Absorptive Capacity and Innovative Capability: An Approach to Estimation

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Abstract

The concepts of absorptive capacity and innovative capability have been introduced to describe abilities of a country to imitate and, accordingly, to create more advanced technologies. In this paper we suggest new indicators of these two abilities. To calculate them, we develop an endogenous growth model and an estimation procedure that combines both calibration and econometric approaches.

The choice of parameters is based on WDI, ICRG and Barro–Lee statistical data for the period of 1981-2005. As a result, the model generates trajectories of 63 countries and, for most of them, gives qualitatively correct pictures of their evolution dependently on their initial states as well as on their absorptive capacity and innovative capability indicators. In particular, club convergence is demonstrated. The calculations affirm our hypotheses about shapes of absorptive capacity and innovative capability dependence on the relative productivity level, human capital, institutional quality and some other factors.

Keywords: imitation, innovation, catching-up development, foreign direct investment, human capital, equilibrium, evolution of countries distribution

JEL: O33, O41, O43, O57

1. Introduction

Each developing country tries to catch up with the developed world. Unfortunately, only few economies were able to reach this purpose during last sixty years. Well known Gershenkon's argument – "advantage of backwardness" – does not work properly in most cases (Gershenkon (1962)). Though imitations of technologies and governance methods are much cheaper than innovations, the imitation process is also costly and requires sophisticated approaches of choosing and harmonizing different kinds of economic policies.

Different abilities of countries to imitate and to innovate are reflected in the concepts of absorptive capacity and innovative capability.

The concept of absorptive capacity has been originally introduced as a characteristic of a firm, namely its "ability to recognize the value of new, external information, assimilate it, and apply it to commercial ends" (Cohen, Levinthal, 1990). Later on, this concept was applied to a country as a whole. The imitation process is understood in a broad sense including a choice of technology (or a method of governance), an acquisition of the rights to use it, its adaptation to the conditions of the recipient's country, its modification and, possibly, some improvements.

L. Suarez-Villa was probably the first one who has used (in 1990) a concept of innovative capability (see http://www.innovativecapacity.com). In Furman, Porter, Stern (2002, p.1), it is defined as "the ability of a country – as both a political and economic entity – to produce and commercialize a flow of innovative technology over the long term».

Modeling of imitation and innovation processes constitute the core of modern theories of endogenous economic growth (Barro and Sala-I-Martin, 1995; Aghion, Howitt, 1998; Acemogly, Aghion, Zilibotti, 2002*a*,*b*). It is widely believed that absorptive capacity is a main determinant of successful catching-up development.

However, to the best of our knowledge, up to now there is neither general strict definitions of the absorptive capacity and innovative capability nor convincing methodology to measure them.

There are a number of papers that try to find main determinants of economic growth (see Barro (1991), and again Barro and Sala-I-Martin (1995), Aghion and Howitt (1998) for surveys). However, different factors play different roles at different stages of development. Successful catching-up is possible only if appropriate policies are implemented at each stage and switching from one policy to another one is made in time (Acemoglu, Aghion, Zilibotty (2002 *a*), Polterovich, Popov (2006a,b), Unido (2005)).

Possibilities to arrange good policies depend on our knowledge of absorptive capacity and innovative capability as well as on factors which influence both quantities. However, the task to separate and measure two abilities is not trivial. Instead, a number of researches try to suggest indicators that characterize technological capabilities of countries. In Archibugi , Coco (2005), authors describe and compare five indicators developed by The World Economic Forum (WEF), the UN Development Program (UNDP), the UN Industrial Development Organisation (UNIDO), and the RAND Corporation, and then they suggest their own measure of technological capability, ArCo. All these indicators are based on a set of country characteristics and, unfortunately, on "arbitrary weighting schemes with limited theoretical or empirical bases" (World Bank, 2008).

For example the index of innovation capability is published by the United Nations Conference on Trade and Development (UNCTAD) and consists of an unweighted average of an index of human capital (a weighted average of tertiary and secondary school enrollment rates and the literacy rate) and a technological activity index (an unweighted average of three per capita indicators: R&D personnel, U.S. patents granted, and scientific publications).

Rank correlations between indicators are high enough (not less than 0.85) though for some countries big divergence is observed. For example, Israel ranks 3rd by ArCo, but it ranks 7th by RAND, 21st according to WEF, and 18th according to UNDP (Archibugi , Coco (2005), p. 186).

In UNIDO (2005), weights were chosen through factor analysis that was carried out on 29 indicators, and five principal factors were labeled as knowledge, inward openness, financial system, governance, and the political system. The first factor correlates highly with R&D and innovation, scientific publications, information and communications technology infrastructure, production certifications and education. Inward openness means imports and inward FDI. Financial system composite indicator reflects market capitalization, country risk and access to credit. Then, these factors as well as nine geographical, cultural and natural resource indicators were taken as regressors for growth rate. The sample included data on 135 countries for two three years periods: 1992-1994 and 2000-2002. Only financial system, governance, knowledge and/or their increments were found to be significant.

A similar methodology has been used in World Bank (2008). As much as 34 variables were used over the 1990–2006 period. To calculate overall index of technological absorptive capacity four types of characteristics were taken into account: Macroeconomic environment (general government balance, CPI inflation rate, real exchange rate volatility); Financial structure and intermediation (liquid liabilities, private credit, financial system deposits); Human capital (primary educational attainment, percent of population aged 15 and secondary educational attainment percent of population aged 15; tertiary educational attainment percent of population aged 15); Governance (Voice and accountability, Political stability, Government effectiveness, Regulatory quality; Rule of law).

What are the problems these indicators may help to solve? The answer is not quite clear. Nevertheless Archibugi and Coco write : "Both policy analysts and academic researchers need new and improved measures of technological capabilities on the performance of nations to understand economic and social transformations. With regard to policy analysis, this has relevance for public and business practitioners. Governments constantly require information about the performance of their own country, and this is often better understood in comparison to the performance of their partners and competitors" (Archibugi and Coco , 2005, pp.175-176).

The short survey above demonstrates that, up to now, there are neither general strict definitions of absorptive capacity and innovative capability nor convincing methodology to measure them. This paper tries to fill in this gap.

In this paper we try to build indicators that could not only serve for comparisons of different countries technology levels but also could help to choose most efficient direction to invest.

Having in mind this goal we introduce the following definitions.

The absorptive capacity of an economy is defined as the cost of 1% increase of its TFP through technology transfer from other economies.

Analogously, the innovative capability of an economy is defined as the cost of 1% increase of its TFP through technology innovation.

In both definitions, the cost may be measured as percentage of GDP or capital of a country.

In this paper, the latter measure is used.

In these definitions, technology is understood in a broad sense as a method of production, trade, governance, etc.

In what follows we will also use the terms adaptive and innovative abilities, having in mind that the less is absorptive capacity of a country the larger is its adaptive ability; similarly, the less is innovative capability of a country the larger its innovative ability.

Different kinds of policies and institutions are required to increase adaptive or innovative abilities. If for example adaptive ability of a country is much larger than its innovative ability then it is reasonable to invest into imitation projects. Thus, it is important to measure both abilities.

Basing on many empirical and theoretical researches one might put forward the following six hypotheses about dependencies of absorptive capacity and innovative capability on different factors.

1) Absorptive capacity is negatively connected with relative level of development; the higher is this level the larger is innovative capability.

The level of development is defined as a ratio of the country productivity parameter to the productivity of the most advanced economy. A similar assumption is used in Acemoglu, Aghion and Zilibotti (2002a), where the costs per unit of the productivity increase are taken to be constant for imitation and linear for innovation. In what follows we assume (and then check), that the imitation cost function increases and the innovation cost function decreases when the economy approaches a leader. A similar assumption about the cost of imitation may be found in

Barro and Sala-I-Martin (1995). The reason is that less advanced economies may borrow well-known and cheap technologies that may be obsolete for advanced economies.

The shape of dependence of innovation cost on development levels is more questionable. On one hand, decreasing rate of return might take place. On the other hand, accelerating effects of the technical progress occur. We will show that innovation costs are less for most advanced economies (see also Polterovich, Tonis (2005)).

2) International trade positively influences absorptive capacity.

Import and export both are channels through which new knowledge penetrates into a country. Import is a source of more advanced equipment. Export orientation is an incentive and an opportunity to apply new technologies and to study new marketing approaches.

However, there are evidences that the influence of international trade policy on growth depends on institutional quality and stage of development (Rodríguez, Rodrik (2000), Polterovich, Popov (2006a,b)). In any case, it is not clear to what extent international trade volumes are connected with innovative capabilities.

3) Human capital has positive impact on innovative capability. The influence of human capital on absorptive capacity is much less pronounced since imitation requires less creative workforce.

This is particularly underlined in Acemoglu, Aghion, Zilibotti (2002a), Vandenbussche, Aghion, Meghir (2004), Rogers (2004). The role of human capital for development was studied in many earlier papers (see Lucas (1988), Mankiw, Romer, Weil (1992), Nonneman, Vanhoudt (1996) and more references in Aghion, Howitt (1998)). However some researchers cast doubt on significance of human capital, measured as share of education cost in GDP or as literacy rate, for economic growth (see Levine, Renelt (1992) and polemics in Sala-I-Martin (1997)).

4) Institutional quality positively influences both absorptive capacities and innovative capabilities.

One may expect, however, that absorptive capacity is much more sensitive to this factor than innovative capability: innovations start to play substantial role at higher levels of development when institutional quality is strong enough so that its additional enhancing does not give any substantial effect.

5) Foreign direct investment may be an effective channel of enhancing absorptive capacity. However, they may be harmful as well if institutional quality is low and regulation is not rational enough (Kinoshita Y. (2008)).

6) Banking system is more important for imitation whereas financial markets play decisive role for innovative development.

This is a conclusion from a number of researches (see Chakraborty, Ra (2006), Deidda, Fattouh (2008)).

In what follows we try to check these hypotheses.

To be reliable, the measurement method has to be based on a model which is able to reproduce a general picture of world economic development. We use data sets for 63 countries and the time period 1980-2006, and find that this picture is complicated enough. Advanced economies seem to be converging to each other. Another converging group includes a number of Latin American and some other countries with 15-30% of the USA GDP per capita. These two groups seem to be growing with almost equal rates whereas most of African countries fall behind. It looks like world income is moving toward a distribution with two peaks. This observation, made by Quah (1993), gave birth to a number of research about ”club convergence”.

Some explanations of this phenomenon may be got in framework of underdevelopment or poverty trap theories. There are four different classes of development trap models that consider the trap as a result of a lack of physical capital, human capital, productivity, and low quality of economic and political institutions (see Azariadis and Drazen (1990) and Feyrer (2003) for a survey and references).

Easterly, Levine (2001), and Feyrer (2003) found, however, that factor accumulation can not explain two peaks distribution: “the output per capita is tending toward twin peaks despite the tendency toward convergence in the accumulable factors. The productivity residual, on the other hand, shows movement similar to the distribution of per capita output...” (Feyrer (2003), p.31). Thus, interactions between innovation and imitation processes and institutional development should play dominant roles in modeling of the club convergence behavior.

The interactions were studied in a number of papers (see Segerstrom (1991), Barro and Sala-I-Martin (1995), Aghion , Howitt(1998), Henkin, Polterovich (1999) for surveys, and also Acemoglu, Aghion, and Zilibotti (2002), Howitt and Mayer-Foulkes (2002), Polterovich, Tonis (2003, 2005)).

