Investigating the Efficiency of ICT Infrastructure Utilization: A Data Envelopment Analysis Approach

'yinka Oyerinde, Felix Bankole

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'Yinka Oyerinde [1][0000-0002-9537-4093] and Felix Bankole [2][0000-0002-0094-6854]

[1]University of South Africa, UNISA Science Campus, Florida, Johannesburg, South Africa.
57645752@mylife.unisa.ac.za (Corresponding Author)
[2]University of South Africa, UNISA Science Campus, Florida, Johannesburg, South Africa.
bankofo@unisa.ac.za

Abstract. A lot of research has been done in the field of Information and Communication Technology for Development (ICT4D) investigating and measuring the impact of Information and Communication Technology (ICT) investments on Human Development. Education is a major component of the Human Development Index (HDI) which affects the core of Human Development. This research investigates the relative efficiency of ICT infrastructure utilization with respect to the educational component of the Human Development Index (HDI). A Novel conceptual model is proposed, and the Data Envelopment Analysis (DEA) methodology used to measure the relative efficiency of the components of ICT infrastructure (Inputs) and the components of education (Outputs). Results show a strong impact of ICT infrastructure on educational attainment and adult literacy rates, a strong correlation between this infrastructure and literacy rates as well as provide a theoretical support for the argument of increasing ICT infrastructure to provide an increase in human development especially within the educational context.

Keywords: ICT4D, Data Envelopment Analysis, ICT Infrastructure, Educational Attainment/Adult Literacy Rates, Human Development Index, Learning Analytics.

1. Introduction

The field of Data Analytics in Education, otherwise known as Learning Analytics (LA) and Educational Data Mining (EDM) is fast gaining grounds in term of research interests and advancement in technology [39]. The ever-demanding need for knowledge and knowledge management drives the thirst for technological advancements in the aid of learning delivery [43]. With the overwhelming successes gained in Data Analytics in the Business Industry, it is little wonder that Data Analytics has found its way into the Education Sector especially in ICT4D research. Considering that the amount of data produced inside and outside higher education institutions is growing exponentially, more and more educational institutions, seem to

be exploring the potentials of Data Analytics [32]. As new findings and outcomes of research crop up daily, it is evident that successes in Data Analytics in Education can have overwhelmingly positive impacts on learning management and delivery. With Educational Attainment being one of the core indices for measuring Development with respect to the Human Development Index [8, 11, 52], there is no doubting the viability of any Data Analytics in Education research.

Recently, researchers and developers in the education community began to explore the potentials in adopting analogous techniques for gaining insight into learning management and delivery. Two major areas currently under development and which are oriented towards the inclusion and exploration of big data capabilities in the educational environment are Educational Data Mining (EDM) and Learning Analytics (LA) [40]. Romero and Ventura [43], postulated that although prior researches have focused more on the implementation of data mining techniques and models to discover educational data, EDM is however an emerging discipline for developing methods to explore unique types of data from within the educational context. In fact, according to Zorrilla et al., [54], EDM is an application of data mining techniques implemented in education for better comprehension on students' learning processes and acknowledging the ways they participate in it with the sole aim of improving the quality of the educational system.

With regards to ICT4D, national development encapsulates the notion of human development as the means of enlarging people's choices to acquire knowledge, amongst others, in order to have access to the resources needed for a decent standard of living [11, 52]. Over the last three decades, the lexicon of national development has been expanded to certain intervening variables and social factors such as education and some other aspects of human welfare. [5, 11, 17]. In line with this, countries have defined policies that show an emphasis on creating support mechanisms for the use of ICT, including for example, technical and pedagogical support, and putting special attention on the use of ICT in teaching and learning [27]. However, in providing and defining these policies, a crucial question all policy makers must answer is if increased investments in ICT infrastructure provides any improvement in human development especially for Africa [9].

