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THE EFFICIENCY OF TRIPLE-HELIX RELATIONS IN INNOVATION SYSTEMS: MEASURING THE CONNECTION BETWEEN A COUNTRY'S NET INCOME AND ITS KNOWLEDGE BASE

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THE EFFICIENCY OF TRIPLE-HELIX RELATIONS IN INNOVATION SYSTEMS:

MEASURING THE CONNECTION BETWEEN A COUNTRY'S NET INCOME AND ITS KNOWLEDGE BASE[5]

We apply the Method of Reflections developed by Hidalgo and Hausmann for measuring economic complexity to a Triple Helix system of innovations by defining the Patent Complexity Index in analogy and addition to the Economic Complexity Index and extending MR to three dimensions. PCI is operationalized in terms of patent groups instead of product groups. PCI and ECI are computed for three groups of countries. We find no correlation between economic complexity and technological complexity which means that the two measures capture different information. Adding the third dimension of governance to the Method of Reflections, one can incorporate knowledge dimension in Hidalgo and Hausmann defined ECI and use MR for evaluation the efficiency of Triple-Helix system of innovations. The Method of Reflections can thus be used for evaluating the efficiency of a TH system of innovations in terms of its contribution to the net national income.

JEL Classification: C63

Keywords: Triple-Helix innovation system, Method of Reflections, economic complexity, technological efficiency, patent complexity index PCI

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Introduction

A country's economic growth and income can be expected to depend on the diversity of products which this country produces (Cadot *et al*. 2013). Hidalgo & Hausmann (HH) (2009) proposed to use the economic complexity index (ECI) to measure the complexity of a country's economy. ECI can be evaluated using their so-called Method of Reflections (MR) and is inferred from the diversity and ubiquity of the products that a country produces (this method is also used for evaluating the product complexity index (Hausmann et al., 2011, p. 24). Furthermore, ECI is strongly correlated with a country's income measured as GDP per capita or GDP per capita growth (Ourens, 2013, at p.24). From this perspective, the correlation between income and HH's complexity measure can also be considered as a consequence of the well-known relation between export and income growth (Kemp-Benedict, 2014). According to HH, ECI can be expected to reflect also the manufacturing capabilities of countries.

However, these authors did not provide a precise definition of *capabilities.* Do these include the technological capabilities and their respective knowledge bases? In other words, HH did not endogenize knowledge-based innovations into ECI. However, technological complexity is connected with the knowledge base of an economy. As the OECD (1996, at p. 3), for example, formulated: "Knowledge is now recognized as the driver of productivity and economic growth, leading to a new focus on the role of information, technology and learning in economic performance"

In our opinion, there is a need for a synthetic measure of technological capabilities of nations according to the amount of knowledge that they have currently accumulated in the form of patents. Moreover this measure of technological capabilities should be in some way linked with the measure of manufacturing capabilities since according endogenous growth theory (Romer, 1986) economic growth is provided through combination of technology and manufacturing. We propose to quantify the patent portfolio as a proxy for the technological complexity of a country in analogy to the product portfolio as the basis for the ECI. By constructing a patent complexity index (PCI) the technological dimension of the complexity can be explicated by this proxy.

Patents have been considered as a reliable measure of innovative activity (Arcs & Audretsch, 2002), although patents are indicators of invention, not innovation, and there always exists some disparity between patents and products because not all patents are meant to lead to innovation; for example, defensive patents. Extending HH's Method of Reflections to additional dimensions provides a method for evaluating the efficiency of a Triple Helix (TH) model of innovations in terms of net economic income. This also provides the opportunity to gain more information about the functional structure and productivity of innovation systems.

The research question of this study thus addresses a link between the study of the knowledge base of an economy, the prevailing type of innovation systems, and the net economic income of nations. Innovation systems can be considered as institutional arrangements. The innovation system mediates between the knowledge production process and the economy. Freeman and Perez (1988), for example, suggested that radical innovations in crucial factors can lead to a structural shift in the economy.

The paper is structured as follows. Section 2 shortly describes HH's Method of Reflections. We analogously define the Patent Complexity Index (PCI). Section 3 presents the evaluation of technological complexity for three selected sets of countries. In Section 4 HH's Method of Reflections is generalized to additional dimensions and a parallel with the TH system is drawn. Major findings and conclusions are summarized in Section 5.

Method

a) Economic Complexity Index

Hidalgo and Hausmann (HH) developed the Method of Reflections with which to evaluate the complexity of a country's export (Hidalgo & Hausmann, 2009). They show that the complexity value of a country's export is correlated with the log of the income. The structure of the country's export reflects the underlying "capabilities" of a country.

In HH's Method of Reflections one constructs a matrix $M_{c,p}$ where the index c refers to country and p refers to product. The corresponding matrix elements are assumed to be 1 if Balassa's revealed comparative advantage index (RCA) (Balassa, 1965) is larger than or equal to one and otherwise zero.

$$RCA_{c,p} = \frac{x_{c,p} / \sum_p x_{c,p}}{\sum_c x_{c,p} / \sum_{c,p} x_{c,p}}, \qquad (1)$$

where $x_{c,p}$ is the value of product p manufactured by country c. In other words, it is implied that a country can be expected to export a product if it produces this product proportionally more than average in the world. The sums $\sum_p x_{c,p}$ and $\sum_c x_{c,p}$ in Eq. 1 can be interchanged without altering the result.

Summing the elements of matrix $M_{c,p}$ by rows (countries) one obtains a vector with components referring to corresponding products and indicating a measure of product ubiquity relative to the world market. The sum of matrix elements by columns (products) provided a vector defining the diversity of countries exports.

$$\begin{aligned} k_{p,0} &= \sum_{c=1}^{N_c} M_{c,p} \\ k_{c,0} &= \sum_{p=1}^{N_p} M_{c,p} \end{aligned}, \tag{2}$$

N_c is the number of countries and N_p is the number of product categories. HH used N_c =178 and N_p=4948. More accurate measures can be obtained by adding the following iterations:

$$\begin{aligned} k_{p,n} &= \frac{1}{k_{p,0}} \sum_{c=1}^{N_c} M_{c,p} k_{c,n-1} \\ k_{c,n} &= \frac{1}{k_{c,0}} \sum_{p=1}^{N_p} M_{c,p} k_{p,n-1} \end{aligned}. \tag{3}$$

That is, each product is taken with corresponding weight proportional to its ubiquity on the market, and each country is also taken with weight proportional to the country's diversity. Substituting the first equation of system (3) into the second one obtains:

$$k_{c,n} = \frac{1}{k_{c,0}} \sum_{c'=1}^{N_c} \sum_{p=1}^{N_p} M_{c,p} \frac{1}{k_{p,0}} M_{c',p} k_{c',n-2}. \tag{4}$$

