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Paths of technology upgrading in the BRICS economies☆

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ABSTRACT

This paper explores technology upgrading of BRICS economies based on a three-pronged approach, which distinguishes between the intensity of technology upgrading, structural change and global interaction. We develop a statistical framework based on patent indicators to measure technological upgrading and apply it to BRICS economies in the period 1980–2015. The paper shows that there is no single path of technology upgrading. Instead, we find several unique paths with different trade-offs between intensity, structural change and the nature of the global interaction. All BRICS economies display increased generation of frontier technological activities, while China and Russia have also increased the intensity of behind frontier technological activities. China has also diversified its technology knowledge base and entered into dynamic frontier areas. With increasing intensity of frontier technology activities of the BRICS, the relative, but not absolute, the importance of foreign actors and international collaboration has declined. However, BRICS economies seem to lack the organisational and complementary capabilities to match the extent of technology sourcing from abroad, observed in high-income countries. Our result represents the application of a new conceptual framework and contributes to assessing the sustainability of innovation-based growth among BRICS.

1. Introduction

The process of structural transformation of the global economy, in which the world's economic centre of gravity has been gradually moving towards the East and South, from OECD members to emerging economies, has been denoted by the OECD (2010) as 'shifting wealth'. This suggests that the rise of the emerging economies will inevitably have significant global effects regarding distribution, and also affect the generation of global resources and knowledge. The start of the 21st century witnessed the emergence of multi-polar growth with large developing economies as the newest and the most dynamic growth poles (Lin and Rosenblatt, 2012). Among the emerging economies the so-called BRICS – Brazil, Russia, India, China and South Africa – has received particular attention. However, it is not certain and evident that a blunt distinction between advanced and emerging economies is very helpful to understand the future growth trajectories of the emerging economies. Equally, putting all BRICS into one basket may blind us to understanding the differences in their growth trajectories. Whether the growth of emerging economies and BRICS, in particular, is sustainable depends on the extent of their technology upgrading, and this cannot be answered in general for all emerging economies or all BRICS. Whether the initial opening of emerging economies (*shifting wealth I*) will stretch into *shifting wealth II* or sustainable technology-based growth requires a more nuanced exploration of individual countries (OECD, 2004).

It has been suggested that technological development is a binding constraint for sustained growth – in particular for middle-income countries (Lee and Kim, 2009; Lee, 2013). The new Schumpeterian perspective argues that drivers of growth are different for countries at various income and technological levels (see, for example, Aghion and Howitt, 1992). By the same token, we can infer that there are no universal metrics by which growth (including technology-based growth) can be measured. Growth theory shows that technology is an important growth factor in economic catch-up, but it cannot be reduced to a narrowly defined single variable such as R&D or exogenously derived total factor productivity. Technology as a driver of growth is a multi-dimensional phenomenon. This is well reflected in policy-relevant frameworks like the *Global Competitiveness Index* or the *Global Innovation Index* which suggests that there is a need for conceptualisations of

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technology-based growth as a multi-dimensional phenomenon.

Against this background, there has been a call for new metrics to understand how technology upgrading takes place – emphasising the challenges of middle-income countries (Radosevic and Yoruk, 2016). In response to this call, we extend recent models that differentiate (1) the intensity of technology upgrading reflected in different types of capabilities; (2) the breadth of technology upgrading; and (3) the relevance of global interaction for technological upgrading (see Radosevic and Yoruk, 2016, 2018). We conceptualise technology upgrading as an outcome of the interaction of these three dimensions and derive a set of generic hypotheses on technology upgrading. We develop a multi-dimensional statistical framework based on patent indicators to measure technological upgrading for the BRICS economies in comparison to selected advanced economies (EU15, US and Japan) in the period of 1980–2015. The value of this investigation is in discovering technology profiles (paths) of different BRICS and in demonstrating the viability of the approach to other emerging economies. We advance the state-of-the-art by developing a measurement approach based on the concept of technology upgrading. This is a multidimensional framework which is open to sensitivities of different levels of development. It is empirically informed but also has theoretical relevance. We consider it as an appreciative theorising framework, which aims to overcome a common weakness of composite indicators that often represent 'measurement without theory' (Koopmans, 1947).

The paper shows that there is no single path of technology upgrading within the group of BRICS economies. Instead, we find evidence of several unique profiles of technology upgrading with different trade-offs between intensity, structural change and the nature of interaction with the global economy.

The next section develops the theoretical framework and derives a general hypothesis about the characteristics of technology upgrading processes. Section 3 outlines the methodology to tests the hypothesis on the BRICS economies using patent indicators. The empirical analysis is presented in Section 4. Finally, Section 5 discusses the results.

2. Conceptual framework for technology upgrading

Conventional models of technological development or upgrading are based on either exogenous model of growth (Solow, 1957) or endogenous growth theory (Romer, 1990). The Solow model cannot explain the technology and treats it as an unexplained part of growth, which makes it of very limited relevance for our research. In endogenous growth theory, R&D is the primary source of innovation and growth. This might be less applicable to developing countries, and therefore it has been questioned whether endogenous growth theory pays sufficient attention to economic catch-up (Lin and Rosenblatt, 2012).

A new Schumpeterian approach to growth has been developed by Aghion and Howitt (1992) who base their modelling on different distances of countries from the technology frontier.[1] This enables them to distinguish between growth based on innovation and imitation which seems much closer to the real-world processes of growth and the catching up of developing economies.

Closely related to Schumpeterian modelling are different neo-Schumpeterian contributions which emphasise innovation capabilities as enabling factors for catch-up in developing and emerging economies (see, for example, Verspagen, 1991; Nelson, 1995; Nelson and Pack, 1999; Lee, 2005; Fagerberg and Godinho, 2005; Mazzoleni and Nelson, 2007).

Our framework follows from the neo-Schumpeterian approach, but we also address the multidimensional nature of the technology which is an important, but poorly dealt with, the dimension of economic growth.[2] Our departing proposition is that technology upgrading is a multidimensional process. By this, we mean that it is based on a broader understanding of innovation, which goes well beyond R&D. It is also a multi-level process, i.e. it is micro, mezzo and macro grounded.[3] At its core is a structural change in various dimensions: technological, industrial and organisational. Finally, it is also strongly shaped by global forces embodied in international trade and investment flows, interacting with local strategies pursued by host country firms and governments (Ernst, 2008; Lall, 1992; Radosevic and Yoruk, 2016, 2018). We approach technology upgrading as a three-dimensional process. Thus, we differentiate between the intensity of technology upgrading as depicted by different types and levels of innovation, the breadth of technology upgrading in terms of changes to the structure of technological knowledge, as well as the role of global interaction in terms of inflows of foreign technology and coupling with domestic technological efforts.

2.1. The intensity of technology upgrading

The intensity of technology upgrading is about the accumulation of different types of capabilities, which also reflect the various technological levels of economies. Bell and Pavitt (1993, 1995) emphasised two kinds of accumulation processes within late industrialising firms and economies. One is the accumulation of technology embodied in physical capital and the associated human capital required to operate the facilities at given levels of efficiency. This has been described as *production capability*. This capability requires good operational efficiency as well as a skilled technical and blue-collar workforce. The other process, not well recognised in conventional growth analysis, is the accumulation of *innovation capabilities*.[4]

Bell (2009) argues that the first accumulation process is concerned with firms' capabilities to use existing technologies in production. This catching up can be reflected, for instance, in measures of productivity and the narrowing of productivity gaps over time between latecomer firms and firms at the world technology frontier. The second accumulation process is concerned with firms' capabilities to *create* new technology and *change* the technology they already use. This catching up is about closing the gap between copying or adopting existing technology on the one hand, and improving or creating it on the other (see also Kim, 1997). In this process, latecomer firms close the gap towards those of frontier-innovating firms. Catching-up along this dimension is harder to measure, but it can be assessed regarding the increasingly different levels of innovative capability (Lall, 1992) and the rate at which firms move through them (Ariffin and Figueiredo, 2004).

The empirical firm-level literature on capabilities documented

[1] The term 'frontier' used in this research differs from its use in Stochastic Frontier Analysis (see Fu and Yang, 2009) or Data Envelope Analysis (Wang and Huang, 2007). We are not concerned by an international boundary as in productivity or efficiency analyses as we do not try to measure the technology frontier but only the extent to which a country is engaged in innovation activities at the world 'frontier' as measured by transnational patent applications per GDP.

[2] One dimensional approach to innovation which reduces it to one output variable like R&D can naturally focus on efficiency of the combination of innovation inputs for the innovation capacity across countries and time. However, multidimensional nature of our approach which is not based on input - output function is not suitable for efficiency type of analyses.

[3] Although we recognise the multi-level nature of technology upgrading we do not explicitly consider micro level factors. However, our hypotheses are informed by research on firm capabilities and firm level upgrading in global value chains and our analysis is based on individual firms' patenting activities.

[4] Bell and Pavitt (1993, 1995) originally used the term 'technological capability' to describe what Bell (2009) refers to as 'innovation capability'. He argues that the notion of technological capability is commonly used, especially in literature about the advanced economies, to refer much more broadly to both production capacity and innovation capability – hence clouding the distinction that the authors originally wanted to highlight.

several successful cases of upgrading from production capability to innovation capability by latecomer firms in East Asia (Hobday, 1995; Hobday et al., 2004; Ernst, 2013), Latin America (Dutrenit, 2000) and Central and Eastern Europe (Radosevic and Yoruk, 2004). However, production capabilities remain essential as economies technologically upgrade. It is important to note that production capabilities and innovation capabilities, as well as R&D/knowledge intensity, are present in each economy, to different degrees. Similar to R&D, which is not only valuable in its role of knowledge generation but also in its role of knowledge absorption (Cohen and Levinthal, 1989, 1990), production and innovation capabilities are reinforcing each other. This does not mean that there is some fixed optimal proportion between different types of capabilities and/or R&D. Equally, technology upgrading is not well represented by the increasing share of some of these activities and reduction of others. The individual importance of production capabilities, R&D capabilities and innovation capabilities as drivers of growth vary according to their dependence on achieved income, technology levels and the structural features of the economy (Radosevic and Yoruk, 2016). What matters are their interaction and complementarity and not only individual levels. A high share of world frontier technology activities in an economy with weak production capabilities (or where the rest of firms have weak absorptive R&D capabilities) will lead to enclave type of growth with limited diffusion and productivity spillovers. In a stylised manner, we would propose the following hypothesis:

H1. Countries at different income levels pursue varying degrees of production, innovation and R&D activities. In that context, their technology upgrading is the best represented as complementary relationships between production, innovation and R&D activities which cumulatively lead to increased technology intensity.