In this paper, we aim to investigate the efficiency of ICT Infrastructure utilization on Education as a component of National Development vis a vis adult literacy rates and educational attainment for post-secondary and tertiary education levels. We also employ the same education index employed by Bankole et al., [9] introduced by Orbicom [37] and ITU to emphasize the impact of higher education on ICT development. With most of the research in Learning Analytics focusing on the teaching and learning activities, this research aims to show how LA can be implemented for policy and decision making within the general context of ICT4D research and thus show it is not limited to enhancing class room interactions. The rest of the article is organized as follows: Section two provides the overview of literature, section three discusses the theoretical framework, section four provides the research methodology, section fives provides the DEA analysis, section six provides discussion of findings, section seven limitations and section eight conclusion and future work.

2. Overview of Literature

The need to understand the relevance of education in Human Development cannot be over-emphasized. A lot of research postulates that increase in ICT investments and penetration on the continent will bring about a corresponding increase in Human Development [4, 33]. Ganju et al., [19] believe that the use of ICT enables the transfer of information to communities that may not have access to education. However, in Africa, three quarters of the population is illiterate and live in rural areas that lack basic facilities [34] and lack of these facilities, which include infrastructure, on which ICT development requires to run, limit the effectiveness of ICT interventions and penetrations especially in education [38]. Even though the last decade has seen an explosion in the use of ICTs in developing countries [53], it is important to consider the unequal distribution of access to the affordances of ICT in Africa [42].

Bankole et al., [9] showed that any empirical investigation with regards to education for ICT4D research, needs to consider higher education as one of the main parameters. The empirical study carried out by Kiiski [29] found that tertiary education has a positive and statistically significant impact on ICT development. Briede [12] believes this is so because those who have attained levels of higher education usually are the leading persons and have an important impact on public events and its development. Many Higher Education institutions in the Developing Economies have invested heavily in the use of ICT for teaching and learning i.e. use of mobile and/or home-based ICT infrastructure as tools to extend teaching and learning possibilities [27] however, its impact has been minimal [36], despite the differences in the level of ICT development across countries [27].

Recent studies also believe that Higher Education quality and attainment are necessary to bridge the "digital divide" defined by [20, 31, 35]. An example of such is India's National Mission on Education through Information and Communication Technology (NMEICT) which seeks to bridge the digital divide by formulating an educational policy which, amongst others, aims at enhancing the use of computing devices for the purpose of teaching and learning among urban and rural teachers/learners in the Higher Education domain [44]. Also, the Plan Ceibal initiative in Uruguay [25], seeks to bridge this digital divide by being both a social and an educational policy that, amongst others, has the purpose of establishing the conditions for equal access to ICT; facilitate the construction of new learning environments adequate to demands of the information and knowledge-based society; and making available to students and teachers new tools that can widen their learning, increase their knowledge, and develop their awareness of lifelong learning [27]. ICT facilitates and improves students' knowledge and promotes positive attitude to learning. Therefore, if students in developing economies are to compete with their counterparts in the developed world, effort must be made to develop their ICT abilities [36].

Moving to ICT and its effects on educational technologies, a New Media Consortium (NMC) Horizon report in 2013 identified, amongst other things, emerging technologies that would have significant impacts on education within a 5-

year window. One of such technologies identified was Learning Analytics which would impact education by customizing the learning experience and/or measuring performance through analysis of massive amounts of student learning data [28]. In the context of higher education, Big Data and Learning Analytics promises increased efficiency and cost-effectiveness [23, 40, 46-48]. With the potential of educational technologies to positively improve educational quality and attainment, there is great optimism that ICT in education can greatly increase both average literacy rates and educational attainment levels in developing economies. However, despite these promises being included in education policies that are related towards achieving a positive impact of ICTs on students' achievements, there is no conclusive evidence to support this, especially in developing countries [26]. This situation has posed new questions to the research community and policy makers, who are now looking for much more precise definitions of the role of ICT in teaching and learning [27]. It is in search for these precise definitions that we carry out this study to investigate the efficiency of ICT infrastructure utilization on education with respect to human development.

