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Hierarchical network systems: An application to high-technology industry in China☆

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ABSTRACT

In real world situations, there is a hierarchical structure exists in a specific organization and each component has its network process. However, such hierarchical network system has not been well studied in previous literature, and misleading results often are produced. The current paper discusses a data envelopment analysis (DEA) modelling technique for a network structure where a hierarchical system consists of components having two-stage series processes. An additive network DEA is proposed to evaluate the performance of this type of network structure. The overall and divisional efficiencies of the system and each component can be derived, and the relationship between system efficiency, divisional efficiency and the ones of components is discussed. The newly developed additive network DEA is nonlinear and cannot be converted into a linear program. A semidefinite programming (SDP) approach is developed for effectively solving this model and the global solution can be guaranteed. Another linear multiplicative network DEA also developed for this hierarchical system. The two newly developed models are illustrated with a case of the performance evaluation of high-technology industry in China.

1. Introduction

Data envelopment analysis (DEA) is a technique for measuring the relative efficiency of a set of decision making units (DMUs) applying multiple inputs to produce multiple outputs [4,9]. DEA has been applied to an enormous number of practical problem settings, and its modelling structure has been extended in many directions (see, e.g. [15,42,43]). In many real-world cases, DMUs may consist of internal or network structures with intermediate measures or links. Compared with the standard DEA model where the internal structure of DMUs is not taken into account, the network DEA refers to applying the DEA technique to DMUs of multistage processes composed of a number of divisions operating interdependently with each other. See for example, Färe and Grosskopf [21], Tone and Tsutsui [46], Fukuyama and Weber [24], Cook and Zhu [17], An et al. [2], Fukuyama and Matousek [23] and Kao [33].

Usually, almost all organizations have a hierarchical structure. An organization has several levels and each level consists of a number of subunits. A unit at the higher level is divided into several subordinate units at the lower level. At the first level, for example, there are several units, under which some subunits are located at the second level. Some larger units in the second level sometimes maybe further divided into several subordinate units with different functions at the third level, and so on (see also [31]). It is noted that each component in each level usually has a multistage operational process. In other words, a multistage network process is embedded in each component of hierarchical system. However, such hierarchical network structure has attracted relatively little attention. How to evaluate the performance of the hierarchical network system to identify the efficiency relationship in such cases is a valuable research issue in DEA.

Some approaches in DEA are developed for the hierarchical structure. For example, a distance function model is developed by Färe and Primont [20] to measure the efficiency of multi-plant firms, which is applied by Kao [28] to measure the efficiency of 8 forest districts in Taiwan, with a total of thirty-four subordinate working circles. Cook et al. [13] and Cook and Green [14] propose a CCR-type model to measure the efficiency of ten Canadian power plants, with forty subordinate power units. Castelli et al. [7] propose two models to measure single-level and two-level hierarchical structures where the units at the first level can have common subunits at the second level. However, the operation of each component is treated independently in Castelli et al.' [7] models for two-level systems. The relationship among these components is not considered in their models, which only measure the whole DMU.

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Table 1
Data for high-technology industry in the Mainland of China from 2002 to 2015.

DMUs	years	Regional high-technology industry in China									Manufacture of medicines				
		Per.	Exp.	Pat.	Inv.	POR	SRNP	EDV	Per.	Exp.	Pat.	Inv.	POR	SRNP	EDV
1	2002	118,448	1,869,660	5590	1851	14,614.25	34,161,091	6020.02	18,220	216,359	999	484	2279.98	2,488,566	203.95
2	2003	127,849	2,224,468	8270	3356	20,411.52	45,150,436	9098.27	17,518	276,684	1305	459	2750.73	3,037,923	300.23
3	2004	120,830	2,921,314.8	11,026	4535	27,846.2	60,989,505	14,830.9	13,931	281,812.4	1696	902	3033	3,887,152.5	343.4
4	2005	173,161	3,624,985.2	16,823	6658	33,916.2	69,146,633	17,635.97	19,584	399,510.2	2708	1134	4019.8	4,693,607.7	439.28
5	2006	188,987	4,564,367.2	24,301	8141	41,584.56	82,488,646	23,476.46	25,391	525,856.4	2383	1965	4718.82	5,699,190.6	538.69
6	2007	248,227.65	5,453,244	34,446	13,386	49,714.1	103,032,217	28,422.8	30,778.28	658,836	3056	2482	5967.1	7,126,886.1	639.4
7	2008	285,079.15	6,551,994	39,656	23,915	55,728.9	128,794,741	31,503.9	40,191.65	790,879	3917	3170	7402.3	9,489,106.1	746.7
8	2009	389,220.3	8,921,215	71,337	41,170	59,566.7	137,367,222	29,499.7	70,065	1,345,385.1	8601	6017	9087	15,924,583	747.2
9	2010	399,073.8	9,678,300	59,683	50,166	74,482.8	163,647,630	37,001.6	55,233.68	1,226,262	5767	5672	11,417.3	16,755,263	948.6
10	2011	511,174.89	14,409,133	101,267	82,240	87,527.204	224,733,493	40,600.332	93,466.78	2,112,461.8	11,115	10,506	14,484.38	23,170,435	1030.5
11	2012	623,249	17,338,101	127,821	115,799	102,284	255,710,383	46,701.1	106,684	2,833,055	14,976	15,058	17,337.7	29,286,008	1164.9
12	2013	670,222	20,343,380	143,005	138,785	116,048.9	312,296,100	49,285.091	123,200	3,476,553	17,124	19,558	20,484.22	36,061,674	1184.2
13	2014	701,440	22,742,749	166,709	180,601	127,367.67	354,941,746	50,765.2	133,902	3,903,161	19,354	24,799	23,350.33	43,018,345	1312.3
14	2015	717,490	25,813,283	156,674	239,265	137,331.83	404,899,708	50,541.1	128,589	4,414,576	16,020	31,259	25,729.53	47,362,675	1342