Equation (4) can be presented as a matrix equation

$$\vec{k} = W \cdot \vec{k} , \tag{5}$$

where vector $\vec{k}$ is a limit of iterations

$$\vec{k} = \lim_{n\to\infty} k_{c,n} \ . \tag{6}$$

HH introduced the economic complexity index (ECI) as an eigenvector $\vec{k}$ of the matrix $M_{c,c'}$

$$M_{c,c'} = \sum_p \frac{M_{c,p} M_{c',p}}{k_{c,0} k_{p,0}} \tag{7}$$

associated with the second largest eigenvalue. ECI is defined according to the formula

$$ECI = \frac{\vec{k} - <\vec{k}>}{stdev(\vec{k})} \tag{8}$$

HH present the complexity measure as a vector with components referring to corresponding countries. ECI is orthogonal to a country's diversity score, defined by the second equation of

System (2). Consequently it was argued that complexity and diversity measures capture different kinds of information (Kemp-Benedict, 2014). But this conclusion refers to a set of all countries, considered as components of the diversity vector. The orthogonality between the vectors is achieved via rearrangement of the diversity-vector components and by attributing different weights to them. With respect to a single component of a diversity vector, however, one still can argue that it keeps the trace of initial diversity. Kemp-Benedict (2014) noted that the correlation between ECI and the logarithm of the national income is a consequence of the relationship between export and income growth.

b) Patent Complexity Index

HH hypothesize that diversity and ubiquity scores of the countries reflect underlying "capabilities." By capabilities they imply the ability of countries to make corresponding products, but this can also be interpreted as technologies. The corresponding technologies are legally documented as patents, so that patents can also be assumed as a proxy measure for capabilities. In this design one constructs a matrix $M_{c,t}$, which is essentially matrix $M_{c,p}$ in which product groups, indicated by index *p*, are substituted by patent technology groups, indicated by index *t*. Following the MR formalism explained in Eqs. 2-8 one can derive a matrix $M_{c,c'}$

$$M_{c,c'} = \sum_t \frac{M_{ct} M_{c\prime,t}}{k_{c,0} k_{t,0}} \qquad (9)$$

and a patent complexity index (PCI) estimated according to Eq. (8), as follows:

$$PCI = \frac{\vec{k} - <\vec{k}>}{stdev(\vec{k})} \, . \qquad (10)$$

The condition for RCA index (Eq. (1)) in this case would mean that a country's "specialization" or efforts in promoting certain technology with respect to other technologies is above or below the average of that of the world. This index is a threshold that separates countries which make an accent on developing technologies from those that do not make such accent. The diversity score (second equation of (3)) would reflect the diversification of the corresponding specializations, but not the diversification of a country's patent portfolio.

For example a less developed country may have a single patent in each of four technology groups so that each group occupies 25% of this country's patent portfolio. But a developed country may have 10 patents in each of 25 technology groups, so that each group occupies 4% of total number of this country's patents. If the world average value exceeds 4%, the less developed country will be ranked as more technologically diversified than the developed one according to this diversity score. Whereas the developed nation is more technologically diversified since it possesses more patents in more technology groups, a less developed country may have a leading position in terms of percentages of patents per specific technology group.

In other words, PCI captures the technological diversification of a country expressed in patent portfolios. This measure is more volatile when applied to less developed countries as compared with developed ones, because in case of less developed countries small changes in the number of patents may entail large changes in the PCI. In the next section we present the results of calculations of PCI for a set of three different groups of countries and compare the results with the corresponding ECI.

Results

The first group of countries comprises Pacific-region countries: Japan, USA, Canada; the second group includes three European middle-size countries: Sweden, Norway, Switzerland; and the third group consists of three BRICS nations: China, India, and Russia. The data cover the period 1980-2012.

The values for ECI were retrieved from the internet resource entitled “The Observatory of Economic Complexity” at http://atlas.media.mit.edu/about/team/. Data on patents for 196 countries subdivided into 36 technology groups for the period 1980-2013 were retrieved from the WIPO statistics database (at http://ipstats.wipo.int/ipstatv2/?lang=en). We considered national patents issued where patent families are distributed by origin and first filing office, and by total count by filing office for 196 countries. In other words, these are national patents. ECI values and results of the calculations of PCI are presented in Figs. (1-6)

The first group of countries includes technologically developed ones. Japan’s ECI values are among the highest ones and Japan therefore ranks first and second during the observed time interval. The USA is ranked at places six to twelve, and Canada assumes the places six to forty one. While the curve for Japan shows a gradual increase of economic complexity, the USA and Canada exhibit slight decreases on the ECI (Fig.1). Following the interpretation of HH, one can conclude that the set of “capabilities” of the last two countries is shrinking over time. Since “capabilities” are related to technologies used this may also be interpreted as some degree of specialization which is inherent to countries at more advanced stages of development (Klinger & Lederman, 2006; Cadot et al., 2011). In terms of national innovation system effectiveness specialization would indicate some kind of a “lock-in”.

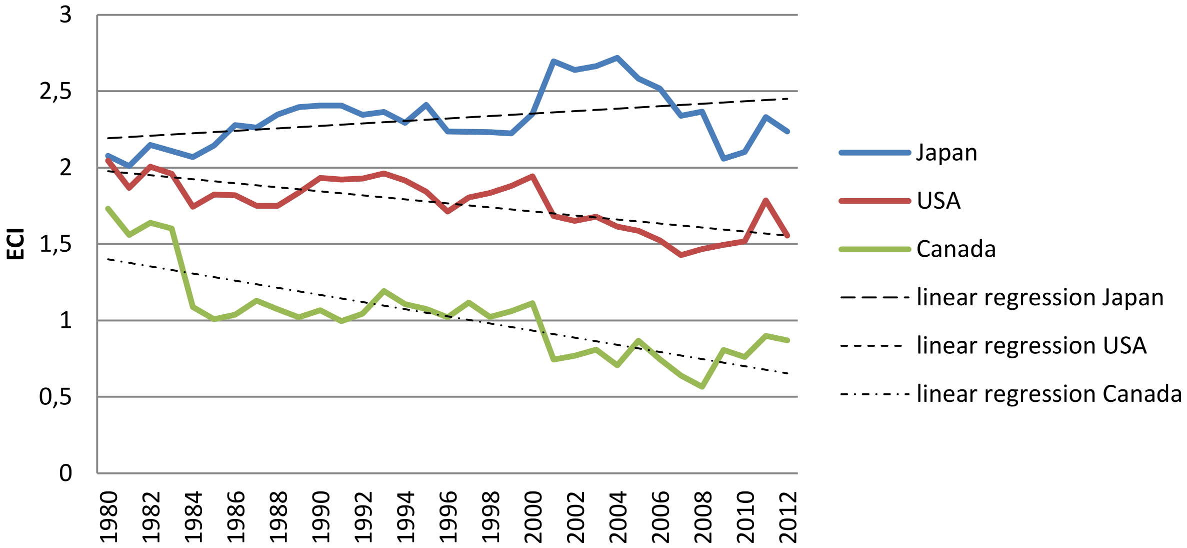


Fig.1. Economic complexity index (ECI) for Japan, USA, and Canada for 1980-2012 (source: https://atlas.media.mit.edu/en/rankings/country/)

Is this decrease in efficiency also the case when the techno logical diversification is taken into account? In order to answer this question one can study the behavior of the Patent Complexity Index (Eq. 9) indicating the "rate of growth" of the corresponding technology bases (Fig.2).