In this paper we consider two modifications of the model developed in Polterovich, Tonis (2003, 2005) . This model has a number of attractive features that make it a good instrument of measuring adaptive capacities and innovative capabilities.

a). It is not assumed, as it is done in many other papers, that a country always imitates the most advanced technology. Every developing country experiences a lot of failures connected with attempts of borrowing the most recent achievements of the developed world. A rational policy admits borrowing not only best achievements but experience of many other countries as well (compare Aghion, Howitt (1998, Chapter 12)).

b). The model takes into account a difference between global and local innovations. The first ones may be borrowed by other countries whereas the second ones are country specific.

c). The model takes into account that the larger is an innovation or an imitation project, the less probable is its success (in accordance with Howitt and Mayer-Foulkes, 2002). Therefore, both policies exhibit decreasing rate of return, and the tradeoff between innovation and imitation may result in producing both of them.

d). In accordance to our model, costs of imitation and innovation in a country may depend not only on its relative level of development but also on a number of exogenous parameters. This gives a possibility to study dependence of adaptive capacity and innovative capabilities on broad variety of parameters.

e). In most investigations, steady states are studied only. However, to generate a picture that reproduces a real set of countries trajectories, one has to consider transition paths. To do that, we were forced to simplify our model drastically. The model is quasi-static and generates trajectories as sequences of static equilibria. The model makes use of many other simplifications as well.

It was shown that, under stationary exogenous conditions, three types of stable steady states are possible, where only imitation, only innovation or a mixed policy prevails.

It turned out that the model indeed generates a picture qualitatively similar to the real one. Roughly speaking, three groups of countries behave differently. There is a tendency to converge within each group. Countries with low institutional quality have stable underdevelopment traps near the imitation area. Increase in the quality moves the steady state toward a better position and turns into a new stable steady state where local innovations and imitations are jointly used. Under further institutional improvements, a combined imitation-innovation underdevelopment trap disappears. All countries with high quality of institutions are moving toward the area where pure innovation policy prevails (see Polterovich and Tonis (2005) where a model with no human capital is considered).

Below, we use this model to demonstrate how adaptive capacity and innovative capability can be calculated. Our method combines calibration and econometric approach. In the calculation process we find how adaptive ability and innovative capability depend on a broad set of indicators such as level of development, investment risk, international trade, human capital, availability of physical capital, and some others. Two key values and a few other parameters are chosen to reproduce trajectories of more than 60 countries from 1980 to 2006. This methodology permits to check, at least partially, hypothesis a)-e).

Our calculations are based on assumptions about the relationship between royalty receipts and royalty payments of a country, on the one hand, and innovation and imitation costs on the other hand.

We also suggest a modification of the model where a dynamic equation for human capital is introduced. It is shown that our main conclusions are stable with respect to variations of the model.

The plan of the paper is as follows. A static model is described in the next section. In Section 3 we study comparative statics of the model. Section 4 contains the descriptions of a dynamic model. Data description, the methodology of calibrations and main results are presented in Sections 5-7. Two approaches to calibration are presented. The first one (sections 5-7) is based on growth-based separation hypothesis: ratio of rates of growth induced by innovations and imitations is proportional to royalty receipts over royalty payments. In Section 8, an alternative, cost-based separation hypothesis is used: the ratio of royalty receipts to royalty payments is proportional to the ratio of innovation to imitation costs. The results of absorptive capacity and innovative capability calculations are presented and discussed in Section 9. Section 10 concludes.

2. A static model

This model is a modification of a model from Acemoglu, Aghion, Zilibotti (2002a).

There are three kinds of goods in our economy: final good, capital and the continuum set of high-technology intermediate goods indexed by $\nu \in [0, 1]$.

Every period, final good is competitively produced from the intermediate goods. Each intermediate good ν is characterized by its productivity A_ν. The production function for the final good is given by

$$Y = \int_0^1 F(NA_\nu, X_\nu)d\nu, \tag{1}$$

where N is the number of workers (so, NA_ν is the "effective labor"), X_ν is the quantity of intermediate good ν involved in the production process, and F is homogeneous of degree 1:

$$F(NA_\nu, X_\nu) = NA_\nu f(x_\nu) \tag{2}$$

where $x_\nu = \dfrac{X_\nu}{NA_\nu}$, x_ν is the "normalized" quantity of intermediate good. Here we assume that f satisfies Inada conditions and $xf''(x) + f'(x)$ falls from ∞ to 0, as x proceeds from 0 to ∞. Throughout this paper, a special case of Cobb — Douglas production function will be considered:

$$F(NA_\nu, X_\nu) = (NA_\nu)^{1-\alpha} \cdot X_\nu{}^{\alpha},\ 0<\alpha<1.$$

Then $f(x_\nu) = x_\nu{}^{\alpha}$.

We suppose that final good can be sold at price 1. The price of intermediate good ν is p_ν . A producer of final good chooses its demand for each of intermediate goods, X_ν, taking all prices as given, so as to maximize its profit:

$$Y - \int_0^1 p_\nu X_\nu d\nu \to \max_{X_\nu} \tag{3}$$

From the optimality conditions, one gets the following inverse demand function:

$$f'(x_\nu) = p_\nu. \tag{4}$$

Intermediate goods can be produced from capital. The production function in the intermediate goods sector is assumed to be linear: one unit of capital can be converted to one unit of intermediate good[1].

In each sector ν ∈ [0, 1], only one firm enjoys the full access to the technology of producing the corresponding intermediate good, so the market for each intermediate good is monopolistic. Let the rental price of capital be *r*. Then firm's profit V_ν is given by

$$V_\nu = (p_\nu - r)X_\nu = NA_\nu\left(f'(x_\nu) - r\right)x_\nu. \tag{5}$$

The firm is facing the demand of the final good sector for its product and monopolistically chooses p_ν so as to maximize its profit V_ν.

In each sector ν, the monopolist firm lives for one period of time. At the beginning of the period, each sector starts with the same (country-specific) physical capital *K*, human capital H and productivity level A. This level represents the cumulative technological knowledge achieved by the economy up to that date. Prior to producing its intermediate good, a firm may spend a part of its future profit and a part of its physical capital to perform technological innovations and imitations, thus raising its productivity from A to A_ν. Afterwards, it produces input with higher productivity A_ν.

It is easy to check that in the case of Cobb – Douglas production function, maximization of (5) entails

$$r(x) = f'(x) + f''(x)x = \alpha^2 x^{\alpha-1}, \tag{6}$$

and

$$V_\nu = e(x)NA_\nu, \tag{7}$$

[1] We can use one-to one production function because the unit of intermediate good ν along with the technological parameter A_ν can be properly adjusted.

where

$$e(x) = -x^2 f''(x) = \alpha(1-\alpha)x^{\alpha}.$$

As follows from the above formulas, under Cobb – Douglas production function GDP is given by

$$Y = N\tilde{A}x^{\alpha} = (N\tilde{A})^{1-\alpha}K^{\alpha} \tag{8}$$

where $\tilde{A} = \int_0^1 A_\nu d\nu$ is the average productivity level over all producers of intermediate product and K is the total amount of capital used in the intermediate product sector. Note that due to (8), $\tilde{A}$ is closely related to the total factor productivity (TFP) of the economy: the growth rate of TFP is $(1 - \alpha)$ times the growth rate of $\tilde{A}$. The same can be said about the initial productivity level A.

Now let us describe the evolution of the productivity variable (and, hence, TFP). The considerations above concern the domestic economy. There are also foreign countries, in which initial productivity levels may differ from domestic one. Denote by $\bar{A}$ an initial productivity level of the most developed economy. Along with the domestic absolute productivity level A, let us consider the relative level $a = \frac{A}{\bar{A}}$ which measures the distance to the world technology frontier. It represents the position of the domestic technologies among other ones.

As we mentioned above, each firm performs imitation and/or innovation prior to production. Let b_1 and b_2 denote, respectively, the sizes of imitation and innovation projects. Each project may result in one of two outcomes, success or failure. If the imitation (innovation) was successful, firm's productivity rises at growth rate b_1 (b_2); otherwise, it remains the same. If both projects were successful, the productivity turns out to be $(1+b_1)(1+b_2)$ times higher. Thus, after both actions, the technology parameter A_ν is given by

$$A_\nu = (1+\xi_1)(1+\xi_2)A, \tag{9}$$

where ξ_1 (ξ_2) is a random variable equal to b_1 (b_2) in the case of successful imitation (innovation) of firm ν, and 0 otherwise. This multiplicative function brings about a complementarity effect of imitation and innovation: a progress in imitation results in greater marginal productivity of innovation, and vice versa.

We postulate that probabilities of imitation and innovation success are given by the functions $\psi_i(b_i),\ i = 1,2$:

$$\psi_i(b_i) = \frac{\mu_i}{\mu_i + b_i},\ i = 1,2,$$

where b_1 (b_2) is a size imitation (innovation) project and μ_1 (μ_2) is a positive parameter. Naturally, larger project is more risky. The expected value of the productivity growth rate as a "proper" result of a project b_i is equal to $\psi_i(b_i)b_i$; μ_i may be interpreted as the expectation of the result of an infinitely large project .

Firms cannot imitate technologies which have not been developed anywhere in the world, so the size of the imitation project is subject to constraint

$$1 + b_1 \leq \frac{1}{a}, \tag{10}$$

where $a = \frac{A}{\bar{A}}$. This constraint takes into account that a firm can imitate not only the most advanced technology but also an "intermediate" one.

Now let us introduce the costs of imitation and innovation. Technological development includes not only invention or adoption of new methods of production, but also implementation of these methods to the existent machinery. To adopt the costs of spreading technological knowledge over the economy, we assume that the costs of imitation and innovation depend not only on the size of the corresponding project b_i, but also on the amount of capital to be upgraded. Specifically, in order to undertake project b_i, the firm has to invest Kq_ib_i units of capital, where K is the average capital stock over the economy (equal to the capital stock of a representative firm).

It is assumed that q_1 and q_2, the per-unit costs of imitation and innovation, depend on the relative average productivity level of our economy (that is "a distance to the world technology frontier") at the beginning of the period, and on the accumulated stock of human capital H: $q_i = q_i(a, H)$, q_i are continuous and differentiable. We assume also (and this is supported by empirical evidences) that q_1 is increasing and q_2 is decreasing in a. According to this assumption, it gets more difficult to imitate and easier to innovate as the domestic technology gets closer to the world technology frontier. Indeed, for less developed countries, it may be reasonable to imitate not very advanced technology which are cheaper to buy (some of them are not protected by intellectual property laws at all) and simpler to implement using experience accumulated by other countries. The innovation process is likely to exhibit some economy of scale due to a positive externality exerted by the stock of accumulated knowledge, so more advance countries incur less costs.

Evidently, human capital accumulation decreases the innovation costs. This is not so obvious for imitation costs since low level imitation does not require high level human capital. In what follows, we assume for simplicity that imitation cost, q_1 does not depend on human capital. This assumption will be checked below.

Generally, q_1 and q_2 may depend on some other country-specific parameters as well. In the empirical section, we consider q_i as functions of savings rates and indicators of institutional quality.

Both forms of technological development are modeled in a similar way here. However, the opportunities for imitation and innovation change in different directions as a increases. In particular, when a is close to 1, there is almost nothing to imitate. This is taken into account by constraint (10).

Under the above assumptions, the expected profit of the firm ν (net of technology investment expenditures) is given by

$$E(\Pi_\nu) = E(V_\nu) - rZ = E(V_\nu) - rK\left(q_1(a)b_1 + q_2(a, H_\nu)b_2\right), \tag{11}$$

where V_ν is given by (5), the expectation is taken over the four possible realizations of success/failure of innovation/imitation. H_ν is the amount of human capital used by firm ν, and Z is the total expected amount of physical capital invested in innovation and imitation:

$$Z = K\left(q_1(a)b_1 + q_2(a, H_\nu)b_2\right). \tag{12}$$

In the beginning of each period, the firm chooses b_1 and b_2 to maximize its expected net profit (11). We assume that H_ν does not depend on ν: $H_\nu = H$ for all ν.

In what follows we assume that firms' demand for human capital is satisfied, and do not take into account the costs of physical capital involved in human capital increase.

Denote

$$w(b_1, b_2) = w_1(b_1)w_2(b_2), \quad w_i(b_i) = (1 + \psi_i(b_i)b_i), \quad i = 1, 2, \tag{13}$$

and let $k = \dfrac{K}{NA}$ – per capita capital stock over the initial productivity.

Then, taken into account (7), (9), (10), (11) and (13), the firm maximization problem may be written as follows.

$$E(\Pi_\nu) = NA\left(e(x)w(b_1, b_2) - r(x)k(q_1(a)b_1 + q_2(a, H)b_2)\right) \to \max, \tag{14}$$

$$0 \le b_1 \le \bar{b}_1, \; b_2 \ge 0, \tag{15}$$

where $\bar{b}_1 = \dfrac{1}{a} - 1$.

