Technological Forecasting & Social Change 120 (2017) 77–89

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Economic and technological complexity: A model study of indicators of knowledge-based innovation systems

Inga Ivanova[a,*], Øivind Strand[b], Duncan Kushnir[c], Loet Leydesdorff[d]

[a] Institute for Statistical Studies and Economics of Knowledge, National Research University, Higher School of Economics (NRU HSE), 20 Myasnitskaya St., Moscow 101000, Russian Federation
[b] Norges teknisk-naturvitenskapelige universitet (NTNU), Department of International Business, Larsgårdsvegen 2, 6009, ÅLESUND, Norway
[c] Chalmers University of Technology, Göteborg 412 58, Sweden
[d] Amsterdam School of Communication Research (ASCoR), University of Amsterdam, PO Box 15793, 1001 NG, Amsterdam, The Netherlands

ARTICLE INFO

Keywords:
National innovation system
Complexity
Patent
Technology
Triple helix
Indicator

ABSTRACT

The Economic Complexity Index (ECI; Hidalgo and Hausmann, 2009) measures the complexity of national economies in terms of product groups. Analogously to ECI, the Patent Complexity Index (PatCI) can be developed on the basis of a matrix of nations versus patent classes. Using linear algebra, the three dimensions—countries, product groups, and patent classes—can be combined into a measure of "Triple Helix" complexity (THCI) including the trilateral interaction terms between knowledge production, wealth generation, and (national) control. THCI can be expected to capture the extent of systems integration between the global dynamics of markets (ECI) and technologies (PatCI) in each national system of innovation. We measure ECI, PatCI, and THCI during the period 2000–2014 for the 34 OECD member states, the BRICS countries, and a group of emerging and affiliated economies (Argentina, Hong Kong, Indonesia, Malaysia, Romania, and Singapore). The three complexity indicators are correlated between themselves; but the correlations with GDP per capita are virtually absent. Of the world's major economies, Japan scores highest on all three indicators, while China has been increasingly successful in combining economic and technological complexity. We could not reproduce the correlation between ECI and average income that has been central to the argument about the fruitfulness of the economic complexity approach.

1. Introduction

Hidalgo and Hausmann (2009) proposed the Economic Complexity Index (ECI) using the portfolios of countries in terms of product groups which they export to quantify a country's economic complexity. A country's economic growth and income can be expected to depend on the diversity of the products in its portfolio (Cadot et al., 2011, 2013). Given the two axes of the matrix of countries versus product groups, Hausmann et al. (2011, p. 24) also introduced the product complexity index (PCI) which measures the spread of the production of each product group over nations. The complexity of a country's economy, in turn, refers to the set of capabilities, accumulated by that country.

According to Hidalgo and Hausmann (2009; henceforth HH) ECI is correlated with a country's income as measured by GDP per capita (Hidalgo and Hausmann, 2009: Fig. 3 at p. 10573). HH submit that the deviation of ECI from a country's income can be used to predict long-term future growth because a country's income can be expected to approach a competitive level associated with its economic complexity (Ourens, 2013, p. 24).[1] Hence, ECI could be considered as a predictive measure of a country's competitive advantage in the future.

Since based on the product portfolios, ECI values can be expected to reflect the manufacturing capabilities of countries (Hausmann et al., 2011, p. 7). However, HH did not provide an explicit definition of the manufacturing capabilities and their respective knowledge bases. In our opinion, manufacturing complexity is inevitably related to the knowledge intensity and sophistication of exports of products with comparative advantages (e.g., ECR, 2013; Foray, 2004; Foray and Lundvall, 1996; OECD, 1996). One needs an advanced indicator of competitiveness which indicates whether manufacturing industries in a country have a relatively high degree of complexity.

New industries are more likely to be generated in regions where they can be technologically related to existing industries (Boschma et al., 2013; Frenken et al., 2007; Neffke et al., 2011). Although regional diversification is often studied in terms of industrial dynamics,

---

* Corresponding author.
E-mail addresses: inga.iva@mail.ru (I. Ivanova), oivind.strand@ntnu.no (Ø. Strand), kushnir@chalmers.se (D. Kushnir), loet@leydesdorff.net (L. Leydesdorff).

[1] Kemp-Benedict (2014) noted that the correlation between income and ECI can also be considered as a consequence of the well-known relation between export and income growth.

http://dx.doi.org/10.1016/j.techfore.2017.04.007
Received 3 August 2016; Received in revised form 8 December 2016; Accepted 10 April 2017

specification of the technological (knowledge) dynamics would enable us to make a direct link between urban diversification and technology portfolios. Boschma et al. (2014, at p. 225), for example, concluded from a study of 366 US cities during the period 1981–2010 that "technological relatedness at the city level was a crucial driving force behind technological change in US cities over the past 30 years."

