Dynamic model of knowledge growth of the OECD Countries and knowledge capacities measuring

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Abstract

The measurement of knowledge is one of the most important issues in *Scientometrics* and knowledge management. According to the dynamic point of view, the increase of science and technology knowledge indexes depends mainly on the effects of three determinants: reproduction, creativity, and environmental restriction of the science and technology system. Present paper develops two models that measure the rapid production of knowledge in OECD countries and then apply them to form a function which deals with the knowledge capacity of the OECD countries in a certain period. The sample used here is the relevant data of 21 OECD countries during 1995-2000. The knowledge capacities of the 21 OECD countries are ranked. There are great gaps among countries in knowledge capacity and the possibility of scientific revolution is slim. At the end, the authors discuss the importance of R&D expenditures, researchers in knowledge production, the productivity of knowledge production, and the relationship between a country's capacities to produce etc.

Keywords

Dynamic model, knowledge growth, knowledge production, OECD

1. Introduction

There has been significant development in Science and Technology since the first scientific revolution in 1543. A great deal of historical materials of science and technology was accumulated during this time. *Scientometrics*, which appeared in 1940s, focuses on the quantitative research of the dynamic developing process of science and technology. A lot of achievements have been accomplished in this field, such like Price's law of exponential growth, Carol's law of subrogation of the leading subjects, Lotka's law of frequency distribution of scientific productivity etc. According to those theories, we can reach a conclusion that, to a certain extent, the history of S&T is also the history of knowledge production.

Knowledge production is one of the most important parts of knowledge management; therefore it is necessary to summarize the development of knowledge management briefly. Knowledge management in recent years has become a hot topic in organization sciences (Nonaka, 1994; Davenport and Prusak, 1998; Tuomi, 1999). In this discourse "knowledge" is often not only identified as the new dominant production factor in post-fordistic societies but as a product on its own. Thus, from an economic perspective – knowledge needs to be *located and estimated* in order to determine its exchange value. From this perspective, "knowledge" may easily become reified as an isolated entity abstracted from its practical, process or problem driven actualization in situated actions (Suchman, 1987).

Many scientists and researchers has been studying the issue of measure of knowledge production and came up with different kinds of evaluation models, among which Gibbons' model is one of the most influential models.

On the basis of those theories, this paper sets out to build the dynamic model of knowledge growth from the point of dynamic mechanism of knowledge increasing, which could promote the research of *Scientometrics* from the state of kinematics research to the state of dynamics research. The former is concerned with specific laws while the later focuses on general laws.

2. Methods and sample

2.1. Methods

The development of science and technology take the form of quantities increase, such as number of patents and papers, and qualitative change in the scientific theory system. From the dynamics' point of view, the increase of science and technology knowledge indexes depends mainly on the effects of three determinants, namely the reproduction, creativity, and environmental restriction of the S&T system. The dynamic model is as following:

$$\frac{dx}{dt} = px - rx^2 + c \qquad \text{\_1\_}$$

In equation (1), x represents a certain index (patents, papers etc.), t represents time, px represents reproduction, it is on direct ration with the science and technology in existence. This is called the Mathew effect in the social science; rx^2 represents the restrictions (when r>0)or propulsion (when r<0) in and out of the science and technology system, C represents creativity. In the model, p, r, and c are usually constants, and also functions of researchers, R&D expenditure, R&D equipments and S&T policies.

If

$$c - rx^2 = k_1 x \text{ \_or } k_1 e^{px}\text{\_} \qquad \text{\_2\_}$$

Then

$$\frac{dx}{dt} = px + k_1 x = kx \qquad \text{\_3\_}$$

If k is constant, the solution of equation (3) is

$$x = x_0 e^{kt} \qquad \text{\_4\_}$$

This is known as Price's law of exponential growth. In the "Science since Babylon", Price worked out the total number of magazines which were published from1665 to the middle of 20th century with the discovery that the number increased by 10 times every fifty years(namely , the doubling time is 15years). It turned out that it accords with exponential increase.

However, the law is only tenable under certain terms (when $c - rx^2 = k_1 x$,or $k_1 e^{px}$), which is true only in the accumulation period of the whole developing course of science and technology. In the period of scientific revolution, the law is invalid. If p, r and c are constants, then the solution of equation (1) is:

$$x = \frac{1}{2r}\left[\frac{(d+p) - m(d-p)e^{-dt}}{1 + me^{-dt}}\right] = \frac{1}{r}\left(\frac{2d}{1 + me^{-dt}} - d + p\right) \qquad \text{\_5\_}$$

well,

$$d = \sqrt{p^2 + 4rc}, m = \frac{(d+p) - 2rx_0}{(d-p) + 2rx_0} \quad \text{_6_}$$

This is a logistic curve, its asymptote is $x = \frac{d+p}{2r}$.

