Journal of Scientific & Industrial Research
Vol. 69, May 2010, pp. 330-341

Integrated DEA-ANOVA for performance assessment and optimization of telecommunication sectors in Central Asia

A Azadeh[1]*, G R Ataei[2], H Izadbakhsh[3], S M Asadzadeh[1] and A Bukhari[4]

[1]Department of Industrial Engineering and Center of Excellence for Intelligent-Based Experimental Mechanics, College of Engineering, University of Tehran, Iran
[2]Department of Systems and Methods, Ministry of Petroleum, Iran
[3]Department of Industrial Engineering, Iran University of Science and Technology and Teachers Training University, Iran
[4]Department of Telecommunication, A James Clark School of Engineering, University of Maryland, College Park, MD, USA

Received 23 November 2009; revised 17 February 2010; accepted 02 March 2010

This study evaluated status of telecommunication sectors in Central Asia comparing 6 countries with 62 countries in 6 regions (Africa, Central Asia, East Asia, Middle East, Europe, and South America) using DEA and ANOVA. Data using 7 IT indicators were collected and analyzed by DEA. This paper implements Knox's corollary for DEA in assessment, ranking and optimization of telecommunication sectors. Principal Component Analysis (PCA) was applied to verify rankings of DEA. Central Asia was found at the bottom of all regions studied.

Keywords: Analysis of variance (ANOVA), Assessment, Central Asia, Data envelopment analysis (DEA), Information technology, Optimization, Telecommunication sector

Introduction

A well developed telecommunication infrastructure attracts foregin direct investments for business economy. Telecommunications may also cause firms to be more productive and perform at lower cost[1,2]. Identification of drivers of productivity growth and examination of efficiency changes form a significant part of government policy reforms on telecommunications performance against international best practice. Measurement of efficiency and productivity growth is widely applied to several industries using data envelopment analysis[3] (DEA), which was first applied by Charnes *et al*[4] for measuring efficiency in not-for-profit organizations in US programs, using constant returns to scale (CRS) model. Later, variable returns to scale (VRS) model[5-7] was proposed. Consequently, after Charnes *et al*[8], DEA was widely used to measure efficiency and productivity. Zhu[9] illustrated a model for efficiency evaluation with strong ordinal inputs and outputs measures. Cooper *et al*[10] illustrated application of Integrated Data Envelopment Analysis (IDEA) to a Korean mobile telecommunication company. Shin & Sohn[11] proposed a multi-attribute customer evaluation procedure for mobile telecommunication subscribers. It was expected that telecommunication companies can focus on target marketing to maximize overall profit based on efficiency score of customers[12,13].

Need for an integrated approach for continuous assessment and improvement of Information Technology (IT) sectors based on standard performance parameters has become essential[14,15]. In selecting a performance measure or indicator, it is important to consider measure's suitability to control system's objectives, measure invasiveness and its complexity[16,17]. An integrated study[18-22] must consider not only traditional productivity but also efficiency, effectiveness and profitability.

This study presents indicators (efficiency, effectiveness and profitability) to evaluate status of telecommunication sectors in Central Asia comparing six countries (Turkey, Mongolia, Uzbekistan, Bangladesh, Afghanistan, and Tajikistan) with 62 countries in six regions (Africa, Central Asia, East Asia, Middle East, Europe, and South America) using DEA and analysis of variance (ANOVA).

*Author for correspondence
E-mail: aazadeh@ut.ac.ir

DEA[4,5] measures efficiency of decision making units (DMUs), which have multiple outputs and inputs. Standard DEA method assigns an efficiency score (< 1) to inefficient DMUs, from which a ranking can be derived. However, no ranking is given to efficient DMUs[23] having an efficiency of 1. In this paper, an alternative definition of efficiency[24] for ranking of DMUs is taken into consideration. Difficulties arising from Anderson/Peterson model were successfully removed in this model.

Principal Component Analysis (PCA)

PCA is widely used in multivariate statistics to reduce number of variables under study and consequently ranking and analysis of DMUs, such as industries, universities, hospitals, cities, etc[25-33]. PCA identifies a new set of variables such that each new variable, called a principal component (PC), is a linear combination of original variables. First new variable y_1 accounts for maximum variance in sample data, second new variable y_2 accounts for second maximum variance in sample data and so on.

Integrated DEA-ANOVA Model

A comprehensive study was conducted to locate all economic and technical indicators, which influence IT performance of telecommunication sectors. IT indicators (outputs) given by ITU[34] (International Telecommunication Union) are as follows: y_1, cable modem internet subscribers; y_2, DSL internet subscribers; y_3, international internet bandwidth (Mbps); y_4, internet hosts; y_5, internet subscribers; y_6, estimated internet users; and y_7, internet users per 100 persons. A comparative study was conducted through PCA by considering 7 indicators. This in turn shows weak or strong DMU with respect to IT performance. PCA could also identify indicators that have major impacts on IT performance of DMUs. After verification and validation of DEA by PCA, DEA results may be used for optimization purpose. Optimization procedure is based on surplus and slack results of DEA. Integrated approach suggests continuous monitoring and assessment of IT performance of telecommunication sectors by DEA and PCA. This may be achieved by annual or monthly checkups and diagnosis of sectors depending on management policy of systems under study.

Integrated model is composed of DEA verified by PCA. Assuming there are 62 DMUs to be evaluated, each consumes varying amounts of 1 virtual input to produce 7 different outputs. In model formulation, *Xp* and *Yp (p=1... 62)* denote, respectively, nonnegative vectors of input and output values for DMU*p*. This paper uses MAJ CCR model with an alternation to form BCC model as

$$j_p^* = \min w_p + 1 \qquad \ldots(1)$$

Subject to

$$\sum_{\substack{j=1 \\ j \neq p}}^{62} \lambda_j X_j \leq X_p + w_p 1 \qquad \ldots(2)$$

$$\sum_{\substack{j=1 \\ j \neq p}}^{62} \lambda_j Y_j \geq Y_p - w_p 1 \qquad \ldots(3)$$

$$\sum_{\substack{j=1 \\ j \neq p}}^{62} \lambda_j = 1$$

Although optimal objective function values for MAJ-model depends upon units of measurement of input data, *Xj*, j =1.....62, Unit independence is obtained by normalization (dividing input data by maximum input for each input). In case of full inefficiency, when a DMU uses maximum inputs for no production, both models (AP and MAJ) provide zero scores. In case of full efficiency, both models provide not less than one scores. Hence, j_p^* lies between 0 and ∞.