From this follows that technology upgrading is not a linear and autonomous process of growth of mutually independent production, technology and R&D capabilities, but is a non-linear process involving several threshold levels (Radosevic and Yoruk, 2016). The move from one stage to another stage is not guaranteed and requires a new set of mutually complementary technical, financial, and organisational preconditions. Our evidence is based on patent data and does not allow us to test for all three dimensions of increased technology intensity (production, innovation and R&D activities). However, by using transnational and priority patents, we can show the transition in technology upgrading from behind the technology frontier to technology frontier activities.

2.2. *Breadth of technology upgrading*

Technology upgrading is more than the intensity or scale of technological activities we observe during catch-up. Past contributions point towards the importance of the extent or scope of structural factors. Early approaches have already depicted development as an evolving process that goes through several stages (see, for example, Rostow, 1960). This was based on the idea of industry life cycles and 'leading sectors', driving economic growth in specific stages. A common feature of these models is the assumption that 'all nations [go] through the same stages in the same order, though not necessarily at the same time' (von Tunzelmann, 1995, p. 69). However, there is not a general theory of structural change but a variety of theoretical approaches of different methodological nature that aim to explain structural shifts between broad sectors and among industries within these sectors (Krüger, 2008). There is a common understanding that technological changes affect structural change in the way that industries with relatively lower rates of productivity growth tend to shrink, in terms of shares, while those with higher rates of productivity growth expand. However, the empirical evidence on the role of structural change shows that it generates positive as well as negative contributions to aggregate productivity growth. Since many of these effects average out, structural change appears to have only a weak impact (Peneder, 2003).

So, instead of being focused on structural changes at the level of industries, it seems more appropriate to track variations in the structure of technological knowledge. Empirical results do not support the idea that growth is correlated with the share of the high-tech sectors (Sandven et al., 2005). We also find evidence for the adoption of high-tech activities in low-tech industries as well as low-tech activities in industries classified as high-tech, i.e. intensive regarding R&D (von Tunzelmann and Acha, 2005). Instead of structural change being reflected in shares at the industry level, we observe a change in the nature of industries and services and their convergence. These changes are exemplified by the increasing role of knowledge-intensive business services (KIBS) as well as the growing importance of knowledge-intensive activities (KIA)[5] across all economic sectors (European Commission, 2011). Against this background, we would argue that the accumulation of production and innovation capabilities in catch-up is associated with changes in the underlying knowledge intensity. These changes reflect a structural change in knowledge generation and absorption towards a high share of high-technology knowledge and higher knowledge intensity of economic activities. We propose the following:

H2. Low-income countries are more likely to be associated with a low share of knowledge-intensive activities, while middle-income and high-income increase their shares of knowledge-intensive economic activities.

The sectoral concentration of countries seems to follow a U-shaped pattern in relation to per capita income. Imbs and Wacziarg (2003) show that economies grow through two stages of diversification. At first, sectoral diversification increases, but there exists a level of per capita income beyond which the sectoral distribution of economic activity starts concentrating again. The knowledge base of the successful catching-up economies also seems to follow a non-linear, though inverse, trend. Lee (2013) shows that technological diversification, rather than specialisation, is one of the significant factors in catching up to high-income levels. While New Structural Economics accounts (Lin, 2012; Lin and Rosenblatt, 2012) show the path to technology upgrading as based on 'copying industries' using latent comparative advantages in the transition from low to middle-income levels, Lee (2013) shows that middle-income economies are taking 'detours' or temporary specialise in so-called short cycle technologies. He shows that Korea and Taiwan have entered into a smaller number of knowledge areas with great technological opportunities but in an increasing number of sectors. However, as Korea and Taiwan continued to grow, they have successfully moved to the high-income group by process of substantial technological diversification. Against this background, we would expect that:

H3. Low-income countries predominantly imitate foreign technologies and are characterised by a narrow specialisation of the domestic technological knowledge. Prosperous middle-income countries may temporarily specialise in narrow areas with high technological opportunities, but the path of technology upgrading (though possibly non-linear) is characterised by increasing knowledge diversification.

2.3. *Global interaction in technology upgrading*

Growth and technology upgrading are never entirely independent processes but linked to global interaction. For example, Akamatsu (1962) describes technology upgrading as an interactive process

[5] KIBS are defined according to the NACE Rev. 1.1 as including the categories computer and related activities (NACE 72), research and development (NACE 73), and other business activities (NACE 74). KIA are defined as economic sectors in which more than 33% of the employed labour force have completed an academic tertiary education (ISCED 5 and 6 levels).

between 'leaders' and 'followers'. This argument can be tied to different lines of development-oriented research, which relate to foreign direct investment (FDI), learning by importing/exporting, as well as upgrading in global value chains (GVCs). Arguably, all three channels of global interaction potentially affect the intensity of technological upgrading in the catch-up process.

Inward FDI has been traditionally associated with a centrally accumulated technological advantage originating in the home country, which is transferred to the host country where it diffuses to the domestic economy. In fact, Findlay (1978) argued that the potential for technological diffusion via FDI is positively related to the relative technology gap between the home and host economy. He referred to the 'contagion effect' whereby technical innovations are most effectively copied when there is personal contact between those who already know the innovation and those who eventually adopt it (Nelson, 1968; Mansfield, 1961, 1968).

Wang and Blomström (1992) criticised this approach in which a host country's production efficiency is modelled merely as an increasing function of foreign capital. They explicitly recognise the costs associated with technology transfer in multinational enterprises (MNEs), as suggested by Teece (1976, 1977), and learning costs of domestic firms. Thus, FDI externalities depend positively on the technical and managerial competence of the foreign subsidiary as well as the domestic firm's decision to invest in learning (Marin and Bell, 2006; Castellani and Zanfei, 2006; Damijan et al., 2013; Jindra, 2011; Giroud et al., 2012).

Emerging market firms can also improve their innovation capabilities through outward FDI (Mathews, 2006; Li, 2010; Ramamurti, 2012; Narula, 2012). Some investigations demonstrated the existence of knowledge-driven outward FDI strategies (see, among others, Makino et al., 2002; Buckley et al., 2007; Jindra et al., 2016).

There is also an established line of research, which points towards technological learning from importing/exporting (Grossman and Helpman, 1991; Drivas et al., 2016; Eaton and Kortum, 2001; Keller, 2002; Keller and Yeaple, 2009). Given that foreign affiliates often show higher levels of imports and/or exports compared to domestic firms, technology accumulation via trade and FDI can be considered as complementary effects. International licensing or knowledge flows in a disembodied form also represents essential channels of technology transfer. However, these are closely tied and thus inseparable from either trade or FDI flows.

In the GVC literature upgrading manifests itself through various forms: efficiency gains by reorganising the production system or introducing superior technology; product upgrading, where a firm moves into more sophisticated product lines; functional upgrading, where a firm acquires new functions (or abandons existing ones) to increase the overall skill content of activities (Kaplinsky and Morris, 2001; Humphrey and Schmitz, 2002, 2004; Sturgeon and Gereffi, 2009; Gereffi and Fernandez-Stark, 2011). Therefore, the entry of emerging market firms into GVCs creates opportunities for technological upgrading through learning and interaction. This leads to the following hypothesis:

H4. In low-income countries, global interaction is of high relevance to gain access to frontier technology. However, low-income economies have weak organisational capabilities, and their patentable knowledge is often commercialised by foreign applicants. As countries' incomes grow and technological capabilities upgrade, they can enter into a process of knowledge co-generation. In high-income economies, the generation of frontier technology is based much more on domestic actors who can actively source and commercialise technological knowledge from abroad.

In a stylised manner, we argue that low-income countries primarily benefit from technology transfer via inward FDI and learning by exporting/importing. At this stage, low-income countries have weak organisational capabilities to commercialise their own patentable knowledge. At later stages, middle-income countries start to engage in upgrading processes, primarily process and product upgrading, and are gradually able to enter into knowledge co-generation activities with foreign partners. Advanced middle-income countries also begin to engage in functional upgrading to knowledge-intensive business functions, as well as to inter-chain upgrading and the establishment of domestic lead firms. We also begin to observe increased levels of outward FDI, which is partially motivated by technology-seeking motives and reverse technology transfer to compensate for home country disadvantages.

2.4. Technology upgrading as an outcome of the interaction between its three dimensions

The three dimensions of technology upgrading, as outlined above, are not isolated but complementary and mutually dependent. For example, a critical point that emerges from the literature is that technology upgrading can be linked to inflows of foreign knowledge and technology. However, this needs to be coupled with intensive domestic technology efforts (Radosevic, 1999; Pietrobelli and Rabellotti, 2011). Otherwise, upgrading effects due to global interaction remain limited or do not develop at all. Arguably, the key to catch-up is leverage of domestic innovation efforts with global industrial or knowledge networks (Ernst, 2008). Criscuolo and Narula (2008) argue that assimilation of foreign knowledge is not only confined to catching-up economies but is also carried out by countries at the frontier-sharing phase. Hence, the magnitude of knowledge inflows *and* their coupling to domestic innovations efforts are critical dimensions of technology upgrading.

Furthermore, the structural change in economy and industry has direct effects on the intensity of technology upgrading. For example, R&D intensities of economies are strongly determined by the economic structure to the extent that accounting for industrial structure substantially affects the traditional country rankings of R&D intensity (Mathieu and van Pottelsberghe de la Potterie, 2010). Rodrik (2016) documents a significant premature deindustrialisation trend in groups of developing economies in recent decades that goes considerably beyond the advanced, post-industrial economies. The premature deindustrialisation reduces the knowledge intensity of these economies as manufacturing is still the primary locus of R&D activities.

