CEREAL\_PROD) = CONSTANT_{CEREAL\_PROD} + \beta_3\Delta(ICT\_READINESS) + \beta_4\Delta(ln\ FERT\_CONS) + \beta_5\Delta(ln\ TRAC) + \beta_6\Delta(ln\ PRIM\_EDUC) + \beta_7\Delta(ln\ SEC\_EDUC) + \phi \quad (19b)$$

$$\Delta(ln\ PATENT\_APPS) = ln\ CONSTANT_{PATENT\_APPS} + \beta_8\Delta(ICT\_READINESS) + \beta_9\Delta(ln\ R\&D\_EXP) + \beta_{10}\Delta(ln\ R\&D\_EMP) + \beta_{11}\Delta(ln\ GDP\_CAP) + \eta \quad (19c)$$

$$\Delta(HDI) = CONSTANT_{HDI} + \beta_{12}\Delta(ICT\_READINESS) + \beta_{13}\Delta(GDP\_CAP) + \mu \quad (19d)$$

$$\Delta(ICT\_READINESS) = lnCONSTANT_{ICT\_READINESS} + \beta_{14}\Delta(lnGDP\_CAP) + \beta_{15}\Delta(lnTRADE) + \beta_{16}\Delta(lnCEREAL\_PROD) + \beta_{17}\Delta(lnPATENT\_APPS) + \beta_{18}\Delta(HDI) + \tau \quad (19e)$$

The reader should note that the Δ(*ICT_READINESS*) is a dependent variable in Equation 19e but an independent variable in Equations 19a to 19d. Thus, the system of equations forms a *simultaneous equation model.* This is used to estimate the impacts of ICTs on *TRADE, CEREAL_PROD, PATENT_APPS*, and *HDI* at the country level. For estimation purposes, the development dummies (and the ICT readiness dummies, as the case may be) are now reintroduced so as to capture the differential impacts on the development area outputs for countries in different states of development. These relationships are estimated both with contemporaneous values of Δ(*ICT_READINESS*) and with a one-year lagged value. Equations 19a to 19d all have a lagged term, Δ(*ICT_READINESS*), for lagged estimation.

Since the growth of one development area may be related to growth in another, the individual equations in the system of equations are *interdependent.* Each equation can be independently estimated using standard econometric techniques, but this is likely to result in *biased statistical estimates* due to the possible *correlation of the error terms* in the equations.[10] In addition, because the independent variable of one equation can be the dependent variable of another equation, there will also be *endogeneity* in this modeling specification.

A simultaneous equation modeling approach is proposed to jointly estimate these equations [63]. *Simultaneous equation models* are systems of regression equations in which one or more of the equations contain two or more *endogenous variables* (i.e., variables determined within the system of equations). Simultaneous equation models handle the correlation between error terms in the system of equations, and can account for the interdependence between the equations representing the different development areas. This approach solves the problem that Hausman calls *joint endogeniety,* resulting in more efficient statistical estimates [63].

Data Collection and Descriptive Statistics

There are three important requirements for an empirical estimation of the impacts of ICTs at the country level. First, the *units of measurement* for different variables should be same across countries. Second, the data should be available for a sufficiently large number of countries to satisfy *asymptotic assumptions.* Third, since the study proposes to account for possible changes over time, there should be longitudinal data. These requirements impose a severe constraint on data availability. Countries report their aggregate statistics based on different fiscal-year definitions and have different accounting practices and data-collection procedures. The present study uses the variables available in the World Development Indicators database of the World Bank to minimize the negative impacts associated with pulling together secondary data to cover the variables of interest [154]. The World Bank collects and annually publishes more than 800 indicators for nearly 150 countries. The World Development Indicators data met all three requirements required for this study. The Human Development Index (*HDI*) [140], which also satisfies the three requirements, was used to measure country-level *quality of life.* Descriptive statistics and an explanation of the sources for the data are shown in Table 2.

Finally, the estimation uses three ICT readiness index measures: the ERI, the NRI, and the DAI. These were selected because they meet the essential requirement for the study—they assess the state of a country's ICTs and complementary assets. Moreover, they are all developed by experts in internationally reputed organizations: the E-Readiness Index by the Economist Intelligence Unit in collaboration with the IBM Institute for Business Value; the Network Readiness Index by the Center for International Development, Harvard University; and the Digital Access Index by the International Telecommunication Union. The details of their methodologies have been made public by their sponsors. The sponsoring organizations also have taken necessary precautions in the collection of survey response data. These indices have been used in previous empirical research and are widely accepted both by practitioners and in the academic community.

The use of three ICT readiness index measures provides a means to carry out robustness checks for the results of the models. However, not all of them offer longitudinal data for the years of the assessment. For example, the DAI is available only for 2002 [69]. As hinted in an earlier note, under the circumstances the ERI is the best choice. Measures of the ERI are available for 2001 to 2005 across the 64 countries. In addition, three direct measures of the use of ICTs in a country were selected: *TEL* representing the number of fixed and mobile telephones per 1,000 population, *PC* representing the number of computers per 1,000 population, and *INTERNET* representing the number of Internet users per 1,000 population.

The different ICT readiness indices are highly correlated both over time for the same indices and across indices. For the *cross-index correlations,* the

Variables	Obs.	Mean	SD	Min	Max
ICT measures					
ERI	294	5.72	1.93	2.37	8.74
DAI	61	0.58	0.17	0.15	0.85
NRI	159	4.08	0.90	2.10	6.05
TEL	313	850.63	510.82	8.31	1804.05
PC	264	232.34	220.30	4.24	864.58
INTERNET	308	249.87	199.88	0.96	763.52
Other variables in the models					
GDP	320	5.10e+11	1.43e+12	5.79e+09	1.18e+13
GDP_CAP	320	11,250.36	11,395.80	358.00	39,666.00
LABOR	320	3.83e+07	1.07e+08	662,500.00	7.76e+08
CAPITAL	257	9.79e+10	25.30e+10	13.50e+08	192.00e+10
TRADE	272	2.29e+11	3.69e+11	4.86e+09	2.58e+12
CEREAL_PROD	305	3,965.03	1,873.44	886.00	9,184.00
FERT_CONS	124	2,083.13	3,155.28	23.00	24,180.00
PRI_EDN	245	103.70	9.90	67.20	147.66
SEC_EDN	240	93.57	23.85	24.55	178.38
TRAC	186	6.71	10.63	0.10	68.38
PATENT_APPS	173	25,922.53	75,051.52	33	403,435
R&D_EXP	168	1.38	1.09	0.05	5.01
HDI	315	0.82	0.10	0.49	0.96

Table 2. Descriptive Statistics for 64 Countries, 2001–2005.