3. Theoretical Framework

This research falls within the progressive perspective of ICT-enabled development as postulated and defined by Avgerou [7]. The theory behind this perspective is that it considers ICT as an enabler of transformations in multiple domains of human activities. ICT-enabled developmental transformations are assumed to be achieved within the existing international and local social order [7]. Central in this theoretical perspective is the view that investment in ICT and effective use do matter for the economic development of a country [30]. It is however acknowledged that ICT needs to be accompanied by organizational or national restructuring to deliver productivity gains [16, 18].

This research proposes a novel conceptual model for measuring efficiency of ICT Infrastructure on Education and is derived from Bankole et al., [9] model for measuring Impact on Human development. From this study Human Development is expressed as:

HDI = f[Standard of living (GDP per capita), Education (Literacy rates / Enrolments) and Health (life expectancy)]

For this research we focus solely on the Education component of Human Development and propose a model which takes on a linear equation derived from Bankole et al., [9] model for measuring impact on education within the Human Development Index. In this model, we make use of ICT infrastructure available for utilization from 2010-2016 and obtained from ITU and not ICT investments as was done by Bankole et al., [9]. We also focused on educational attainment and not enrolment as we are measuring impact of a utilized infrastructure within the educational context and not its potential utilization which will be valid for enrolment. Finally, this research does not consider the interaction of the facets of ICT investments as was done by Bankole et al., [9] because it is not considering investments anymore but the infrastructure available for utilization.

The model for this study is:

The impact on Education (Adult Literacy rates / Attainments) = f[Internet Infrastructure (II) + Computer Infrastructure (CI) + Mobile Phone Infrastructure (MPI)].

4. Research Methodology

The research methodology employed in this study is the Data Envelopment Analysis (DEA) model. DEA is a well-known non-parametric linear programming method for measuring the relative efficiency [10, 50] and has also been used for understanding the impacts of IT investments on performance and productivity [24]. DEA is a data-oriented method for evaluating the performance (efficiency) of entities known as Decision Making Units (DMUs) [10] which uses input-output data to compute an efficient production frontier produced by the most efficient DMU's. DEA, unlike a parametric method, is context specific with respect to the interpretations of the results of the analysis, which are restricted to the sample and should not be generalized beyond the sample [45].

DEA, therefore, can then be viewed as a multiple-criteria evaluation methodology where DMUs are alternatives, and DEA inputs and outputs are two sets of performance criteria where one set (inputs) is to be minimized and the other (outputs) is to be maximized [15]. In DEA, these multiple criteria are generally modelled as in a ratio form, e.g., the CCR ratio model [13, 15] which is expressed as:

Maximise:

$$h_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}}$$

Subject to:

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1$$

Where:

$$j = 1, \ldots, n, v_r v_i \geq 0; r = 1, \ldots, s; i = 1, \ldots, m.$$

where x_{ij} and y_{rj} represents DEA inputs and outputs of the jth DMU, and u_r ,$v_i \geq 0$ are unknown variable weights to be determined by the solution of the problem (Charnes et al., 1978). Although x_{ij} and y_{rj} can be referred to in different terms, rather than "inputs" and "outputs", for this research, ICT infrastructure serve as the Inputs and Educational Attainment/Adult Literacy Rates serve as the Outputs.

There have been some studies that have used DEA to measure efficiency in education. Gupta & Verhoeven [22] measured the efficiency of education in Africa and Clements [14] measured efficiency of education in Europe. St. Aubyn [49] and Afonso and St. Aubyn [1-3] measured with respect to OECD countries. However, only Tondeur et al., [51] and Gülbahar, [21] have examined the efficiency of countries in utilising their ICT resources for educational outputs and the Impact of

ICT on eduction. Recently, Aristovnik, [6] did a study on the impact of ICT on educational performance and its efficiency in select EU and OECD countries using DEA.