Finally, the extent to which FDI, GVCs and trade can impact economic structure is the subject of a vast amount of literature, which looks at this interaction from their specific angles. In the case of FDI, this is about the extent to which FDI has direct versus indirect effects on other linked sectors, which can lead to structural change in the economy. In the case of GVC, the issue is tackled through different types of upgrading at micro-level which lead to different value-added positions in international trade, i.e. to different technology structure. Against this background, we would expect that:

H5. Interactions among three components lead to nationally specific paths and profiles of technology upgrading. The scope for substitution between different dimensions does exist, but we would expect that cases of catching-up are characterised by dynamic complementarities between three components of technology upgrading.

The benefits of the multidimensional framework are not in a simple summation of outcomes on particular dimensions but in the emerging profiles of technology upgrading. Catching-up economies are characterised by dynamic complementarities among three components while lagging economies have numerous missing linkages among three components. Alternatively, they are lagging behind regarding the technology intensity of upgrading, despite positive structural changes or high openness towards the global economy. The emerging profiles that stem from the interaction of three components may hopefully be much more informative regarding the sustainability of growth and the nature of technology upgrading in BRICS.

3. Method

The body of research on measuring countries' performance in growth, competitiveness and innovation offers a variety of composite indicators.[6] It is important to bear in mind that different indices treat 'technology' in different ways. Some of them cannot be taken as a direct measure of innovative performance. For example, the *Global Competitiveness Index* depicts the quality of the current endowment of a country (including institutions) and among them also the technological activities as one of the determinants of growth. We confine ourselves to measuring technology upgrading, and we do not aim to unravel a complex picture of the institutional factors that determine the growth and competitiveness of economies. Also, we do not aim at establishing a ranking, but the identification of different paths of technology upgrading to facilitate comparative research.

It is important to note that by capturing patterns of technology upgrading we focus on middle-income countries and catching-up processes in terms of innovation capabilities (Bell, 2009). We do not aim at measuring production capability. For this purpose, we study patterns of technology upgrading by relying entirely on patent data. Analytically, we treat technology as a stock of knowledge separate from production, although in reality they are strictly interconnected (Bell and Pavitt, 1997). Using exclusively patent-based indicators means that, similar to Archibugi and Coco (2005), we exclude production capability from innovation capability. The exclusive reliance on patents has costs in terms of capturing only a part of innovation efforts. Their intangible character is more appropriate as countries move up towards the technology frontier and less relevant for countries behind the technology frontier where intellectual property rights (IPRs) are not the dominant form of protection of technological know-how. This is especially important as innovation in latecomer economies is mainly about adoption and improvements on imported machinery.

Catch-up in innovation capability can be measured by different levels of increasingly innovative capability (Lall, 1992; Bell, 2009). Using both transnational and priority patents, our approach tracks 'frontier' and 'behind frontier' technological activities. In other words, it captures different levels of innovation capability ranging from incremental technological improvements relevant for domestic markets (behind the technology frontier) up to more sharp and radical solutions relevant for international markets (at the technology frontier). A priority patent is the first patent application filed to protect an invention. Priority filings include the overall technology effort: incremental innovation relevant for domestic economies (usually patented first and exclusively in national patent office) as well efforts at the technology frontier (usually protected directly as transnational patent applications). Transnational patent applications include all Patent Cooperation Treaty (PCT) applications (whether transferred to the European Patent Office EPO or not) and all direct EPO applications without a precursor PCT application[7] (Frietsch and Jung, 2009). Indicators based on transnational patent applications reflect the innovation capability relevant for competitiveness in international markets. Therefore, we use transnational patent applications as an indicator of frontier technological activities in our analysis. According to de Rassenfosse et al. (2013) indicators based on priority, patents are more effective in capturing inventive technological activities in catching-up economies which are closer to incremental innovation, with lower commercial potential and which often take place behind the technology frontier. For advanced economies, the difference between transnational patent applications and priority filings is very low as their firms operate closer to or at the technology frontier when compared to catching-up economies. A priority filings count represents the total number of patent families, regardless of their spatial protection scope (i.e. overall technological intensity). The transnational patent applications indicator represents the number of families that are protected in global (across the border) markets. Therefore, we use in our analysis a novel indicator of 'behind frontier' technological activities, which is defined as the number of patent families that do not contain transnational applications. This indicator is calculated as the mathematical difference between the priority filings count and the transnational patent applications count. This way we can better differentiate between frontier and behind-the-frontier technological activities.

Using patents has some significant advantages for the empirical analysis of technology upgrading. We can derive a long and consistent time series as well as define technological fields using the patent classification. Unlike macroeconomic indicators, innovation capabilities change very slowly even during periods of deep economic crises or high growth (Archibugi et al., 2009). By using patents, we can quickly detect stock and flows and thus depict, much better compared to other indicators, changes in technology intensity as well as a structural change in technological knowledge. In sum, the benefits of using patent-based indicators surpass the costs as they enable us to track the changing nature of technological knowledge as countries move from 'followers' to 'leaders' and as they shift from behind frontier technology effort to world frontier technology efforts.

4. Analysis

In this section, we implement the comparative analysis of technology upgrading processes in the BRICS economies between 1980 and 2015. The analysis is structured along the three conceptual dimensions of technology upgrading. Each dimension is proxied by the specific set of patent indicators.[8] Finally, we provide an integrated analysis by discussing changes in the relative position of the BRICS economies along the three dimensions comparing changes in selected indicators over time.

4.1. *Intensity of technology upgrading*

The intensity of technology upgrading in the middle-income countries considered is reflected in the accumulation of innovation capability. We differentiate between (i) innovation capability pushing the world technology frontier and (ii) domestic innovation capability behind the world technology frontier.

4.1.1. *Innovation capability pushing the world technology frontier*

To measure domestic technological activities pushing the technology frontier we rely on transnational patent applications of domestic inventions (TN). Fig. 1 gives the number of transnational patent applications per 1 billion GDP (in US$ constant prices 2010) for the period 1980–2015 (see in Annex Table A2). The indicator adjusts the scale of technological upgrading for the size of the economy and thus measure relative 'technology (patent) intensity' of the economy. We present the

[6] Examples are: the Global Competitiveness Index (WEF, 2012), the Knowledge Economy Index (Chen and Dahlman, 2004), the World Competitiveness Report Index (by IMD), Technological capability of countries, (Archibugi and Coco, 2004, 2005, Archibugi et al., 2009), UNIDO Industrial Performance Scoreboard, the Summary Innovation Index and the Global Innovation Index (both from the European Commission); the Technological Activity Index (by UNIDO); the Technological Advance Index (by UNCTAD), the Technology Achievement Index (reported in the Human Development Report 2001), and the S&T Capacity Index (by RAND Corporation), the High-Tech Indicators (reported by the National Science Foundation's Science & Engineering Indicators).

[7] The origin of the invention is defined by the country of residence of the inventor. If an application involves inventors from different countries, the national assignment will be fractional depending on the number of countries involved.

[8] Table A1 in the annex includes the descriptions and data sources of the indicators presented in this section

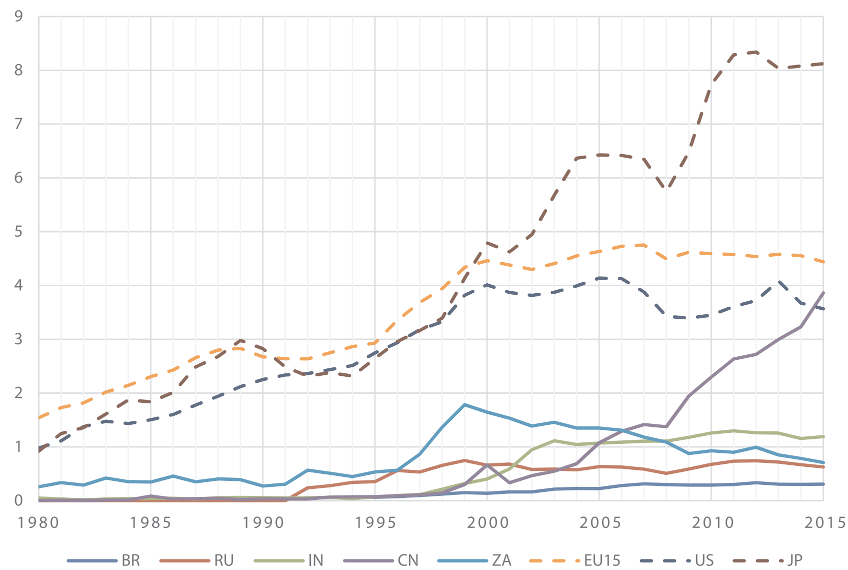

Fig. 1. Frontier patent applications per 1 billion of GDP (in US $) per priority year.
Source: Indicators elaborated by the authors using data from PATSTAT and UNCTADstat.

patent-based indicators for Brazil, Russia, India, China, and South Africa and add the respective indicators for the US, EU15 and Japan as a reference for high-income economies.

The most striking trend is that the Chinese economy moved up into the group of high-income economies. In 2009/2010 China's scale of frontier activities per unit of output surpassed the level of the US. This catch-up does not apply to any other BRICS economy, although these economies witnessed a twofold increase in their frontier activities since the mid-1990s.

4.1.2. Innovation capability behind the world technology frontier

To capture innovation capability related to technological activities behind the world technology frontier, we calculate the mathematical difference between the priority filings count and the transnational patent applications count.[9]

Fig. 2 shows the resulting count per unit of output (1 billion US$ in constant prices 2010) for emerging and advanced economies per priority year (see Annex Tables A1 and A2). Since the 1990s Russia and China have increased their intensities of behind the frontier activities substantially. In the first half of the first decade of the 21st century, China even surpassed the level of Japan. It is important to note that the intensities in behind frontier technologies stayed very low and flat during the whole observation period, not only for the other BRICS economies but also for the US and EU15 economies. The relationship between technology frontier and behind frontier technology effort can be better visualised on a scatter diagram (see Fig. 3).