In view of (6) and (8), one has

$$\frac{e(x)}{r(x)}=-\frac{x^2f''(x)}{f'(x)+xf''(x)}=\frac{\alpha(1-\alpha)x^{\alpha}}{\alpha^2x^{\alpha-1}}=\left(\frac{1}{\alpha}-1\right)x=\eta x,\quad \eta>0, \tag{16}$$

where $\eta=1/\alpha-1$. Therefore, (14) is equivalent to the following problem:

$\eta xw(b_1,b_2)-k[q_1(a)b_1+q_2(a,H)b_2]\to\max$. (17)

In accordance to (17), and (9), a firm, having capital K and human capital H in a state a, spends $Z=K(q_1(a)b_1+q_2(a,H)b_2)$, chooses b_1, b_2, and demands $X_v=NA_vx$ capital units. In equilibrium, one has to get

$$K=X+Z\ \text{, or}\ k=xw(b_1,b_2)+k[q_1(a)b_1+q_2(a,H)b_2], \tag{18}$$

where $X=\int_0^1 X_v dv$, $k=\dfrac{K}{NA}$.

An equilibrium is defined as a triple x,b_1,b_2 such that the pair (b_1,b_2) is a solution of (17), (15) under given x, and equality (18) holds.

We assume that the equilibrium exists and is unique.

In the framework of the model described above, absorptive capacity and innovative capability may be calculated as $c_1=q_1b_1$, $c_2=q_2b_2$ where projects b_1, b_2 each gives 1% increase of TFP of a capital unit. This means $b_1\psi_1(b_1)=0.01(1-\alpha)^{-1}$, $b_2\psi_2(b_2)=0.01(1-\alpha)^{-1}$. Therefore,

$$c_i=0.01(1-\alpha)^{-1}\mu_iq_i/(\mu_i-0.01(1-\alpha)^{-1}), i=1,2. \tag{19}$$

Formula (19) will be used to measure the absorptive capacity and innovative capability of countries.

3. Analysis of the static model

Let us denote

$$\varphi_i(b_i)=\frac{dw_i(b_i)}{db_i}=\psi_i(b_i)+\psi_i'(b_i)b_i=\frac{\mu_i^2}{(\mu_i+b_i)^2},\quad i=1,2, \tag{20}$$

and write down the first order conditions for the problem (17), (15).

$$\eta x\cdot w_2(b_2)\varphi_1(b_1)\le kq_1(a), \tag{21}$$

$$\eta x\cdot w_1(b_1)\varphi_2(b_2)\le kq_2(a,H), \tag{22}$$

If an inequality holds in (21)-(22) then a related variable $b_i=0$ or $H_v=H$.

In view of (21), (22), equilibrium values of the function

$$z(b_1,b_2)=\frac{Z_v}{NAx_v}=\frac{k}{x_v}\Big(q_1\big(a\big)b_1+q_2\big(a,\ H\big)b_2\Big)=\eta\Big(w_2(b_2)\varphi_1(b_1)b_1+w_1(b_1)\varphi_2(b_2)b_2)\Big) \tag{23}$$

do not depend on x_v, H_v. Therefore, the balance condition (18) takes the form

$$R_i(b_i)=\frac{\varphi_i(b_i)b_i}{w_i(b_i)}=\frac{b_i}{S_i(b_i)},\quad k=x_v\left(w(b_1,b_2)+z(b_1,b_2)\right), \tag{24}$$

where $S_i(b_i)=w_i(b_i)/\varphi_i(b_i)$.

The following system of equations follows from (21) – (22), (24) and determines an interior equilibrium.

$$\frac{1}{q_1(a)}=\frac{w_1(b_1)}{\eta\varphi_1(b_1)}+b_1+\frac{w_1(b_1)}{\varphi_1(b_1)}\frac{\varphi_2(b_2)b_2}{w_2(b_2)}, \tag{25}$$

$$\frac{1}{q_2(a,H)}=\frac{w_2(b_2)}{\eta\varphi_2(b_2)}+b_2+\frac{w_2(b_2)}{\varphi_2(b_2)}\frac{\varphi_1(b_1)b_1}{w_1(b_1)}, \tag{26}$$

Let us define:

$$\mathrm{Q}_1(a\ )=\frac{1}{q_1(a)},\ \ Q_2(a,H)=\frac{1}{q_2(a,H)},$$

(27)

$$S_i(b_i)=\frac{w_i(b_i)}{\varphi_i(b_i)}=\frac{(\mu_i+b_i+b_i\mu_i)(\mu_i+b_i)}{\mu_i^2},\quad i=1,2,\quad R_i(b_i)=\frac{\varphi_i(b_i)b_i}{w_i(b_i)}=b_i/S_i(b_i). \tag{28}$$

Then one gets from (25), (26)

$$\mathrm{Q}_1(a)=S_1(b_1)[1/\eta+R_2(b_2)]+b_1, \tag{29}$$

$$\mathrm{Q}_2(a,H_v)=S_2(b_2)[1/\eta+R_1(b_1)]+b_2. \tag{30}$$

Assume that b_i are not too large so that R_i are increasing functions. Then right-hand sides of (29), (30) both are increasing in each b_i; Q_1 is decreasing in a; Q_2 is increasing in both variables. Differentiating (29), (30), it is easy to check that $b_1(a,H)$, is decreasing in a, $b_2(a,H)$ is increasing in a, and both functions are increasing in H.

Thus, we have proved the following statement:

Consider the interior solution case, and let b_1, b_2 be not too large for some a. Then there exists a segment of a where $b_1(a)$ is decreasing and $b_2(a)$ is increasing in a.

This comparative statics result is analogous to Proposition 1 in Pikulina (2009), where firms rationally choose the amount of human capital.

4. Dynamic model

We consider a quasi-dynamic model that generates trajectories by iterations of the static model described above. Thus it is assumed that firms have one period horizon, and that all of them get the average (expected) technology $\tilde{A}$ that were found at a previous period but partially depreciated[2]. Therefore,

$$A_{+1} = (1-\rho)\tilde{A}, \qquad A_{+1} = (1-\rho)\tilde{A} \tag{31}$$

where $\tilde{A} = \int_0^1 A_v dv = (1+\psi_1(b_1)b_1)(1+\psi_2(b_2)b_2)A$ and ρ is the knowledge depreciation rate ($0 \leqslant \rho \leqslant 1$).

Assume that output Y of the final good producers is taxed to finance education sector. Let $\tau(a)$ be the education tax rate depending on a. It is simple to check (see formulas (3)-(5), (11)) that this tax does not influence the choice of projects b_1 , b_2 so that equations (25), (26) hold.

We assume that the evolution of human capital H is subject to the following equation:

$$N_{+1}H_{+1} = (1-\delta_H)NH + m(a)\tau(a)Y, \tag{32}$$

where δ_H is the human capital depreciation rate ($0 \leq \delta_H \leq 1$), $m(a)$ is a multiplier measuring the impact of education on human capital.

Here A_{+1} , H_{+1} play the same role for the next-period firms as A, H for the current-period firms. In each period, all firms start from the same initial productivity and human capital due to assumed total spillovers of technology and human capital among sectors. The assumptions about one period horizon as well as about independence of industry's future productivity level on its current innovation/imitation efforts seem to be very restrictive. In particular, the model does not describe the behavior of long-run investors. To eliminate these shortcomings, one could use an OLG model. In this case, however, it would be difficult to investigate transition dynamics rather than steady states.

To finish with the description of the model, we need to specify, how labor and capital evolve over time. We assume that the number of workers N grows at a constant rate g_N:

$$N_{+1} = (1+g_N)N,$$

where N and N_{+1} denote the number of workers, respectively, in the current and the next period.

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[2]Note that despite all A_v are stochastic, their average $\tilde{A}$ is non-random because the set of sectors is continual.

Let K and K_{+1} be the capital stocks at the current period and the next one, respectively. We assume that the next-period capital stock is determined by the following equation

$$K_{+1} = (1-\delta_K)K + \sigma(1-\tau(a))Y \tag{33}$$

where $\delta_K \in [0,1]$ is the capital depreciation rate, Y is the total output of the final good, and $\sigma \in [0,1]$ is a (constant) saving rate. Parameter σ is assumed to be country-specific. It may depend on the quality of institutions and investment climate in the country. We also assume that $\rho < \delta_K$, i. e. physical capital depreciates faster than technology.

A dynamic equilibrium in the model is defined as a sequence of variables $\{K_t, A_t, x_t, H_t, b_{1t}, b_{2t}\}_t$ such that, in each period t, four quantities x_t, H_t, b_{1t}, b_{2t} form a static equilibrium under K_{t-1}, A_{t-1}, H_{t-1}, and evolution equations (31)-(33) hold.

To summarize, the economy evolves as follows. At the beginning of the period, all firms in a country start from the same productivity level A. Firms choose the sizes of their imitation and innovation projects which maximize their profits. Then random events are realized; success or failure of these projects and, correspondingly, random values A_v turn out to be known. Production takes place and profits are revealed. The next-period productivity level, human and physical capital stocks are determined. All next-period firms start their projects from the new productivity level. They make their innovations and imitations determining their successors' productivity level, and so on.

Assume that the productivity of the most developed country $\bar{A}$ increases with a constant growth rate $\bar{g}$. Then

$$a_{+1} = \frac{A_{+1}}{\bar{A}_{+1}} = \frac{(1-\rho)\, w(b_1,b_2)A}{(1+\bar{g})\bar{A}} \text{ or } a_{+1} = \frac{w(b_1,b_2)}{\bar{\gamma}}a, \tag{34}$$

where $\bar{\gamma} = \dfrac{1+\bar{g}}{1-\rho}$.

Equation (33) takes the following form:

$$k_{+1} = \frac{K_{+1}}{N_{+1}A_{+1}} = \frac{(1-\delta_K)K + \sigma(1-\tau(a))Y}{(1+g_N)(1-\rho)\, w(b_1,b_2)A}, \text{ or } k_{+1} = \frac{\sigma(1-\tau(a))f(x) + (1-\delta_K)k}{(1+g_N)(1-\rho)\, w(b_1,b_2)}. \tag{35}$$

In addition to the model described above, another, simplified version of the model will be considered. The only difference of the simplified model from the original one is that the evolution of H is given exogenously rather than determined by (32); in this case, $\tau(a)$ is supposed to be zero. This model is equivalent to the model presented in Polterovich and Tonis (2005). The two versions of the model will be referred to as the model with, respectively, endogenous and exogenous human capital.

A stationary equilibrium for the model with exogenous human capital is defined as a dynamic one at which variables k and a are not changing over time (and exogenous human capital H is also stationary). As follows from (34) and (35), equations for a stationary equilibrium take the form

$$w(b_1, b_2) = \bar{\gamma}, \tag{34'}$$

$$k = \frac{\sigma(1-\tau(a))f(x)}{(1+g_N)(1-\rho)w(b_1,b_2)-(1-\delta_K)}. \tag{35'}$$

$$x = \frac{k}{w(b_1,b_2)+z(b_1,b_2)} \tag{24'}$$

$$\frac{1}{q_1(a)} = \frac{w_1(b_1)}{\eta\varphi_1(b_1)} + b_1 + \frac{w_1(b_1)}{\varphi_1(b_1)}\frac{\varphi_2(b_2)b_2}{w_2(b_2)}, \tag{25'}$$

$$\frac{1}{q_2(a,H)} = \frac{w_2(b_2)}{\eta\varphi_2(b_2)} + b_2 + \frac{w_2(b_2)}{\varphi_2(b_2)}\frac{\varphi_1(b_1)b_1}{w_1(b_1)}, \tag{26'}$$

An important question is whether a given stationary equilibrium is stable or not. If it is stable, then convergence takes place within the corresponding group of countries. Otherwise, the equilibrium marks the boundary between the attraction areas of different centers of convergence. Stability conditions for stationary equilibria under exogenous human capital are established in Polterovich and Tonis (2005).