Based on Bankole et al., [9] investigation of the impact of ICT investment on human development, this research goes a step further to measure ICT infrastructure available for utilization and no longer investments in ICT which are available for potential utilization. Hence the variables used will be individuals with access to computers, internet and mobile phones. Since the focus of this paper is to investigate with respect to education only as an aspect of human development, the education component will include educational attainment from post-secondary level through to bachelors' level and adult literacy rates. An Input-Oriented Basic Radial Model (BRM) with Constant Returns to Scale (CRS) DEA approach is used for this research. This is based on the theoretical assumption that the ICT infrastructure (Input) are controllable and increase or decrease in the levels of these inputs is expected to bring about a corresponding increase or decrease in the levels of Educational Attainments and Literacy Rates (Output) respectively.

For this study, time series data from UNESCO; educational attainments; World bank; literacy rates and ITU; individuals with computers, internet and mobile phones were obtained. Available data was collected for all countries in Sub-Saharan Africa, Northern Africa, and select countries in Europe and Northern America. These were compared with world values to measure relative efficiency. Data for the past 7 years, 2010-2016 was collected and the average was calculated and used for the values representing each DMU.

5. DEA Analysis

The analysis was done using the Data Envelopment Analysis Online Software (D.E.A.O.S.) available online at https://deaos.com . An Input oriented BRM model using the Constant Returns to Scale method was used for calculating the relative efficiency of the DMU's. Table 1 shows the data collected computed as ratios to population as well as the indices and their respective parameters. Tables 2 and 3 show the outcomes of the analysis carried out while table 4 gives an overview of the data statistics.

Table 1. Data Envelopment Analysis Values

Regions	Individuals using Computers	Individuals using Internet	Individuals using Mobile Phones	Educational Attainment (Post-Secondary)	Educational Attainment (Short Cycle Tertiary)	Educational Attainment (Bachelors)	Adult Literacy Rate
	INPUT	INPUT	INPUT	OUTPUT	OUTPUT	OUTPUT	OUTPUT
Sub-Saharan Africa	0.24	0.1399	0.7495	0.1086	0.056	0.0288	0.6287
Northern Africa	0.4257	0.3004	0.8827	0.1235	0.1327	N/A	0.7236
Europe & North America	0.7631	0.7074	0.9134	0.2962	0.2539	0.2168	0.9915
World	0.61	0.4343	0.8772	0.2695	0.2167	0.1507	0.8559

Table 2. Basic Radial Models (Envelopment Forms) Weights

Regions	Individuals with Computers	Individuals with Internet	Individuals with Mobile Phones	Educational Attainment (Post-Secondary)	Educational Attainment (short cycle tertiary)	Educational Attainment (Bachelors)	Adult Literacy Rates
Sub-Saharan Africa	3.984	0	0.058	9.208	0	0	0
Northern Africa	2.349	0	0	0	4.737	0	0.475
Europe & North America	1.31	0	0	1.073	0	2.159	0.216
World	1.605	0	0.024	3.711	0	0	0

Table 3. DEA Analysis Summary for the Regions

DMU	DEA Parameters	Individuals with Computers	Individuals with Internet	Individuals with Mobile Phones	Educational Attainment (Post-Secondary)	Educational Attainment (short cycle tertiary)	Educational Attainmnet (Bachelors)	Adult Literacy Rates
Sub-Saharan Africa	Slacks	0	0	0	0	0	0	0
	Weights	3.984	0	0.058	9.208	0	0	0
	Values	0.24	0.14	0.75	0.109	0.056	0.029	0.629
	Targets	0.24	0.14	0.75	0.109	0.056	0.029	0.629
Northern Africa	Slacks	0	0.013	0.065	0.061	0	0.087	0
	Weights	2.349	0	0	0	4.737	0	0.475
	Values	0.426	0.3	0.883	0.124	0.133	0	0.724
	Targets	0.414	0.279	0.793	0.184	0.133	0.087	0.724
Europe & North America	Slacks	0	0	0	0	0	0	0
	Weights	1.31	0	0	1.073	0	2.159	0.216
	Values	0.763	0.707	0.913	0.296	0.254	0.217	0.992
	Targets	0.763	0.707	0.913	0.296	0.254	0.217	0.992
World	Slacks	0	0	0	0	0	0	0
	Weights	1.605	0	0.024	3.711	0	0	0
	Values	0.61	0.434	0.877	0.27	0.217	0.151	0.856
	Targets	0.61	0.434	0.877	0.27	0.217	0.151	0.856