PCA is performed by identifying Eigen structure of covariance or singular value decomposition of original data. There are 7 variables (indicators) and 62 tele communication sectors. Let $X = (x_1 ... x_7)_{62\times 7}$ is a 62×7 matrix composed of x_{ij} defined as value of jth index for ith DMU. Therefore, $x_m = (x_{1m} ... x_{nm})^T (m = 1,...,7)(n = 1,...,62)$. Further more, suppose $\hat{X} = (\hat{x}_1 ... \hat{x}_7)_{62\times 7}$ is standardized matrix of $X = (x_1 ... x_7)_{62\times 7}$ with x_{ij}'s defined as value of jth standardized index for ith sector. Therefore, $\hat{x}_m = (\hat{x}_{1m} ... \hat{x}_{nm})^T (m = 1,...,7)(n = 1,...,62)$. PCA is performed to identify new independent variables or PCs (Y_j for $j = 1 ... 7$), which are respectively different linear combination of $\hat{x}_1 ... \hat{x}_7$. This is achieved by identifying Eigen structure of covariance of original data. PCs are defined by $k \times 7$ matrix $Y = (y_1 ... y_7)_{62\times 7}$ composed by y_{ij}'s. Following models are used to find out PCs Y_j, weights (w_i) of PCs and PCA scores (z_i) of each telecommunication sector for ($i = 1 ... 62$):

$$Y_m = \sum_{j=1}^{7} l_{mj} \hat{x}_{ij} \text{ for } m = 1...7 \text{ and } i = 1...62 \qquad \ldots(4)$$

Table 1—Standardized matrix for 62 countries in order to perform DEA-PCA analysis[34]

Country	Virtual input (Kep constant)	Cable modem Internet subscribers	DSL Internet subscribers	International Internet bandwidth Mbps	Internet hosts	Internet subscribers	Internet users (estimated)	Internet users per 100 persons
Afghanistan	1	0	0	30	4	700	20000	0.10
Albania	1	0	0	12	250	20000	30000	0.98
Bangladesh	1	0	0	50	1	81000	243000	0.18
Belarus	1	0	123	200	4971	22714	1391903	14.10
Benin	1	6	0	47	854	5585	70000	1.00
Bhutan	1	0	0	6	985	2107	15000	2.04
Bulgaria	1	0	0	189	49969	6243	1545143	20.58
Burkina Faso	1	70	75	16	442	12619	48000	0.39
Cambodia	1	0	350	18	818	7152	35000	0.25
Cape Verde	1	0	0	8	63	5011	20000	4.36
China	1	2400000	8119000	27216	160421	67746496	79500000	6.32
Colombia	1	49286	10406	3620	115158	776734	2300202	5.25
Cuba	1	0	0	87	1529	12193	98000	0.87
Cyprus	1	0	10033	245	5778	57181	250000	33.71
Djibouti	1	0	0	2	670	2100	6500	0.97
Ecuador	1	1866	443	483	3188	107350	569727	4.50
Egypt	1	0	4850	1148	3338	2805075	3000000	4.37
Eritrea	1	0	0	2	1045	3000	9500	0.23
Estonia	1	28300	51300	1600	64048	137300	600000	44.41
Fiji	1	0	0	12	493	9000	55000	6.66
France	1	393854	2967434	200000	2403459	10617186	21900000	36.56
French Polynesia	1	0	900	24	5123	13000	35000	14.00
Gabon	1	0	50	45	283	7800	35000	2.62
Hong Kong	1	258000	640657	28737	591993	2326969	3212800	47.18
Hungary	1	77189	114813	10000	369720	673732	2400000	23.22
India	1	87289	53073	3000	86871	4140000	18481044	1.75
Italy	1	0	2200000	119794	626536	17000000	22880000	41.64
Jordan	1	0	4996	310	3123	91566	444000	8.11
Korea (Rep. of)	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Kuwait	1	0	13000	287	2709	227000	567000	22.82
Latvia	1	337	19196	510	41263	47011	936000	40.36
Lebanon	1	70000	0	60	7552	140000	500000	14.29
Macau	1	0	27744	509	89	59552	120000	26.76
Malta	1	9735	13001	310	7117	76814	190000	47.50
Marshall Islands	1	0	0	2	6	695	1400	2.59
Micronesia (Fed. States of)	1	0	0	2	686	1913	10000	9.27
Moldova	1	231	331	79	11984	16466	288000	7.98
Mongolia	1	50	370	22	40	46000	142800	5.81
Myanmar	1	0	0	9	3	16201	28002	0.05
Netherlands	1	930000	920000	50000	3521932	5000000	8500000	52.19
New Caledonia	1	0	1668	20	4449	16668	60000	26.20
Panama	1	6731	8308	622	7129	69234	260000	8.34
Paraguay	1	500	0	100	9243	35000	120000	2.02
Qatar	1	0	2800	465	221	31053	140760	19.93
Romania	1	32600	6700	2484	47428	906430	4000000	18.40
Saudi Arabia	1	0	8400	390	15830	700000	1500000	6.66
Slovak Republic	1	3498	4210	9931	114088	182143	1375809	25.59
Slovenia	1	21154	36838	2510	42888	240471	800000	40.06
Solomon Islands	1	0	205	1	398	1000	2500	0.52
Somalia	1	0	0	1	4	2000	85000	0.71
Sri Lanka	1	395	2929	93	1882	85500	250000	1.30
Suriname	1	0	60	45	18	5726	23000	4.37
Taiwan, China	1	452459	2552164	44923	2777085	11320438	11740000	51.94
Tajikistan	1	10	0	2	75	452	4120	0.06
Thailand	1	10000	35000	1438	103700	2403000	6030000	9.56
Tunisia	1	0	2590	136	271	91727	630000	6.37
Turkey	1	42700	56624	2200	359188	1195225	6000000	8.49
Tuvalu	1	0	0	0	12912	310	1800	18.75
Uzbekistan	1	1067	1690	32	1040	37420	492000	1.92
Vanuatu	1	15	0	3	512	1500	7500	3.61
Viet Nam	1	1067	7228	1038	340	917121	3500000	4.30
Zimbabwe	1	3436	0	1461	4501	83722	800000	6.80

Table 3—DEA analysis for telecommunication sectors of 62 countries (2002)