Proposition (Polterovich and Tonis, 2005). Consider a stationary equilibrium, at which $b_1 < \bar{b}_1$. Then

1. If there is no innovation in equilibrium, then the equilibrium is asymptotically stable.
2. If there is no imitation in equilibrium, then the equilibrium is unstable.
3. If both imitation and innovation are present in the equilibrium, then its stability is depends on the relation between the absolute values of ${\partial q_1}/{\partial a}$ and ${\partial q_2}/{\partial a}$: if $\frac{-\partial q_2/\partial a}{\partial q_1/\partial a}$ is high, then the stationary equilibrium is unstable; otherwise, it is stable.

A stable stationary equilibrium may be considered as prediction of long-run development of the economy. In some cases, there could be multiple stable stationary equilibria. Country-specific exogenous parameters affecting the normalized cost functions (institutional quality, international trade and so on) thereby influence possible stable stationary equilibria – not only their position but even their structure: steady states may emerge or vanish. Even if the equilibrium structure does not change, the long-run outcome may change substantially. For example, if a country is within the area of attraction of a stationary equilibrium with low *a*, but close to the upper boundary of this area, a short-run positive shock of exogenous parameters may get it out of the trap.

Note that under endogenous human capital, there is no natural concept of stationary equilibrium, because equation (32) suggests that $h = \frac{H}{A}$ is to be stationary over time, so that

$$h = \frac{m(a)\tau(a)w(b_1, b_2)f(x)}{(1+g_N)(1+g_A)-(1-\delta_H)}, \tag{32'}$$

whereas according to (26'), b_2 depends on H rather than on h. There could be a stationary equilibrium, if b_2 were depending on h. Note also that when we calibrate the model, a proper interpretation of human capital is needed: what H (or h) is? If human capital is measured in schooling years, as in Barro – Lee dataset used here, then it cannot grow exponentially as H does in a stationary equilibrium. Not only the duration but also the quality of education should be taken into account, if we want to calibrate stationary regimes.

5. Calibration of the model: data and methodology

Sections 5–9 give an empirical adjustment of the model considered above. We are going to test some of basic assumptions of the model (in particular, those concerning the per-unit cost functions of innovation and imitation) and to adjust the parameters of the model to the statistical data. Our approach to empirical investigation combines two methods: estimation of a linear regression model (calculating TFP and estimating the normalized cost functions for imitation and innovation) and non-linear optimization procedure used for calibration of "basic" parameters of the model.

One of the most important questions concerning calibration of the model is how to calculate proxies for q_1 and q_2, the normalized costs of imitation and innovation. Saying this by a different way, we have to separate TFP growth effects of imitation and innovation. As follows from the previous section (see (25) and (26)), q_1 and q_2 can be calculated, if we know which part of the growth rate can be explained by imitation and which one by innovation. Obtaining this information from regular cross-country data is a non-trivial problem. We suggest using the ratio of royalty receipts over royalty payments to deal with it (with bought licenses being a proxy for the result of imitation and sold ones for innovation). We suggest also two alternative ways to separate imitation-based and innovation-based growth. One way called "growth-based separation" divides the growth rate proportionally to the royalty-receipts-payments ratio.

Another way entails such separation that the ratio of imitation costs to innovation costs is proportional to the royalty-receipts-payments ratio.

The estimation process consists of a preliminary stage and an iteration cycle. At the preliminary stage, TFP is calculated using basic national account data (GDP, population, capital, investment) and initial values of basic parameters are set. Then a cyclical routine starts. Given the basic parameters and the data on royalty receipts and royalty payments q_1 and q_2 are calculated. Then the normalized cost functions are estimated using regressions with q_1 and q_2 as dependent variables and a number of explanatory variables. After the set of regression coefficients is derived, the dynamic model of Section 4 (or similar) is run with the estimated cost functions. The predictive quality of the dynamic model is used as a criterion based on which the basic parameters are corrected and a new loop starts until the error of prediction becomes close to minimum. A more detailed description of the algorithm will be given later on.

We use data from the following sources: World Development Indicators (WDI, 2008), International Country Risk Guide (ICRG, 2004), physical capital stock dataset (Nehru and Dhareshwar, 1993), Barro-Lee dataset on human capital. The data structure is as follows:

Y – GDP, years $1980,\dots,2006$, 180 countries; source: WDI;

N – population, years $1980,\dots,2006$, 188 countries; source: WDI;

I – gross fixed capital formation, years $1980,\dots,2006$, 173 countries; source: WDI;

K – capital stock, years $1980,\dots,1990$, 89 countries; source: Nehru and Dhareshwar;

R – ICRG composite risk index, measure of the institutional quality, years $1984,\dots,2003$, 129 countries; source: ICRG; $R\in[0,100]$; R is higher for lower risks;

L_B – royalty payments, total value of licenses bought, years $1980,\dots,2006$, 123 countries; source: WDI;

L_S – royalty receipts, total value of licenses sold, years $1980,\dots,2006$, 88 countries; source: WDI;

T – manufactures trade (export+import) , years $1980,\dots,2006$, 164 countries; source: WDI;

B – domestic credit provided by banking sector, years $1980,\dots,2006$, 180 countries; source: WDI;

F – foreign direct investment, years $1980,\dots,2006$, 172 countries; source: WDI;

P – the number of scientific publications per 1000 people, years $1981,\dots,2005$, 182 countries; source: WDI;

H – total years of schooling (age 15+), measure of human capital stock, years 1980,…,2000, 111 countries; source: Barro-Lee dataset.
ED – public spendings on education, years 1990-2006, 105 countries; source: WDI;

Using WDI data on GDP, all these variables (except for N, R, P and H) are put to the same unit of measure, namely, constant 2005 international $ (adjusted to PPP).

In order to smooth fluctuations, we have averaged the data by 9 three-year periods (1980-1982,…,2004-2006). The time subscript refers to the median year of the corresponding three-year period: for example, Y_{1981} for period 1980-1982 and so on.

Using the above data, we are going to calibrate our dynamic model, i. e. estimate its parameters so as to obtain good quality of prediction. We consider two versions of our model: a simplified one where human capital is considered as an exogenous parameter and a full version with endogenous human capital, as in Section 4.

We assume also that the per-unit cost functions of innovation and imitation q_1 and q_2 depend not only on a but also on country-specific variables N, H, R, I, T, B, F and P. We are going to estimate these functions parametrically: we assume that they are quasi-polynomial functions determined by an array of coefficients β which is to be estimated. The specific form of the cost functions and their coefficients β will be defined later on.

So, the calibration of the model involves estimating the following parameters:

α – the parameter of the Cobb-Douglas production function;
μ_1 – maximal growth rate due to imitation;
μ_2 – maximal growth rate due to innovation;
ρ – technology obsolescence rate;
λ – adjustment ratio used for estimating the share of innovation and imitation in TFP growth (see below);
β – a set of regression coefficients of two cost functions q_1 and q_2 (with dependent variables listed above: relative level of development, population, human capital etc). Coefficients β are found using the OLS method.

Parameters μ_1, μ_2, ρ and λ are called “basic” and are estimated using a non-linear optimization procedure. The other parameters are estimated using regressions.

To obtain plausible results, we need to suggest estimators for the above parameters so as to reproduce the actual growth dynamics in various countries. To measure the level of country's development, we use its relative per capita GDP y which can be defined as the ratio of country's per capita GDP to that of the USA:

$$y = \frac{Y / N}{Y_{USA} / N_{USA}}$$

We start from y_{1981}, the relative per capita GDP in 1981 (corresponding to the earliest period 1980-1982 in our data series) and, using the dynamic model, try to predict y_{2005}, the relative per capita GDP in 2005 (corresponding to the latest period 2004-2006). There are many possible ways to measure the quality of prediction. Here we use the minimal sum of squares criterion: the sum of squares of logarithmic errors

$$E = \sum \left(\ln(\hat{y}_{2005}) - \ln(y_{2005}) \right)^2$$

should be minimized, where y_{2005} and $\hat{y}_{2005}$ are, respectively, the actual and the predicted relative per capita GDP values.

The problem of minimizing E as a function of the parameters is difficult because of its large dimension. To simplify the problem, we decompose it into three stages. At the first, preliminary stage, we estimate α, the parameter of the Cobb-Douglas production function, from the standard growth regression and calculate the productivity variable. The second and the third stage are repeated cyclically. At the second stage, we fix the basic parameters μ_1, μ_2, ρ, λ and calculate q_1, q_2 using L_B, L_S and the basic parameters. Then we estimate β as the set of coefficients in two regressions with dependent variables q_1 and q_2 and explanatory variables a, N, H, R, I, T, B, F, P (so β is a function of the basic parameters). At the third stage, all these data are put into the dynamic model and it is iterated starting from y_{1981} and predicting y_{2005}. Here the basic parameters are given; coefficients β are determined at the second stage; variables N, R, I, T, B, F, P (and H in the case of exogenous human capital) are taken from the statistical data; a (and H in the case of endogenous human capital) is calculated for the previous 3-year period (for 1981 – taken from the data). Then the second and the third stages are repeated for slightly perturbed values of the basic parameters in order to calculate the gradient of prediction quality E which determines the direction of adjusting the basic parameters. Then basic parameters are changed in the direction opposite to the gradient and the procedure returns to the second stage. Thereby, the basic parameters μ_1, μ_2, ρ and λ are calibrated through minimization of E.

Such decomposition of the calibration problem not only simplifies the process of calibration but also allows estimation of statistical significance of factors contributing to the absorptive capacity and innovative capability. A seeming disadvantage of this method is that its result is not an exact solution to the calibration problem because at the first stage, not E but other function is minimized (actually, the sum of squares of errors in regression for each of q_i is minimized). In fact, we restrict our opportunities for adjustment getting in return for an opportunity to interpret key results at intermediate stages, and, in the case of success, to get higher confidence that the success is not occasional.

Now we are going to describe the procedure in more detail. Let us start with a description of the first stage. We need to decompose the per capita GDP growth rate into three components: growth due to capital accumulation, innovation and imitation. Firstly, we need to extract the growth rate of the total factor productivity from the annual per capita GDP growth rate. In period $t = 1984, 1987, \ldots, 2005$, the latter is given by

$$g_t = \left(\frac{Y_t / N_t}{Y_{t-3} / N_{t-3}} \right)^{1/3} - 1.$$

Due to our assumption about the Cobb-Douglas form of the production function, GDP can be represented as follows (see (8)):

$$Y = \left(N\tilde{A} \right)^{1-\alpha} X^{\alpha},$$

where X is the amount of capital used in production and $\tilde{A}$ is the average productivity level proportional to the TFP. Denote by g_X the growth rate of $\frac{X}{N}$, the per capita value of the intermediate good, and by g_K, the growth rate of $\frac{K}{N}$ the capita stock per capita. According to the model, X is equal to the total capital stock K less the imitation and innovation expenditures which constitute a small share of K. So, g_K could be a good proxy for g_X. Hence, as follows from the standard growth accounting considerations, α can be estimated from the following growth regression:

$$\ln(1+g) = \alpha \ln(1+g_K) + \text{const} \tag{36}$$

We have found systematic cross-country data on capital stock only for the period until 1990. For more recent years, we have to apply the perpetual inventory estimation[3] method using the recursive formula of capital stock evolution:

$$K_{t+1} = (1-\delta_K)K_t + I_t,$$

where δ_K, the rate of physical capital depreciation, is estimated from the capital stock data before 1990. The estimated levels of δ for different countries vary from 2% to 7%, with average 4.13% per year[4].

It can be seen from the data that the expenditures on imitation and innovation (R&D and royalties) constitute a small part of GDP, typically, less than 2%, so we can put $X = K$ for simplicity. Thus, to extract the productivity, we use the following formula:

$$\tilde{A} = \left(\frac{Y}{K^{\alpha}}\right)^{\frac{1}{1-\alpha}},$$

where α can be found from regression (36). In our computations, the estimate for α is close to 0.50.