2.2. Sample

Numbers of Papers and patents are the two most important factors in the measure of knowledge capacity and the comparison between different units. According to the dynamic model of science and technology, the knowledge production function with papers and patents as its main indexes also includes researchers, R&D expenditures, R&D equipments and R&D policies etc. In this paper, we chose researchers (total number) and R&D expenditures as constant because they are easy to be measured.

The sample used in this paper is the relevant data of 21 OECD countries dated form 1995 to 2000, which includes: total numbers of researchers, R&D expenditures, number of scientific papers, patents granted by either USPTO (the US Patent and Trademark Office) or UPO (European Patent Office,) or JPO (the Japanese Patent Office), which can be called number of triadic patent families. It is agreed that there is so called lagged effect in the production of knowledge (for instance, the output which are corresponding to the input of 1996, namely the papers and patents, are often searched by the retrieval institution or granted by the patents offices in 1999), the lagged time we use is 3 years. In our analysis, the average of the input indexes from 1996 to 1998 correspond to the average of output indexes of 1998, 1999 and 2000.The data adjusted can be seen in table 1.

Table1. The test of model

	Adjusted R Square	St. Error of Estimates	Change Statistics	
Model			R Square Change	F Change
1	1.000	144.38269550289750	1.000	309524.032

3. Mathematics

3.1. Dynamic model of paper growth

The indexes used in the building of dynamic model of paper growth are as following:

(1)$X_1(t+1)$: number of scientific papers (average of the numbers of this year, the next year and the year after that_;

（2）$X_1(t)$: number of scientific papers last year (can be worked out in the same method as $X_1(t)$)

(3)$X^2_1(t)$: the square of $X_1(t)$

(4)$X_2(t)$: number of triadic patent families of last year (can be worked out in the same way as $X_2(t+1)$, see the next chapter)

(5)R: R&D expenditure (value measured at purchasing power, unchanged price, million US dollars, average of expenditures of 1996 to 1998)

(6)E: number of researchers_average of the numbers of 1996 to 1998_

(7)W: E* $X_2(t)$/R

The model based on the data during 1996-2000 is listed bellow_

$$X_1(t+1)=0.002998\ E+0.993\ X_1(t) -0.000000178\ X^2_1(t)-0.00981W -8.684 \quad \text{_7_}$$

The analysis of data can be found in table 1 and table 2.

Table2. The t test values for variables

Model		Non-standardized Coefficients B	Std. Error	t	Sig.
1	(Constant)	-8.684	51.412	-.169	.868
	Number of researchers E	2.998E-03	.001	4.295	.001
	$X_1(t)$	.993	.005	196.727	.000
	$X^2{}_1(t)$	-1.780E-07	.000	-6.394	.000
	W	-9.810E-03	.004	-2.224	0.41

3.2. *Dynamic model of the patent growth*

The indexes used in the building of dynamic model of patent growth are as following:

(1)$X_2(t+1)$: number of triadic patent families (average of the numbers of this year, the next year, and the year after that_

(2)$X_2(t)$: number of triadic patent families of last year (can be worked out in the same way as $X_2(t+1)$)

(3)$X_1(t+1)$: number of scientific papers

(4)$X_1(t)$: number of scientific papers of last year

(5)$X^2{}_2(t)$: the square of $X_2(t)$

(6)X: $X_2(t)*X_1(t)/10000$

The model based on the data dated from 1996 to 2000 is listed bellow_

$$X_2(t+1)=0.992X_2(t)+0.001415X_1(t+1)+0.000002588X^2{}_1(t)-0.002514X-1.048 \quad (8)$$

The analysis of data can be found in table 3 and table 4.

Table3. The test of model

Model	Adjusted R Square	St. Error of Estimates	Change Statistics R Square Change	F Change
1	1.000	18.33318562870742	1.000	240895.727

Table4. The t test values for variables

Model		Non-standardized Coefficients B	Std. Error	t	Sig.
1	(Constant)	-1.048	5.493	-0.176	
	$X_2(t)$	0.992	.008	117.50 2	0_000
	Number of scientific papers	1.415R-03	.001	1.984	0.065
	$X^2{}_2(t)$	2.588E-06	.000	3.115	0.007
	X	-2.514E-03	.001	-3.750	0.002

4. *Knowledge production function and the measure of knowledge capacity*

Firstly, we will have to distinguish between two concepts: knowledge reserve and knowledge capacity. Knowledge reserve is a accumulated index. Consequently, we must take the accumulation from the very beginning of the knowledge production into consideration if we want to measure it. On the contrary, knowledge capacity is a flux index. Therefore, the measure of knowledge capacity is concerned with the increment within a certain period, one year for example.