Region	Country	DEA analysis Efficiency	Rank
AFRICA	Egypt	0.70	33
	Zimbabwe	0.70	34
	Fiji	0.70	35
	Tunisia	0.70	37
	Suriname	0.69	41
	Cape Verde	0.69	42
	Gabon	0.68	44
	Bhutan	0.68	47
	Benin	0.67	50
	Djibouti	0.67	52
	Somalia	0.67	54
	Burkina Faso	0.67	57
	Eritrea	0.67	58
CENTRAL ASIA	Turkey	0.71	27
	Mongolia	0.70	38
	Uzbekistan	0.68	48
	Bangladesh	0.67	55
	Afghanistan	0.67	61
	Tajikistan	0.67	62
EAST ASIA	China	1.75	
	Korea (Rep. of)	1.55	2
	Taiwan, China	0.96	6
	Hong Kong	0.90	
	Macau	0.78	4
	New Caledonia	0.78	
	Tuvalu	0.75	21
	India	0.73	22
	French Polynesia	0.73	25
	Thailand	0.72	26
	Micronesia (Fed. States of)	0.71	28
	Moldova	0.70	31
	Viet Nam	0.69	39
	Vanuatu	0.69	43
	Marshall Islands	0.68	45
	Sri Lanka	0.68	49
	Cambodia	0.67	56
	Myanmar	0.67	59
	Solomon Islands	0.67	60
MIDDLE EAST	Kuwait	0.77	17
	Lebanon	0.73	23
	Qatar	0.75	19
	Jordan	0.73	20
	Saudi Arabia	0.73	22
EUROPE	France	1.42	3
	Italy	0.99	7
	Netherlands	0.98	5
	Malta	0.89	8
	Estonia	0.85	9
	Latvia	0.84	10
	Slovenia	0.84	11
	Cyprus	0.81	12
	Slovak Republic	0.78	13
	Hungary	0.75	16
	Bulgaria	0.76	18
	Romania	0.75	20
	Belarus	0.73	24
	Albania	0.67	51
SOUTH AMERICA	Panama	0.71	29
	Colombia	0.70	36
	Ecuador	0.69	40
	Paraguay	0.68	46
	Cuba	0.67	53

Table 3 - One-way ANOVA for six regions including Central Asia

Source	Degrees of Freedom	Sum Squares	Mean Squares	F-value	P-value
Regions	5	8916	1783	9.13	0.000
Error	56	10939	195		
Total	61	19856			

S = 13.98 R-Sq = 44.91% R-Sq(adj) = 39.99%

$$w_j = \lambda_j / \sum_{j=1}^{7} \lambda_j \quad \lambda_j / 7 \qquad j = 1...7 \qquad ...(5)$$

$$z_i = \sum_{j=1}^{7} w_j Y_j \qquad i = 1...62 \qquad ...(6)$$

Analysis by Country

For applicability of integrated DEA model, data of IT output indicators were collected with respect to 62 developed and developing countries (Table 1) selected from 6 regions (Africa, Central Asia, East Asia, Middle East, Europe, South America) to encompass developed (or industrialized) and developing (or unindustrialized) DMUs to compare their performance on telecommunication sectors. Using above proposition by Knox, a virtual input was added to data set and then DEA model was run. Above procedure was repeated for remaining 62 countries in telecommunication sectors and results of DEA efficiency scores and rankings with respect to IT indicators (Table 2) were classified based on each region to clarify both total ranking for 62 countries and sort between countries in each category.

Analysis by Region

In addition to DEA, ANOVA was performed for 6 regions (Africa, Central Asia, East Asia, Middle East, Europe, and South America) with a hypothesis as follows: H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = \mu_6$; and H_1, otherwise. Values of $\mu_1, \mu_2, ..., \mu_6$ are mean of DEA rankings of 6 regions, respectively. This analysis, at first step, tests normality of residuals, which are prerequisite for ANOVA. Residuals (Fig. 1) had normal distribution, so ANOVA was allowed to be used to test mean rankings of regions. ANOVA result shows that H_0 is rejected at $\alpha = 0.05$ (Table 3). Also, under 95% confidence for regions (Fig. 2), Central Asia had worst ranking among 6 regions.

Results and Discussion

Verification and Validation of DEA-ANOVA Model

In order to verify results of integrated DEA-ANOVA model, a PCA approach was employed. Then, Spearman