Based on $\tilde{A}$, we construct some other country-specific variables useful for our analysis:

$\tilde{a} = \dfrac{\tilde{A}}{\tilde{A}_{USA}}$ – relative productivity level (compared to that of the USA), a measure for the distance to the frontier;

$\hat{a} = \ln(\tilde{a})$;

$\tilde{w}_t = \dfrac{1}{(1-\rho)} \dfrac{\tilde{A}_{t+3}}{\tilde{A}_t}$ – a proxy for productivity growth factor w in the model (actually, $\tilde{w} = w$, when the productivity growth in the current period is equal to that in the next one).

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[3] This method is used in a number of papers on growth accounting (e. g., see Bosworth and Collins, 2003 or Senhadji, 2000).

[4] Values of δ typically used in growth accounting calculations are within 4-5%.

Now let us turn to the second stage, the estimation of q_1 and q_2, using the WDI data on royalties[5]. Firstly, we need to separate the imitation and innovation components of the productivity growth factor $\tilde{w}$ based on the values of bought and sold licenses. As it has been already said, we use two alternative ways of separation: growth-based and cost-based. Under growth-based separation, the following heuristic formula is used:

$$\tilde{w}_2 - 1 = \frac{\lambda L_S}{L_B}(\tilde{w}_1 - 1). \tag{38}$$

This is an important hypothesis: ratio of TFP rates of growth induced by innovations and imitations is proportional to royalty receipts over royalty payments. We have no microfoundations behind this hypothesis. Implicitly, it describes a mechanism by which domestic knowledge, embodied into royalty receipts, and foreign knowledge, embodied into royalty payments, both influence domestic rate of growth.

In Section 8, an alternative method of determining contributions of imitation and innovation will be presented. We call it cost-based separation. Under cost-based separation, the ratio of royalty receipts to royalty payments is proportional to the ratio of innovation to imitation costs rather than growth rates.

Since $\tilde{w}_i = 1 + \tilde{b}_i \psi(\tilde{b}_i)$, one gets

$$\tilde{b}_i = \frac{\mu_i(\tilde{w}_i - 1)}{1 + \mu_i - \tilde{w}_i},$$

where $\tilde{b}_i$ are proxies for b_i.

If a country is so close to the world technology frontier that the size of the imitation project $\tilde{b}_1$ exceeds the feasible level (that for which the imitated technology does exist), then $\tilde{b}_1$ and $\tilde{b}_2$ are recalculated so as to satisfy this requirement (see (13)).

Now from the first-order conditions for the firm's optimal choice of b_1 and b_2, we obtain $\tilde{q}_1$ and $\tilde{q}_2$ which are proxies for q_1 and q_2:

$$\tilde{q}_1 = \frac{\eta \tilde{w}_2}{\left(1 + \frac{\tilde{b}_1}{\mu_1}\right)^2}; \quad \tilde{q}_2 = \frac{\eta \tilde{w}_1}{\left(1 + \frac{\tilde{b}_2}{\mu_2}\right)^2}. \tag{39}$$

[5] We also have WDI data on R&D spending but they cover only a short recent period 1996-2005, so we do not use them.

Our next task is to estimate q_1 and q_2 as functions of the phase variable $\tilde{a}$ (relative level of technology) and exogenous variables[6] H (human capital), R (institutional quality), I (investment), T (total manufactures trade), B (total bank credits), F (foreign direct investment) and P (scientific publications), taking parameters μ_1, μ_2, ρ and λ as given.

In order to make the distribution of our variables proper for the regression model and avoid multi-collinearity, we construct new variables $\tilde{N}$, $\tilde{H}$, $\tilde{R}$, $\tilde{T}$, $\tilde{I}$, $\tilde{B}$, $\tilde{F}$ and $\tilde{P}$:

$\tilde{N} = \ln(N)$;

$\tilde{H}$ – residual in OLS regression $H = \varepsilon_1 \tilde{a} + \text{const}$;

$\tilde{R}$ – residual in OLS regression $R = \varepsilon_2 \tilde{a} + \text{const}$;

$\tilde{T} = \ln(T / Y)$;

$\tilde{I} = I / Y$ (according to the (33), $\tilde{I} = \left(1 - \tau(a)\right)\sigma$);

$\tilde{B} = \ln(B / K)$;

$\tilde{F} = F / Y$.

Thus, for H and R, modified variables are used instead of the initial ones; $\tilde{H}$ can be treated as the deviation of the human capital from the "standard" level (average for the given level of $\tilde{a}$) and analogously for $\tilde{R}$[7]. The regressions used for construction of these variables are as follows.

Table 1. Regressions for $\tilde{H}$ and $\tilde{R}$[8]

Dependent var	H	R
$\tilde{a}$	7.940*** (35.4)	40.08*** (33.6)
Intercept	3.749*** (40.7)	53.52*** (92.6)
Number of obs R-squared	684 0.648	716 0.566

After having considered various specifications, we have chosen the following representation for the cost functions:

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[6] Although, these variables are endogenous to some extent: in particular, there is evidence that institutional quality may depend on the level of economic development.

[7] This approach may also partially solve the problem of endogeneity provided that the relative level of development mostly affects the trend rather than the deviation of H and R. The method of estimation is OLS with robust

[8] Here, as usual, t-statistics are given in parentheses below the coefficients. Asterisks *, ** and *** mean 10%, 5% and 1% significance levels, respectively.

$$q_i = \beta_{ai}\breve{a} + \beta'_{ai}\tilde{a} + \beta_{Ni}\breve{N} + \beta_{Hi}\breve{H} + \beta_{Ri}\breve{R} + \beta_{Ii}\breve{I} + \beta_{Ti}\breve{T} + \beta_{Bi}\breve{B} + \beta_{Fi}\breve{F} + \beta_{Pi}P + \beta_i \qquad (40)$$

(with publications P standing only in the regression for the innovation cost q_2).

For a given setting of the parameters, the collection of coefficients $\beta = \left\{\beta_{ai}, \beta'_{ai}, \beta_{Ni}, \beta_{Hi}, \beta_{Ri}, \beta_{Ii}, \beta_{Ti}, \beta_{Bi}, \beta_{Fi}, \beta_{Pi}, \beta_i\right\}_{i=1,2}$ determining the cost functions is estimated, using OLS with White robust standard errors. Thus, we have estimators for the remaining parameters of the model.

Now let us describe the last, third stage of the calibration procedure. Given parameters α, μ_1, μ_2, ρ and λ together with the estimated linear cost functions $q_i\left(\breve{a}, \breve{N}, \breve{H}, \breve{R}, \breve{I}, \breve{T}, \breve{B}, \breve{F}, P\right)$, we calculate the evolution of the model economic world and compare it to that of the real world. We have a sample of 63 countries, for which all necessary data are present. The relative productivity level a is approximated by the fraction $\tilde{a} = \dfrac{\tilde{A}}{\tilde{A}_{USA}}$ (with $\breve{a} = \ln(\tilde{a})$ being used in regressions); similarly, k is approximated by $\tilde{k} = \dfrac{K}{N\tilde{A}}$. Thus, under exogenous human capital, each country starts from the known pair $\left(\tilde{a}_{1981}, \tilde{k}_{1981}\right)$. Under endogenous human capital, another phase variable H is added and its initial value is set according to the data. Then, based on the known values of $\tilde{a}, \breve{N}, \breve{H}, \breve{R}, \breve{I}, \breve{T}, \breve{B}, \breve{F}, P$, we calculate the per-unit costs $\hat{q}_i = q_i\left(\breve{a}, \breve{H}, \breve{N}, \breve{R}, \breve{I}, \breve{T}, \breve{B}, \breve{F}, P\right)$ using the least squares method for equation (40). These $\hat{q}_i$ are substituted instead of q_i into the first-order conditions (25), (26) for the firm's optimal innovation-imitation policy (b_1, b_2), so the predicted values $\hat{b}_i$ are derived. In turn, $\hat{b}_i$ determine the predicted values of the imitation and innovation growth rates $\hat{w}_i - 1$. Note that these predicted values are different from the corresponding proxies calculated earlier.

Now we just apply the evolution equations for a and k to obtain a_{t+3} and k_{t+3} as functions of a and k (the evolution equations for). In particular, $\hat{a}_{t+3}$, the predicted value of a_{t+3}, is determined as follows:

$$\hat{a}_{t+3} = a_{+1}\left(\hat{a}_t, \breve{N}_t, \breve{H}_t, \breve{R}_t, \breve{I}_t, \breve{T}_t, \breve{B}_t, \breve{F}_t, P_t\right) = \frac{\hat{w}_1 \hat{w}_2}{\hat{w}_{1[USA]}\hat{w}_{2[USA]}}\hat{a}_t,$$

where $\hat{a}_{1981} = \tilde{a}_{1981}$. In order to check, whether the model is consistent with the reality, we try to predict the relative productivity level of countries in 2005, given that in 1981:

$$\hat{a}_{2005} = a_{+1}\left(\ldots\ a_{+1}\left(\tilde{a}_{1981}, \vec{N}_{1981}, \vec{H}_{1981}, \vec{R}_{1981}, \vec{I}_{1981}, \vec{T}_{1981}, \vec{B}_{1981}, \vec{F}_{1981}, P_{1981}\right)\ldots\right) \quad \text{(8 times)}$$

We do not need to build a prediction for k_{2005} because we just have derived a proxy $\tilde{k}_{2005}$ for this variable in a similar way using the perpetual inventory estimation method. Now the predicted relative per capita GDP $\hat{y}_{2005}$ can be calculated as follows[9]:

$$\hat{y}_{2005} = \frac{\hat{Y}_{2005} / N_{2005}}{\hat{Y}_{2005[USA]} / N_{2005[USA]}} = \hat{a}_{2005}\left(\frac{\tilde{k}_{2005}}{\tilde{k}_{2005[USA]}}\right)^{\alpha}.$$

We compare the predicted relative per capita GDP to the actual one which is given by

$$y_{2005} = \frac{Y_{2005} / N_{2005}}{Y_{2005[USA]} / N_{2005[USA]}}$$

We choose the basic parameters μ_1, μ_2, ρ, λ (only those four, because α has been already estimated) so as to achieve the best prediction, i. e. to minimize the sum of squares of logarithmic errors

$$E(\mu_1, \mu_2, \rho, \lambda) = \sum\left(\ln(\hat{y}_{2005}) - \ln(y_{2005})\right)^2,$$

where y_{2005} and $\hat{y}_{2005}$ are, respectively, the actual and the predicted relative GDP values. The objective function is unimodal, so it is easy to find its minimum using the gradient descent method.

The calibration algorithm looks as follows. We start with some initial combination of parameters: $\mu_1 = \mu_1^0$, $\mu_2 = \mu_2^0$, $\rho = \rho^0$, $\lambda = \lambda^0$. For these values of the parameters, we run the regressions for q_1 and q_2, make 8 iterations of the transition function $a_{+1}(\hat{a}, \vec{H}, \vec{R}, \sigma, \vec{T}, \vec{B}, \vec{F}, P)$ and calculate $E(\mu_1^0, \mu_2^0, \rho^0, \lambda^0)$. Then we numerically estimate the gradient of E at the initial

[9] The formula for y_{2005} relies on the assumption that the innovation and imitation expenditures are negligible when comparing to the capital stock.

combination of parameters and put $\mu_1^1 = \mu_1^0 + \frac{\partial E}{\partial \alpha} d\mu_1, \ldots, \lambda^1 = \lambda^0 + \frac{\partial E}{\partial \lambda} d\lambda$, where increments $d\mu_1, \ldots, d\lambda$ are parameters of the procedure chosen heuristically so as to speed up the process of convergence. Then the same operation is made with $\mu_1 = \mu_1^1, \ldots, \lambda = \lambda^1$, new values of the parameters $\mu_1^2, \ldots, \lambda^2$ are calculated and so on. The process is finished at step j, when the difference between $E\left(\mu_1^j, \mu_2^j, \rho^j, \lambda^j\right)$ and $E\left(\mu_1^{j-1}, \mu_2^{j-1}, \rho^{j-1}, \lambda^{j-1}\right)$ becomes lower than the accuracy threshold which is put to be 10^{-5}.