Notes: Source and explanation of variables. Categorization of countries (64 total) into high (27 obs.), upper-middle (16), lower-middle (17), and low-income (4), based on World Bank classification. ICT readiness index measures: (1) E-Readiness Index (ERI) [48] for 2001 to 2005; (2) Digital Access Index (DAI) [69] for 2002; Network Readiness Index (NRI) [47, 82] for 2001 to 2005. The World Bank [154] Development Indicators provided data on (1) *GDP* in terms of gross domestic product in constant 2000 US$; *LABOR* based on total labor force; *CAPITAL* based on gross fixed capital formation in constant 2000 US$; *TRADE* based on (imports of goods and services) plus (exports of goods and services) in constant 2000 US$; *CEREAL_PROD* in terms of cereal productivity in kilograms per hectare; *FERT_CONS* in terms of fertilizer consumption: per hectare of arable land; *TRAC* is tractors per 100 hectares of arable land; *PRI_EDN* is enrollment in primary school as a percentage of gross; *SEC_EDN* is enrollment in secondary school as a percentage of gross; *PATENT_APPS* in terms of total of (resident patent applications) plus (nonresident patent applications); *R&D_EXP* in terms of R&D expenditures as percent of GDP; *R&D_EMP* in terms of researchers in R&D per million people; *TEL* in terms of number of fixed and mobile telephones per 1,000 population; *PC* in terms of number of computers per 1,000 population; *INTERNET* in terms of number of Internet users per 1,000 population. World Development Reports [140] provided data on *HDI*.

minimum was 89.9 percent for DAI in 2002 and NRI in 2002, and most other correlations were in the 90 percent–plus range. The high correlations between different index measures shows that the values they arrive at are closely related even though they use different indicators. They apparently do quite well at measuring the same things. For the *intra-index correlations,* which show the similarity of values of the same index across different years, the maximum correlation was 99.7 percent for the ERI in 2001 and 2002. All other correlations, again, were in the 90 percent–plus range. The high intra-index correlation indicates the substantial path dependence in the ICT readiness of countries, and the difficulties associated with changing things very much year to year.

Empirical Model Estimation Issues and Results

We now turn to a discussion of the econometric considerations related to the proposed estimation approach, the details of the estimation results, and additional sensitivity analysis to provide addition robustness checks on the results.

Econometric Considerations

The likelihood of endogeneity is a difficulty in any empirical estimation of the impact of ICTs on development area outputs. One reason for endogeneity may be that contemporaneous shocks to a region will affect both the independent variable and the regressor in one of the models. For example, the boom in the IT outsourcing industry in India has affected both exports from the country and also its overall ICT readiness. This could introduce bias in the results [119]. Since ICT readiness is a composite index measure comprising several indicators, another source of endogeneity might arise if one of the indicators is also included in the dependent variable. Endogeneity may also occur due to reverse causality. ICT readiness affects growth in development areas and is also affected by the growth in development areas. Endogeneity is likely to lead to inconsistent estimation results, however. Typically, in a macroeconomic setting, it is difficult to find good instrumental variables, as one can always argue that most instrumental variables may also be correlated with the error term [123]. Thus, although it is difficult to totally rule out endogeneity, every effort was made to control for its possible negative impacts.

A simultaneous equation model estimation technique is applied using *three-stage least squares* (3SLS) regression [157]. 3SLS is appropriate, as Anderson, Banker, and Ravindran have pointed out, because the 3SLS estimator "is asymptotically more efficient than the two-stage least squares (2SLS) estimator if the equation disturbances are correlated" [7, p. 540]. It is indeed expected that the error terms in Equations (19a) to (19e) will be correlated. In addition, 3SLS does not assume that the error terms are normally distributed. This is a less stringent requirement. This methodology has been applied to the study of IT value and investments [8].

The results for the 64 countries were validated by repeating the estimation for two ICT readiness indices: ERI and NRI. To account for the possible bias due to the overlap between indicators in the ICT readiness index and the development area outputs, the estimation was repeated using three ICT variables: Internet usage, computer usage, and fixed and mobile telephone usage, instead of the ICT readiness index. The impacts were estimated with and without lag impacts. The time-differencing method that was adopted further reduced the possibility of bias from omitted fixed country effects. The study's findings and results, therefore, are based on the *consistency* of the overall results from these different estimations.

A typical approach in econometric methods when estimating a 3SLS simultaneous equations model is to check whether every equation in the system, as well as every individual equation, is identified [76]. This was done within Stata 9.0, using its tools to check the applicable rank and order conditions, which were met. Also checked was whether the cross-correlations of the error terms exceeded the appropriate threshold to make 3SLS more efficient than 2SLS [100]. The cross-correlations for the observations were approximated based on the number of observations in the most constraining regression. Several cross-equation error term correlations were greater than 40 percent—for example, the correlations between error terms were –61 percent between Equations 19a and 19b, +55 percent between Equations 19a and 19c, and +62 percent between Equations 19c and 19d. Appendix Table A4 gives the details of cross-correlation between the error terms of these equations. The cross-correlations were potentially high enough to cause large differences between the results of 2SLS and 3SLS.[11] Thus, the 3SLS results are reported because this estimation approach does a better job of taking into account the information structure of the error terms.

Main Results

The results obtained from the estimation of the system of equations are shown in Table 3.

These results pertain to the system of equations when developmental dummies were used.[12] The four columns in the table represent four different proxies for ICT readiness in a country: *ERI* for e-readiness, telephone usage per 1,000 population (*TEL*), Internet usage per 1,000 population (*INTERNET*), and computer usage per 1,000 population (*PC*). All the models are highly significant.[13] The R^2 values for all the equations are similar and high across the four different variations, which indicates that the variables have good explanatory power.