There are four key messages from this analysis: First, the increase of patent intensity of GDP in the US and EU15 came entirely due to an increase in technology frontier activities. Second, this applies also to Japan, which shows a very distinct institutional bias towards high intensities of behind the frontier activities. Third, both Russia and China have substantially increased the patent intensity of their GDP by pursuing both behind and at the technology frontier activities. However, the Chinese dynamics is superior as the increases in both types of effort (at the technology frontier and behind) seem to complement each other. Simple regression suggests that a 10% increase in priority patents intensity leads to a 0.5% increase in the transnational patent intensity of GDP. For Russia, the dynamics of mutually supportive growth falters very early in the observation period, but it still shows extensive behind the technology frontier activities. Fourth, Brazil, India and South Africa are characterised by the moderate growth of technology frontier activities and almost no growth of behind the frontier activities, which differs from the trends observed for China and Russia. This is most likely related to institutional differences related to the technological openness of the different BRICS rather than deficient innovation capabilities since the BRICS economies (except for China) are comparable regarding technology frontier patenting (Fig. 1).

In sum, high-income countries (EU15, US and Japan) are more engaged in frontier technologies compared to all BRICS economies. In the most recent period, only China has managed to increase the scale of technological frontier activities to the levels observed in high-income countries. The other BRICS economies did not reduce the gap in frontier activities to high-income economies. China and Russia have been able to catch up with high-income countries in terms of behind the frontier activities. This does not apply to India, South Africa and Brazil. Our evidence supports hypothesis one on the observation that middle-income countries accumulate innovation capabilities moderately while high-income economies are characterised by robust innovation capabilities at the technology frontier.

4.2. Breadth of technology upgrading

To analyse the breadth of technology upgrading, we focus on the features of structural change in the technological knowledge base. We define two structural change indicators to measure (i) the shifts in the knowledge intensity of technological activities and (ii) the diversification of the technological activities.

4.2.1. Knowledge intensity

We calculate the share of patent applications in high technology fields and knowledge-intensive services[10] (HKTI) in all transnational

[9] For South Africa (1999–2015) and India (2004–2015) this difference is negative due to two factors: first, differences in the timing of patent publications and their types, second, missing country codes for some data in PATSTAT (de Rassenfosse et al., 2013, p. 723). The shares of negative values in total priority patents for India and South Africa are 10.7% and 9.4% respectively. However, this margin of error in data does not change our conclusions for these two economies.

[10] We follow the EUROSTAT definition of high tech activities (last accessed 13.01.2015): HYPERLINK http://ec.europa.eu/eurostat/cache/metadata/Annexes/htec_esms_an6.pdf.

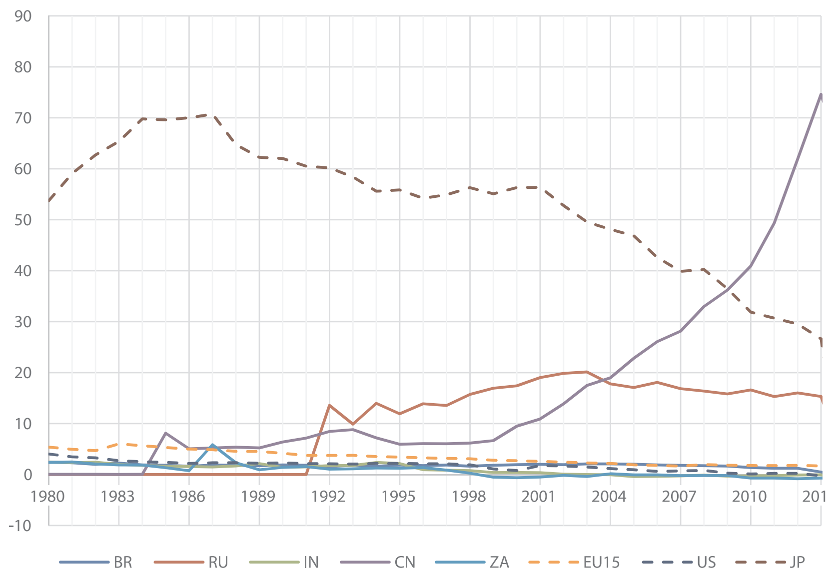

Fig. 2. Behind Frontier Patent Applications per 1 billion of GDP (in US$) per priority year.
Source: Indicators elaborated by the authors using data from PATSTAT and UNCTADstat.

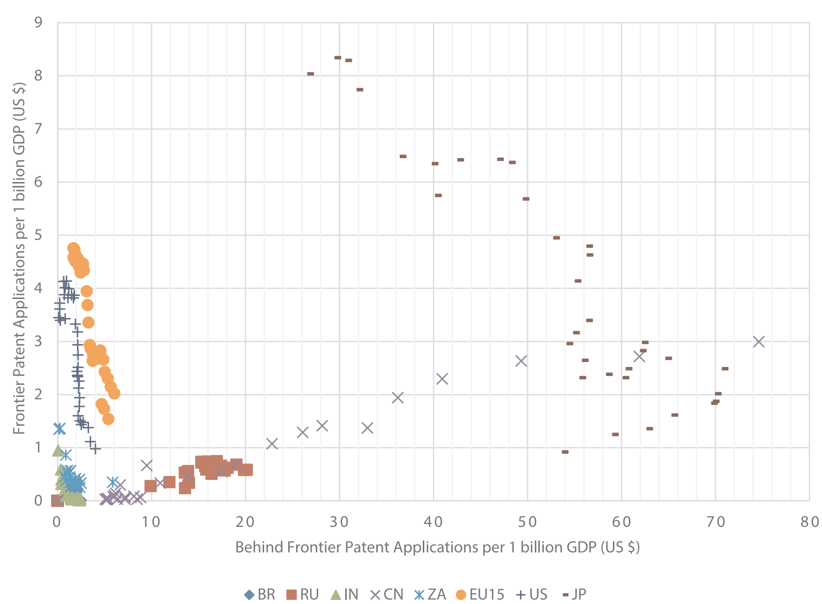

Fig. 3. Frontier and Behind Frontier patent applications over GDP (1 billion US$ in constant prices 2010) during.1980–2015.
Source: Indicators elaborated by the authors using data from PATSTAT. (see footnote 6).

patent applications with at least one domestic applicant for the period 1980–2015 (see Fig. 4) (see Annex Table A2). We consider HTKI patents as an indicator of 'knowledge intensity of technological activities' or proxy for 'dynamic technology frontier activities'.

Fig. 4 shows that the US and Japan have a high share of high technology fields and knowledge-intensive services. The relatively low share of the EU15 compared to the US/Japan reflects differences in industry structure (Moncada-Paternò-Castello et al., 2016). Since the 1990s the BRICS have experienced irregular and moderate growth in the share of high-tech and knowledge-intensive activities. China, India, and to a lesser extent South Africa, show increased rates in the 2000s. In the case of China, we witness a remarkable structural change towards dynamic technology frontier activities, which started at the end of the 1990s. Today China has the highest share of HKTI patents in transnational patents and has surpassed the levels observed in the high-income countries. This could signal the entry of China into particular 'dynamic frontier activities' with potentially positive effects for the observed increases in the scale of frontier activities.

The indicators seem to support our second hypothesis with regard to the increasing knowledge-intensity of innovation capability, as countries move from middle-income to high-income economies. The BRICS economies have consistently lower but gradually growing shares of high-tech and knowledge-intensive patents in their overall frontier technology compared to the high-income countries (the US, and Japan) throughout the observation period.

4.2.2. *Technology diversification*

To measure the general diversification of technological knowledge we select a proxy proposed by Lee (2013). We count the number of IPC subclasses (in total 639 fields)[11] in which each country filed transnational applications during the period 1980–2015 (see Annex Tables A1

[11] Lee (2013) uses USPTO data and the US patent classification system to define the 417 fields (3-digit USPC codes).

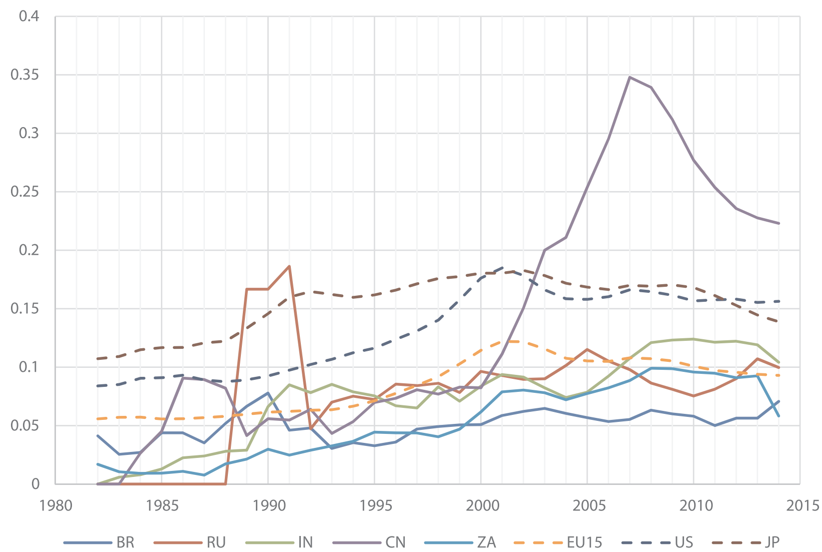

Fig. 4. Share of high technology and knowledge-intensive fields in transnational patents (3-Year moving averages - MA) (in%).
Source: Indicators elaborated by the authors using PATASTAT. *max. IPC subclasses = 639.