6. Calibration of the model: growth-based separation, exogenous human capital

As a result of this three-level procedure, we obtain the following best-predictive values of the parameters:

$\alpha = 0.5003$;
$\mu_1 = 0.4477$ per three-year period (or 0.1312 per year);
$\mu_2 = 0.2672$ per three-year period (or 0.0821 per year);
$\rho = 0.0493$ per three-year period (or 0.0167 per year);
$\lambda = 3.543$.
Standard error of calibration (average difference $|\ln(y) - \ln(\hat{y})|$): 0.0912.

The estimated parameters of the normalized cost functions q_1 and q_2 are shown in Table 2. Table 2 confirms, at least partially, our main hypotheses about the absorptive capacity and innovative capability (note that the per-unit cost functions q_1 and q_2, respectively, are inversely related to these capacities). In particular, other things being equal, more developed countries have higher innovation capacity and lower absorptive capacity (this is correct for all countries from our sample, even though the functions are quadratic). For poor countries, both indicators are less sensitive to changes of the distance to the frontier than for rich ones.

The innovative capability is positively related to the size of the country (population). This seems natural: larger countries can enjoy economies of scale in the research sector. Note that the influence of population on the absorptive capacity is insignificant, so both large and small countries can successfully imitate.

Human capital enhances the innovative capability and does not affect significantly the absorptive capacity. This does not contradict our hypothesis that imitation is less sensitive to educational level. However, it may happen that another indicator – literacy rate – could be more appropriate for this case. Unfortunately, we have data on literacy rates only for short period of time.

Table 2. Regressions for: q_1 and q_2 (growth-based separation, exogenous human capital)

Dependent var	q_1	q_2
$\dot{a}$	0.3317*** (5.13)	–0.1497** (–2.03)
$\dot{a}^2$	0.05762*** (2.87)	–0.00143 (–0.06)
$\dot{N}$	0.01349 (1.05)	–0.04610*** (–3.38)
$\dot{H}$	–0.01346 (–1.31)	–0.03533*** (–3.13)
$\dot{R}$	–0.00624** (–2.38)	–0.00307 (–1.10)
$\dot{I}$	0.3492 (0.99)	2.169*** (5.79)
$\dot{T}$	–0.06670** (–2.20)	–0.03550 (–1.10)
$\dot{B}$	0.03903 (1.12)	–0.01883 (–0.49)
F	–0.00823 (–0.57)	–0.00493 (–0.32)
P	N/A	–0.06738*** (–3.19)
Intercept	0.5655*** (2.71)	0.8652*** (3.81)
Number of obs R-squared	264 0.286	264 0.390

Institutional quality positively influences the absorptive capacity and is insignificant for the innovative capability. This is not contradictory to our hypothesis.

In accordance with our hypothesis, the absorptive capacity is positively affected by the international trade.

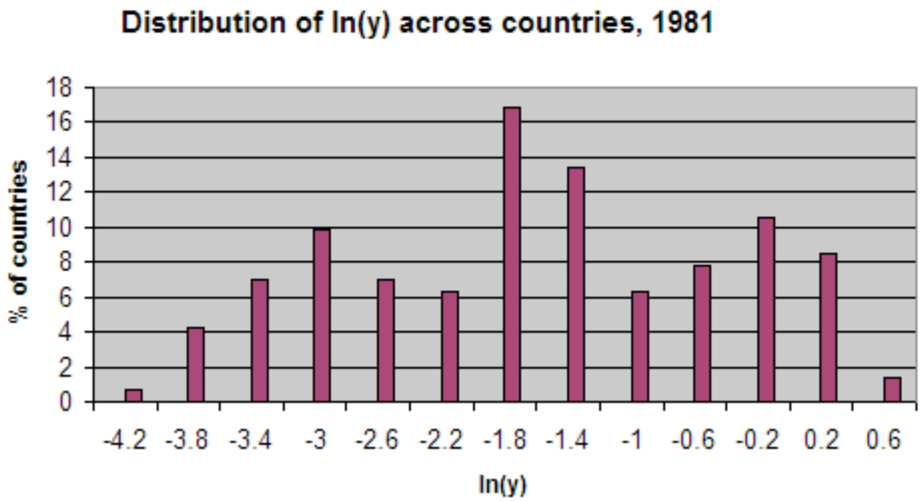
The share of investment in GDP does not affect significantly the absorptive capacity and negatively affects the innovative capability. The latter effect may occur due to decreasing rate of return: the larger innovative efforts already done the more difficult get further positive effect.

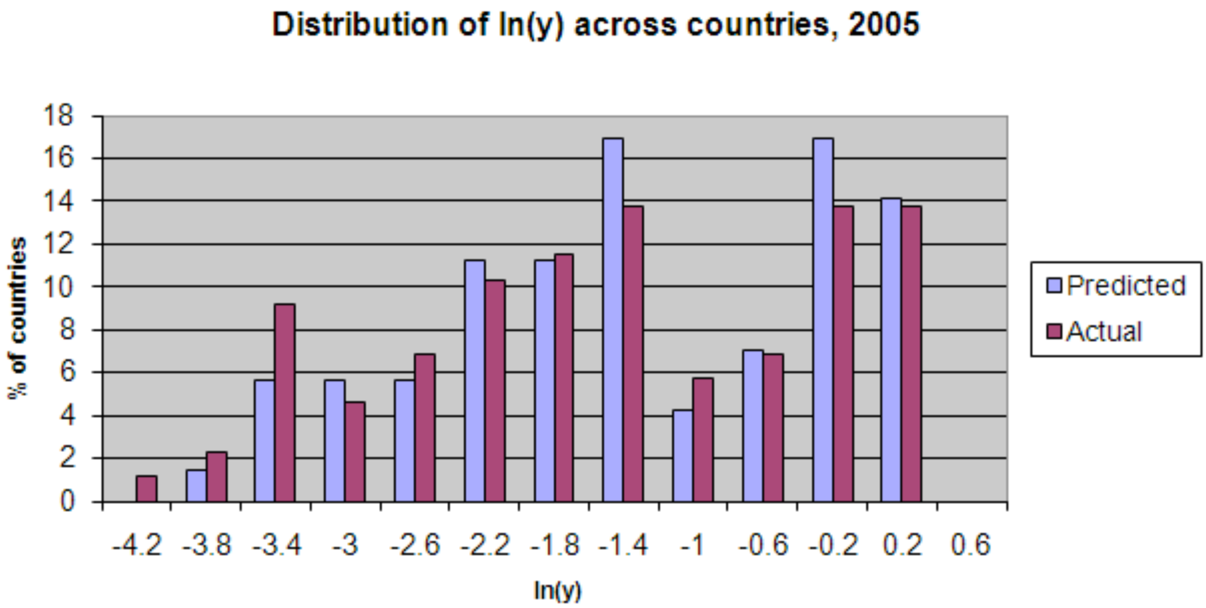
The impacts of banking system and foreign direct investment are not significant. The insignificance of FDI does not contradict to the observation (mentioned in Introduction) that FDI influence on rate of growth is mixed.

In accordance with the natural intuition, the number of scientific publications is positively related to the innovative capability.

Figure 1 demonstrates the quality of the calibration. The model predicts main feature of the real evolution of countries distribution by GDP per capita. However the distribution tail, containing four countries in 2006, is not predicted. The precision of the model may be characterized by the following indicator: the standard error of calibration (average difference $|\ln(y) - \ln(\hat{y}))$ is equal to 0.0912. This means that having set the correct values of relative per capita GDP in 1981, after iterating the step of the dynamic model, we can predict the relative per capita GDP in 2005 with an error of about 9% on average.

Figure 1. Evolution of countries distribution





7. Calibration of the model with endogenous human capital

So far we have been doing the calibration based on a simplified version of the model with the human capital being an exogenous variable. Now we are going to calibrate the model taking into account that human capital is endogenous and its evolution depends on the relative level of technology development as supposed in Section 4.

As before, we decompose the process of calibration but now there will be one additional stage including the calibration of the human capital depreciation rate δ_H, multiplier $m(a)$ and the education tax rate $\tau(a)$ determining the evolution of human capital.

First of all, we introduce $\tilde{\tau}$, a proxy for $\tau(a)$:

$\tilde{\tau} = ED / Y$.

Then we calculate $\tilde{m}$, a proxy for $m(a)$, in accordance with the equation (32) describing the evolution of human capital:

$$\tilde{m} = \frac{N_{t+3}H_{t+3} - (1-\delta_H)N_t H_t}{ED_t},$$

where δ_H is the human capital depreciation rate which is to be calibrated. Suppose that δ_H is fixed at some level. Then one can estimate function $m(a)$ and $\tau(a)$ using the following regression equations:

$$\ln(\tilde{m}) = \beta_a \ln(\tilde{a}) + \beta_a' \ln(\tilde{a})^2 + \text{const}, \tag{41}$$

$$\ln(\tilde{\tau}) = \beta_\tau \ln(\tilde{a}) + \beta_\tau' \ln(\tilde{a})^2 + \text{const}. \tag{42}$$

Then, as $m(a)$ and $\tau(a)$ can be estimated for any given δ_H, we choose such value of δ_H for which the best prediction of H in the last period is obtained. We start from (over all $\delta_H \geq 0$).

We obtain $\delta_H = 0.0175$ per three-year period (or 0.00586 per year), with the following estimations for (41) and (42).

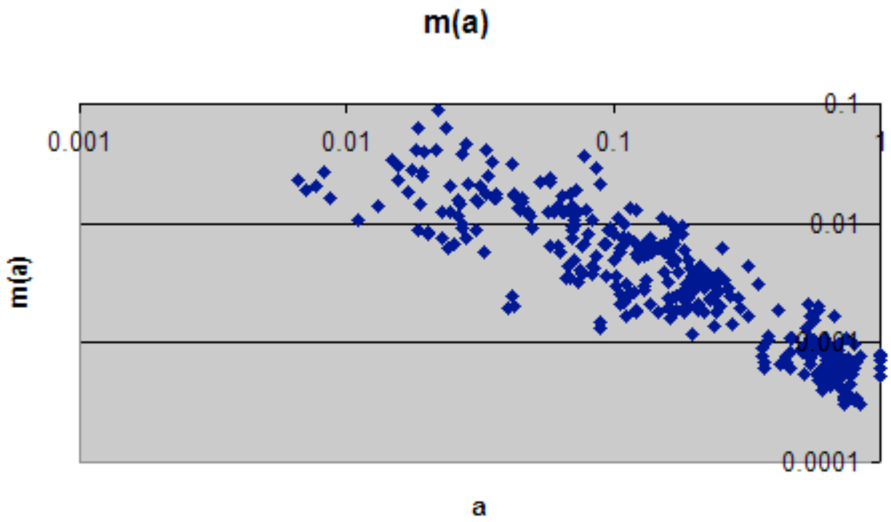
Regressions for $\tilde{m}$ and $\tilde{\tau}$ are given in Table 3.

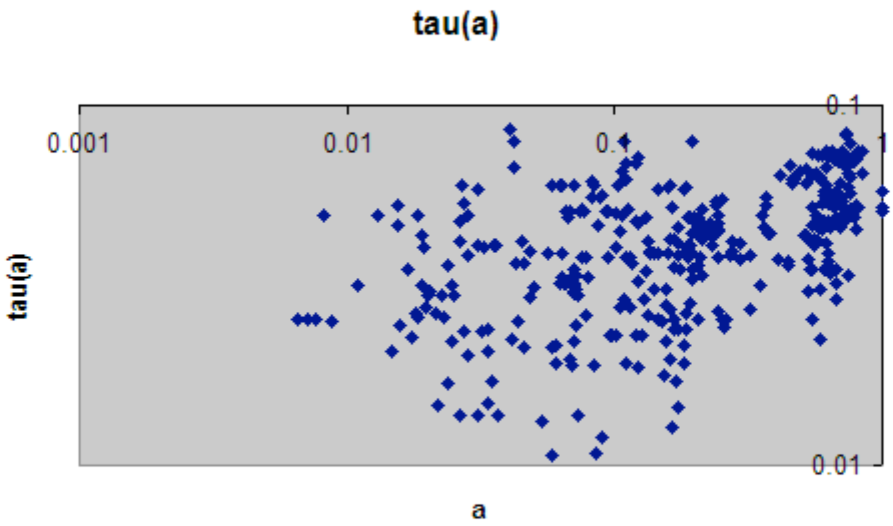
Table 3. Regressions for $\tilde{m}$ and $\tilde{t}$

Dependent var	$\tilde{m}$	$\tilde{t}$
$\tilde{a}$	–1.550*** (–19.5)	0.3382*** (6.81)
$\tilde{a}^2$	–0.1389*** (–7.59)	0.0432*** (3.73)
Intercept	–7.901*** (-128.8)	–2.831*** (–79.1)
Number of obs R-squared	368 0.812	368 0.236

As can be seen from Table 3, $\tilde{m}$ is decreasing in $\tilde{a}$ and $\tilde{t}$ is increasing in $\tilde{a}$ (with both dependencies being relatively more sensitive for developed countries) This character of dependencies is illustrated by the following pictures:

Figure 2.