ERI is significant only for agriculture productivity. It is not significant for other development areas. However, other proxies of ICT readiness, namely, phone usage (*TEL*), show significance for trade, R&D, and quality of life. Internet usage (*INTERNET*) is significant for trade and R&D only. Computer usage (*PC*), on the other hand, shows significance for trade, agriculture productivity, and R&D. Based on these results, the following results emerge. The impact of ICTs seems to have a positive impact on trade (*TEL:* $\beta_1 = 0.662$, SE = 0.408,

Variables	***ERI* (1)**	***TEL* (2)**	***INTERNET* (3)**	***PC* (4)**
TRADE equation				
ERI/TEL/INTERNET/PC (β_1)	-0.048	0.662*	0.112***	0.136***
	(0.043)	(0.428)	(0.036)	(0.052)
GDP_CAP (β_2)	1.742***	1.544***	1.445***	1.032**
	(0.524)	(0.553)	(0.462)	(0.528)
LOW-INCOME	Dropped	Dropped	Dropped	Dropped
LOWER-MID-INCOME	0.033	-0.092	0.033	0.054
	(0.038)	(0.096)	(0.034)	(0.035)
UPPER-MID-INCOME	0.006	-0.094	-0.035	-0.019
	(0.026)	(0.73)	(0.027)	(0.025)
CONSTANTTRADE	0.032	-0.011	-0.009	0.003
	(0.024)	(0.016)	(0.010)	(0.009)
R^2	77.5%	72.9%	83.1%	80.0%
χ^2 (Dummies=0)	0.85	2.19	5.49*	4.92*
CEREAL PRODUCTIVITY equation				
ERI/TEL/INTERNET/PC(β_3)	-0.319***	1.372	-0.140	-0.231**
	(0.092)	(1.045)	(0.107)	(0.099)
FERT_CONS (β_4)	-0.813***	-0.543**	-0.243	-0.448
	(0.234)	(0.239)	(0.225)	(0.161)
TRAC (β_5)	0.161***	0.264***	0.313***	0.148***
	(0.061)	(0.60)	(0.077)	(0.050)
PRI_EDN (β_6)	-0.016*	0.013	0.206*	0.004
	(0.010)	(0.010)	(0.011)	(0.008)
SEC_EDN (β_7)	0.016	0.023**	-0.002	0.021**
	(0.015)	(0.013)	(0.019)	(0.09)
LOW-INCOME	Dropped	Dropped	Dropped	Dropped
LOWER-MID-INCOME	0.023	-0.250	0.091	0.052
	(0.067)	(0.217)	(0.063)	(0.051)
UPPER-MID-INCOME	-0.146**	-0.446***	-0.166**	-0.114**
	(0.060)	(0.1670	(0.065)	(0.058)

(continues)

Variables	***ERI* (1)**	***TEL* (2)**	***INTERNET* (3)**	***PC* (4)**
CONSTANTFERT_CONS	0.135**	-0.058*	0.026	0.001
	(0.054)	(0.041)	(0.032)	(0.022)
R^2	0.34%	61.9%	52.8%	61.9%
χ^2 (Dummies=0)	6.95***	24.35***	13.95***	6.81**
PATENT APPLICATIONS equation				
ERI/TEL/INTERNET/PC (β_8)	0.192	3.876**	0.401***	0.643***
	(0.279)	(2.008)	(0.129)	(0.130)
R&D_EXP (β_9)	0.155	-0.606	0.005	0.678***
	(0.494)	(0.443)	(366)	(0.234)
R&D_EMP (β_{10})	0.001	-0.001	-0.001	-0.001
	(0.002)	(0.001)	(0.001)	(0.000)
GDP_CAP (β_{11})	0.664	2.917*	1.258	–1.506
	(2.761)	(2.026)	(1.617)	(1.277)
LOW-INCOME	Dropped	Dropped	Dropped	Dropped
LOWER-MID-INCOME	0.084	-0.783*	-0.099	0.077
	(0.184)	(0.444)	(0.095)	(0.088)
UPPER-MID-INCOME	0.097	-0.588*	-0.009	-0.038
	(0.124)	(0.348)	(0.119)	(0.064)
CONSTANTPATENT_APPS	-0.158	-0.149	-0.093**	-0.069***
	(0.158)	(0.066)	(0.038)	(0.025)
R^2	10.6%	32.1%	55.7%	72.3%
χ^2 (Dummies=0)	0.61	3.11	1.43	2.07
HDI equation				
ERI/TEL/INTERNET/PC (β_{12})	0.001	0.024*	-0.003	-0.001
	(0.002)	(0.017)	(0.002)	(0.002)
GDP _CAP (β_{13})	-0.040*	-0.028	-0.023	-0.023
	(0.022)	(0.021)	(0.022)	(0.025)
LOW-INCOME	Dropped	Dropped	Dropped	Dropped
LOWER-MID-INCOME	0.006***	0.001	0.006***	0.005***
	(0.002)	(0.004)	(0.002)	(0.002)

UPPER-MID-INCOME	0.001	-0.003	0.003**	0.001
	(0.001)	(0.003)	(0.001)	(0.001)
CONSTANTHDI	0.003***	0.003***	0.004***	0.004***
	(0.001)	(0.000)	(0.001)	(0.000)
R^2	57.81	56.14	58.64	50.05
χ^2 (Dummies=0)	16.03***	7.83**	13.44***	9.80***
ICT_READINESS equation				
GDP_CAP (β_{14})	11.254	16.318***	1.393	4.126
	(10.178)	(6.140)	(6.805)	(5.868)
TRADE (β_{15})	-10.052***	-9.516***	-7.106***	-7.814***
	(3.510)	(2.551)	(1.683)	(2.239)
CEREAL_PROD (β_{16})	-1.734	0.757	-3.166**	-3.315**
	(1.765)	(1.021)	(1.417)	(1.388)
PATENT_APPS (β_{17})	1.698**	1.392***	1.590***	0.855
	(0.724)	(0.556	(0.505)	(0.657)
HDI (β_{18})	27.495	78.387*	-29.199	-34.230
	(65.360)	(42.626)	(51.483)	(55.455)
LOW-INCOME	Dropped	Dropped	Dropped	Dropped
LOWER-MID-INCOME	0.455	-0.113	0.942	1.001
	(0.775)	(0.472)	(0.629)	(0.662)
UPPER-MID-INCOME	-0.127	-0.187	-0.115	-0.086
	(0.185)	(0.141)	(0.159)	(0.188)
CONSTANICT_READINESS	0.635**	0.382*	0.862***	0.847***
	(0.332)	(0.209)	(0.266)	(0.279)
R^2	64.7%	68.2%	17.0%	12.8%
χ^2 (Dummies=0)	1.17	1.79	4.02	3.39

Table 3. ICT Impacts for Countries at Different Development Levels, Simultaneous Estimation.