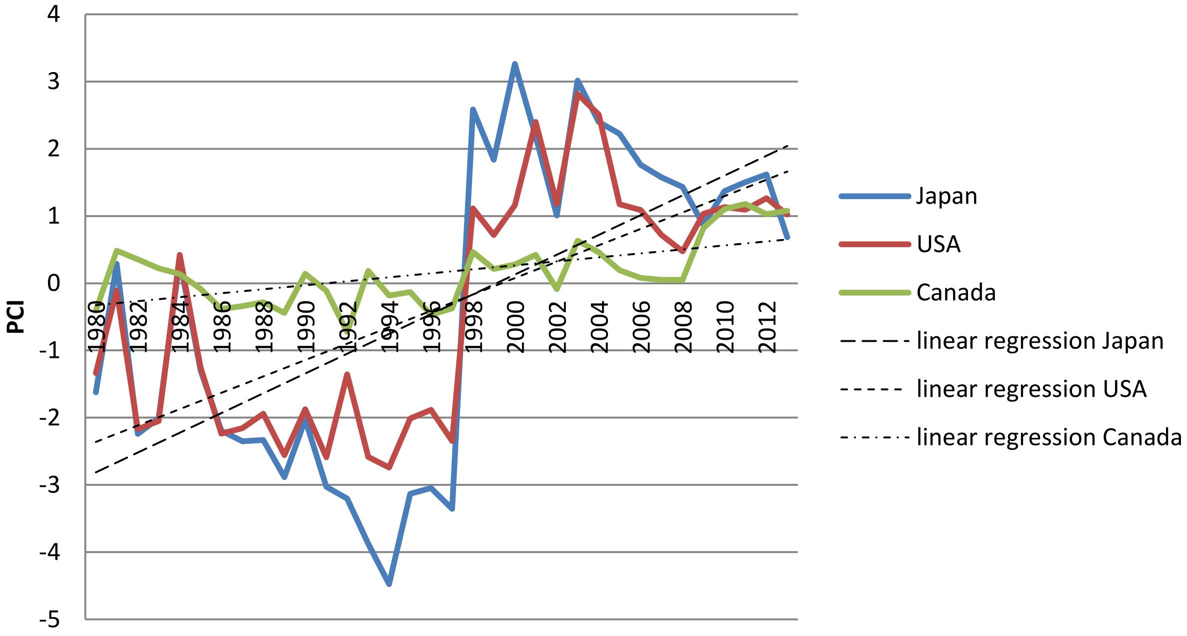


Fig.2. Patent complexity index (PCI) for Japan, USA, and Canada for 1980-2012

Figure 2 shows similar behavior of Japan's and the American PCI which indicates an accentuated growth during the observed period, and comparatively weaker growth for Canada PCI. Canadian growth, however, is stable, while the curves for the USA and Japan correlate highly in showing different cycles. The break in 1997-1998 may have to do with the type of patents used and specific registration features such as the introduction of a new classification system. Also the break can be connected with changing procedures of patent offices. Linear regression lines in the Figure 2 are introduced for the more obvious indication of the general trend than fitting the data. The markedly upward trend would show an increase in the country's ranking positioning in technological complexity over the years.

The second group of middle-sized European nations consists of Sweden, Norway, and Switzerland. Sweden and Switzerland score the highest values of ECI among 101 countries, listed in the Atlas of Economic complexity (at http://atlas.media.mit.edu), during the entire period 1980-2012: Sweden varies between the ranks two and four in the list and Switzerland is always among the top four. Sweden and Swiss PCI behave in a similar way which may be attributed to correlation between the knowledge generating systems of the two countries. The corresponding ECI values for Norway are lower; this country occupies the places thirteen to forty-tree in the observed range and the curve indicates a decrease in economic complexity.

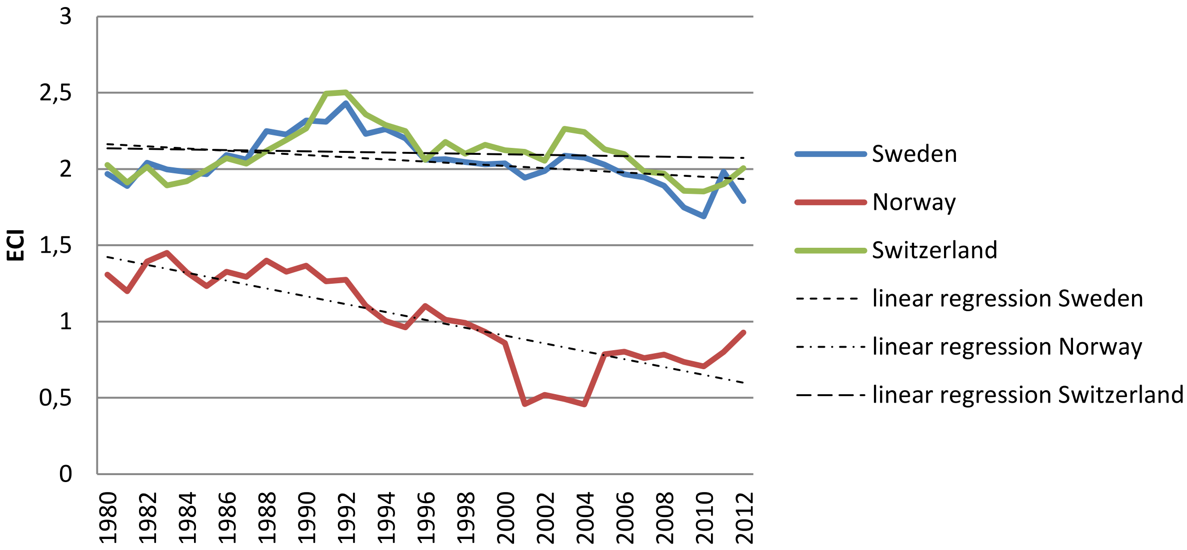


Fig.3. Economic complexity index (ECI) for Sweden, Switzerland, and Norway during 1980-2012 (source: https://atlas.media.mit.edu/en/rankings/country/)

It has been argued that a decrease in diversification is a common feature among countries at the advanced stage of development since these countries rely more on specialization than on diversification (Klinger & Lederman, 2004 and 2006). Note that in these sets the only developed nation with increasing diversification was Japan.