The summation of all the coefficients of the variables on the right sides of equation (7) is 0.986. Divide all the coefficients of equation by 0.986, than the coefficient of X_1 is 1.0142. Similarly, we can work out the coefficient of X_2, which is 1.0091. Add the changed equations (7) and (8); an equation which reflects the complex relationship between multi independent variables and dependent variable can be worked out.

It is of great importance for us to use the coefficients of X_1 andX_2 as their weights in our evaluation. The weights of X_1 andX_2 are 0.5013 and 0.4987. Therefore, we can use the following equation in the measure of knowledge capacity.

$$F_1\_\ 0.5013X_1\_0.4987X_2 \qquad \_9\_$$

In equation (9), F_1 represents knowledge capacity, X_1 represents average of number of papers of three years, X_2 represents average of number of triadic patent families of three years.

5. Conclusions

5.1. *Great gaps exists between different countries in knowledge capacity*

We rank the knowledge capacity of the 21 OECD countries by using equation (9). X1 represents average of number of papers of 1998 to2000, X2 represents average of number of triadic patent families of 1998 to 2000, as is seen in table 5.

As can be seen in table 5, there are great gaps between different countries as far as knowledge capacity is concerned. The knowledge capacity of USA, which is No.1, tripled that of Japan, which is No.2. The No.1’s knowledge capacity was as much as four times that of Germany and Britain, which ranked 3rd and 4th. The score of Iceland (No.21) is only 1/13000 of USA. It is easy to come to the conclusion that USA is absolutely the leading country in science and technology knowledge production in the world.

Table 5 Results of OECD countries knowledge capacities evaluation

Year	Country	X_1	X_2	F_1	Rank
2000	USA	164115	14958	89730.63	1
2000	Japan	47555	11560	29604.07	2
2000	Germany	37534	5878	21746.82	3
2000	Britain	39043	1791	20465.38	4
2000	France	26641	2161	14433.04	5
2000	Canada	19537	538	10062.55	6
2000	Italy	16959	741	8871.222	7
2000	Australia	12355	309	6347.582	8
2000	Spain	12127	115	6136.563	9
2000	Netherlands	10548	840	5706.226	10
2000	Korea Re.	6267	466	3374.358	11

2000	Belgium	4891	371	2637.021	12
2000	Finland	3949	445	2201.611	13
2000	Denmark	4116	244	2184.815	14
2000	Turkey	2653	5	1332.734	15
2000	Czech	2033	10	1023.876	16
2000	Hungary	1949	27	990.4052	17
2000	Ireland	1249	49	650.6582	18
2000	Portugal	967	7	488.4428	19
2000	Slovak	921	3	463.2757	20
2000	Iceland	127	4	65.73685	21

5.2. The importance of R&D expenditures and researchers in knowledge production

It is agreed that the there are several factors that affecting the knowledge production of a system, no matter it is a firm, a sector, or a country. Those factors are thought to be important in shaping the way knowledge is produced and accumulated, namely the R&D expenditure, the number of researchers, the governmental supporting systems, the innovation systems of both national and regional lever and so on, among which the R&D expenditure and total number of researchers are considered as two most important factors because to a certain extent they can reflect the total effects of other factors

According to the result of the analysis of the model, we can also reach the conclusion that the ultimate drive of science and technology knowledge growth lies in the increase of R&D expenditures and number of researchers. In equation (7) and (8), "number of scientific papers of last year" is the key determinants of indexes W (number of researchers * number of scientific papers/R&D expenditures) and X (number of triadic patent families of last year*number of scientific papers of last year). According to equation (7), the number of scientific is determined by the previous R&D input, namely R&D expenditures and number of researchers.

5.3. The possibility of scientific revolution

If $y = \frac{r}{p} x$ _equation (1) transforms to_

$$\frac{dy}{dt} = py(1-y) + c \qquad \_10\_$$

Its difference form is__t is step length__

$$y(t+\Delta t) - y(t) = py(t)[1-y(t)]\Delta t + c \qquad (11)$$

If $u = 1 + p\Delta t$ (12)

$$z_n = \frac{p\Delta t}{1+p\Delta t} y(t) \qquad (13)$$

$$z_{n+1} = \frac{p\Delta t}{1+p\Delta t} y(t+\Delta t) \qquad (14)$$

Then equation_8_transforms to_

$Z_{n+1}=u\,Z_n$_1-Z_n_+c (15)

According to relevant studies, if u >3, there will be divergence in the solution path of equation (15) (2-periods), if u keeps on increasing, new divergence (4-period) can be predicted. When u equals to 3.569945, there will be periodic chaotic solutions. The periodic path (orbit) of is made up of broadband rather than a series of points because of the existence of C. We believed that divergences and chaos imply the normality, "crisis" and revolution of science and technology.

As far as papers are concerned, according to equation (7), u=1.000006799_far from the chaotic phase, which indicates that the scientific researches of the OECD countries are not in the phase of scientific revolution.