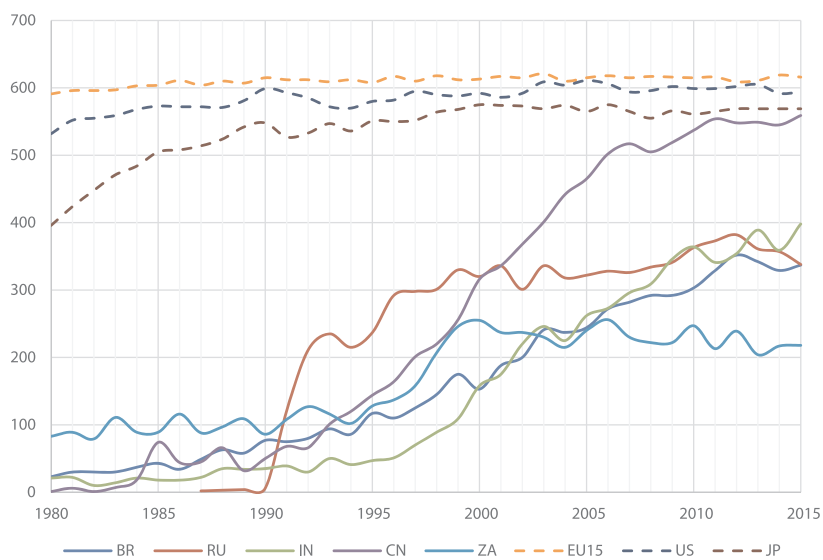

Fig. 5. Number of technological fields (IPC subclasses)* used in transnational patents per priority year.
Source: Indicators elaborated by the authors using REGTAT.

and A2). China has been diversifying into different technological fields in frontier activities (measured with transnational patents) since the mid-1980s (see Fig. 5). Most recently China has converged to the levels of diversification observed for high-income countries. Russia had a clear diversification trend in the 1990s that slowed down afterwards to develop at a similar path as in Brazil and India. Even though India and Brazil had steady diversification since the 1990s, their levels of diversification have not converged to the diversification structure observed for the high-income countries. Finally, South Africa still holds a much narrower and stable domestic knowledge base.[12]

In sum, the evidence supports hypothesis three: that middle-income countries are in the process of diversifying their domestic technological knowledge, while high-income economies already possess a diversified technological knowledge structure. However, it seems relevant to note that we also observe middle-income countries such as South Africa, which have slowed down their diversification in frontier activities.

4.3. Global interaction

Patent indicators also allow us to trace international knowledge flows in technological activities. Guellec and van Pottelsberghe de la Potterie (2001, 2010) develop the concept of 'cross-border ownership' to identify patents where inventors and patent applicants are located in different countries. Cross-border ownership is relevant in the context of technology upgrading because the technological inventive activity is not of economic relevance unless organisational capabilities exist for exploiting or protecting the invention. For Teece (1986) these capabilities are 'complementary assets'. In the context of patent protection, inventors and applicants can be seen as holders of different assets that

[12] We have also used the Herfindahl index of all transnational patent applications with domestic inventors across 35 countries and 639 technological fields during the period 1980 to 2011 as the proxy for structural change. However, we do not include this analysis, as results are much less persuasive than simple counts of IPC subclasses. We followed a methodology proposed by Schmoch (2008) to classify patents in different technology fields. These data (available upon request) suggests that long term diversification in both China and India are also present though less discernible.

are combined through global interaction if they are located in different countries. From the perspective of technology upgrading, cross-border ownership leads to interesting interpretations. We use three indicators using this concept: First, we use foreign applications of native inventions (FANI) to measure the extent to which the exploitation of frontier technology in an emerging country is driven by foreign actors. Second, we use international co-inventions (COINV) in frontier technological activities to measure international technological collaboration. Third, we consider native applications of foreign inventions (NAFI) as a proxy for the extent to which frontier activities of emerging economies are based upon technology sourcing from abroad (see Annex Tables A1 and A2). We interpret these indicators not only for the direction of knowledge flows but also as proxies for the origin of the complementary assets.

4.3.1. Foreign applications of native inventions

Following Guellec and van Pottelsberghe de la Potterie (2001, 2010), we compute the share of transnational patent applications with at least one inventor[13] located in the respective country and an applicant located abroad. The number of transnational patents applied by foreigners and invented by natives (FANI) is divided by the total number of transnational patents with at least one national inventor to calculate the 'FANI-Rate' (see Annex Tables A1 and A2). We calculate the FANI-Rates for the countries under investigation in the period 1980–2015 (see Fig. 6). A high FANI-Rate on transnational patents suggests the relatively high importance of foreign actors for the exploitation of frontier technology in the own economy and low organisational capabilities to exploit the knowledge. A low FANI-Rate suggests relatively high organisational capabilities of domestic players to commercialise their technological knowledge and *vice versa*.

Our data suggest clear differences between high-income and BRICS economies (see Fig. 6). High-income countries are characterised by low levels of FANI-Rates which suggest the dominant importance of domestic actors for the generation of frontier technology and the prevalence of complementary assets in the group of high-income countries. Throughout the observation period, Japan had the lowest FANI-Rates that stands today at only 2%, which reflects still very much domestically-controlled technology development. FANI-Rates have been increasing slightly, especially for the US and EU15, which reflects increasing internationalisation of R&D within the group of high-income economies. In the initial phase, all BRICS economies relied heavily on foreign actors to exploit frontier technologies. At the beginning of the observation period, FANI-Rates stood at up to 70% in BRICS. Today the rates have fallen dramatically, but still to levels above the FANI-Rates observed for the high-income economies. Interestingly, there are considerable differences within the BRICS, where India has currently the highest FANI-Rate (about 41%) and China the lowest FANI-rate (about 14%). This suggests that complementary assets to exploit their inventions have increased in China but not in India.

These insights broadly support our hypothesis H4 which proposes that middle-income economies show increasing the relative importance of domestic actors in frontier technologies, while in high-income economies the generation of frontier technology is mainly based on domestic actors. However, we need to recall that, in this phase, the overall level of frontier activities in these large emerging countries was very low. Over time, and with slowly increasing scales of frontier activities, the relevance of foreign actors and international collaboration relatively (not absolutely) decreases.

4.3.2. International co-inventions

Again, we follow Guellec and van Pottelsberghe de la Potterie's (2001,2010) method to measure international collaboration using counts of transnational patent applications with inventors residing in different countries. Our indicator is the share of transnational patent applications resulting from international technological co-invention in the total number of patents by inventors located in a given country (COINV-Rate) (see Annex Tables A1 and A2). A high COINV-Rate reflects the high importance of international collaboration in the generation of frontier technology. Below we present the COINV-Rates for the countries under investigation in the period 1980–2015 (see Fig. 7).

First, we observe significantly different levels of co-invention between BRICSs and the high-income economies, which have been reduced in the last two decades. Second, the intensity of co-invention in high-income economies, especially in the US, has slightly increased reflecting the globalisation of R&D but, at the same time, has been reduced in BRICS. This relative reduction in co-inventions can be interpreted as the reduced dependence of BRICS on technology transfer. This is particularly strong in the case of China whose COINV-Rate dropped below the rate observed for the US. In sum, these trends are in line with our hypothesis four. For BRICS economies international collaboration is still relatively crucial for frontier technology activities compared to major high-income economies. Nonetheless, the engagement in co-invention activities is quite variable among BRICS, suggesting different dependency degrees on technology transfer to develop frontier technologies as well as the various international strategies in their technology upgrading process.

4.3.3. Native application of foreign inventions

Native applications of foreign inventions are a proxy for the extent to which an emerging economy is exploiting inventions in frontier technology sourced from abroad. Following Guellec and van Pottelsberghe de la Potterie (2001, 2010) we count the transnational patent applications with an applicant located in a selected country that involve at least one inventor located abroad (NAFI). The indicator (NAFI-Rate) is calculated by dividing NAFI by the total number of transnational patents with at least one national applicant in the period 1980–2015 (see Annex Tables A1 and A2). A relatively high NAFI-Rate indicates that a significant share of technologies protected and exploited by home actors are based on foreign inventions. This reflects increasing organisational capabilities or building up of complementary assets by domestic firms (Teece, 1986).

NAFI-Rates have been at about 5% to 20% for BRICS economies at the start of the observation period. At this stage, we also observed very low overall levels of transnational patents (see Fig. 8). NAFI-Rates declined to levels below the ones observed for the US and EU15 over time. The NAFI-Rates of all high-income economies under investigation have been gradually increasing as a sign of increasing technology sourcing from abroad and organisational capabilities. Again, Japan shows a pattern, which is distinct from the other high-income economies, with a relatively low NAFI-Rate (4%) in comparison to the EU15 and US. Today NAFI-Rates of BRICS economies are between 1% (Russia) and 8% (South Africa), whereas we observe 11% and 19% for the EU15 and US respectively.

These differences are in line with our hypothesis four, suggesting that the organisational capabilities of middle-income economies to source technology from abroad is significantly lower when compared to high-income countries (except Japan).

4.4. An integrated perspective

In this and the following section, we integrate all three dimensions to explore levels and patterns of changes of technology upgrading over time. Guided by Hypothesis number 5 we assume that countries do not follow a uniform and standard upgrading process. Considering now all indicators, we study the extent to which the i*nteractions among three dimensions lead to nationally specific paths and profiles of technology upgrading.*

Figs. 9 and 10 include all seven indicators investigated above:

[13] If an application involves inventors from different countries the national assignment will be a fractional count.

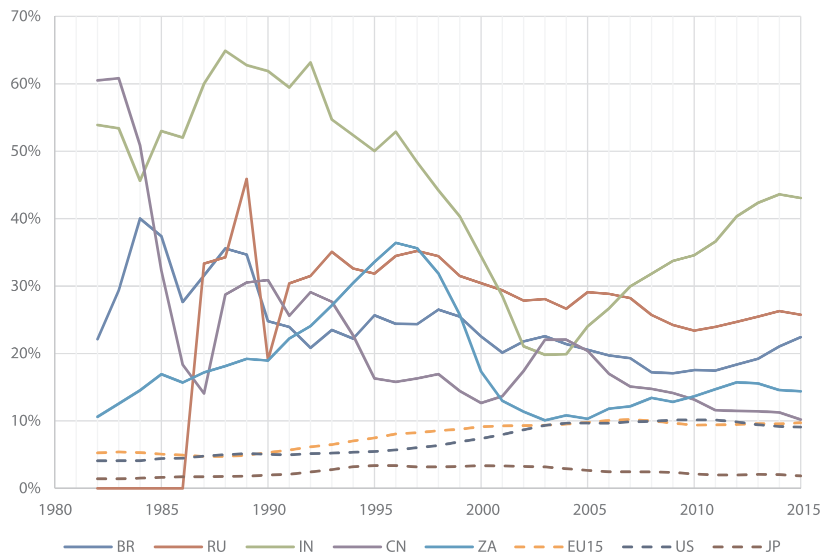

Fig. 6. FANI Rate for transnational patents per priority year (3-year MA).
Source: Indicators elaborated by the authors using REGTAT.