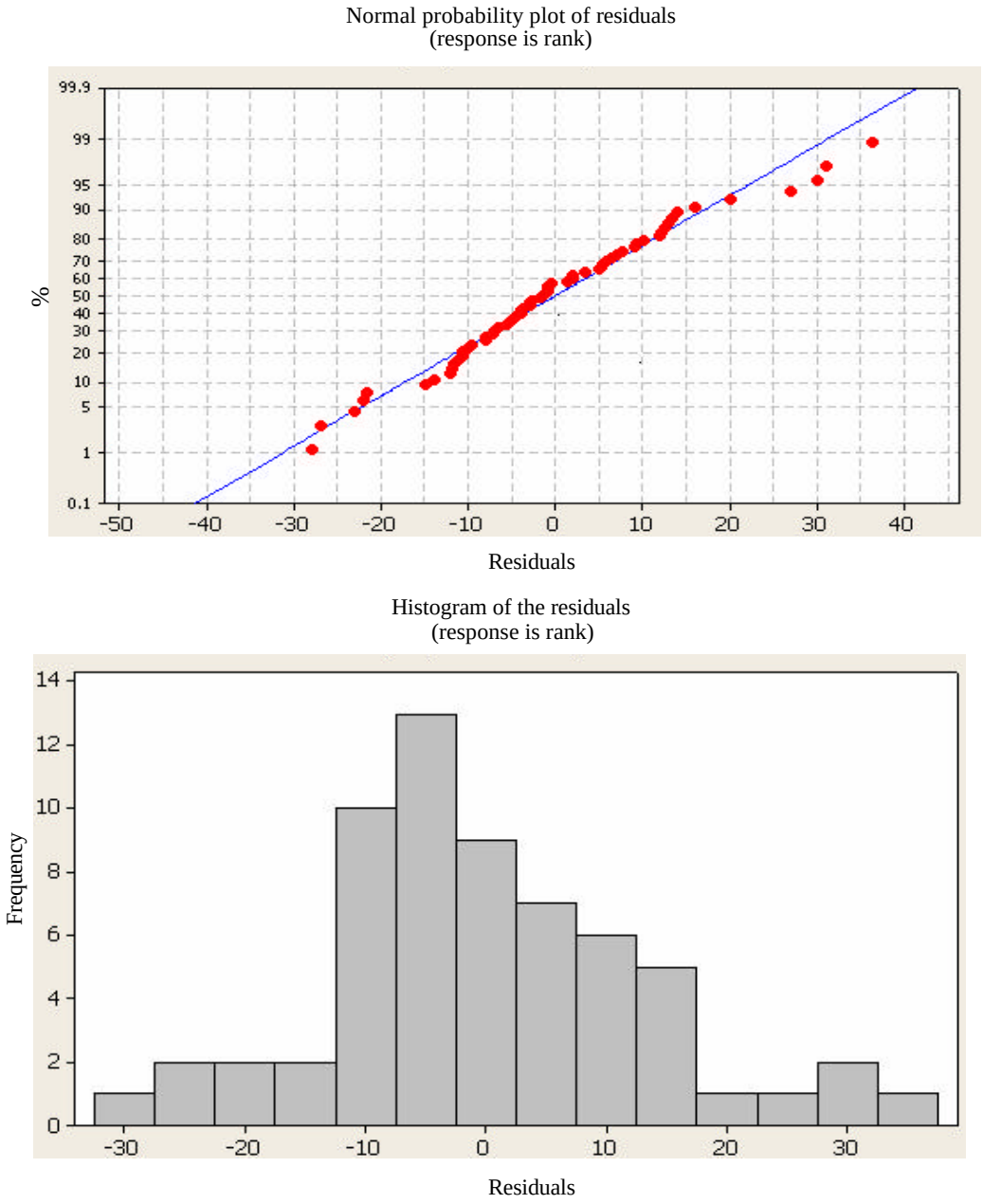

Fig. 1—Test of normal distribution for residuals

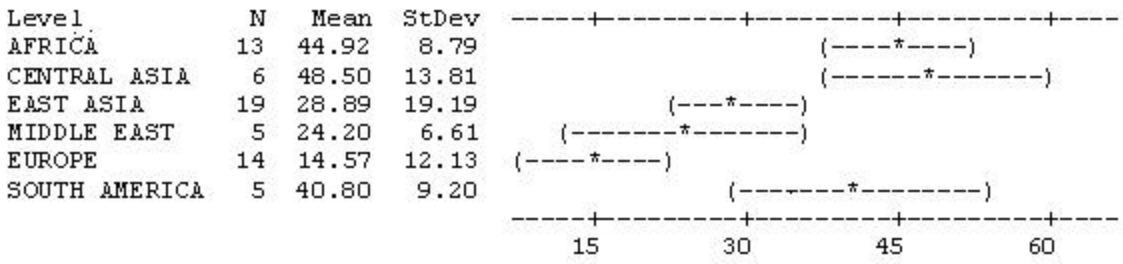

Fig. 2—Individual 95% confidence interval for mean based on pooled standard deviation

Table 4—Normalized data for PCA

	Cable modem Internet subscribers	DL Internet subscribers	International Internet bandwidth Mbps	Internet hosts	Internet subscribers	Internet users (estimated)	Internet users per 100 persons
Afghanistan	-0.242	-0.281	-0.293	-0.316	-0.253	-0.334	-0.858
Albania	-0.242	-0.281	-0.293	-0.316	-0.251	-0.333	-0.805
Bangladesh	-0.242	-0.281	-0.292	-0.316	-0.245	-0.314	-0.853
Belarus	-0.242	-0.281	-0.287	-0.310	-0.251	-0.213	-0.008
Benin	-0.242	-0.281	-0.292	-0.315	-0.253	-0.329	-0.804
Bhutan	-0.242	-0.281	-0.293	-0.315	-0.253	-0.334	-0.740
Bulgaria	-0.242	-0.281	-0.288	-0.253	-0.253	-0.200	0.385
Burkina Faso	-0.242	-0.281	-0.293	-0.316	-0.252	-0.331	-0.841
Cambodia	-0.242	-0.281	-0.293	-0.315	-0.253	-0.332	-0.849
Cape Verde	-0.242	-0.281	-0.293	-0.316	-0.253	-0.334	-0.600
China	3.897	5.527	0.593	-0.112	7.235	6.623	-0.481
Colombia	-0.157	-0.273	-0.176	-0.170	-0.168	-0.134	-0.546
Cuba	-0.242	-0.281	-0.291	-0.314	-0.252	-0.327	-0.811
Cyprus	-0.242	-0.274	-0.286	-0.309	-0.247	-0.313	1.182
Djibouti	-0.242	-0.281	-0.294	-0.315	-0.253	-0.335	-0.805
Ecuador	-0.239	-0.280	-0.278	-0.312	-0.242	-0.285	-0.591
Egypt	-0.242	-0.277	-0.256	-0.312	0.057	-0.073	-0.599
Eritrea	-0.242	-0.281	-0.294	-0.315	-0.253	-0.334	-0.850
Estonia	-0.193	-0.244	-0.242	-0.235	-0.238	-0.283	1.831
Fiji	-0.242	-0.281	-0.293	-0.315	-0.253	-0.330	-0.460
France	0.437	1.842	6.225	2.739	0.920	1.581	1.355
French Polynesia	-0.242	-0.280	-0.293	-0.310	-0.252	-0.332	-0.015
Gabon	-0.242	-0.281	-0.292	-0.316	-0.253	-0.332	-0.705
Hong Kong	0.203	0.177	0.643	0.436	0.004	-0.054	1.999
Hungary	-0.109	-0.199	0.032	0.154	-0.179	-0.125	0.545
India	-0.092	-0.243	-0.196	-0.206	0.204	1.282	-0.758
Italy	-0.242	1.293	3.611	0.480	1.626	1.667	1.663
Jordan	-0.242	-0.277	-0.284	-0.312	-0.243	-0.296	-0.372
Korea (Rep. of)	6.360	4.323	1.075	4.542	1.022	2.222	2.836
Kuwait	-0.242	-0.271	-0.284	-0.313	-0.228	-0.286	0.521
Latvia	-0.242	-0.267	-0.277	-0.264	-0.248	-0.253	1.585
Lebanon	-0.122	-0.281	-0.292	-0.307	-0.238	-0.292	0.003
Macau	-0.242	-0.261	-0.277	-0.316	-0.247	-0.325	0.760
Malta	-0.225	-0.271	-0.284	-0.307	-0.245	-0.319	2.019
Marshall Islands	-0.242	-0.281	-0.294	-0.316	-0.253	-0.335	-0.707
Micronesia (Fed. States of)	-0.242	-0.281	-0.294	-0.315	-0.253	-0.334	-0.302
Moldova	-0.242	-0.281	-0.291	-0.301	-0.252	-0.310	-0.380
Mongolia	-0.242	-0.280	-0.293	-0.316	-0.248	-0.323	-0.512
Myanmar	-0.242	-0.281	-0.293	-0.316	-0.252	-0.333	-0.861
Netherlands	1.362	0.377	1.336	4.160	0.299	0.409	2.303
New Caledonia	-0.242	-0.280	-0.293	-0.310	-0.252	-0.330	0.726
Panama	-0.231	-0.275	-0.273	-0.307	-0.246	-0.313	-0.358
Paraguay	-0.241	-0.281	-0.290	-0.304	-0.250	-0.325	-0.742
Qatar	-0.242	-0.279	-0.279	-0.316	-0.250	-0.323	0.345
Romania	-0.186	-0.276	-0.213	-0.256	-0.153	0.015	0.253
Saudi Arabia	-0.242	-0.275	-0.281	-0.296	-0.176	-0.204	-0.460
Slovak Republic	-0.236	-0.278	0.030	-0.171	-0.233	-0.215	0.689
Slovenia	-0.206	-0.254	-0.212	-0.262	-0.227	-0.265	1.567
Solomon Islands	-0.242	-0.281	-0.294	-0.316	-0.253	-0.335	-0.833
Somalia	-0.242	-0.281	-0.294	-0.316	-0.253	-0.328	-0.821
Sri Lanka	-0.242	-0.279	-0.291	-0.314	-0.244	-0.313	-0.785
Suriname	-0.242	-0.281	-0.292	-0.316	-0.253	-0.333	-0.599

cont.