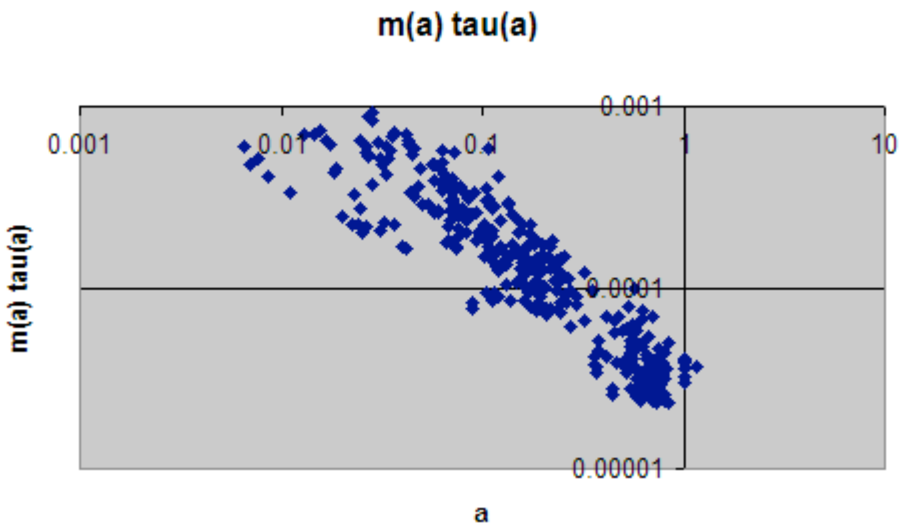




The ratio of the "gross" human capital investment to GDP is equal to $m(a)\tau(a)$. This function is a product of a decreasing and an increasing function and summing up the two above logarithmic regressions shows that $m(a)\tau(a)$ is decreasing in a. This dependency is shown in Figure 3.

The above results show that public spending on education are higher in developed countries but the efficiency of each per cent of GDP invested in education is higher in developing countries. In other words, public spending on education allows to increase the human capital stock in developing countries and only to maintain it in developed countries. This can be thought of as one more aspect of the "advantage of backwardness".

Figure 3.



Now, as all the parameters that determine the evolution of human capital are estimated, we can calculate the predicted amount of human capital $\hat{H}(a)$ as a function of the distance to frontier. Then we just follow through the second and the third stages of the calibration procedure, with the only difference that now $\hat{H}(\hat{a})$ is used instead of H (in each period, the human capital is calculated as a function of the current relative technology level). The results of the calibration are as follows:

$\alpha = 0.5003$ (the same as before, since the results of the first stage do not change);
$\mu_1 = 0.4444$ per three-year period (or 0.1304 per year);
$\mu_2 = 0.2452$ per three-year period (or 0.0758 per year);
$\rho = 0.0606$ per three-year period (or 0.0206 per year);
$\lambda = 3.124$.
Standard error of calibration (average difference $|\ln(y) - \ln(\hat{y})|$): 0.0862
Comparing these results to the results of calibrating the simplified model shows that the way of computing human capital does not matter too much: all the qualitative implications are the same. Thus, our way of modeling the process of human capital accumulation is likely to be relevant. Note that the accuracy of the calibration has become slightly better comparing to the simplified model (standard error 0.0857 versus 0.0881). So, the human capital data implied from the data on the education spending is slightly better predictor than the data based on the schooling years only.

Table 4. Regressions for: q_1 and q_2 (growth-based separation, endogenous human capital)

Dependent var	q_1	q_2
$\breve{a}$	0.3413^{***} (5.24)	-0.1831^{**} (–2.45)
$\breve{a}^2$	0.05912^{***} (2.92)	–0.00567 (–0.25)
$\breve{N}$	0.01611 (1.25)	-0.05149^{***} (–3.71)
$\breve{H}$	–0.01220 (–1.18)	-0.03619^{***} (–3.16)
$\breve{R}$	-0.00657^{**} (–2.48)	–0.00274 (–0.97)
$\breve{I}$	0.3053 (0.86)	2.289^{***} (6.01)
$\breve{T}$	-0.06454^{**} (–2.11)	–0.03527 (–1.08)

B	0.03902 (1.11)	–0.02296 (–0.59)
F	–0.00843 (–0.58)	–0.00363 (–0.23)
P	N/A	–0.07106*** (–3.31)
Intercept	0.5026** (2.40)	0.8730*** (3.79)
Number of obs R-squared	264 0.293	264 0.421

We have also tested other specifications of the regressions excluding or including some factors. The results of these tests are similar to those presented in section 5 and 6. In particular, the set of significant variables and the signs of their coefficients remain unchanged with varying specifications (including the seemingly counter-intuitive results concerning the impact of investment, banking and trade). This fact corroborates the robustness of our results.

8. Cost-Based Separation of Imitation and Innovation Growth Effects

In Sections 5–6, we used formula (37) for separation between the growth due to imitation and innovation, based on the hypothesis that the ratio of the growth rates due to imitation and innovation is proportional to the ratio of bought and sold licenses, (with λ being the proportionality factor). In this section, we consider an alternative method of estimating the contributions of imitation and innovation based on comparing the costs rather than the results of these two ways of modernization. So, the following equations are used instead of (37):

$$\zeta = \frac{L_B}{L_B + \lambda L_S};$$

$$\tilde{w}_1 \tilde{w}_2 = \left(1 + \psi_1\left(\tilde{b}_1\right)\tilde{b}_1\right)\left(1 + \psi_2\left(\tilde{b}_2\right)\tilde{b}_2\right) = \tilde{w}, \tag{43}$$

where $\zeta = \dfrac{\tilde{\psi}_1 \tilde{b}_1}{\tilde{\psi}_1 \tilde{b}_1 + \tilde{\psi}_2 \tilde{b}_2}$ is the share of the imitation costs in the total costs of imitation and innovation.

Equation system (43) should be solved with respect to $\left(\tilde{b}_1, \tilde{b}_2\right)$, provided that equation system (39) holds (recall that (39) is a corollary from the first-order conditions of the optimal choice of b_1 and b_2). Putting together (39) and (43), we obtain the following equation with respect to $\tilde{w}_1$:

$$\frac{1-\zeta}{\zeta} = \frac{\mu_1\left(\tilde{w} - \tilde{w}_1\right)\left(\left(1+\mu_2\right)\tilde{w}_1 - \tilde{w}\right)}{\mu_2 \tilde{w}\left(\tilde{w}_1 - 1\right)\left(1 + \mu_1 - \tilde{w}_1\right)}. \tag{44}$$

Equation (44) is applicable when

$$1 < \tilde{w}_1 < 1 + \mu_1 \text{ and } 1 < \tilde{w}_2 = \frac{\tilde{w}}{\tilde{w}_1} < 1 + \mu_2. \tag{45}$$

The right-hand side of (44) is defined and consistent with (45) for all $\tilde{w}_1 \in (1, \tilde{w})$, when

$$1 < \tilde{w} < 1 + \min(\tilde{w}_1, \tilde{w}_2). \tag{46}$$

The right-hand side of (44) is $+\infty$ when $\tilde{w}_1 \to 1$ and zero when $\tilde{w}_1 \to \tilde{w}$. It is easy to show that if (46) holds, then the right-hand side of (44) is decreasing in $\tilde{w}_1$. Hence, if (46) holds, then (44) has a unique solution $\tilde{w}_1 \in (1, \tilde{w})$ for any $\zeta \in (0,1)$. Let us denote this solution as $\tilde{w}_1(\zeta)$. This is an increasing function of ζ such that $\tilde{w}_1(0) = 1$, $\tilde{w}_1(1) = \tilde{w}$. For example, if $\mu_1 = 0.3$, $\mu_2 = 0.2$, $\tilde{w} = 1.15$, then the graph of $\tilde{w}_1(\zeta)$ under cost-based separation looks like the red curve in Figure 4. Note that under growth-based separation, $\tilde{w}_1(\zeta)$ would be a linear function (see the green line).

The results of the calibration under the cost-based separation and exogenous human capital are as follows:

$\alpha = 0.5003$ (the same as before);

$\mu_1 = 0.4364$ per three-year period (or 0.1283 per year);

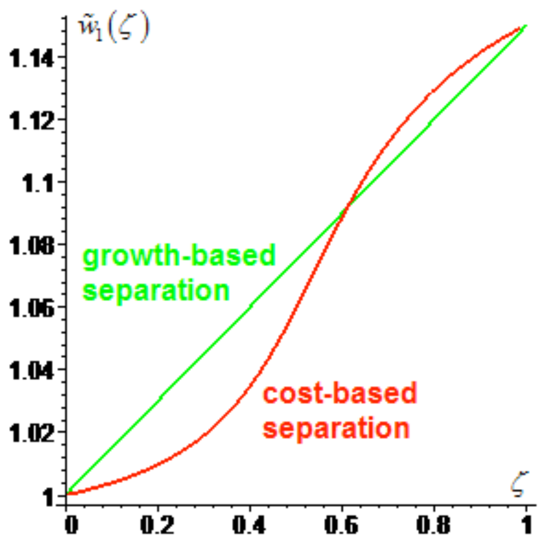
$\mu_2 = 0.2536$ per three-year period (or 0.0782 per year);

$\rho = 0.0500$ per three-year period (or 0.0169 per year);

$\lambda = 1.944$.

Standard error of calibration (average difference $|\ln(y) - \ln(\hat{y})|$): 0.0902

Figure 4. Cost-based vs growth-based separation.



Estimated cost functions are presented in Table 5

Table 5. Regressions for: q_1 and q_2 (cost-based separation, exogenous human capital)

Dependent var	q_1	q_2
$\tilde{a}$	0.3563*** (4.85)	–0.2245*** (–3.38)
$\tilde{a}^2$	0.06146*** (2.82)	–0.01933 (–0.96)
$\tilde{N}$	0.01650 (1.13)	–0.05078*** (–4.13)
$\tilde{H}$	–0.01026 (–0.88)	–0.04016*** (–3.96)
$\tilde{R}$	–0.00847*** (–2.84)	2.38E–5 (0.01)
$\tilde{I}$	0.3927 (0.98)	2.157*** (6.39)
$\tilde{T}$	–0.05279 (–1.53)	–0.05227* (–1.81)
$\tilde{B}$	0.03346 (0.84)	–0.02105 (–0.61)
F	–0.00955 (–0.58)	–7.43E–5 (–0.01)
P	N/A	–0.06162*** (–3.24)
Intercept	0.4998** (2.11)	0.9333*** (4.57)
Number of obs R-squared	264 0.255	264 0.475

If we calibrate the model using endogenous human capital, as in Section 6, then the results will be as follows:

$\alpha = 0.5003$ (the same as before);

$\mu_1 = 0.4111$ per three-year period (or 0.1216 per year);

$\mu_2 = 0.2527$ per three-year period (or 0.0780 per year);

$\rho = 0.0646$ per three-year period (or 0.0220 per year);

$\lambda = 2.287$.

Standard error of calibration (average difference $|\ln(y) - \ln(\hat{y})|$): 0.0854

Estimated cost functions are presented in Table 6.