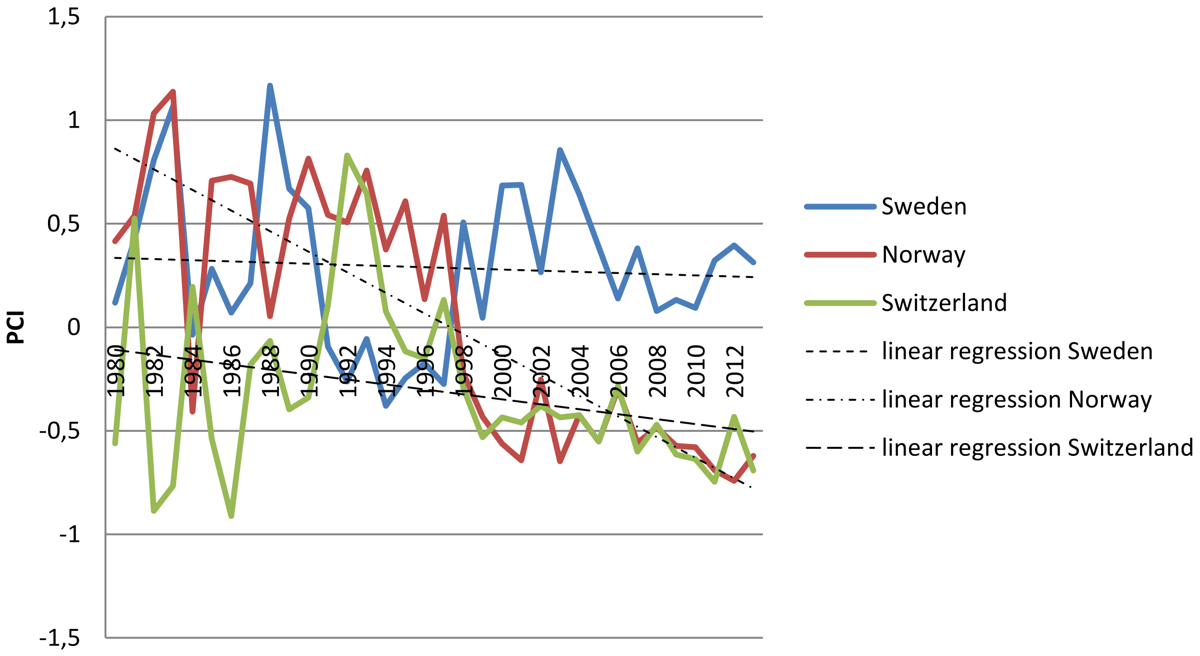


Fig.4. Patent complexity index (PCI) for Sweden, Norway, and Switzerland during 1980-2012

Using the two decades window one can mention that whereas Sweden's PCI is stable, the PCIs of Switzerland and especially of Norway show a marked decrease. In Sweden, the mechanisms of embedding high- and medium-tech manufacturing and KIS are similar to other European nations. Sweden's innovation system functions as a national innovation system (Lundquist & Power, 2002; Asheim & Conen, 2005; Roselio, 2007; Asheim & Gertler 2005; Bennewort et al., 2009; Martin, 2012). Sweden because of contextual stability was able to make the transition to a knowledge-based economy more smoothly during the '80s and '90s, may not sufficiently open up to the challenges and become "locked-in" into the institutional arrangements of the previous period. Sweden, The Netherlands, and Denmark fall into the category of weak formal but strong informal institutions and locking-in institutional arrangements could be inefficient (Williamson, 2009). The country has been placing significant emphasis on creating the conditions for innovation - led growth (http://www.abc.es/gestordocumental/uploads/economia/WEF_GCR_CountryProfilHighlights_2011-12.pdf).

The major factor in the Norwegian economy is the marine and maritime industries. In Norway areas with high concentrations of knowledge institutions are uncoupled from the needs of the industry (Asheim & Isaksen, 1996; Narula, 2002; Isaksen & Onsager, 2010; Herstad et al., 2011, Strand & Leydesdorff, 2013). And this uncoupling unfavorably affects technology complexity.

The third group of BRICS countries occupies above-average positions in the rankings of countries in Atlas of Economic complexity with respect to ECI values. More specifically China occupies the twenty-second to fort-second places, Russia the thirty-first to forty-fifth places, and India the twenty-fourth to sixty-second places in the observed range. The pronounced growth of the Chinese ECI can also be attributed to the fact that the Chinese economy is more manufacturing-oriented which provides diversified product export (Leydesdorff & Zhou, 2014). The curve for China contrasts sharply with the decrease of the ECI values for Russia. If the curve for China is assumed since 1992, the time of opening of China, this contrast would be even more obvious, During the same time, the Indian ECI shows some decrease.

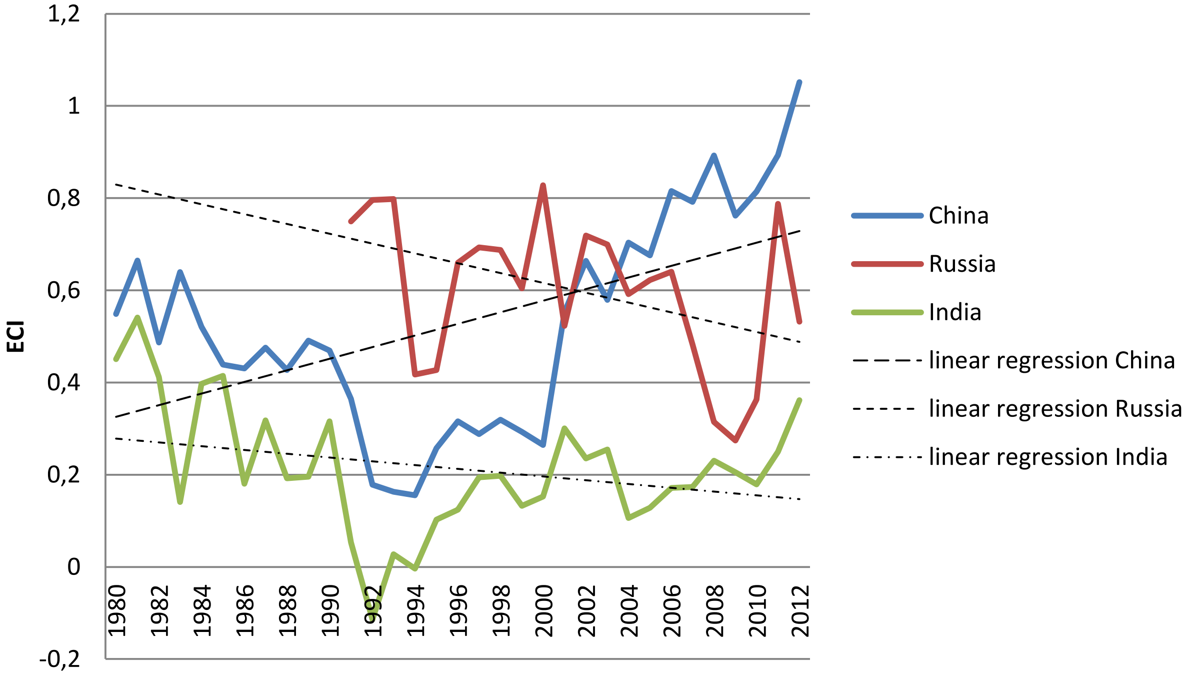


Fig.5. Economic complexity index (ECI) for China, Russia, and India for 1980-2012 (source: https://atlas.media.mit.edu/en/rankings/country/)