Cable	DSL modem Internet subscribers	International Internet subscribers	Internet Internet Bandwidth (Mbps)	Internet hosts	Internet subscribers	Internet users (estimated)	Internet users per 100 persons
Taiwan, China	0.538	1.545	1.171	3.213	0.998	0.692	2.288
Tajikistan	-0.242	-0.281	-0.294	-0.316	-0.253	-0.335	-0.861
Thailand	-0.225	-0.256	-0.247	-0.184	0.012	0.192	-0.284
Tunisia	-0.242	-0.279	-0.289	-0.316	-0.243	-0.280	-0.478
Turkey	-0.169	-0.240	-0.222	0.140	-0.121	0.190	-0.349
Tuvalu	-0.242	-0.281	-0.294	-0.300	-0.253	-0.335	0.274
Uzbekistan	-0.240	-0.280	-0.293	-0.315	-0.249	-0.292	-0.748
Vanuatu	-0.242	-0.281	-0.294	-0.315	-0.253	-0.335	-0.645
Viet Nam	-0.240	-0.276	-0.260	-0.316	-0.152	-0.029	-0.603
Zimbabwe	-0.236	-0.281	-0.246	-0.310	-0.244	-0.265	-0.452

Table 5—Correlation matrix *R*

	Cable modem Internet subscribers	DSL Internet subscribers	International Internet bandwidth Mbps	Internet hosts	Internet subscribers	Internet users estimated	Internet users per 100 persons
Cable modem Internet subscribers	1.00	0.89	0.28	0.67	0.63	0.73	0.40
DSL Internet subscribers	0.89	1.00	0.50	0.58	0.87	0.92	0.37
International Internet, bandwidth, Mbps	0.28	0.50	1.00	0.62	0.36	0.45	0.46
Internet hosts	0.67	0.58	0.62	1.00	0.25	0.37	0.65
Internet subscribers	0.63	0.87	0.36	0.25	1.00	0.97	0.14
Internet users (estimated)	0.73	0.92	0.45	0.37	0.97	1.00	0.21
Internet users per 100 persons	0.40	0.37	0.46	0.65	0.14	0.21	1.00

Kendall-Tau correlation experiments were employed to compare rankings of DEA and PCA. Results of DEA analysis were verified using PCA analysis. PCA was performed by identifying Eigen structure of covariance or singular value decomposition of original data. With assumption of 7 variables (indexes) and 62 DMUs (telecommunication sector), data matrix was composed by d_{jk}: $D = (d_1,...,d_7)_{62*7}$ with each row representing 7 individual ratios of d_i for each DMU and each column representing a specific indicator. Thus, $d_k = (d_{k1}, \ldots, d_{k62})^T$. PCA was employed to find out new independent measures (PCs), which are respectively different linear combinations of $d_1 \ldots d_7$ so that PCs can be combined by their eigenvalues to obtain a weighted measure of d_{jk}. PCA process of D is carried out as follows:

Step 1

Normalize index (indicator) vectors. Seven indicators must be normalized and should have same order to be used in PCA. In this study, outputs were normalized with respect to each indicator. Data (Table 1) is normalized for PCA analysis and results are recorded (Table 4).

Step 2

Calculate sample mean vector and covariance (correlation) matrix *R* (Table 5).

Table 6—Eigenvector and Eigenvalues in PCA

	l_1	l_2	l_3	l_4	l_5	l_6	l_7
Cable modem Internet subscribers	0.415	-0.057	-0.534	-0.261	0.482	0.200	-0.445
DSL Internet subscribers	0.465	-0.166	-0.074	-0.048	0.260	-0.570	0.596
International Internet bandwidth, Mbps	0.302	0.346	0.771	-0.207	0.343	0.032	-0.180
Internet hosts	0.345	0.479	-0.180	-0.467	-0.630	-0.018	0.061
Internet subscribers	0.393	-0.424	0.175	0.269	-0.399	-0.343	-0.535
Internet users (estimated)	0.427	-0.343	0.142	0.133	-0.152	0.717	0.352
Internet users per 100 persons	0.253	0.568	-0.175	0.761	0.056	0.026	0.001
Eigenvalue, λ	4.340	1.444	0.674	0.406	0.102	0.027	0.007
Weight, w	0.620	0.206	0.096	0.058	-0.015	0.004	-0.001