Table 4. Data Statistics

Index	Minimum	Maximum	Mean	Standard Deviation
Individuals with Computers	0.24	0.7631	0.51	0.1963
Individuals with Internet	0.1399	0.7074	0.396	0.2081
Individuals with Mobile Phones	0.7495	0.9134	0.856	0.0628
Educational Attainment Post-Secondary	0.1086	0.2962	0.2	0.0841
Educational Attainment Short-cylce Tertiary	0.056	0.2539	0.165	0.0766
Educational Attainment Bachelors	0	0.2168	0.099	0.0884
Adult Literacy Rates	0.6287	0.9915	0.8	0.1369

6. Discussion of Findings

From the analysis, we can see from table 5 that Northern Africa is 97.2% relatively efficient in its utilization of ICT Infrastructure for the educational component of National Development while Sub-Saharan Africa, Europe and North America and the World are optimally relatively efficient. Interesting to note, however is that even though Sub-Saharan Africa has the average lowest percentage of ICT infrastructure utilization, educational attainments and adult literacy rates, it is optimally using its current ICT infrastructure with respect to Education in the Human Development Index. This may be as an outcome of a well-known bias of Data Envelopment Analysis where the DMU with the lowest input is more likely to have a high efficiency rating, however, this supports the notion that should there be an increase in ICT Infrastructure, there will be a somewhat corresponding increase in educational attainment and Adult Literacy rates which will inevitably bring about an increase in the Human Development Index.

Table 5. Efficiency Summary

DMU	Efficiency
Sub-Saharan Africa	100%
Northern Africa	97.20%
Europe and North America	100%
World	100%

As expected, Europe and North America have the highest average values for ICT Infrastructure utilization, educational attainments and literacy rates and are optimally relatively efficient in this regard. Although Northern Africa have higher average values than Sub-Saharan Africa across most of the indices, the fact that there was no data available for Educational Attainment (Bachelors) may be a mitigating factor against their relative efficiency frontier thus reducing the efficiency value. This is not to say however that Northern Africa is not efficient, but rather has the lowest relative efficiency in this grouping and within the context of the model used.

Another interesting finding from the analysis of the data, as presented in table 6, is the correlation between the input indices and the output indices. Individuals with computers has the strongest correlation with educational attainment and adult literacy rates while individuals with mobile phones has the weakest correlation. This may also be a strong indication of the outcome of pedagogical changes in teaching and learning which now include higher usage of computers. This could be a result of the introduction of online learning and blended learning environments into education. It would be interesting to see, as m-learning initiatives pick up, whether the correlation between mobile phones and educational attainments and literacy rates will become stronger.

Table 6. Correlation between Input and Output Indices

Index	Individuals with Computers	Individuals with Internet	Individuals with Mobile Phones
Educational Attainment (Post-Secondary)	0.9456	0.905	0.6947
Educational Attainment (Short Cycle Tertiary)	0.9942	0.951	0.8794
Educational Attainment (Bachelors)	0.8972	0.8982	0.5709
Adult Literacy Rates	0.9932	0.9913	0.8246
AVERAGE	**0.9576**	**0.9364**	**0.7424**

7. Limitations

The main limitation of this study is the availability of the data for the dataset. The data was collected from the United Nations Educational, Scientific and Cultural Organization (UNESCO) - educational attainments; World bank - literacy rates and the International Telecommunication Union (ITU) - individuals with computers, internet and mobile phones. Considering that the years being investigated are the most recent and the sources of the data are credible and well cited sources for scientific data collection, some countries within each region did not have data available for one or more years being investigated. This may have positive or negative effects on the regional averages calculated as the data collected is represented as a percentage of the population of the countries. Also, the limitation in availability of data make it difficult to

carry out intra-regional comparative analysis in order to see how individual countries within each region fare amongst themselves.