Comparison of the ECI curves in Figure 5 and the PCI curves in Figure 6 teaches us that the behavior of PCI does not closely follow the behavior of ECI. This is also the case for other countries. However there seems to be a trend branch around 1992: the opening of China and the demise of the Soviet Union. The line for India is positive since that date. The line for China sharply upward The Chinese PCI demonstrates a slight decrease as opposed to India PCI which gradually increases, while Russia PCI sharply descends. The Russian economy relies increasingly on oil and gas revenues more than on diversified manufacturing.

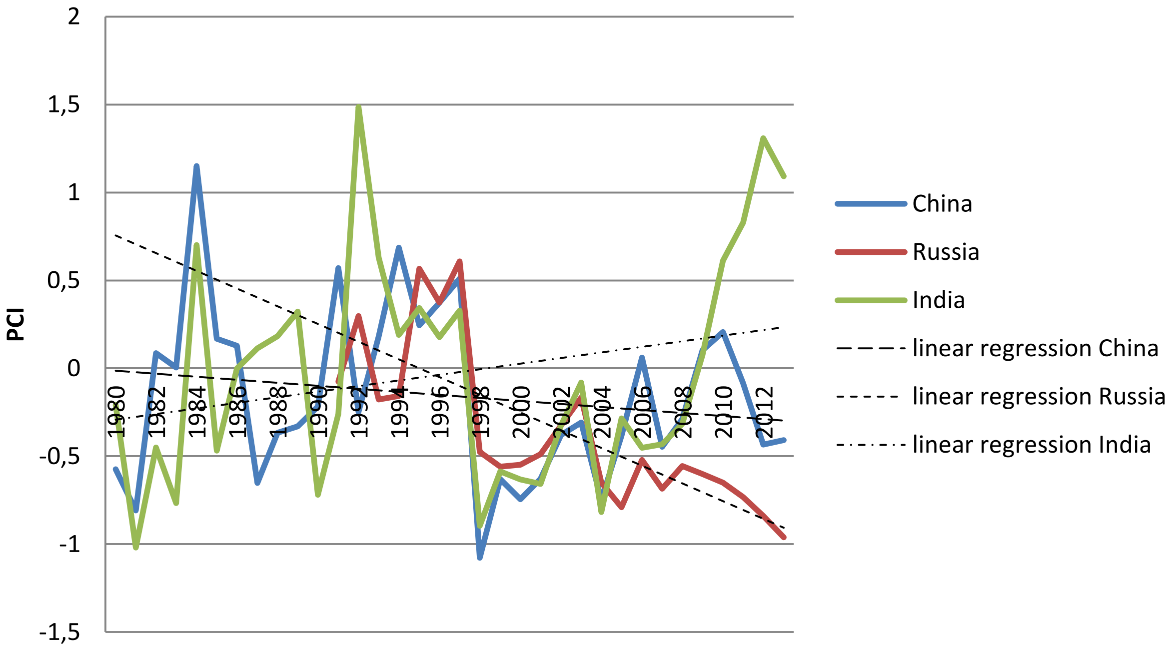


Fig.6. Patent complexity index (PCI) for China, Russia, and India for 1980-2012

Comparing Figures 5 and 6, one can reach the following conclusions:

China can be considered as an economy with high growth rates (World Bank Group, 2015). Caporale et al., (2015) show, based on trade data from 1992-2012, that there has been a shift from resource- and labor-intensive to capital- and technology-intensive exports. Fisher-Vanden and Jefferson (2008) point to three main factors explaining the growth rate in China: capital-biased technical change which drives neoclassical growth, internal R&D which drives efficiency based on competitive advantages and deliberate acquisition of foreign technology. Increase in economic (i.e. manufacturing) complexity is provided by more thorough implementation of available technologies. However, limited effort is made for new technology development for future growth which may account for decreasing linear regression trend in Chinese PCI. This complies with the results of a previous study (Leydesdorff & Zhou, 2014) which suggest that most synergy in the knowledge base of the Chinese economy is generated at the provincial level and provinces are less profiled in terms of high and medium tech firms than large industrial cities and municipalities.

India, in turn, demonstrates the other development model. Preserving relatively stable manufacturing complexity the country tries to develop a wider spectrum of technological opportunities which can play a role in the future. India's linear regression of PCI slightly increases during the period. India is doing remarkably well on this indicator during the last decade however the study of ECI showed that MR complexity indicators are exposed to multiple sources of noise which is especially the issue for less developed countries (Ourens, 2013).

The shrinking Russian economic capabilities are complicated by a weakening technological base. An analysis on the base of the commercial database (*Orbis*™) confirmed that the Russian economy is not knowledge based. "The knowledge base of the economy is concentrated in the Moscow region (22.8%); St. Petersburg follows with 4.0%. Only 0.4% of the firms are classified as high-tech; and 2.7% as medium-tech manufacturing (NACE, Rev. 2). Except in Moscow itself, high-tech manufacturing does not add synergy to any other unit at any of the various levels of geographical granularity" (Leydesdorff et al., 2015, p.1229).

The question may arise why the PCI values of Japan and the USA demonstrate a behavior which is different from the group of European and Asian Pacific countries? The PCI behavior is connected with connected with the number of patents issued. Figures 7-9 present the change in the number of patents for the observed period in the three different groups of countries (data for Russia start from 1992 because till 1991 this country was part of the Soviet Union). One can mention the prominent increase in the number of patents around 1996 for USA and Japan which perhaps can be attributed to the change in patent system. This change may also be the reason for the break in the curves for PCI. We also mention that Sweden has this trend breach in 1995, though much less accentuated. The growth in the number of Chinese patents, though impressive, still lags behind the numbers of patents of Japan and the USA. E.g. the total number of Chinese patents by 2012 is about 80,000 (Fig.9) whereas the same number for US and Japan is above 200,000 (Fig.7).