Table 7— Scores of principle components in PCA

	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7
Afghanistan	-0.89	-0.46	0.04	-0.48	0.01	-0.07	-0.01
Albania	-0.87	-0.43	0.03	-0.44	0.01	-0.07	-0.01
Bangladesh	-0.87	-0.47	0.04	-0.47	0.01	-0.06	-0.01
Belarus	-0.62	-0.01	-0.09	0.18	0.04	0.04	0.03
Benin	-0.87	-0.43	0.03	-0.44	0.01	-0.06	-0.01
Bhutan	-0.86	-0.39	0.02	-0.39	0.02	-0.06	-0.01
Bulgaria	-0.49	0.23	-0.17	0.45	0.02	0.06	0.04
Burkina Faso	-0.88	-0.45	0.04	-0.47	0.01	-0.07	-0.01
Cambodia	-0.88	-0.45	0.04	-0.47	0.01	-0.07	-0.01
Cape Verde	-0.82	-0.31	-0.01	-0.28	0.03	-0.06	-0.01
China	9.88	-6.60	0.28	1.10	-0.34	-0.09	-0.09
Colombia	-0.57	-0.28	0.05	-0.31	-0.04	0.07	-0.03
Cuba	-0.87	-0.43	0.03	-0.44	0.01	-0.06	-0.01
Cyprus	-0.35	0.70	-0.31	1.07	0.12	0.00	0.00
Djibouti	-0.87	-0.43	0.03	-0.44	0.01	-0.07	-0.01
Ecuador	-0.79	-0.32	0.01	-0.27	0.02	-0.03	0.00
Egypt	-0.58	-0.52	0.11	-0.17	-0.13	0.02	-0.09
Eritrea	-0.89	-0.45	0.04	-0.47	0.01	-0.07	-0.01
Estonia	-0.10	1.09	-0.43	1.51	0.15	0.02	0.00
Fiji	-0.79	-0.23	-0.03	-0.18	0.03	-0.05	-0.01
France	5.24	2.97	4.09	-1.29	0.57	0.04	0.02
French Polynesia	-0.67	0.02	-0.11	0.16	0.06	-0.04	-0.01
Gabon	-0.85	-0.37	0.01	-0.36	0.02	-0.06	-0.01
Hong Kong	1.00	1.54	-0.06	1.12	0.21	-0.04	-0.09
Hungary	-0.06	0.55	-0.07	0.31	-0.07	0.08	-0.01
India	0.16	-1.08	0.30	-0.18	-0.36	0.95	0.26
Italy	3.53	0.96	2.96	0.95	0.35	0.00	-0.02
Jordan	-0.74	-0.19	-0.03	-0.11	0.03	-0.03	0.00
Korea (Rep. of)	8.61	1.89	-3.71	-1.48	1.11	0.08	0.07
Kuwait	-0.50	0.30	-0.19	0.58	0.08	-0.01	0.00
Latvia	-0.20	0.93	-0.37	1.36	0.11	0.05	0.03
Lebanon	-0.59	0.01	-0.17	0.15	0.10	0.00	-0.06
Macau	-0.46	0.46	-0.23	0.75	0.11	-0.03	0.00
Malta	-0.13	1.17	-0.46	1.70	0.18	0.01	-0.01
Marshall Islands	-0.85	-0.37	0.01	-0.37	0.02	-0.06	-0.01
Micronesia (Fed. States of)	-0.75	-0.14	-0.06	-0.06	0.04	-0.05	-0.01
Moldova	-0.75	-0.19	-0.04	-0.12	0.03	-0.04	0.00
Mongolia	-0.79	-0.27	-0.02	-0.21	0.03	-0.05	-0.01
Myanmar	-0.89	-0.46	0.04	-0.48	0.01	-0.07	-0.01
Netherlands	3.46	3.36	-0.77	-0.71	-1.46	0.28	-0.38
New Caledonia	-0.48	0.44	-0.24	0.72	0.10	-0.02	-0.01
Panama	-0.73	-0.17	-0.04	-0.11	0.04	-0.04	-0.01
Paraguay	-0.85	-0.39	0.02	-0.40	0.01	-0.06	-0.01
Qatar	-0.57	0.23	-0.16	0.43	0.08	-0.03	-0.01
Romania	-0.35	0.06	-0.07	0.38	0.00	0.19	0.03
Saudi Arabia	-0.69	-0.30	0.01	-0.15	-0.02	0.01	0.00

cont.

	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7
Slovak Republic	-0.29	0.55	0.01	0.58	0.10	0.06	-0.03
Slovenia	-0.16	0.93	-0.34	1.33	0.15	0.03	-0.01
Solomon Islands	-0.88	-0.44	0.03	-0.46	0.01	-0.07	-0.01
Somalia	-0.88	-0.44	0.03	-0.45	0.01	-0.06	-0.01
Sri Lanka	-0.85	-0.43	0.03	-0.42	0.01	-0.05	-0.01
Suriname	-0.82	-0.31	-0.01	-0.28	0.03	-0.06	-0.01
Taiwan, China	3.67	2.30	-0.21	0.14	-1.33	-0.58	0.38
Tajikistan	-0.89	-0.46	0.04	-0.48	0.01	-0.07	-0.01
Thailand	-0.34	-0.35	0.06	0.02	-0.19	0.22	0.04
Tunisia	-0.76	-0.26	-0.01	-0.18	0.02	-0.02	0.01
Turkey	-0.26	-0.17	-0.02	-0.24	-0.31	0.26	0.11
Tuvalu	-0.60	0.19	-0.16	0.37	0.07	-0.04	-0.01
Uzbekistan	-0.84	-0.41	0.03	-0.39	0.01	-0.04	0.00
Vanuatu	-0.83	-0.34	0.00	-0.32	0.02	-0.06	-0.01
Viet Nam	-0.64	-0.45	0.08	-0.23	-0.05	0.12	0.04
Zimbabwe	-0.73	-0.24	0.01	-0.17	0.04	-0.01	0.00

Table 8—Comparison of DEA and PCA analysis (2002)

Region	Country	DEA analysis		PCA analysis	
		Efficiency	Rank	Zpca	Rank
AFRICA	Egypt	0.70	33	-0.46	29
	Zimbabwe	0.70	34	-0.51	35
	Fiji	0.70	35	-0.55	38
	Tunisia	0.70	37	-0.54	37
	Suriname	0.69	41	-0.59	41
	Cape Verde	0.69	42	-0.59	42
	Gabon	0.68	44	-0.62	44
	Bhutan	0.68	47	-0.63	48
	Benin	0.67	50	-0.65	50
	Djibouti	0.67	52	-0.65	53
	Somalia	0.67	54	-0.66	54
	Burkina Faso	0.67	57	-0.66	57
	Eritrea	0.67	58	-0.67	59
CENTRAL ASIA	Turkey	0.71	27	-0.20	19
	Mongolia	0.70	38	-0.56	39
	Uzbekistan	0.68	48	-0.63	46
	Bangladesh	0.67	55	-0.66	55
	Afghanistan	0.67	61	-0.67	60
	Tajikistan	0.67	62	-0.67	62
EAST ASIA	China	1.75	1	4.86	2
	Korea (Rep. of)	1.55	2	5.27	1
	Taiwan, China	0.96	6	2.76	4
	Hong Kong	0.90	7	0.99	7
	Macau	0.78	14	-0.17	16
	New Caledonia	0.78	15	-0.19	18
	Tuvalu	0.75	21	-0.33	24
	India	0.73	22	-0.10	15
	French Polynesia	0.73	25	-0.41	27
	Thailand	0.72	26	-0.27	22
	Micronesia (Fed. States of)	0.71	28	-0.50	33
	Moldova	0.70	31	-0.52	36
	Viet Nam	0.69	39	-0.49	30
	Vanuatu	0.69	43	-0.61	43
	Marshall Islands	0.68	45	-0.62	45
	Sri Lanka	0.68	49	-0.64	49
	Cambodia	0.67	56	-0.67	58
	Myanmar	0.67	59	-0.67	61
	Solomon Islands	0.67	60	-0.66	56
MIDDLE EAST	Kuwait	0.77	17	-0.23	20
	Lebanon	0.73	23	-0.37	25
	Qatar	0.75	19	-0.30	23
	Jordan	0.70	30	-0.51	34
	Saudi Arabia	0.70	32	-0.50	31
EUROPE	France	1.42	3	4.18	3
	Italy	0.99	4	2.72	6
	Netherlands	0.98	5	2.74	5
	Malta	0.89	8	0.21	8
	Estonia	0.86	9	0.21	9
	Latvia	0.84	10	0.11	11
	Slovenia	0.84	11	0.13	10
	Cyprus	0.81	12	-0.04	14
	Slovak Republic	0.78	13	-0.03	13
	Hungary	0.78	16	0.09	12
	Bulgaria	0.76	18	-0.25	21
	Romania	0.75	20	-0.19	17
	Belarus	0.73	24	-0.38	26
	Albania	0.67	51	-0.65	52
SOUTH AMERICA	Panama	0.71	29	-0.50	32
	Colombia	0.70	36	-0.42	28
	Ecuador	0.69	40	-0.57	40
	Paraguay	0.68	46	-0.63	47
	Cuba	0.67	53	-0.65	51