DMUs	years	Manufacture of aircrafts and spacecraft								Manufacture of electronic equipment and communication equipment					
		Per.	Exp.	Pat.	Inv.	POR	SRNP	EDV	Per.	Exp.	Pat.	Inv.	POR	SRNP	EDV
1	2002	36,112	222,912	176	126	499.9	1,431,626	45.64	49,675	1,121,617	2956	1068	7658.67	22,060,613	3286.9
2	2003	28,165	222,590	282	141	547.2	2,151,105	54.52	61,643	1,385,038	4890	2100	9927.14	29,261,877	4401.8
3	2004	24,026	252,501.6	155	73	498.4	2,124,848	42.4	60,514	1,885,461.6	6986	2453	13,819.1	40,264,332	7259.9
4	2005	29,870	277,969.2	328	192	781.4	3,373,540.4	77.76	95,091	2,347,164	11,022	4268	16,646.3	38,520,369	9410
5	2006	27,374	333,417.6	510	228	798.88	3,050,430.9	121.1	97,816	2,768,853.5	16,708	3807	21,068.86	41,734,821	12,131
6	2007	27,181.99	425,938	810	270	1006.4	3,791,329.6	154.6	142,408	3,245,208	24,680	6532	24,823.6	60,130,164	14,963
7	2008	19,345.88	519,869	1036	400	1162	4,729,806.3	205.7	172,230.2	4,029,384	25,909	15,418	27,409.9	67,590,765	16,760
8	2009	23,265	662,648.7	1609	622	1322.8	2,760,871.9	208.2	209,668.4	5,011,508.8	40,499	24,562	28,465.5	86,981,738	15,542
9	2010	28,248.994	928,427	2172	700	1592.4	4,721,627.3	202.5	211,511.8	5,724,094	35,575	33,677	35,984.4	90,714,882	19,589
10	2011	32,329.26	1,495,895.1	2693	1494	1934.3079	5,270,130.8	274.95	272,062.3	7,904,869.4	60,335	51,234	43,206.34	115,181,309	22,240
11	2012	43,071	1,701,358	3882	2153	2329.9	6,391,332	358.7	340,679	9,540,946	78,764	71,584	52,799.1	136,954,427	27,049
12	2013	47,875.1	1,747,135	4336	3133	2853.1501	7,566,092	370.06	356,884.9	11,703,282	83,168	88,636	60,633.89	193,907,207	28,738
13	2014	41,043	1,940,455	5375	3805	3027.5631	11,185,051	405.4	380,683	13,239,470	98,573	119,115	67,584.21	223,221,172	31,487
14	2015	45,832.1	1,805,926	6279	6234	3412.5711	13,801,343	433.5	402,512.5	15,454,606	97,956	167,800	78,309.93	267,002,580	35,322