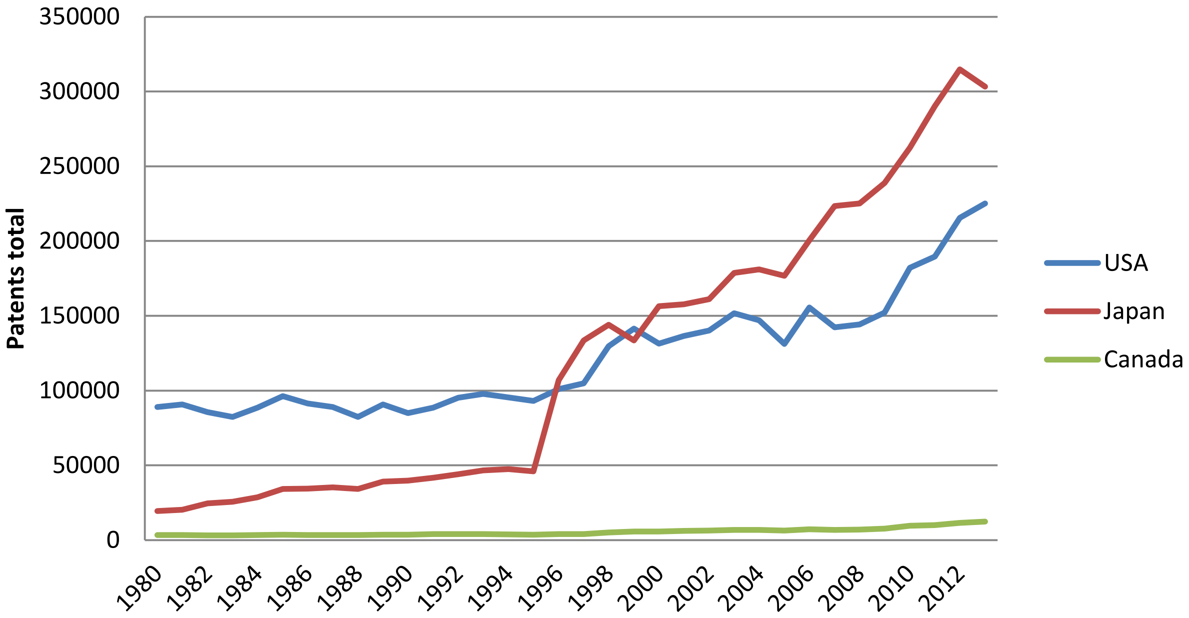


Fig. 7. Total number of patents issued for USA, Japan, and Canada (source: WIPO Statistics database at http://ipstats.wipo.int/ipstatv2/IpsStatsResultvalue)

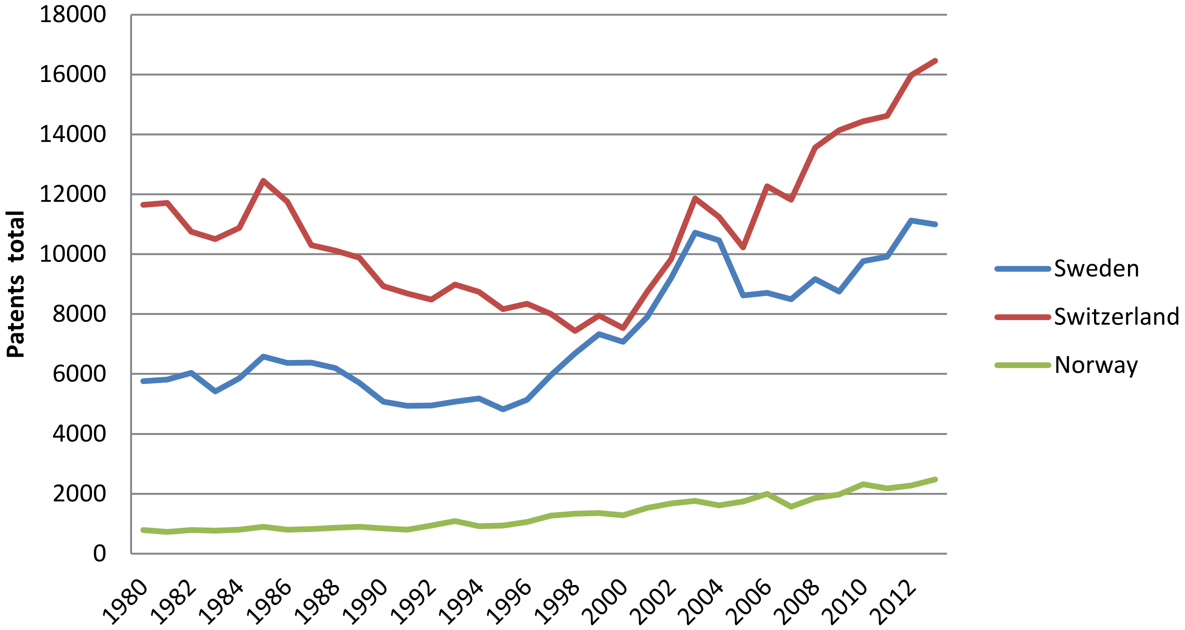


Fig. 8. Total number of patents issued for Sweden, Switzerland and Norway (source: WIPO Statistics database at http://ipstats.wipo.int/ipstatv2/IpsStatsResultvalue)

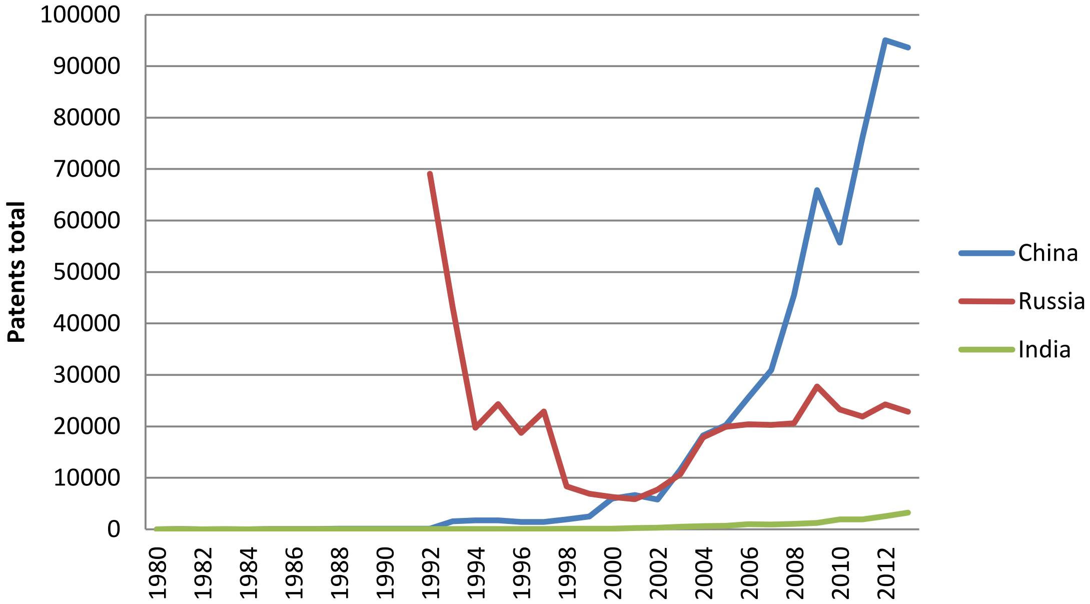


Fig. 9. Total number of patents issued for China, Russia and India (source: WIPO Statistics database at http://ipstats.wipo.int/ipstatv2/IpsStatsResultvalue)