Arguing that the knowledge dimension is "intangible," Cristelli et al. (2013) proposed to model capabilities as a hidden layer between products and countries. In a series of studies, Luciano Pietronero and his colleagues (e.g. Cristelli et al., 2015; Tacchella et al., 2013) have further developed this alternative model of economic complexity from a data-driven perspective. The resulting models predict GDP and other economic parameters in much detail. From the perspective of innovation studies, however, there remains a need for an *explicit* measure of the technological capabilities of nations. Can the missing link between product groups and technology (patent) portfolios be endogenized into the model (Nelson and Winter, 1977, 1982) instead of being handled as a residual (Solow, 1957) or latent factor? Proponents of endogenous growth theory, for example, have argued that economic growth is the result of combinations of technologies and manufacturing (Romer, 1986). The longer-term research question is how to compare (national) systems of innovation in terms of their efficiency in coupling the global dynamics of markets and technologies at the level of firms, institutions, and nations (Freeman and Perez, 1988; Lundvall, 1988 and 1992; Nelson, 1993; Reikard, 2005).

In this study, we address this question step by step. In addition and analogously to HH's product diversity, the technological diversity of a country can be measured, for example, in terms of patent portfolios. Patents have been considered as a measure of innovative activity in the innovation studies literature (e.g., Arcs and Audretsch, 1989), although patents are indicators of invention, not innovation. However, it is less problematic to consider patents as indicators of the dynamics of technological knowledge (Alkemade et al., 2015; Verspagen, 2007). Patents can also be strategic (Blind et al., 2006; Hall and Ziedonis, 2001; cf. Jaffe and Trajtenberg, 2002).

Using the patent portfolio as a proxy for the technological complexity of a country, we first develop the Patent Complexity Index (PatCI; cf. Balland et al., 2016). We then use patent-product concordance tables to construct a third matrix of product groups versus technology classes. In a three-partite network of relations among countries, product groups, and patent categories, each third category can be expected to provide feedbacks or feed-forwards on the relation between the other two. The feedbacks and feed-forwards generate loops that can provide new options, synergies, and integration (Petersen et al., 2016). The endogenization of the technological dimension in a three-partite network will enable us to derive a "Triple Helix"-type indicator for the measurement of relative integration in national systems of innovation.

Since the model is developed at the macro-level of nations, the empirical elaboration can be policy relevant at that level. We follow HH's choice for data at this macro-level. Our model is therefore not micro-founded. From a formal perspective, however, one can similarly (alternatively) study the relations among firms, product groups, and patent classes as another empirical domain; but using the same algorithms. More generally, one can argue that positive feedback in the cycling among three dimensions models the potential synergy in the interactions, whereas negative feedback models a form of institutional lock-in. In empirical cases, both processes can be expected to operate simultaneously. Accordingly, the Triple Helix Complexity Indicator (THCI) derived below evaluates the resulting configuration by aggregating two dynamics: the organizational and integrating dynamics of localized retention and the self-organizing dynamics of markets and the techno-sciences as globalizing selection environments (Leydesdorff et al., 2017). One can also consider the cycling as a form of autocatalysis that has the potential to bi-furcate and thus develop long-term cycles (Ulanowicz, 2009; cf. Ivanova and Leydesdorff, 2015).

In summary, this study aims to extend ECI in the technological dimension and then integrate the model across the three dimensions. Our first contribution is to derive the other two indicators (PatCI and THCI) and their relationships to ECI. Secondly, the empirical results raise questions for future research. For example, HH's choice for the Revealed Comparative Advantage index (RCA; Balassa, 1965) may be unfortunate from the perspective of complexity analysis and indicator development. Whereas RCA is firmly embedded in classical (Ricardian) trade theory, one binarizes the matrix and thus throws away valuable information about a country's comparative advantages in products or technologies. A valued measure may much improve the indicator when compared with a binary one.

The paper is structured as follows: Section 2 first provides the derivation of ECI. We then specify the analogous construction of the Patent Complexity Index (PatCI), generalize HH's so-called Method of Reflections (MR) to three (or more) dimensions, and derive the Triple Helix Complexity Index (THCI). Section 3 describes the data collection and Section 4 presents the empirical results. The main findings and conclusions are summarized in Section 5.

2. Methods

2.1. Economic complexity index

HH's ECI is derived from a matrix $M_{c,p}$ where the index c refers to a country and p refers to a product group. The matrix elements are assumed to be one if Balassa's (1965) RCA is larger than or equal to one and otherwise zero:

$$RCA_{c,p} = \frac{x_{c,p} \big/ \sum_p x_{c,p}}{\sum_c x_{c,p} \big/ \sum_{c,p} x_{c,p}} \tag{1}$$

where $x_{c,p}$ is the value of product p manufactured by country c. According to HH (at p. 10571) "a country can be considered to be a significant exporter of product p if its Revealed Comparative Advantage (the share of product p in the export basket of product p in world trade) is greater than 1" (Hidalgo and Hausmann, 2009, p. 10571).

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

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

where N_c is defined as the number of countries and N_p as the number of product groups—HH use $N_c = 178$ and $N_p = 4948$; see section 3 below—more accurate measures of diversity and ubiquity can be obtained by adding the following iterations:

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

HH (at p. 10571) call this "the method of reflections" (MR): each product is weighted proportionally to its ubiquity on the market, and each country is weighted proportionally to the country's diversity. Substituting the first equation of system (3) into the second, one obtains:

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

Because empirically the sequence $k_{c,n}$ converges to a limit Eq. (4) can be formulated as a matrix equation:

$$\vec{k} = W \bullet \vec{k} \tag{5}$$