DMUs	years	Manufacture of computers and office equipment								Manufacture of medical equipment and measuring instrument					
		Per.	Exp.	Pat.	Inv.	POR	SRNP	EDV	Per.	Exp.	Pat.	Inv.	POR	SRNP	EDV
1	2002	6589	248,386	953	38	3441.67	7,527,523	2320.3	7852	60,386	506	135	734.04	652,763	163.25
2	2003	12,393	257,491	1243	271	6305.97	9,549,554	4137.3	8128	82,665	550	385	880.48	1,149,977	204.44
3	2004	13,578	395,998.7	1334	711	9192.7	13,420,050	6845.7	8782	105,540.5	855	396	1303	1,293,122.8	339.4
4	2005	17,484	434,479.7	1863	473	10,716.6	20,700,912	7194.6	11,132	165,862.1	902	591	1752.2	1,858,204	514.42
5	2006	24,591	729,250.5	3221	1174	12,634.18	29,631,088	9997.7	13,815	206,989.2	1479	967	2363.82	2,373,115.6	688.22
6	2007	29,711.64	818,169	3266	3210	14,887.3	28,147,354	11,859	18,147.72	305,093	2634	892	3029.8	3,836,483.3	806.8
7	2008	31,051.62	808,960	4540	3344	16,499	42,277,386	12,976	22,259.81	402,902	4254	1583	3255.6	4,707,678.2	814.8
8	2009	39,486.9	1,048,091	9178	5016	16,432	23,009,386	12,143	46,735	853,581.4	11,450	4953	4259.4	8,690,643.3	859.3
9	2010	68,509.036	1,175,661	10,810	7552	19,957.7	44,214,684	15,178	35,570.3	623,856	5359	2565	5530.9	7,241,173	1084
10	2011	49,248.447	1,580,581	12,125	11,153	21,163.534	68,085,415	15,880	64,068.06	1,315,325.9	14,999	7853	6738.638	13,026,204	1175.1
11	2012	62,783	1,694,003	11,156	16,216	22,045.2	67,173,270	16,926	70,029	1,568,738	19,043	10,788	7772.1	15,905,343	1202.1
12	2013	59,939.8	1,484,825	13,408	14,349	23,214.167	57,374,228	17,641	82,322.4	1,931,585	24,969	13,109	8863.475	17,386,899	1351.8
13	2014	60,181	1,555,573	14,151	13,720	23,499.067	57,159,199	16,155	85,631	2,104,090	29,256	19,162	9906.501	20,357,979	1405.8
14	2015	57,035.1	1,738,188	12,159	9832	19,407.948	54,940,528	11,995	83,521.2	2,399,987	24,260	24,140	10,471.85	21,792,583	1449

DMUs	years	Manufacture of medical equipment and appliances									Manufacture of measuring instrument				
		Per.	Exp.	Pat.	Inv.	POR	SRNP	EDV	Per.	Exp.	Pat.	Inv.	POR	SRNP	EDV
1	2002	994	12,211	61	46	219.43	126,704	54.95	6858	48,176	445	89	514.61	526,059	108.29
2	2003	840	10,884	98	49	194.53	120,543	57.26	7288	71,781	452	336	685.95	1,029,434	147.18
3	2004	1421	19,482	68	114	285	228,244.9	100.8	7361	86,058.5	787	282	1018	1,064,877.9	238.6
4	2005	1262	34,480.7	401	90	341.6	319,049.5	114.52	9870	131,381.4	501	501	1410.6	1,539,154.5	399.89
5	2006	2354	52,409	503	202	454.01	368,768.1	168.02	11,461	154,580.2	976	765	1909.81	2,004,347.5	520.2
6	2007	3467.73	73,163	995	180	588.1	757,239.5	205.3	14,679.99	231,930	1639	712	2441.6	3,079,243.8	601.6
7	2008	3485.14	95,907	1326	527	795.4	946,911.7	259.9	18,774.67	306,995	2928	1056	2460.2	3,760,766.5	554.9
8	2009	9192.5	207,525	2719	1426	939.3	1,657,648.3	280.6	37,542.5	646,056.4	8731	3527	3320	7,032,995	578.8
9	2010	7303.268	148,612	1217	658	1148.5	880,562.7	352	28,267.03	475,244	4142	1907	4382.4	6,360,610.3	732
10	2011	11,115.289	298,445.3	2969	2410	1362.9224	1,499,572.2	414.47	52,952.77	1,016,880.6	12,030	5443	5375.716	11,526,632	760.67
11	2012	13,521	373,870	4438	3311	1602	2,504,121	394.2	56,508	1,194,867	14,605	7477	6170.1	13,401,222	807.9
12	2013	16,065.1	486,942	6579	4147	1853.5963	3,014,633	445.22	66,257.3	1,444,643	18,390	8962	7009.879	14,372,266	906.57
13	2014	16,044	481,492	7789	5291	2182.5533	3,398,094	476.1	69,588	1,622,598	21,467	13,871	7723.947	16,959,886	929.7
14	2015	19,172	663,731	7270	8013	2431.2573	3,799,665.8	478	64,349.2	1,736,256	16,990	16,127	8040.589	17,992,917	971