Similarity, as for the patents, according to equation (8), u= 0.9999915_ far from the chaotic phase, which indicates that the development of science and technology is the combination of technological innovation, introduction and reconstruction rather than technological revolution.

6. Discussions

6.1. The productivity of knowledge production

Knowledge has several properties that economists identify as those characterizing the general class of 'public goods'. Because it is a public good, there are considerable benefits when it is shared. Knowledge is not depleted by intensive use but instead is likely to be enriched the more that individuals are allowed to access, use and improve it. Knowledge is often produced in activities in which other motivations are dominant. This process of 'learning-by-doing' occurs within many contexts of manufacturing products, providing a service or using equipment. Knowledge is 'sticky', i.e. difficult and costly to transfer from one site to another, especially where it is highly tacit rather than explicit and codified. (DOMINIQUE FORAY, Centre for Education, Research and Innovation, OECD, Paris, France, 2003)

Although knowledge is identified as "public goods", the production, transmit and use of production is by no means the same as traditional products. Consequently, the concept of productivity of knowledge production can not be treated as we did to the traditional products.

Knowledge produced is applied into practical use (Industrial production, agricultural production etc.).The productivity of knowledge production is determined by the research, development, creativity, transmission, application of knowledge. There are some difficulties in measuring the knowledge productivity because of the characteristics of knowledge production and application, but it is possible for us to conduct a qualitative analysis.

There are economies of scale and accumulated effect in knowledge production. Therefore, it is an effective approach to improve the productivity by increasing the R&D input. In addition, the production of knowledge is different from the production of traditional products, it doesn't dependent on the natural resources. Therefore, the productivity of knowledge production is determined by the qualification of human resources. In the knowledge economy age, the qualification of human resources relies on the education. It is worth mentioning that, the R&D expenditures as percentage of GDP of the OECD countries has been 2.2% or so and the education expenditures as percentage of government expenditures has reached around 12% since 1990s.

6.2. Interacting relationship between knowledge capacity and economy level of a country

While knowledge has always been at the heart of economic development, there is evidence that the capacity to produce and use knowledge has more explanatory value in explaining current levels of economic welfare or rates of growth. Factors determining the success of firms and national economies are more dependent than ever on the capacity to produce and use knowledge. As a result, innovation and technological changes have become more central to economic performance (Foray & Lundvall, 1996; OECD, 2000).

Acknowledgement

We greatly appreciate to the warmest help and directions we get from Dr. Kretschmer, Mayer, Heinz, Lamirel.

Appendix table 1[a]

Year	Country	Resear-chers[b]	R&D expend-itures[c]	Patents[d]	Papers[e]	patents of last year[f]	papers of last years[g]	W	X
2000	Canada	180221	12372	538	19537	540	19610	7869.7	1059.4
2000	USA	2150938	204960	14958	164115	14884	165167	156197.6	245832.7
2000	Australia	124228	6721	309	12355	301	12112	5569.8	365.0
2000	Japan	1178910	87054	11560	47555	11376	46240	154061.0	52603.7
2000	Korea Re.	210588	14562	466	6267	436	5590	6305.5	243.7
2000	Belgium	61054	4301	371	4891	383	4829	5434.0	184.9
2000	Czech	25281	1514	10	2033	10	2038	169.2	2.1
2000	Denmark	32217	2469	244	4116	233	4056	3038.0	94.4
2000	Finland	43675	2894	445	3949	420	3906	6340.9	164.1
2000	France	350228	27671	2161	26641	2185	26363	27660.9	5761.4
2000	Germany	482936	40919	5878	37534	5830	37189	68804.8	21680.4
2000	Hungary	28396	674	27	1949	26	1865	1109.9	4.9
2000	Iceland	2396	124	4	127	4	131	77.3	0.1
2000	Ireland	16618	1011	49	1249	46	1209	758.7	5.6
2000	Italy	170218	12382	741	16959	723	16707	9932.8	1207.1
2000	Holland	75803	7033	840	10548	834	10734	8990.3	895.3
2000	Portugal	28895	921	7	967	6	818	200.2	0.5
2000	Slovak	21411	500	3	921	3	946	145.3	0.3
2000	Spain	133928	5398	115	12127	113	11748	2809.7	133.0
2000	Turkey	52816	1901	5	2653	5	2423	130.3	1.1
2000	Britain	302243	21583	1791	39043	1722	38650	24120.4	6657.3

a. Data source, website of the OECD, http://www.oecd.org/home.

b. Number of researchers, average of 1996_1998.

c. R&D expenditure (value measured at purchasing power, unchanged price, million US dollars, average of expenditures of 1996 to 1998)

d. Number of triadic patent families (average of 1996-1998_

e. Number of scientific papers (average of 1996-1998)

f. Number of patents of last year

g. Number of papers of last year

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