Notes: Data: 64 countries from 2001 to 2005. Model: 3SLS simultaneous equation model run; rank/order conditions met; better match for error terms than 2SLS. Signif.: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regression terms are in log time-differences (except the index measures *ERI* and *HDI*). The standard errors are indicated in parentheses. Observations for each regression vary with the most constraining number of data points for individual variables in the regression.

$z = 1.55$, $p < 0.10$; *INTERNET:* $\beta_1 = 0.112$, SE = 0.036, $z = 3.13$, $p < 0.002$; and *PC:* $\beta_1 = 0.136$, SE = 0.052, $z = 2.62$, $p < 0.009$). The impact of ICTs also seems to have a positive impact on R&D (*TEL:* $\beta_1 = 3{,}876$, SE = 2.008, $z = 1.93$, $p < 0.054$; *INTERNET:* $\beta_1 = 0.401$, SE = 0.129, $z = 3.10$, $p < 0.002$; and *PC:* $\beta_1 = 0.643$, SE = 0.130, $z = 4.95$, $p < 0.001$). The relationships with cereal productivity seem to be negative, though (*ERI:* $\beta_1 = -0.319$, SE = 0.093, $z = -3.45$, $p < 0.001$; and *PC:* $\beta_1 = -0.231$, SE = 0.100, $z = -2.32$, $p < 0.020$). The relationship with *HDI* does not appear to be significant. Significance occurs only when ICTs are represented by telephone usage, and then only at the 10 percent level.

Other variables in the models show consistent results across estimations. Per capita GDP is consistent and positive in the *TRADE* equation, indicating that growth in per capita GDP is associated with positive changes in a country's trade. The use of tractors is positive in the *CEREAL PRODUCTIVITY* equation across estimations, indicating a positive impact from increases in the number of tractors per acre on cereal productivity. Two results show a positive impact for secondary education on cereal productivity; the other two do not.

Similarly, two of the estimates show a negative impact for fertilizer consumption; two others do not. These results convey possible correlations that may need to be verified with a bigger data set. There is slight evidence of R&D expenses and per capita GDP differences being related to the number of patents filed (*PATENT APPLICATIONS* equation). However, these relationships appear to be significant only in one estimation and need verification. None of the variables included is significant in the *HDI* equation.

Comparisons Across Low-Income and High-Income Countries

For each model we evaluated whether the development dummies could jointly be zero. The χ^2 values are shown in Table 3. The results show that the development dummies are highly significant for the *HUMAN DEVELOPMENT* and *CEREAL PRODUCTIVITY* equations, weakly significant for *TRADE* equation (for the *INTERNET* and *PC* models) and not significant for the *R&D* and *ICT_READINESS* equations. These results suggest that the ICT impacts are different for countries with different development levels, and may also be different for some development areas.

Lag Effects and Additional Model Estimations for Network Readiness Index

A series of additional estimates was carried out. Feasible generalized least squares (FGLS) was used to estimate the models with a one-year lag for each of the ICT readiness measures. Using more than a one-year lag was infeasible because of missing observations for one or more variables. The *CEREAL PRODUCTIVITY* equation did not have enough observations even for a one-year lag, so it was not possible to perform a 3SLS estimation for it. Instead, FGLS was used to estimate the effect of ICT with a one-year lag. The results are shown in Table 4.

Variables	*ERI LAG*	*TEL LAG*	*INTERNET LAG*	*PC LAG*
TRADE Equation				
ERI LAG/TEL LAG/INTERNET LAG/	-0.017	-0.089*	-0.046*	0.019
PC LAG (β_1)	(0.013)	(0.052)	(0.024)	(0.030)
GDP_CAP (β_2)	1.230***	1.282***	1.414***	1.339***
	(0.195)	(0.188)	(0.176)	(0.174)
LOW-INCOME	0.053**	0.078*	0.071**	0.056
	(0.033)	(0.045)	(0.030)	(0.035)
LOWER-MID-INCOME	0.028**	0.036**	0.027*	0.022*
	(0.012)	(0.018)	(0.014)	(0.012)
UPPER-MID-INCOME	0.029***	0.021*	0.016	0.008
	(0.011)	(0.013)	(0.010)	(0.010)
CONSTANTTRADE	0.019***	0.025***	0.025***	0.018***
	(0.006)	(0.006)	(0.006)	(0.006)
R^2	44.0%	40.5%	42.9%	44.2%
PATENT APPLICATIONS equation				
ERI LAG/TEL LAG/INTERNET LAG/	-0.474	3.829	0.246	0.119
PC LAG (β_1)	(0.476)	(2.894)	(0.313)	(0.486)
R&D_EXP (β_9)	-2.705	-0.765	-0.502	-1.012
	(3.230)	(2.122)	(2.083)	(2.343)
R&D_EMP (β_{10})	0.001	0.001	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
GDP_CAP (β_{11})	9.965	1.765	4.831	6.177
	(10.215)	(5.640)	(5.573)	(5.898)
LOW-INCOME	Dropped	Dropped	Dropped	Dropped
LOWER-MID-INCOME	-0.518	-0.881	-0.315	-0.324
	(0.625)	(0.613)	(0.386)	(0.391)

(continues)