Step 3

Solve Eq., $|R-\lambda I_7|=0$. Those characteristic vectors compose PCs, Y_i. Components in eigenvectors (Table 6) are respectively coefficients in each corresponding Y_i as

$$Y_{im}=\sum_{j=1}^{p} l_{mj}\hat{x}_{ij} \quad \text{for} \quad m=1...7 \quad \text{and} \quad i=1...62$$

Step 4

Calculate weights (w_i) of PCs and PCA scores (z_i) of each DMU (i = 1,..., 62). Furthermore, *z* vector (z_1 ,..., z_7), where z_j shows score of j^{th} DMUs, is given as

$$z_{pca}(i)=\sum_{j=1}^{7} w_j Y_{ij} \qquad i=1...62$$

Table 9—Results from DEA model -targets for optimization

DMU	Virtual Input (kept constant)	Cable modem Internet subscribers	DSL Internet subscribers	International Internet Bandwidth (Mbps)	Internet hosts	Internet subscribers	Internet users (estimated)	Internet users per 100 persons
Afghanistan	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Albania	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Bangladesh	1	3216992.803	7156202	35673.3	2255405	35594183	50736958	37.58
Belarus	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Benin	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Bhutan	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Bulgaria	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Burkina Faso	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Cambodia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Cape Verde	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
China	1	2400000	8119000	27216	160421	67746496	79500000	6.32
Colombia	1	3827375.019	6435156	42036.39	3822286	11541577	29218314	60.96
Cuba	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Cyprus	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Djibouti	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Ecuador	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Egypt	1	3396443.129	6944726	37530.92	2715562	28532012	44419232	44.45
Eritrea	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Estonia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Fiji	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
France	1	393854	2967434	200000	2403459	10617186	21900000	36.56
French Polynesia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Gabon	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Hong Kong	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Hungary	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
India	1	2478128.933	8026928	28024.77	360764.1	64671774	76749393	9.31
Italy	1	1899864.471	4834347	121806.1	2685794	17285539	31011488	42.34
Jordan	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Korea (Rep. of)	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Kuwait	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Latvia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Lebanon	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Macau	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Malta	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Marshall Islands	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Micronesia (Fed. States of)	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Moldova	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Mongolia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Myanmar	1	3669457.304	6622988	40357.09	3415642	17787686	34807497	54.90
Netherlands	1	3591651.025	6197084	52881.18	3724878	11478114	28715885	59.29
New Caledonia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Panama	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Paraguay	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Qatar	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Romania	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Saudi Arabia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Slovak Republic	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Slovenia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Solomon Islands	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Somalia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Sri Lanka	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Suriname	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Taiwan, China	1	3604623.957	6279055	50510.79	3662547	12728541	29918522	58.40
Tajikistan	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Thailand	1	3672509.438	6619391	40388.68	3423469	17667570	34700044	55.01
Tunisia	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Turkey	1	3605377.862	6698503	39693.76	3251326	20309498	37063477	52.45
Tuvalu	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Uzbekistan	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Vanuatu	1	3828166	6435955	42000	3822613	11541790	29220000	60.97
Viet Nam	1	3520616.069	6798392	38816.32	3033974	23645252	40047600	49.20
Zimbabwe	1	3828166	6435955	42000	3822613	11541790	29220000	60.97

Table 10—Results from DEA model-targets separated for Central Asia optimization

Country	Values	Cable modem Internet subscribers	DSL Internet subscribers	International Internet bandwidth Mbps	Internet hosts	Internet subscribers	Internet users (estimated)	Internet users per 100 persons
Turkey	I*	42700	56624	2200	359188	1195225	6000000	8.49
	R**	3605377.862	6698503	39693.76	3251326	20309498	37063477	52.45
Mongolia	I	50	370	22	40	46000	142800	5.81
	R	3828166	6435955	42000	3822613	11541790	29220000	60.97
Uzbekistan	I	1067	1690	32	1040	37420	492000	1.92
	R	3828166	6435955	42000	3822613	11541790	29220000	60.97
Bangladesh	I	0	0	50	1	81000	243000	0.18
	R	3216992.803	7156202	35673.3	2255405	35594183	50736958	37.58
Afghanistan	I	0	0	30	4	700	20000	0.10
	R	3828166	6435955	42000	3822613	11541790	29220000	60.97
Tajikistan	I	10	0	2	75	452	4120	0.06
	R	3828166	6435955	42000	3822613	11541790	29220000	60.97

I*, initial; R**, recommended

PCA provides scores of PCs for countries (Table 7). Comparing DEA and PCA results (Table 8), correlation was found by Kendall Tau technique (92.27%) and by Spearman Rho correlation technique (98.68%). Integrated DEA-ANOVA was verified and validated by PCA.

Optimization

DEA suggests that inefficient units can become efficient by increasing output proportionately to their efficiency score level (Table 9). Targets defined by efficient projections give an indication of how a DMU could improve to be efficient. In Asia, only China (1.75) and Korea (1.55) are found efficient DMUs. In order to be efficient, as shown under recommended values for countries in Central Asia (Table 10), Turkey should increase its cable modem internet subscribers from 42700 to 3605378, DSL Internet subscribers from 56624 to 6698503, international internet bandwidth (Mbps) from 2200 to 39694, internet hosts from 359188 to 3251326, internet subscribers from 1195225 to 20309498, internet users (estimated) from 6000000 to 37063477 and internet users per 100 persons from 8.5 to 52 to be placed on efficiency frontier and become efficient. For efficient units, target and real values of input/output(s) are equal. Target value for each input/output is computed as

$$(X_o, Y_o) \rightarrow (\hat{X}_o = \theta_B^* X_o - s^{-*}, \hat{Y}_o = Y_o + s^{+*})$$

Conclusions

This study presents a robust integrated mathematical approach to assess and optimize performance of telecommunication sectors with respect to IT output indicators in Central Asia. DEA analysis showed that first 10 countries [China, Korea (Rep. of), France, Italy, Netherlands, Taiwan, China, Hong Kong, Malta, Estonia and Latvia] had best scores based on their performance with respect to seven indicators. Spearman and Kendall Tau correlation techniques between ranks obtained by DEA and PCA were 92.27% and 98.68%, respectively at ± = 0.01. Under classification of 62 countries in six regions (Africa, Central Asia, East Asia, Middle East, Europe, and South America) with respect to their mean of rankings, a difference was observed in performance of each region based on seven indicators in IT sectors. According to this analysis, Europe was found to be the best but Central Asia had worst mean rankings among other regions. This study recommended to improve those countries, which were inefficient in their performance on IT indicators. This study extracted targets for optimization from DEA for each 62 country in general and for Central Asia in particular, to aid decision makers with know how to improve telecommunication sectors in Central Asia. Finally, modeling approach of this study may be extended to include external units (competitors) to identify standings,weak and strong factors in global senario.