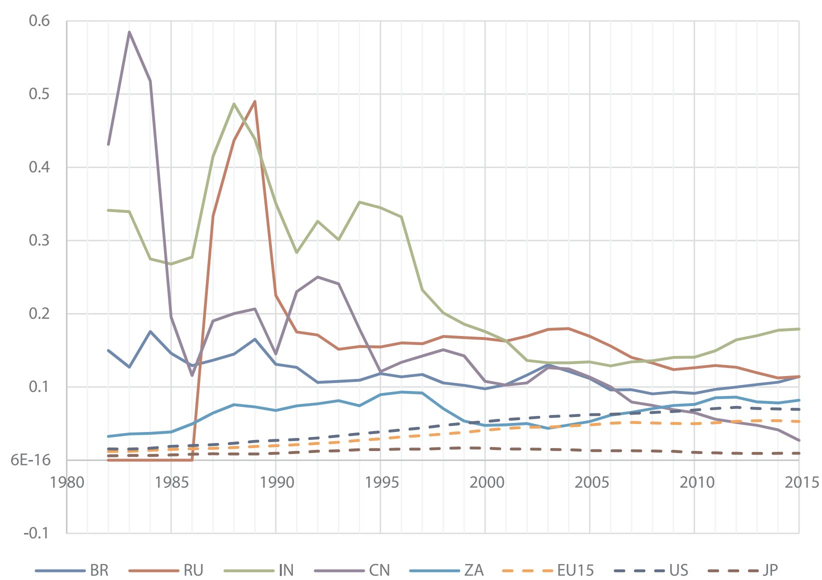

Fig. 7. Co-Invention Rate for Transnational Patents per priority year (3-year MA).
Note: *Figures for RU are given on secondary axis.
Source: Indicators elaborated by the authors using REGTAT.

frontier technological intensities; behind the frontier technological intensity; the share of high-tech and knowledge-intensive transnational patent applications in total transnational patent applications (*High tech patents*); and the level of diversification in transnational patents (*DIV_TN*). Global interaction is represented by the FANI-Rate, the COINV-Rate and the NAFI-Rate.

Fig. 9 includes network diagrams for the periods 1989–1997 and 2007–2015 for BRICS, EU, USA and Japan. Diagrams profile the upgrading paths and trade-offs between indicators which represent different dimensions of technology upgrading. The values for the indicators in each period are the average of the annual values in each period. The network diagram provides for each indicator the relative position of each economy to the economy with the maximum value for each indicator.

In the period 1989–1997 high-income economies lead BRICS economies in terms of technological intensity at the frontier and behind the frontier (in the latter case only Japan). BRICS are also behind in high-tech patents (except for the EU15 in this case) and the diversification of technological knowledge base.[14] We find a relatively low global interaction of all economies in the period 1989–1997. In this period India is the only emerging economy with relatively high global interaction in terms of co-inventions and the relative importance of foreign actors in frontier activities (FANI-Rate).[15] All in all, the integrated perspective in the period 1989–1997 suggests a clear latecomer position of BRICS. In the second period (2007–2015) BRICS have upgraded technologically but at different levels and following different paths. To analyse this upgrading process, we now focus on the BRICS profiles and on the changes in the respective indicators over time.

[14] A high share of high-tech patents and high NAFI rate for Russia in this period should be ascribed to small number of TN patents and to turbulent economic period.

[15] A high NAFI rate for Russia is aberration reflecting very low values and idiosyncrasies of the late socialist and early transition period.

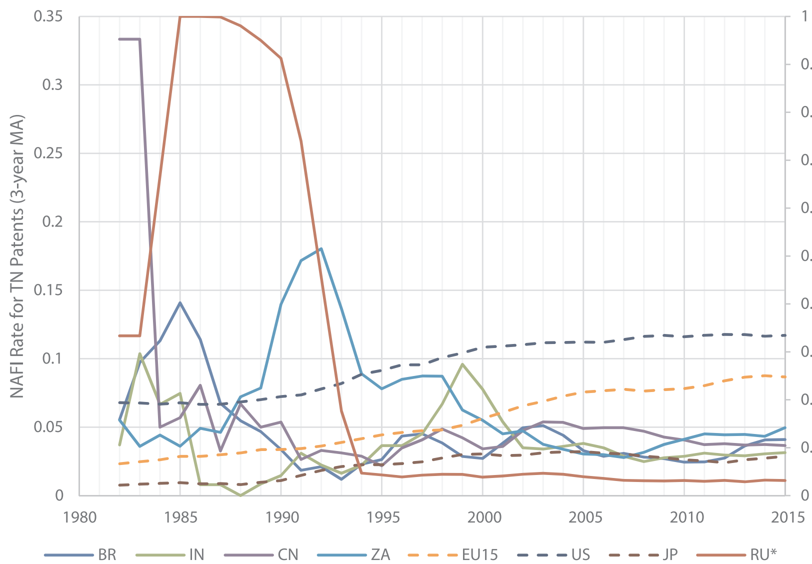

Fig. 8. NAFI Rate for Transnational Patents per priority year (3-year MA).
Note: Values of each indicator scaled between 0 and 1 across BRICS, US, EU15 and Japan in each period.
Source: Indicators elaborated by the authors using data from PATSTAT, OECD REGPAT and UNCTADstat.

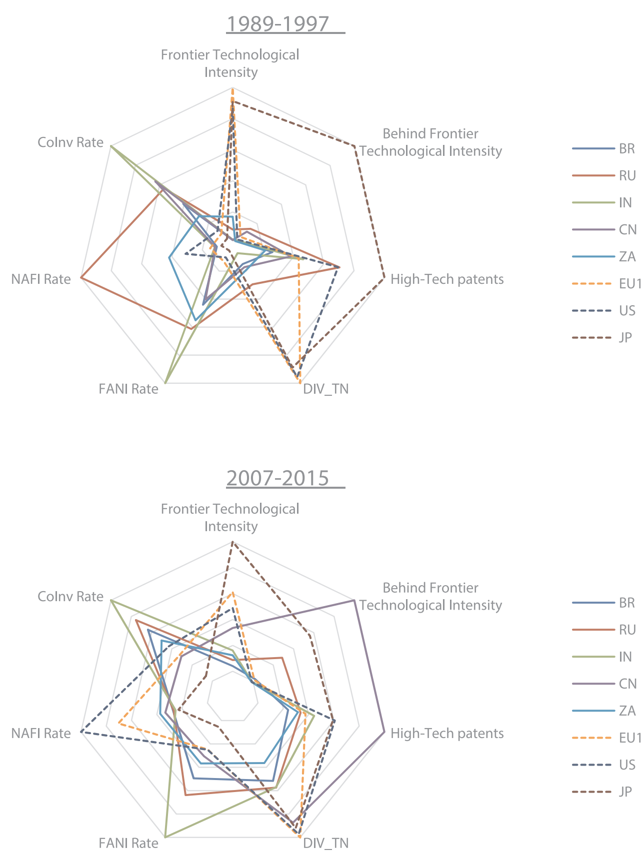

Fig. 9. Country profiles with relative indicators in the periods 1989–1997 and 2007–2015*.
Note: Values for each indicator scaled between 0 and 1 across BRICS within each period.
Source: Indicators elaborated by the authors using data from PATSTAT, OECD REGPAT and UNCTADstat.

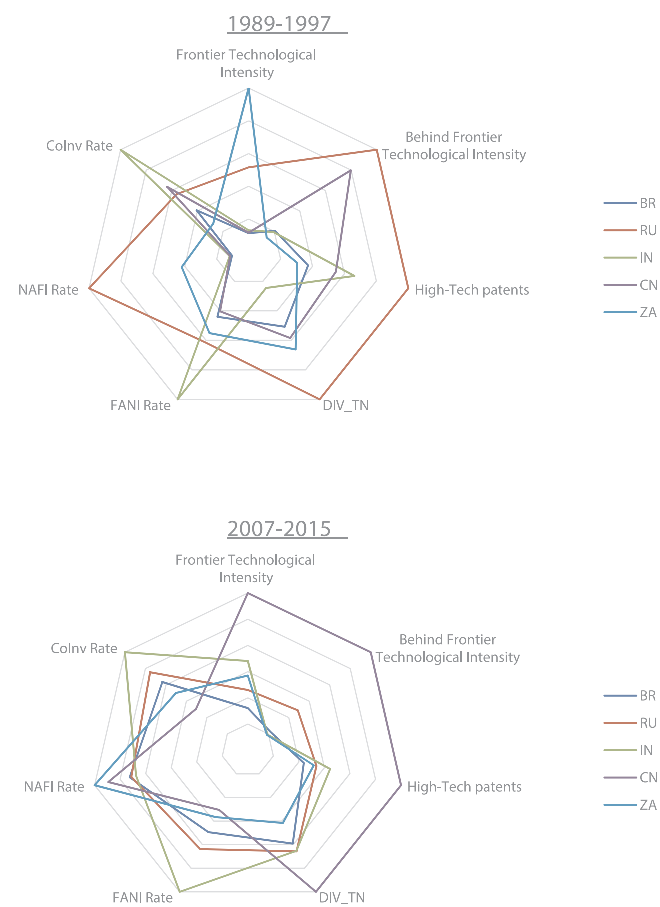

Fig. 10. BRICS technology upgrading profiles in the periods 1989–1997 and.2007–2015.

4.5. BRICS technology upgrading profiles in 1989–1997 and 2007–2015

Please note that we now rescale the indicators only across BRICS economies for each period. In the period 1989–1997 (see Fig. 10), Russia had a distinctive profile characterised by comparatively high technological intensity and by the highest share of high-tech and knowledge-intensive frontier activities among BRICS. South Africa still had a leading position regarding frontier activities, jointly with Russia.[16] All BRICS economies showed reasonably similar levels of low diversification across technological fields. Brazil had the lowest degree of global interaction, whereas India was relatively more engaged in co-generation of patentable knowledge compared to other BRICS economies. Overall, in the period 1989–1997 technology upgrading profiles of BRICS show unexpected homogeneity, which reflects their limited involvement in technology frontier activities and (except India) also a low degree of integration with the global economy at the time.