Variables	*ERI LAG*	*TEL LAG*	*INTERNET LAG*	*PC LAG*
UPPER-MID-INCOME	-0.907	-1.024*	-0.703	-0.673
	(0.590)	(0.554)	(0.375)	(0.402)
CONSTANTPATENT_APPS	0.284	-0.110	-0.020	-0.018
	(0.324)	(0.096)	(0.084)	(0.082)
R^2	60.7%	48.7%	47.7%	42.8%
HDI equation				
ERI LAG/TEL LAG/INTERNET LAG/ PC LAG (β_1)	-0.001	0.007	0.001	0.003
	(0.002)	(0.006)	(0.002)	(0.004)
GDP _CAP (β_{13})	-0.019	0.012	0.009	0.009
	(0.034)	(0.034)	(0.035)	(0.037)
LOW- INCOME	0.003	0.001	0.002	0.001
	(0.004)	(0.004)	(0.005)	(0.003)
LOWER-MID-INCOME	0.001	-0.002	-0.001	-0.001
	(0.001)	(0.002)	(0.002)	(0.002)
UPPER-MID-INCOME	0.001	-0.001	-0.001	0.001
	(0.001)	(0.002)	(0.002)	(0.002)
CONSTANTHDI	0.005***	0.005***	0.005***	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)
R^2	1.9%	1.4%	0.7%	0.7%

Table 4. Selected Outputs with One-Year Lag, for FGLS Models.

Notes: Data: 64 countries from 2001 to 2005. Model: FGLS. Signif.: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regression terms are in log time-differences (except the index measures *ERI* and *HDI*). The standard errors are indicated in parentheses. Observations for each regression vary with the most constraining number of data points for individual variables in the regression. *CEREAL_PROD* equation did not have sufficient observations with time-differencing and lags, and thus was excluded.

Estimation Results with One-Year Lag

The estimates in Table 4 show that the models have reasonably good explanatory power for *TRADE* and *R&D* but not for *HDI.* The R^2 values for the *TRADE* and *R&D* equations range between 40 percent and 61 percent. Further, the ICT readiness variables are not significant for *R&D* and *HDI.* The results for *TRADE* were mixed, with negative impacts for two of the models and no significant results for the other two. In general, the results show that lagged proxies of the *ICT_READINESS* proxies have a less significant effect on the selected development area output than the contemporaneous time-differenced variables. There are two possible explanations for the lower significance of ICT readiness variables in the lag estimations. First, the impacts of ICTs may be related to the existing stock and not to the differences, especially when the differences relate to lagged ICT readiness. Second, since only a single equation model is estimated, the estimations do not capture the interrelationships between development areas.

Estimation with Network Readiness Index

Additional estimates were carried out for comparison with the results in Table 4. The impacts of the Network Readiness Index, *NRI,* were estimated, since enough observations were available with time-differencing. Although there is insufficient space in this article to report the details, note that the impact of ICTs for *NRI* estimation is similar to the results in Table 3, col. 1. The coefficient values for *NRI* were slightly different from those generated for ERI because the values for these index measures differ—the values of *ERI* ranged from 1 to 10, while the corresponding range for *NRI* was 1 to 7. Overall, the results show consistency with respect to the other variables included in the model. The impacts of ICTs were mixed—significant for some development areas but not for others.

Discussion

The impact of ICTs at the country level can be felt in many different spheres of human activity. This study estimated the ICT impacts on four selected development area outputs (trade, agricultural productivity, R&D, and quality of life). Since these outputs are related—for instance, volume of trade and quality of life depend on GDP, and ICT investments depend on the level of development area demand—isolated estimation of the impact of ICTs on these development area outputs may lead to estimations that yield less than consistent results.

Assessment of Main Findings

Analyzing a simultaneous equation model with three-stage least squares made it possible to account for the relationships between the different equations as the impact of ICTs was estimated. Four different proxies for ICT readiness index measures were used to represent ICT use and investment at the country level, with fairly similar results. The Information Economy Report of UNCTAD reported on the assessment of impacts of ICTs on GDP [138]. These results were extended in the present approach by endogenizing the level of use of ICT and taking into account the interaction of different development areas.

Although the research design and estimation procedures used to assess the impact of ICTs on the development area outputs of interest suggest a high-level proof-of-concept, it was *not* possible to provide a country-specific measure of ICT impact. For example, if region-specific or state-specific data had been incorporated in the panel data analysis—in effect, bringing the level of analysis to a more micro level—it might have been possible to assess the impact of ICTs on a selected development area output *within* a country, as well as *in aggregate* across many countries. It must be recognized that this procedure is recursive. *Only* when the necessary data become available will it be possible to estimate ICT impacts at the state or city level and not lose information about the aggregate impacts.

The relationship between ICTs and cereal productivity was negative. In most developing countries, ICT use mostly occurs in cities, so the available benefits may not yet have reached the rural areas [55]. Consequently, improvements in the availability of ICTs (probably in urban areas first) has not had commensurate effect on cereal production. This suggests that governments may wish to consider putting greater emphasis on the use of ICTs for agriculture-related activities. The proposed model can distinguish between impacts that are significant and insignificant from an empirical perspective. For example, the impact of ICT readiness shows mixed significance in terms of cereal productivity or quality- of-life effects, but is strongly significant with respect to trade or R&D.

The model can also be adapted to assess both short-term and long-term impacts. The long-term impacts would require the use of a longitudinal data set covering more years. The illustrative estimation used data from 2001 to 2005, and to that extent the impacts measured are short- to medium- term. This approach is able to capture some structural and systemic changes, provided they can be suitably modeled in the input-output formulation. For example, it may be possible to study the growth of on-line retailing and bricks-and-mortar retailing, to assess their structural impacts on retail markets. For assessing stakeholder impacts, it is possible to do the same thing in a way complementary to this assessment process. That may help to provide greater understanding of the impacts.

The proposed analysis procedure can be further adapted to study whether other contextual factors play a significant role in determining the impact of ICTs on a specific output. For example, Molla and Licker [104], and also Kauffman and Techatassanasoontorn [79], have argued that the evaluation process for deciding whether to make ICT investments in a developing country should be different from the process in a developed country. Another variable of interest is whether the domestic use of English influences the ICT impacts. This can be tested by controlling for language in an expanded version of the model. Similarly, other contextual factors, including the openness of a country to trade, its form of government, the inflation level, the presence of a budget surplus or deficit, the quality of national institutions (e.g., legal, medical, and educational institutions), its ethnic diversity, and its geographic location within a region where ICTs are diffusing rapidly, could also be tested.