We were not able to find pronounced correlation between ECI and PCI. Corresponding Pearson correlation coefficient *r* and is presented in Table 1.

Tab. 1. Pearson correlation coefficient *r* for ECI and PCI variables

	R
USA	-0.6141**
Japan	0.2861
Canada	-0.2348
Sweden	-0.1063
Norway	0.7825**
Switzerland	0.5377**
China	-0.2043
Russia	0.2090
India	-0.2727

**. $p<0.01$.

ECI and PCI would not be considered statistically significant in the situation with all the countries except USA, Norway, and Switzerland. In other words, these two indicators can be expected to capture different kinds of information.

Method of Reflections in the Triple Helix

HH discussed product complexity with respect to countries and products. In this study, we added patent complexity with respect to countries and patent technology groups. The allusion of the TH metaphor that deals with geographical, technological, and organizational distributions suggests the addition of one more relation. In addition to matrices $M_{c,p}$ and $M_{c,t}$ one can introduce matrix $M_{p,t}$ where index p refers to product and t refers to technology, defined by the corresponding patent technology groups. Certain technology is used in different products. Corresponding matrix element by analogy with Eq.1 is taken to be

$$\begin{cases} 1 \; if \; RCA_{p,t} \geq 1 \\ 0 \; if \; RCA_{p,t} < 1 \end{cases}, \tag{11}$$

where

$$RCA_{p,t} = \frac{x_{p,t} / \sum_p x_{p,t}}{\sum_t x_{p,t} / \sum_{p,t} x_{p,t}} . \tag{12}$$

Each technology is used in different products. Matrix element $x_{p,t}$ corresponds to the quantity of product p export of certain country manufactured with the technology *t*. That is according Eq. 12 matrix element equals 1 if $RCA_{p,t} \geq 1$or zero otherwise. Analogously with Eq. 2 one can define as the product-technology diversity vector $\rho_{p,0}$ and technology-ubiquity vector $\rho_{t,0}$, as follows:

$$\begin{aligned} \rho_{p,0} &= \textstyle\sum_t M_{p,t} \\ \rho_{t,0} &= \textstyle\sum_p M_{p,t} \end{aligned} . \tag{13}$$

So constructed three two-dimensional matrices $M_{c,p}$, $M_{c,t}$, and $M_{p,t}$ can be considered as representations of one three-dimensional array $\mathfrak{M}_{c,p,t}$ where index c refers to country, p refers to product, and *t* refers to technology. The elements of the array are 0 or 1, and defined with help of Eqs.1 and 12. Specifically the array $\mathfrak{M}_{c,p,t}$ contains the information referring to three different spheres: geographical (country), industrial (product), and scientific (technology). The structure built in such a way brings an analogy with the Triple Helix model describing the interaction among the three institutional actors: university, industry, and government where geographic dimension is a proxy of administrative actor (government), technology is a proxy of university, and product manufacturing is a proxy of industry. One can further construct three vectors

$$\eta_{c,0} = \sum_{p,t} \mathfrak{M}_{c,p,t} \ , \tag{14}$$

$$\eta_{p,0} = \sum_{c,t} \mathfrak{M}_{c,p,t} \ , \tag{15}$$

$$\eta_{t,0} = \sum_{c,p} \mathfrak{M}_{c,p,t} \ . \tag{16}$$

The first two vectors defined by Eqs. 14 and 15 are essentially the diversity and ubiquity vectors of Eq. 2. But this time diversity is estimated as a sum of products where each product has a weight coefficient, which is proportional to a number of technologies, associated with the product. In other words weight coefficient accounts for the product technological capacity. Accordingly the equation for product ubiquity $\eta_{p,0}$ counts the number of countries exporting product *p* and a number of technologies comprised in this product, and $\eta_{t,0}$ counts the countries implementing technology *t* and the number of products relying on this technology they export. One can generate higher-order elements in the series by iterative sequences similar to Eq. 3:

$$\eta_{c,n} = \frac{1}{\eta_{c,0}^2} \sum_{p,t} \mathfrak{M}_{c,p,t} \eta_{p,n-1} \, \eta_{t,n-1} \tag{17}$$

$$\eta_{p,n} = \frac{1}{\eta_{p,0}^2} \sum_{c,t} \mathfrak{M}_{c,p,t} \eta_{c,n-1} \, \eta_{t,n-1} \tag{18}$$

$$\eta_{t,n} = \frac{1}{\eta_{t,0}^2} \sum_{c,p} \mathfrak{M}_{c,p,t} \eta_{c,n-1} \, \eta_{p,n-1} \tag{19}$$

The interpretation of the first few terms is that $\eta_{c,1}$ is the average ubiquity of products, and technologies, comprised in these products, exported by country *c*; $\eta_{p,1}$ is the average diversification of countries exporting product *p* with average technology ubiquity; $\eta_{t,1}$ is the average diversification of countries exploiting technology *t* with average product ubiquity.

Consequentially, $\eta_{c,2}$ is the average diversification of countries exporting products and technologies with average ubiquity. Eqs. 17 to 19 provide an intermixture of geographical, technological, and manufacturing distributions. This overlay resembles the structure of the TH model of innovations, containing three institutional actors: university-industry-government, responsible primarily for knowledge (technology) generation, (product) manufacturing, and legislative regulation, respectively. Due to the very similar structures of these constructs, one can expect that the vectors η_c, η_p, η_t can be used to measure the efficiency of TH innovation system because they capture the same information as TH system (in terms of geographical, product and technology distributions). This may not only provide an opportunity for numerical evaluation of the efficiency in relative units, but also link the TH efficiency with existing economic indicators.