In the period 2007–2015, the relative positions had changed considerably. China has practically delinked from the BRICS group by its largely increased scale of behind the frontier and frontier technological activities, a very high share of patents in high-tech areas, as well as a high position in terms of diversification of the technological knowledge base. This reflects an increasing scale of technological activity as well as structural change. Simultaneously, the relative importance of foreign actors and international collaborations in frontier activities has been reduced to very low positions. This indicates strong domestic-led technology modernisation of China coupled with the strategic use of technology cooperation and sourcing of foreign knowledge. To some extent, India moved into the opposite direction, i.e. it enhanced foreign-led technology modernisation. It could not improve its relatively low position in terms of the scale of domestic and frontier technological activities and scored very low in dynamic frontier activities (high-tech patents). At the same time, India continued to be relying on foreign actors and on international collaboration for its frontier activities. Russia lost its leading position among BRICS in behind the frontier and frontier technologies as well as in dynamic frontier activities. It kept a relatively high degree of diversification, but its reliance on foreign actors and international collaboration in frontier activities was comparatively high (though below the Indian levels). South Africa also underwent dramatic changes, since the country lost its leading position in frontier technology and did not substantially diversify (in terms of an overall knowledge base as well as dynamic frontier activities). A particularity seems to be the relatively high rate of technology sourcing from abroad for frontier activities. However, a relatively large technology sourcing was not coupled with behind the frontier technology activities and thus seems to be of limited impact and as a substitute rather than a complement to frontier activities. The Brazilian case of technology upgrading is particular with respect to very few changes in the three dimensions. It kept its relatively high level of technology diversification but did not substantially increase the scale of behind the frontier and frontier activities. Brazil has also been characterised by limited levels of global interaction in both periods.

To analyse the upgrading process further, we calculate the changes in the values of the indicators of technology upgrading between the two periods for each BRICS individually (see Table 1). We include a *t*-test for the equality of each indicator between the periods 1989–1997 and 2007–2015.

The aggregate index of technology upgrading (TU Index) is the simple average of seven indicators of technology upgrading which enables us to compare degrees of changes in technology upgrading among BRICS. It is not surprising, based on the evidence so far, that India and China are the economies with by far the highest degree of change in their technology upgrading followed at some distance by Brazil, Russia and South Africa. China is well ahead of India regarding the intensity of changes in levels of technology upgrading, but India is catching up. On average, the increase between 2007–2015 and 1989–1997 is the biggest regarding frontier technology intensity followed by increased diversification of technological knowledge. The behind the frontier technological intensity has increased in China and Russia but decreased in other BRICS economies. A relative decline in knowledge interaction with global economy (FANI, COINV and NAFI) should be seen in the light of absolute strengthening of BRICS' technology capabilities, this last especially in China and only partly in India. These results are supported by the *t*-test on equality of indicators between the two periods (see the lower part of Table 1). Statistically, the most significant changes took place regarding diversification of technological knowledge (DIV-TN) and the reduced role of foreigners in commercialising national patents (FANI). Earlier analyses showed the dependencies of BRICS on foreigners for exploiting their technological capabilities (as captured by the FANI indicator) which now have been significantly reduced. BRICS still have limited capabilities in technology sourcing abroad (NAFI Rate) (see Figs. 6–8). The data in Table 1 shows that these dependencies are gradually being reduced.

4.6. Changing BRICS techno-economic specialisation profiles

In this section, we explore technology specialization by industries in BRICS. By using PATSTAT (2017b), it is possible to convert IPCV8 classes of patent applications to the NACE Revision 2 classification (see Van Looy et al., 2015; Schmoch et al., 2003; Schmoch, 2008), which we analyse at the level of 26 NACE 2-digit industries. We use the revealed technological advantage index (RTA), a concept developed for the country level by Soete (1987). RTA index measures the sectoral specialization of a country relative to the overall specialization of the country in relation to the reference group. In our case, the RTA index is calculated based on the number of transnational patent applications with at least one domestic inventor for each year in relation to all transnational applications by all BRICS and reference countries (EU, US, JP). The RTA index can be written as follows:

$$RTA_{ijt} = \frac{P_{ijt}/\sum_i P_{ijt}}{\sum_j P_{ijt}/\sum_{ij} P_{ijt}}$$

P denotes the number of all transnational patent applications with at least one domestic inventor. The indices denote the sector i, country *j* and year t. Values of RTA > 1 suggest that a country is comparatively specialised in a sector of activity in question relative to the reference group, whereas values of RTA < 1 are indicative of a position of comparative disadvantage. The degree of technological diversification of a country is measured by the inverse of the coefficient of variation (CoV) of the RTA Index, across all sectors of the country (see Cantwell and Piscitello, 2000). Therefore, for the country *j* in each period considered, the proxy DIVj for technological diversification will be reciprocal of the CoVj. In particular:

$$DIVj = \frac{1}{CoVj} = \mu RTAj\ /\sigma RTAj$$

where σRTAj is the standard deviation and μRTAj corresponds to mean value of the RTA distribution of country *j*. A decreased CoV indicates technology diversification or 'spreading' patenting spectrum across a larger surface. The emergence of more areas with positive RTA decreases CoV denoting knowledge diversification. So, the increase of inverse of CoV denotes increased knowledge diversification.

Fig. 11 shows increased knowledge diversification as a general trend in all BRICs which fully supports our hypothesis 3. This result confirms Lee (2013) proposition that at this level of development upgrading is about technology diversification. South Africa and Brazil were more

[16] This may seem puzzling as both economies for different reasons were closed economies during the 1980s. This status has forced them not only to 'reinvent the wheel' i.e. innovate behind the barrier but it also pushed them to invest more in R&D as a way to compensate for difficult access to technology.

Table 1
Changes in indicators and aggregate technology upgrading index 2007–15/1989–1997 (in %).
Source: Indicators elaborated by authors using data from OECD REGPAT, PATSTAT and UNCTADstat.

	Indicators Frontier technological intensity	Behind Frontier Technological Intensity	High-Tech patents	Diversification	FANI rate	NAFI Rate	CoInv rate	Avg. degree of change in TUI[a]
	% Change 2007–2015/1989–1997							
China	4228%	546%	315%	411%	−45%	22%	−73%	772%
India	1743%	−124%	52%	695%	−27%	−10%	−44%	327%
Brazil	440%	−44%	45%	248%	−18%	10%	−13%	95%
Russia	154%	49%	−23%	96%	−24%	−89%	−25%	20%
S. Africa	86%	−147%	136%	88%	−51%	−62%	1%	7%
BRICS average	1330%	56%	105%	308%	−33%	−26%	−31%	244%
	Mean BRICS							
1989–1997	0.19	3.99	0.07	107.89	0.32	0.10	0.17	
2007–2015	1.11	11.34	0.12	356.31	0.22	0.04	0.10	
paired *t*-test[b] p-Value	0.085	0.385	0.216	0.012	0.007	0.265	0.088	

Notes:
[a] Simple average degree of change in technology upgrading indicators (TUI) based on seven indicators.
[b] Null hypothesis (tested with a two-tailed *t*-test at the 5% significance level) is the equality of indicators between the two periods.

diversified at the start of the observation period, but Russia and China diversified rapidly to similar levels already in the 1990s. India remains less diversified than the other BRICS throughout the period. As expected, differences in technological diversification by this measure across 26 industries seems to be less pronounced compared to the prior analysis of diversification across 639 technological fields/IPC subclasses.

Table A3 (see Annex) shows the RTA indices for the period 2007–2015 and changes in the RTA indices compared to the period 1989–1997 for each of the BRICS economies. The key message here is that technological specialisation patterns are very much country specific. However, for the majority of the observed period, all BRICS seems to have specialised in what Lee (2013) call ‘long cycle technologies’ or sectors with relatively higher barriers to entry or accumulated technological capabilities. It is only China that in the last period (2007–15) has specialised in ‘short cycle technologies’ sectors (manufacture of computer, electronic and optical products, and manufacture of electrical equipment). The other BRICS economies are characterised by stronger specialisation of technological efforts into industries, which are closely related to natural resources, agriculture as well as selected services. However, Fig. 11 also shows that in the recent period China started to specialise as the inverse of its CoV has dropped significantly. Table A3 shows that in 2007–17 period China has only three sectors with positive RTA indexes of which two are ‘short cycle technologies’ related sectors which are high growth sectors. This again supports Lee’s (2018) argument that catching up of which China is the exemplar requires ‘detour’ to the short-cycle sectors with low entry barriers.

5. Discussion and conclusions

Based on the conceptualisation of technology upgrading as the three-dimensional process, we explored different paths of technology upgrading of the BRICS economies. We differentiate between the intensity of technology upgrading as depicted by different types and

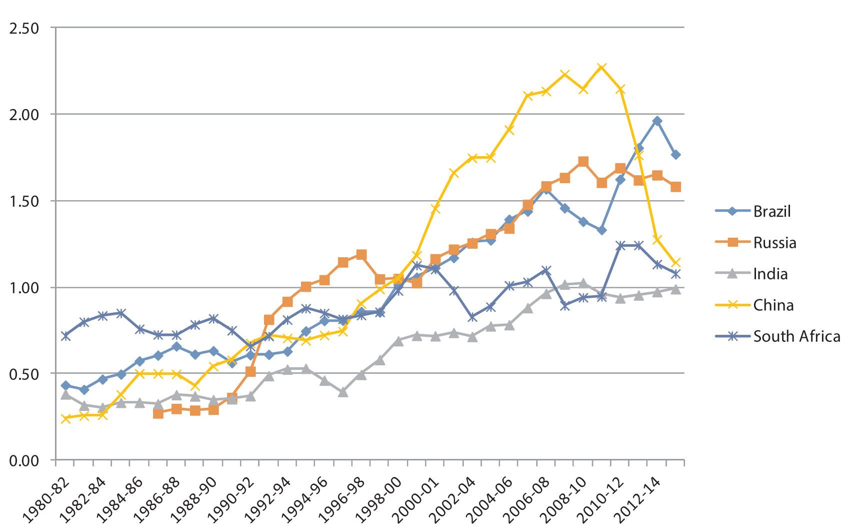

Fig. 11. Inverse coefficient of variation of RTA Indices (1980–2015)(based on 3-year moving averages)*.
Note: *For Russia the values are available starting 1987.

levels of innovation capabilities, the extent of technology upgrading in terms of changes to the structure of technological knowledge, as well as the role of global interaction in terms of inflows of foreign technology and coupling with domestic technological efforts.