Ideally, each equation should include ICTs and complementary assets for the development area analyzed. It would be impractical, however, to segregate ICTs and complementary assets for each development area. For example, telecommunication infrastructure and servers are used in practically all development areas, so it is not feasible to apportion them between areas. An option is to sort ICTs in two categories: *general ICTs* applicable to all development areas, and *specific ICTs* unique to different development areas. Unfortunately, disaggregated data sets of ICTs and complementary assets are not available. Besides, the cost and effort involved in generating development-area-specific data sets may also be large. ICT readiness index measures integrate the relevant ICT indicators and several complementary assets into a single index. Although they do not offer a perfect approach, they nevertheless provide a reasonable measure of the ICTs used by a community [106]. These index measures have been developed by senior economists, analysts, and country experts, and have a gained fair degree of acceptance for their robustness and validity. The ERI and NRI, in particular, have been used in other empirical studies [15, 60, 124], and these are available alternatives to proxy for ICT investments and complementary assets.

Limitations

The proposed model has several limitations.

First, an input-output relationship should ideally include the relevant inputs and technology. This implies that a consideration of cereal production should include ICTs relevant for cereal production. Instead, though, because of the limitations of the available data, ICT readiness was used as a proxy for the relevant ICTs.

Second, it would have been more revealing to use ICT readiness for the specified development area instead of a general ICT readiness measure, but no development-area-specific measures of ICT readiness are readily available.

Third, drawing conclusions based on statistical associations, as opposed to causal relationships, has certain limitations. Most observers will understand the impacts of ICTs on a given development area with *implied causality.* The statistical results obtained in this study should *not* be pushed to that limit. Instead, the results are *association-base findings:* Their co-occurrence is emphasized and not their sequence or precedence relationships. Granger proposed a statistical means to check for causality through what is popularly called *Granger causality analysis* [60]. This method tests whether a one time-series is useful in forecasting another time-series, but not vice-versa. With this approach, it is critical to ensure that past values of the dependent variables used in the analysis do not predict the current values of the independent variables in the analysis, as was seen in the study of the valve-manufacturing industry conducted by Weill [148]. A critical requirement for Granger causality analysis is the availability of a "sufficiently" long time-series of data—a critical constraint in the ICT impacts and international technology adoption research arena.

Fourth, a simultaneous equation model entails the problem of *under-identification.* This occurs when there are more unknown parameters than equations available to solve for them. This problem frequently occurs with the use of structural models, especially when econometric estimation is attempted with a *reduced form of the equation,* with the endogenous dependent variables on the left-hand side of the set of equations and the independent variables on the right-hand side [50]. In the proposed model, the reduced form of Equations (19a) to (19e) implies that the variable *ICT_READINESS,* which figures on the right-hand side of Equations (19a) to (19d), should be transferred to the left-hand side. It turns out that this is not an issue in the present example: The system of equations actually is identified. In certain situations, however, the reduced-form equations may have fewer coefficients than necessary to be determined in the structural form of the set of equations. As a result, it will not be possible to estimate the values of all the outputs of interest. The usual approach is to impose some restrictions on the coefficients being estimated like *equality* and *normality.*

Fifth, the issue of *selection bias* must also be considered. The analysis covered countries for which the E-Readiness Index (ERI) was available for the period 2001 to 2005. The Economist Intelligence Unit comprehensively assesses the e-readiness of the world's *largest* economies. This may have resulted in some upward bias for the ICT impacts in the results presented here, since other research has shown that the availability of complementary assets is helpful for the appropriation of fuller value from ICT investments [27, 45]. This can be overcome once more data become available for a larger number of countries, but will be difficult to resolve in the short run.

Sixth, it was only possible to consider lag effects for one year in the estimations, but the impact of an ICT may take more than one year to develop. Related to this, different countries may have different rates of ICT impact absorption. More advanced estimations may be carried out through the use of *country-level fixed effects* in a simultaneous equation model (e.g., [18]).

Seventh, the ICT readiness index measures include complementary assets required for realizing the potential of ICTs. These are not development area-specific. For example, ERI incorporates complementary assets required for effective use of ICTs in business and trade. Some development areas, such as health services, do not extensively use the business environment for delivery. The relevant complementary assets for health services are better education on health issues, building health-related infrastructure, and so on. This may bias the assessment of ICT impacts on health services. A related issue arises because countries vary in terms of how their development is intertwined with the business environment. Socialist economies have public-sector dominance in several development areas. When public-sector activities constitute a big fraction of a development area, it may be important to consider complementary assets for the public sector. Accounting for complementary assets related to business may confound the overall assessment of ICTs in such cases. The study addressed this limitation by using three different ICT readiness indices, involving different indicators of complementary assets (i.e., ERI, NRI, and

DAI). The consistency of the results with the index measures suggests that this approach was valid.

Finally, it is *never* possible to enumerate all the relationships between the outputs. The estimation model employed reasonably good measures based on the available data for the dependent and independent variables. At the country level, it was not possible to capture intangible variables that many view as important impacts of ICTs. Some examples include the impact of ICTs on social awareness (as seen with crime in large cities), and the impact of ICTs on democracy and freedom of speech (including the use of Google and instant messaging in China). Thus, the model is better suited to settings where the variables of interest can be measured directly (e.g., *TRADE*) or represented by proxies that can be measured (e.g., *R&D* and *PATENT_APPS*).

Conclusion

As is known from prior research, measuring the business value of IT at the firm level is challenging. The present research points out that measuring the value of ICTs at the country level is even more demanding, in part because of the challenges of capturing the appropriate data. The main contributions and findings of this research will be summarized below, together with discussion of some extensions that further demonstrate the potential usefulness of the research approach and proposed model.