References

1 Read W & Youtie J, *Telecommunications Strategy for Economic Development* (Praeger publishers, Westport, Connecticut, London) 1996.

2 Williams F, *The New Telecommunications: Infrastructure for the Information Age* (Free Press, New York) 1991.

3 Zhu J, Data envelopment analysis vs. principal component analysis: an illustrative study of economic performance of Chinese cities, *Eur J Operat Res*, **111** (1998) 50-61.

4 Charnes A, Cooper W W & Rhodes E, Measuring the efficiency of decision- making unit, *Eur J Operat Res*, **2** (1978) 429-444.

5 Banker R D, Charnes A & Cooper W W, Some models for estimating technical and scale inefficiencies in data envelopment analysis, *Mgmt Sci*, **30** (1984) 1078-1092.

6 Banker R D, Conard R F & Strauss M A, Comparative application of data envelopment analysis, *Mgmt Sci*, **32** (1986) 30-44.

7 Cooper W, Seiford L & Tone K, *Data Envelopment Analysis* (Kluwer Academic Publishers, Boston, Dordrecht, London) 2000.

8 Charnes A, Haag S, Jaska P & Semple J, Sensitivity of efficiency classifications in the additive model of data envelopment analysis, *Int J Syst Sci*, **23** (1992) 789-798.

9 Zhu J, Efficiency evaluation with strong ordinal input and output measures, *Eur J Operat Res*, **146** (2002) 477-485.

10 Cooper W W, Park K S & Yu G, An illustrative application of IDEA (imprecise data envelopment analysis to a Korean mobile telecommunication company, *Operat Res*, **49** (2002) 807-820.

11 Shin H W & Sohn S Y, Multi-attribute scoring method for mobile telecommunication subscribers, *Expert Syst with Appl*, **26** (2003) 363-368.

12 Madsen T K, Successful export marketing management: some empirical evidence, *Int Mktg Rev*, **6** (1989) 41-57.

13 Meade N, Strategic positioning in UK car market, *Eur J Mktg*, **21** (1987) 43-56.

14 Azadeh A, Bukhari A & Izadbakhsh H R, Total assessment and optimization of telecommunication sectors by multivariate approach, in *Proc 4th Int IEEE Conf on Industrial Informatics (INDIN'06)* (Singapore) 16-18 August 2006.

15 Bolden R, Waterson P, Warr P & Clegg C, A new taxonomy of modern manufacturing practices, *Int J Operat Prod Mgmt*, **17** (1997) 1112-1130.

16 Garcia T & Grande I, A model for valuation of farmland in Spain: the case of multivariate analysis, *J Property Invest Finance*, **21** (2003) 136-153.

17 McCarthy I, Manufacturing classification: lessons from organizational systematic and biological taxonomy, *Integrated Manuf Syst*, **6** (1995) 37-48.

18 Hong H K, Ha S H, Shin C K, Park S C & Kim SH, Evaluating the efficiency of integration projects using dea and machine learning, *Expert Syst Appl*, **16** (1999) 283-296.

19 Hulten C R, in *Total Factor Productivity: A short Biography*, edited by C R Hulten, E R Dean & M J Harper (University of Chicago Press for the National Bureau of Economic Research, New Developments in Productivity Analysis, Chicago) 2001.

20 Kumar S, *Application of Multivariate Analysis Techniques in Understanding Industrial Process: A Pulp Mill Example* (Pulping and Bleaching Analysis and Control Group, University of Washington, USA) 1998.

21 Madu C, Reliability and quality interface, *Int J Qual Reliab Mgmt*, **16** (1999) 691-698.

22 Matsudaira M & Hong Q, Features and characteristic values of fabric compress ional curves, *Int J Clothing Sci Technol*, **6** (1994) 37-43.

23 Andersen P & Petersen N C, *A procedure for ranking efficient units in data envelopment aanalysis', department of management, Working Paper No. 11/1989* (Odense University, Denmark) 1989.

24 Mehrabian S, Alirezaee M R & Jahanshahloo G R, A complete efficiency ranking of decision making units in data envelopment analysis, *Compu Optim Appl*, **14** (1999)261-266.

25 Azadeh M A, Creating highly reliable manufacturing systems: an integrated approach, *Int J Reliab Qual Safety Engg*, **7** (2000) 205-222.

26 Azadeh M A, Creating high reliable manufacturing systems: an integrated approach, in *Proc Fourth Int Conf on Reliability, Maintainability and Safety (ICRMS'99)* (Shanghai, China) 1999.

27 Azadeh M A & Jalal S, Identifying the economic importance of industrial sectors by multivariate analysis, *J Fac Engg, Univ Tehran, Iran*, **35** (2001) 437-449.

28 Azadeh M A & Ebrahimipour V, An integrated approach for assessment of manufacturing sectors based on machine performance: the cases of automotive and food and beverages industries, in *Proc 2nd Int Manuf Complexity Conf* (University of Cambridge, England) 2002.

29 Azadeh M A & Ebrahimipour V, A multivariate approach for assessment and improvement of machinery and equipment manufacturers based on machine performance, in *6th Int Conf on Engineering Design and Automation* (Maui, Hawaii) 2002.

30 Azadeh M A, A multivariate model for assessment of industrial sectors based on machinery indicators, in *30th Int Conf on Computers & Industrial Engineering* (Tinos Island, Greece) 29 June - 2 July 2002.

31 Azadeh M A, Ebrahimipour V & Ataei G R, A total machine productivity model for assessment and improvement of electrical manufacturing systems, in *32nd Int Conf in Computers and Industrial Engineering* (Limerick, Ireland) August 2003.

32 Azadeh M A & Ebrahimipour A, An integrated approach for assessment and ranking of manufacturing systems based on machine performance, *Int J Ind Engg*, **11** (2004) 349-363.

33 Bhat V N, A multivariate analysis of airline flight delays, *Int J Qual Reliab*, **12** (1995) 54-59.

34 *World Telecommunications Indicators Database*, **8nd edn,** (International Telecommunication Union) 2004: http://www.itu.int/ITU-D/ict/publications/world/world.html.