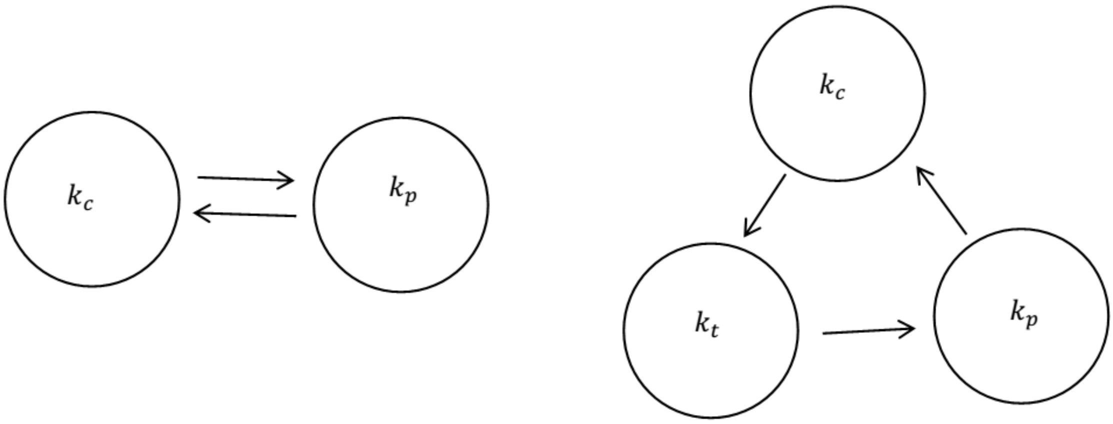
For example, the indicator for economic complexity $\eta_{c,n}$ of Eq. 17 is somewhat similar to two-dimensional indicator $k_{c,n}$ of Eq. 3 which is highly related to countries' income in terms of GDP per capita and can be considered as a predictive tool for a country's long-term growth. The advantage of three dimensional indicator of economic complexity is that it is defined with respect to both product and patent components, unifying thus two dimensional economic and patent complexity indexes. One also obtains an opportunity to measure the efficiency of a TH system of wealth generation in terms of net income. The problem that remains to be solved is that HH define their complexity measure as an eigenvector associated with the *second l*argest eigenvalue. In our extension of the method to the TH case (Eqs. 17-19) the vector $\eta_{c,n}$ can be calculated iteratively. But it would correspond to HH's vector associated with the *first* largest eigenvalue, whereas HH's complexity indicators are associated with vectors corresponding to *second* largest eigenvalue. The difficulty of finding equivalent to the vector corresponding second largest eigenvalue impedes construction of economic, product, and technological complexity measures. The system of non-linear equations 17-19 can be substituted by linear approximation if one re-defines iterative sequences of Eqs. 14-16 as follows:

$$\eta_{c,n} = \frac{1}{\eta_{c,0}} \sum_{p,t} \mathfrak{M}_{c,p,t} \eta_{p,n-1} , \tag{20}$$

$$\eta_{p,n} = \frac{1}{k\eta_{p,0}} \sum_{c,t} \mathfrak{M}_{c,p,t} \, \eta_{t,n-1} , \tag{21}$$

$$\eta_{t,n} = \frac{1}{\eta_{t,0}} \sum_{c,p} \mathfrak{M}_{c,p,t} \eta_{c,n-1} . \tag{22}$$

I.e. instead of reciprocal interdependence between HH coefficients as defined in Eq. 3 one introduces cyclical interdependence between coefficients, as depicted in Fig. 10. Reciprocal interdependence implies that at each iterative step each of two indicators is conditioned by the value of other indicator which is related to the previous iterative step. Cyclical interdependence can be referred to as auto-catalytic process. That is each of complexity coefficients in iterative sequence is modulated by only one another complexity index. So that economic complexity coefficient is conditioned by product complexity coefficient, product complexity coefficient is in turn conditioned by technology complexity coefficient, and technology complexity coefficient is conditioned by economic complexity coefficient.



a) b)

Fig. 10. Reciprocal (a) and cyclical (b) interdependence between complexity coefficients in iterative sequences

In this way each of complexity coefficients can be iteratively defined in an explicit form. For example, one obtains for $\eta_{c,n}$:

$$\eta_{c,n} = \frac{1}{\eta_{c,0}} \sum_{p,t} \mathfrak{M}_{c,p,t} \frac{1}{k_{p,0}} \sum_{c',t'} \mathfrak{M}_{c',p,t'} \frac{1}{k_{t',0}} \sum_{c'',p'} \mathfrak{M}_{c'',p',t'} \eta_{c,n-3} \ , \tag{23}$$

which can conveniently be written as a matrix equation

$$\vec{\eta}_n = \boldsymbol{W} \vec{\eta}_{n-3} \ . \tag{24}$$

Where vector $\vec{\eta}_n$ represents the set of values $\eta_{c,n}$ and matrix $\boldsymbol{W}$ has elements

$$W_{cc''} = \frac{1}{\eta_{c,0}} \sum_{p,t} \mathfrak{M}_{c,p,t} \frac{1}{\eta_{p,0}} \sum_{c',t'} \mathfrak{M}_{c',p,t'} \frac{1}{\eta_{t',0}} \sum_{p'} \mathfrak{M}_{c'',p',t'} \ . \tag{25}$$

Thus the task of finding complexity coefficients can, in analogy with HH's case, be recast as a problem of linear algebra, and it can be as well shown that maximum variability is captured by the eigenvector of $\boldsymbol{W}$ with the largest eigenvalue less than one (Kemp-Benedict, 2014).

Conclusion

An important question which is of significance to researchers and policy makers is the evaluation of the effectiveness of the functioning of a TH system. In a number of studies, this effectiveness has numerically been evaluated using the synergy in interaction among the three TH actors (e.g. Leydesdorff, Dolfsma, and Van der Panne, 2006; Leydesdorff and Zhou, 2014; Leydesdorff, Perevodchikov, and Uvarov, 2015). However this synergy 1) is measured in abstract bits of information, which is an entropy measure and cannot be directly related to basic economic measures (such as turnover, income, etc.); 2) synergy, being an integral measure, cannot be attributed proportionally among three sub-dynamics—technological trajectories, market selections, and control mechanisms that govern TH evolution. In this study we tried to take a step in solving this problem.

We showed that Hidalgo and Hausmann's Method of Reflections (MR) can, with some modifications, be applied to a Triple Helix system of innovations. First, starting from ECI we introduced the measure of technological complexity measured as the patent complexity index (PCI) so that the combination of ECI and PCI can capture more diversified information about the structure and efficiency of the corresponding innovation systems. Economic complexity was not statistically correlated with a country's technological complexity, which means that the two measures capture different kinds of information. Second, we generalized the MR to three relevant dimensions. Introduction of technology component may support the MR more potential when used to predict future country's economic growth, since technology plays an important role in modern economy. Third, the MR when applied to TH model may allow for a direct estimation of the TH efficiency in terms of GDP per capita. We are going to more completely study this aspect in a future study.

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