8. Conclusion and Future Work

This research has been able to show that ICT infrastructure available is currently making an impact on human development with respect to educational attainment and adult literacy rates. This is evidenced by the fact that the data collected was data of ICT infrastructure currently available for utilization by the regions within the specified time and not investments made during this time. This is a direct response to Bankole et al., [10] which asked the question if increased investments in ICT infrastructure provide any improvement in human development in Africa. The research further shows that regions with significantly lower educational attainment and literacy rates are relatively efficiently utilizing their significantly lower ICT infrastructure and therefore provides an albeit assumptive basis for justifying increased spending in ICT infrastructure. Using the CRS model for the DEA analysis, the research has been able to show that while controlling the inputs (ICT Infrastructure) an increase in the input has a tendency to result in a corresponding increase in the output (Educational Attainment / Adult Literacy Rates) and vice-versa, therefore impacting positively the educational component of the Human Development Index.

The research has also been able to show that there is a strong correlation between ICT Infrastructure and Educational Attainment / Adult Literacy rates. The correlation is strongest on the individuals with computers index of the ICT Infrastructure. This shows that increased spending in computer hardware and availability of these resources to individuals may have a strong impact on education. The correlation not only justifies the spending on ICT infrastructure for education, but also justifies the notion that its increased utilization brings about increase in educational attainment and not just enrolment thereby increasing literacy rates. It is important to note that the strongest correlation occurs between the individuals with computers and educational attainment post-secondary indices. This also justifies the increased investments being made in ICT in secondary education and not just tertiary education.

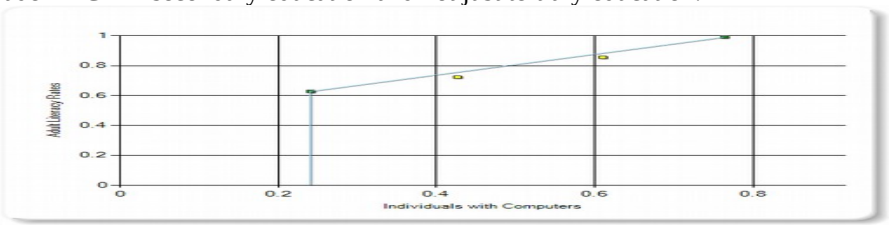

Fig. 1. Correlation between Individuals with Computers and Adult Literacy Rates

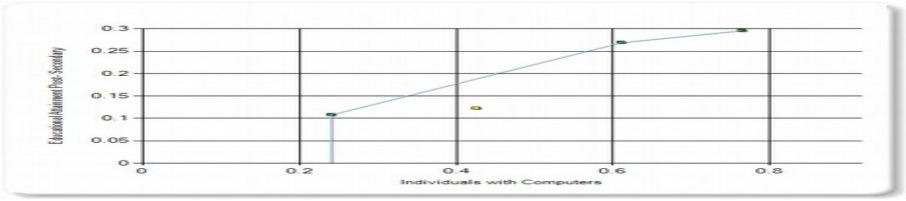

Fig. 2. Correlation between Individuals with Computers and Educational Attainment Post-Secondary

While acknowledging that DEA as a methodology in itself is context specific and by its very nature of being non-parametric does not allow for generalization beyond the context [45], the research has been able to prove that within the sample itself and within the context of educational attainment / adult literacy rates, there is a strong impact of ICT on Human Development albeit within the Educational index. The research has also been able to show how Learning Analytics can be applied for decision making outside the teaching and learning environment and for policy directions. An area of future research would be to expand this context by showing how ICT impacts on each of the components of the Human Development Index within the specified DMU's and determine the correlations, if any between them. Another area of future research also would be to explore the other DEA models available and determine if there are any other significant correlations or findings, which can have strong impacts on ICT infrastructure investments, on the individual Human Development Indices, as well as measure the productivity over time of the ICT infrastructure utilization. Future research can also be carried out to investigate further the impact, if any, of the strong correlations between ICT infrastructure and educational attainment/adult literacy rates and what this may mean in the broader ICT4D context.

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