Existing approaches to the measurement of ICTs were reviewed, and a number of measures of ICT readiness were found. Given the absence of agreement in the literature on a suitable measure or model to assess ICT impacts at the country level, a model was proposed to estimate impacts of ICTs at the country level in different development areas: economy, society, and knowledge. The proposed method is robust to the inclusion of somewhat different measures for ICT readiness, as well as other somewhat different explanatory variables. The discussion showed how its use can be extended for multiple geographical levels of analysis, each increasingly fine-grained (e.g., global, national, regional, city). Issues in estimating an econometric model that appropriately represents the information structure of the error terms were also considered.

Since each development area is the domain of a different academic discipline, prior studies tended to look into the impacts of ICTs within their specific domains. Researchers in economics, public policy, sociology, strategy, operations and IS, among others, have understood the impact of ICTs in their development areas separately—and often with different theoretical and methodological perspectives. However, in the real world, at the macrolevel at least, these development areas are interrelated.

The research discussed in this paper demonstrates that two essential features are needed to effectively measure ICT impacts at the country level. First, since ICT impacts are felt across several development areas, the relevant development areas and their interrelationships should be considered in the model. Second, development of structural models for each development area's output and an appropriate means to estimate the impacts of ICTs comprise a feasible method to assess the impacts. The proposed model is a valuable contribution in this respect, for it integrates several development areas and accounts for their relationships through a set of simultaneous equations. Measurement approaches for ICT readiness, intensity, and impacts at the country macrolevel have been neglected in IS research, even though information at this level of analysis is useful for the purposes of national and international policy-making. This provides opportunities for research that will carry its relevance far beyond the business world to global society.

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NOTES

1. The Comprehensive Development Framework, a process developed by the World Bank to facilitate poverty reduction in countries, includes the role of ICTs [132, 153]. It emphasizes the interdependence of development in terms of social, structural, human, governance, environmental, economic, and financial elements.

2. The World Summit on the Information Society (WSIS) was held in two phases. The first phase took place in Geneva, Switzerland, in December 2003, and the second phase took place in Tunis, Tunisia, in December 2005. The first phase called upon the member nations to partner in setting up an ICT Opportunity (Digital Opportunity) Index, which was subsequently launched. The 2007 ICT Opportunity Index was issued by the International Telecommunications Union for 183 countries [70]. It groups economies in four categories from high to low ICT opportunities and has four subindices: networks, skills, uptake, and intensity. The indicators used to measure the subindices are: *Network index:* fixed telephone lines per 100 inhabitants, mobile cellular subscribers per 100 inhabitants, and international Internet bandwidth (kbps per inhabitant); *Skills index:* adult literacy rate, and gross school enrollment rates; *Uptake index:* computers per 100 inhabitants, Internet users per 100 inhabitants, and proportion of households with a TV; *Intensity index:* total broadband Internet subscribers per 100 inhabitants, and international outgoing telephone traffic (minutes) per capita.

UNCTAD's Information Economy Reports are another important development. UNCTAD began publishing the E-Commerce and Development Report in 2000 [138]. In 2005, it was replaced by the Information Economy Report. This provides the latest information regarding adoption of ICTs by developing countries and the implications for economic and social development. The 2006 report addresses issues regarding access and use of ICTs and their impact on industry, trade in services, productivity and growth, and other related development areas.

3. Other studies that have looked into the impacts of ICTs on international trade include Braga [24], Broersma et al. [25], Graham [59], Schware and Kimberley [128], and Venables [144].

4. Note the equivalence of Equations 3 and 10 in the model for the international trade development area. The output for this development area is TRADE, and the input is GDP in the relevant country.

5. There are a number of appropriate ICT readiness indices that could be chosen. Including more than one will cause undesirable multicollinearity in model estimation. To avoid this problem, the study used only the E-Readiness Index of the Economist Intelligence Unit [48], since it appears to be well measured.

6. Other studies that examine the impacts of ICTs on agriculture productivity include Lindsey et al. [93], Mueller [107], Plant [116], Schiefer [127], Streeter et al. [134], and Zijp [158].

7. Other studies that have looked into the impacts IT on R&D output include Allen [4], Ciborra [34], Ernst and Lundvall [51], McDonough et al. [98], Mitchell et al. [103], Narula [110], Roberts [121], and Salazar et al. [126].

8. Related studies that examine the impact of ICTs on health and life expectancy are Ash et al. [12], Bates et al. [22], Bates and Gawande [21], Chandrasekhar and Ghosh [31], Chaudhry et al. [32], Heathfield et al. [65], and Hersh [67].

9. Several studies have examined the impact of ICT on education at different levels, including the primary, secondary and tertiary levels. See Addo [3], Kumar [84], Latchman et al. [86], Leidner and Jarvenpaa [91], Lelliott et al. [92], Nair and Prasad [109], Volman and van Eck [145], and Watson [146].

10. The study also estimated each of the development models independently. The general results were similar to those obtained using the simultaneous equation model, although the errors were smaller and the R^2 values improved for the simultaneous equation model.

11. The comparative correlations are higher if the time-differencing is not done, indicating that adjusting the modeling formulation reduced cross-equation correlations.

12. The results of the model estimated with ICT readiness dummies were quantitatively and qualitatively similar, and did not produce additional useful insights.

13. The ERI model for the cereal productivity equation (*see Table 3, col. 1*) was not significant, but the models with the other three proxies all were significant.

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Appendix of Supporting Tables

Network Readiness Index. The Network Readiness Index (NRI), developed by the Center for International Development [47, 82], Harvard University, estimated 75 countries in 2002 and 2003, and 102 countries in 2003 and 2004. *Network readiness* is a nation's or a community's degree of preparation to participate in and benefit from ICTs. Since 2003, the NRI has included three components: *environment, readiness,* and *usage.* Environment is divided into equally weighted subindices: the *market environment subindex* (nine indicators), the *political and regulatory environment subindex* (seven indicators), and *the infrastructure environment subindex* (five indicators). Readiness is subdivided into an *individual readiness subindex* (ten indicators), *z business readiness subindex* (five indicators), and *government readiness subindex* (three indicators). *Usage* is based on equal weights of an *individual usage subindex* (four indicators), *a business usage subindex* (three indicators), and a *government usage subindex* (two indicators).