Table 6. Regressions for: q_1 and q_2 (growth-based separation, endogenous human capital)

Dependent var	q_1	q_2
$\tilde{a}$	0.3821*** (5.09)	–0.2470*** (–3.53)
$\tilde{a}^2$	0.06575*** (2.83)	–0.01948 (–0.92)

$\hat{N}$	0.02054 (1.38)	–0.05615*** (–4.34)
$\hat{H}$	–0.00475 (–0.40)	–0.04036*** (–3.77)
$\hat{R}$	–0.00837*** (–2.76)	–0.00021 (–0.08)
$\hat{I}$	0.1406 (0.34)	2.335*** (6.56)
$\hat{T}$	–0.04535 (–1.29)	–0.05718* (–1.88)
$\hat{B}$	0.03987 (0.98)	–0.00265 (–0.73)
F	–0.01271 (–0.76)	–0.00355 (–0.24)
P	N/A	–0.06769*** (–3.37)
Intercept	0.4809** (1.99)	0.9081*** (4.22)
Number of obs R-squared	264 0.281	264 0.494

Comparing the regressions using the cost-based separation versus the growth-based separation (see Table 7), one can see that basic results remain the same. The only marked difference concerns the impact of trade: it affects mainly the imitation cost under growth-based separation and the innovation cost under cost-based one. There are also some minor differences concerning the significance of relative level of development and investment risks in determining the cost of innovation (both are more significant under the cost-based separation).

Table 7. Signs of the coefficients of the cost functions under different specifications

Specification	Growth-based separation; exogenous human capital		Growth-based separation; endogenous human capital		Cost-based separation; exogenous human capital		Cost-based separation; endogenous human capital	
Normalized cost of	imit.	innov.	imit.	innov.	imit.	innov.	imit.	innov.
Relative level of development	+***	–**	+***	–**	+***	–***	+***	–***
Population	0	–***	0	–***	0	–***	0	–***
Human capital	0	–***	0	–***	0	–***	0	–***
Investment climate	–**	0	–**	0	–***	0	–***	0
Investment/GDP	0	+***	0	+***	0	+***	0	+***
Manufactures Trade	–**	0	–**	0	0	–*	0	–*
Bank credits	0	0	0	0	0	0	0	0
Foreign investment	0	0	0	0	0	0	0	0
Scientific papers	N/A	–***	N/A	–***	N/A	–***	N/A	–***

9. Measuring Absorptive Capacity and Innovative Capability

With the calibrated parameters of the model obtained in the previous sections, one can estimate the absorptive capacity and innovative capability of various countries using (19). Let us rewrite this formula once again:

$$c_i = 0.01(1-\alpha)^{-1}\mu_i q_i / (\mu_i - 0.01(1-\alpha)^{-1}), i = 1,2. \quad (47)$$

where c_1 is a measure of the absorptive capacity and c_2 is a measure of innovative capability. Note that c_1 and c_2 are proportional to q_1 and q_2, respectively. The proportionality rates are chosen so that c_1 is the cost of 1% TFP increase due to technology imitation; this cost is normalized to one unit of a country's capital. The higher is c_1 (c_2), the lower is the corresponding capacity.

Table 8 presents the estimation of the absorptive capacity c_1 and innovative capability c_2 for the countries that are present with all necessary data in our dataset. The countries are sorted descending with respect to $\ln(y)$, the logarithm of the per capita GDP relative to USA. These data are visualized in Figure 5.

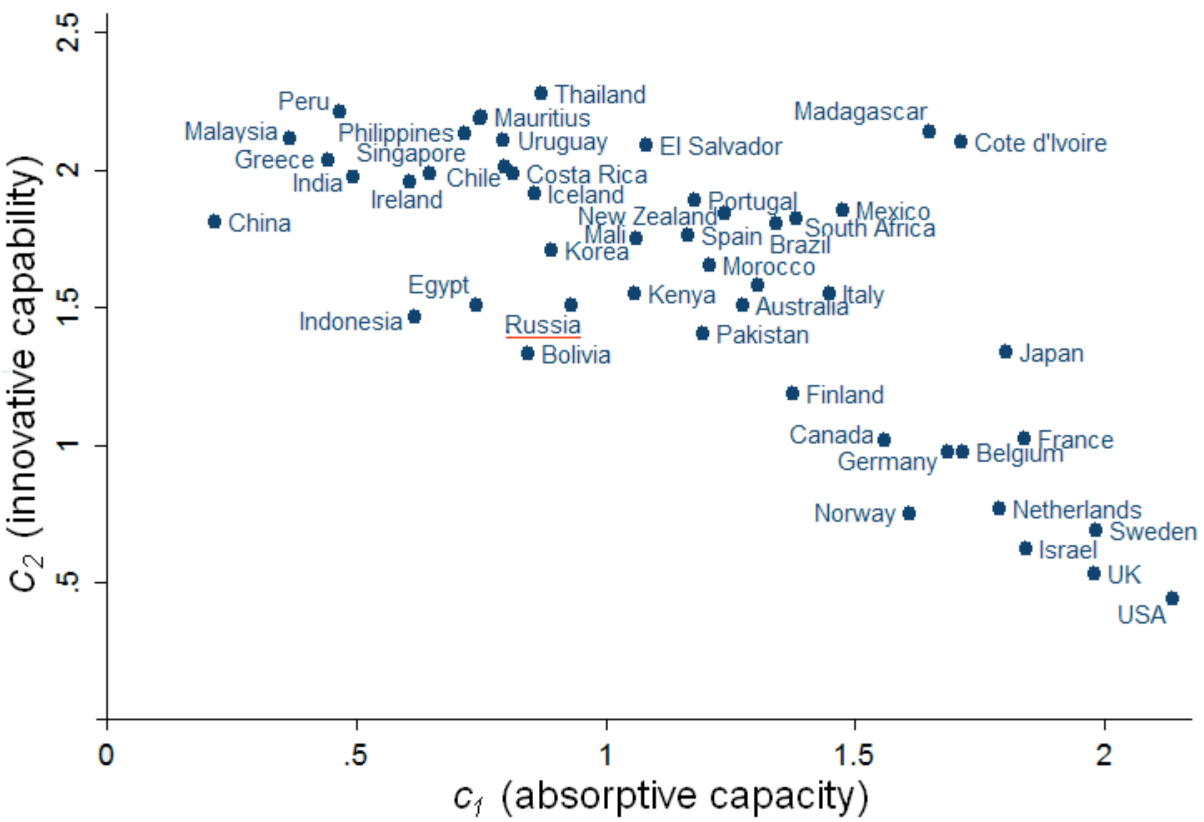
Table 8. Absorptive capacity, innovative capability and distance to the frontier (cost-based separation, endogenous human capital).

Country	c_1	c_2	$\ln(y)$	Country	c_1	c_2	$\ln(y)$
Norway	1.61027	0.75255	0.08390	South Africa	1.38313	1.82299	–1.43651
USA	2.13453	0.44422	0	Malaysia	0.36721	2.11428	–1.44049
Canada	1.55905	1.01823	–0.16742	Chile	0.79895	2.00694	–1.44056
Austria	1.30660	1.58144	–0.18481	Uruguay	0.79608	2.10389	–1.45470
Netherlands	1.78786	0.76930	–0.18587	Brazil	1.34017	1.80566	–1.46811
Iceland	0.85811	1.91495	–0.20468	Costa Rica	0.81563	1.98429	–1.59776
Australia	1.27458	1.50552	–0.21921	Mauritius	0.75257	2.18853	–1.66404
Singapore	0.64768	1.98433	–0.24323	Peru	0.46808	2.20785	–1.79007
Belgium	1.71680	0.97481	–0.24740	El Salvador	1.08150	2.08803	–1.97465
Germany	1.68666	0.97664	–0.26050	Thailand	0.87094	2.27778	–2.02339
France	1.83925	1.02414	–0.26455	Egypt	0.73985	1.50664	–2.25121
Sweden	1.98151	0.69034	–0.26807	Bolivia	0.90634	1.17228	–2.29135
Japan	1.80268	1.33787	–0.26843	Morocco	1.20890	1.65189	–2.46555
UK	1.98022	0.53408	–0.32463	Philippines	0.71879	2.13033	–2.57250
Italy	1.44768	1.54921	–0.32660	Indonesia	0.61798	1.46657	–2.68692
Finland	1.37438	1.18702	–0.35725	Cameroon	1.80071	2.82057	–2.76291
Greece	0.44558	2.03664	–0.40498	Cote d'Ivoire	1.71099	2.09769	–2.85215
Ireland	0.60899	1.95720	–0.46243	Pakistan	1.19644	1.40637	–2.96219
New Zealand	1.23961	1.83888	–0.48147	China	0.21833	1.81270	–3.07968
Spain	1.16422	1.75872	–0.48483	Kenya	1.05749	1.54699	–3.18759
Israel	1.84247	0.62119	–0.56670	India	0.49393	1.97389	–3.20465

Cyprus	1.38241	0.22017	–0.60226	Madagascar	1.64833	2.13464	–3.59822
Portugal	1.17906	1.89010	–0.74979	Mali	1.06047	1.74887	–3.69272
Korea, Rep.	0.89077	1.70664	–1.03238	Bangladesh	0.74676	2.18785	–3.75739
Mexico	1.47608	1.85397	–1.21137	Rwanda	2.29093	3.41939	–3.88865
Argentina	2.43126	2.21765	–1.25601	Sierra Leone	0.00055	2.27009	–4.01360
Russia	1.03613	1.21367	–1.31907	Ethiopia	0.01141	2.25458	–4.18561

One can see from Table 8 and Figure 5 that in accordance with our main hypothesis, c_1 is positively related to the relative level of development, whereas c_2 is negatively related to it, so the points in Figure 5 form a downward sloping cloud. The most developed countries (European Union, Japan, USA, Canada) have relatively high c_1 (low absorptive capacity) and low c_2 (high innovative capability). East Asian countries (China, India, Singapore, Phillipines, Bangladesh, Malaysia), along with some European countries (Greece, Ireland) base their growth mainly on the absorptive capacity. Rwanda, Cameroon and Argentina spend very much money on each per cent of TFP growth, so they are in the upper-right part of Figure 5. Some countries (Cyprus, Bolivia, Pakistan, Egypt, Indonesia) seem to have unexpectedly low c_2, which may be explained by some part of the license receipts possibly irrelevant to the innovation (in particular, these licenses may include permits on natural resource extraction or tourism).

Figure 5. Absorptive capacity and innovative capability.



In Figure 5, Russia is disposed to the right of the East Asian countries ant to the left of the Western Europe. This means that Russian TFP growth is more oriented to imitation (comparing to the developed countries), with innovation still having some impact. One could expect (though we have no regular appropriate statistical data) that during the end of the 20-th century, Russia (and the former Soviet Union) have been moving from a more right (innovation oriented) position to the left. Of course, a significant share of Russian growth can be explained by the fuel export which is not included in our simple model.

10. Conclusion

In this paper, we develop an approach to the estimation of country absorptive capacities and innovative capabilities. The approach is based on new more precise definitions suggested. Therefore, both concepts get clear sense, and it is demonstrated how one can calculate both indicators. The method of calculation uses a simple dynamic model and combines calibration and econometric approaches. This gives a possibility to analyze how calculated indicators depend on different factors. Another important feature of our approach: the estimations are conducted not for each country separately but for a group of economies jointly. This gives us additional information which is not contained in data on a country alone.

There are a lot of possibilities to improve our approach. One could try to use an OLG model instead of one period model, and, in an explicit form, include labor markets with workers of different qualifications as well as sectors of education and research. Maybe, even more important task is to try different hypotheses to reach the separation of imitation and innovation costs and results. In fact, in this paper and in previous one (Polterovich, Tonis (2005)) we use different assumptions about connections between costs of imitation and innovations, on one hand, and data of royalty payments and receipts, on other hand. Results are similar but not exactly the same. It would be very important to know to what extent the estimations are sensitive with respect to model specifications.

In any case, we believe the approach developed above may be improved and will be useful for economic decision making.

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