E-Readiness Index. Since 2000, the Economist Intelligence Unit (EIU) [48] has produced the *E-Readiness Index* (ERI) for 60 large economies. ERI measures a country's e-business environment based on indicators that make a market ready for Internet-based opportunities. Nearly 100 quantitative and qualitative indicators are organized into six categories. ERI characterizes a country's technology infrastructure, business environment, degree to which e-business is adopted, social and cultural conditions that influence Internet usage, and availability of e-business services.

Digital Access Index. The *Digital Access Index* (DAI), developed by the International Telecommunications Union, was estimated for 178 countries in 2002 [69]. DAI measures the overall ability of individuals in a country to access and use new ICTs. The index is built around five main factors: *infrastructure, affordability, knowledge, quality,* and *usage.* These factors are measured for eight indicators: *broadband subscribers per 100 inhabitants; Internet users per 100 inhabitants, fixed telephone subscribers per 100 inhabitants; mobile cellular subscribers per 100 inhabitants; Internet access as percentage of GDP per capita; adult literacy; combined primary/secondary/tertiary school enrollment;* and *Internet bandwidth per capita.* DAI uses mix-max value assessments for each indicator to rank countries. If the maximum value for broadband subscribers per 100 inhabitants is 30 and the minimum is zero, then a country with 20 broadband subscribers per 100 inhabitants will have a score of 0.667. Scores on all indicators are summed based on the weights to obtain the overall DAI.

Infrastructural Readiness. The *World Times Information Society* Index [149] captures infrastructural readiness for information societies in terms of *computer infrastructure, Internet infrastructure, social infrastructure,* and *information infrastructure,* with an additional 23 underlying variables. This index has been calculated for the 55 richest countries and is reported in [101, 102].

National Informatization. In July 2001, the Information Industry Ministry of the People's Republic of China launched the *National Informatization Quotient* (NIQ) [72]. NIQ is a composite index based on twenty indicators across six dimensions. The dimensions are: *development and application of information resources, information network construction, application of ICTs, information industry development, human resources of informatization,* and *environment for informatization development.* The dimensions are weighted based on expert opinions. The framework has been applied to measure informatization of several Chinese provinces and uses indicators for economy, society, and knowledge, similar to what we advocate.

Information State. Orbicom, the Network of UNESCO Chairs in Communications, advocates a framework for measuring the digital divide in e-readiness terms. It has developed such concepts as information density and information use [129]. *Information density* refers to a country's ICT-related capital and labor stocks, and is indicative of productive capacity. *Information use* refers to the consumption of ICT-related outputs. Their aggregate represents the *information state* of a country. The *capital* and *labor* measures involve eight and four indicators each, respectively, while ICT consumption involves *ICT uptake* and *ICT intensity of use.* The former is measured with four indicators and the latter with three indicators. The *Information State Index* (ISI) has been applied to 139 countries, representing all stages of technology diffusion.

Digital Divide. Husing and Selhofer [68] suggested measuring the digital divide on an aggregate level by defining a *Digital Divide Index* (DDI). DDI emphasizes disadvantaged groups in society, by identifying knowledge gaps, and gauging four socio-economic indicators: *gender, age, income,* and *education.* DDI is defined as a weighted sum of: *percentage of computer users, percentage of computer users at home, percentage of Internet users,* and *percentage of Internet users at home.* Since it focuses on computer and Internet use, DDI cannot encompass the diversity of ICT applications across countries.

(continues)

Composite Digitization. Corrocher and Ordanini [37] proposed a model for tracking the digital divide. Their *Composite Digitization Index* (CDI) has six indicators—*markets, diffusion, infrastructures, human resources, competitiveness,* and *competition*—each of which has subindicators, which are aggregated with principal component analysis to aggregate them.

Global Diffusion of the Internet Framework. MOSAIC Group and Global Diffusion of the Internet (GDI) Project [150] proposed the *GDI Framework,* with six indicators: *pervasiveness, geographic dispersion, sector absorption, connectivity infrastructure, organizational infrastructure,* and *sophistication of use.* No ranking: GDI emphasizes Internet diffusion in a country. GDI has been applied to 25 countries in different stages to gauge ICT readiness, intensity, and impacts.

Table A1. Single-Item ICT Readiness Index Measures.

Region	Countries
Africa	Africa: Algeria, Nigeria, South Africa
Asia-Pacific	Australia, China, Hong Kong, Indonesia, Japan, Korea, Malaysia, New Zealand, Philippines, Singapore, Taiwan, Thailand, Vietnam
Central and South America	Central and South America: Argentina, Brazil, Chile, Colombia, Ecuador, Jamaica, Peru, Venezuela
Eastern Europe and Central Asia	Bulgaria, Azerbaijan, Czech Republic, Estonia, Hungary, Kazakhstan, Latvia, Lithuania, Poland, Kazakhstan, Romania, Russia, Slovakia, Slovenia, Ukraine
Middle East	Egypt, Iran, India, Israel, Pakistan, Saudi Arabia, Sri Lanka, Turkey
North America	Canada, Mexico, United States
Western Europe	Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom

Table A2. Countries in ICT Impact Assessment Model.

Low-income countries	Lower-middle-income countries	Upper-middle-income countries	High-income countries
India, Nigeria, Pakistan, Vietnam.	Algeria, Brazil, Bulgaria, Azerbaijan, China, Colombia, Ecuador, Egypt, Indonesia, Iran, Jamaica, Kazakhstan, Peru, Philippines, Sri Lanka, Thailand, Ukraine.	Argentina, Chile, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malaysia, Mexico, Poland, Romania, Russia, Slovakia, South Africa, Turkey, Venezuela.	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Hong Kong, Ireland, Israel, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Portugal, Saudi Arabia, Singapore, Slovenia, Spain, Sweden, Switzerland, United Kingdom, United States.

Table A3. Countries Categorized by Income, 2000.

	TRADE	CEREAL_PROD	PATENT_APPS	HDI	ERI
TRADE	1.000				
CEREAL_PROD	-0.616	1.000			
PATENT_APPS	0.550	-0.3804	1.000		
HDI	0.191	-0.0498	0.621	1.000	
ERI	-0.232	0.2940	-0.312	-0.315	1.000

Table A4. Cross-Equation Error Term Correlations in Model Represented by Equations 19a to 19e.

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