We have formulated five general hypotheses on the characteristics of technology upgrading of middle-income economies such as BRICS. We have applied this three-pronged approach to technology upgrading by using different patent indicators to test these hypotheses. Our evidence shows that hypotheses one and three have been confirmed in the case of the BRICS economies since the generic trends are increased technology intensity reflected in the accumulation of innovation capability (hypothesis one) and increased diversification of technological knowledge (hypothesis three). Hypothesis two on changes in the structure of technological knowledge (captured by the increasing proportion of high-tech and knowledge-intensive patent applications) has been confirmed in all BRICS apart from Russia.

As part of the analysis of technology intensity, we have explored the relationship between innovation capability pushing the technological frontier and innovation capability behind the world technology frontier. All BRICS have increased frontier technology activities. However, we find that increased or stable share of behind the frontier intensity has been present only in the case of China and Russia while it seems that in other BRICS available foreign knowledge substitutes for domestic technology effort. This shows that the relationship between frontier and behind frontier technology activities is country specific and reflects the nature of modernisation of the individual BRICS economy and how it interacts with the globalisation processes.

Hypothesis four refers to global interactions in the process of technology upgrading and the role of organisational capabilities. It assumes that as countries' incomes grow and technological capabilities upgrade, they can move from the stage where foreigners have an essential role in protecting and exploiting the commercial potential of national inventions into a process of knowledge co-generation and technology sourcing from abroad. Indeed, our evidence shows that before the globalisation of the 1990s/2000s, BRICS economies showed a relatively high dependence on foreign actors in their frontier activities when compared to advanced economies. This dependence decreases over time. Also, the relative (not absolute) reduction in international co-inventions is interpreted as the reduced dependence of BRICS economies in technology transfer. In this respect, differences among BRICS are quite significant suggesting different dependency degrees on technology transfer to develop frontier technologies, as well as the various international strategies in their technology upgrading process.

BRICS economies have improved their technology sourcing capabilities, but we do not yet see catching up in that respect or an increase in their organisational capabilities to source technology from abroad. These results suggest some degree of caution is needed, regarding the relevance of technology seeking strategies for outward FDI by emerging market firms as emphasised in recent firm-level investigations (see, for example, Mathews, 2006; Li, 2010; Ramamurti, 2012; Narula, 2012; Jindra et al., 2016). Overall, trends in global interaction suggest that organisational capabilities or complementary assets of the BRICS economies are still significantly low when compared to the US and EU15. In that respect, our hypothesis four has not been fully confirmed.

The novelty of our inquiry is not only in the depiction of trends and ranking of BRICS but in a better understanding of the profiles of their technology upgrading over time which, in turn, can help us understand prospects for their long-term growth. Hypothesis five suggests that interaction among the proposed three dimensions of technology upgrading lead to nationally specific paths and profiles of technology upgrading. The evidence shows that there is no single path of technology upgrading within the group of BRICS economies. Instead, we find several unique profiles of technology upgrading with different trade-offs between intensity, structural change and nature of interaction with the global economy.

China is unique among the BRICS economies in its scale of technological intensity (both behind and at the frontier), the very rapid improvements of the technological intensity, fast structural change in the direction of dynamic frontier activities, and technology diversification. The substantial increases of China in the intensity of frontier technological activities as well as the evidence of the diversification of technological knowledge in China seems to be similar to observations made by Lee (2013, 2018) for South Korea and Taiwan in earlier periods of successful and rapid technology upgrading.

At the same time, China displays a decreasing reliance on foreign actors to protect and potentially exploit its inventions. This also reflects increasing technology bargaining and difficulties between Chinese and foreign firms in ensuring the mutually beneficial sharing of gains from knowledge generation activities (Holmes et al., 2015). Yet, China has not yet reached a stage where it can engage in knowledge co-generation and technology sourcing at levels similar to advanced economies. This is also reflected in its dominance of behind the frontier technology intensity as compared to frontier technology intensity, where it still lags behind the high-income economies (in particular Japan). However, it is well ahead of other BRICS regarding terms of technology sourcing from abroad and corresponding organisational capabilities. The example of China suggests that there are dynamic complementarities between increased intensity, structural change and its specific modes of technology integration which also reflects its strong bargaining position in technology transfer.

India represents quite a different technology profile of technology upgrading when compared to China. It is much more technologically integrated when compared to China, as reflected in higher dependence on foreign actors and international collaboration in frontier activities, but very low technology sourcing from abroad. Its most significant difference, when compared to China, is not only lower frontier technology intensity but low behind the frontier technological intensity. This reflects a much more open technology system of India when compared to China. Although of very different nature, India's technology upgrading has improved most regarding frontier technology intensity and diversification of technology base and has further downscaled its behind the frontier technology effort.

Brazil represents the intermediate case in between the different paths of China and India and the non-dynamic paths of Russia and South Africa. Its technology frontier intensity has improved, and the structural change in the knowledge base seems to be heading in the direction as predicted by our hypotheses. However, its behind the frontier intensity has not increased significantly, which suggests the substitutive effect from its technology openness.

Russia and South Africa displayed comparatively low dynamics with modest improvements regarding frontier technological intensity and increased the breadth of technology upgrading (though less than India). The significant difference between these two economies is that Russia (though much less than China) has grown the relative scale of behind the frontier technology activities which have all but disappeared in the case of South Africa. Similar to India, the behind the frontier technology intensity of South Africa has decreased, while in Russia it is the other way around. This suggests that the basis for the long-term technology-based growth of Russia and South Africa are not only more limited but are also qualitatively different.

Overall, our analysis has applied a new conceptual approach to exploring paths of technology upgrading of middle-income economies at the example of the BRICS economies. We have developed a new statistical framework which is suitable for exploring the extent to which different paths of technology upgrading represent the basis for long-term sustainable growth. Although being a multidimensional framework, it enables comparative analysis of technology upgrading while still retaining the link between indicators and the concepts. This should make our approach useful as an assessment tool to be used for policy purposes. Equally, it is conceptually and theoretically ambitious approach, which can be further developed theoretically.

The main limitation of our analysis is that it is based on hypotheses of a general nature, which are relevant for middle-income economies. These are tested on BRICS economies only and capture only innovation capabilities of technology upgrading but not R&D and production capabilities. So our approach should be extended further by enlarging the scope of countries based on patents indicators and by extending the approach combining patents with other indicators.

Appendix A

Table A1
Overview of variables and measurement.
Source: Authors.

Variable	Measurement	Source
Intensity of technology upgrading		
Innovation capability pushing the world technology frontier (TN)	Number of transnational patent applications[a] per 1 billion GDP (in US$ constant prices 2010)	PATSTAT 2017, UNCTADstat
Innovation capability behind the world technology frontier (B.-Frontier)	Mathematical difference between the priority filings[b] count and the transnational patent applications count per 1 billion GDP (in US$ constant prices 2010)	PATSTAT, 2017, UNCTADstat
Breadth of technology upgrading		
Knowledge intensity of technological activities (HTKI)	Share of patent applications in high technology fields[c] and knowledge-intensive services (HKTI) in all transnational patent applications with at least one domestic applicant (1980-2015)	PATSTAT, 2017
Diversification of the technological activities (DIV)	Number of IPC subclasses (in total 639 fields) in which each country filed transnational applications	PATSTAT, 2017
Global Interaction in technology upgrading		
Extent to which the exploitation of frontier technology in an emerging country is driven by foreign actors (FANI-Rate)	Number of transnational patents applied by foreigners and invented by natives[d] (FANI) divided by the total number of transnational patents with at least one national inventor (FANI-Rate)	OECD REGPAT (2018)
International technological collaboration (Co-Inv Rate)	Share of transnational patent applications resulting from international technological co-invention (COINV) in the total number of patents by inventors located in a given country (COINV-Rate)	OECD REGPAT (2018)
Extent to which frontier activities of emerging economies are based upon technology sourcing from abroad (NAFI-Rate)	Share of transnational patent applications with a native applicant and at least one inventor located abroad[d] (NAFI) in the total number of transnational patents with at least one national applicant in the (NAFI-Rate)	OECD REGPAT (2018)

Notes:
[a] Transnational patent applications are patents filed at the European Patent Office (EPO) or international patents filed under the Patent Cooperation Treaty (PCT), avoiding double counting. (Frietsch and Jung, 2009).
[b] A priority filing is the earliest patent application in the patent family regardless of the patent authority where it was filed. (De Rassenfosse et al., 2013).
[c] High technology fields and knowledge-intensive services (HTKI) are defined according to the EUROSTAT definition: (http://ec.europa.eu/eurostat/cache/metadata/Annexes/htec_esms_an6.pdf).
[d] FANI and NAFI indicators are defined based on (Guellec and van Pottelsberghe de la Potterie, 2001).

Table A2
Absolute values of indicators used along the paper (years 1985, 1995, 2005, and 2015).
Source: Authors' own elaboration.

Yr.	Indicators	BR	RU	IN	CN	ZA	EU15	US	JP
1985	Population(m)	135.7	143.9	781.7	1051.0	33.7	360.2	237.9	120.8
	GDP (b$)	1102.9	–	341.3	564.3	205.3	9379.7	7727.5	3669.9
	Frontier (TN)	34.4	–	13.0	48.5	71.3	21632.6	11633.8	6744.3
	B.-Frontier	1986.3	489.7	544.6	4573.8	272.6	50015.5	18547.0	255449.6
	HTKI	2.9	–	0.2	2.8	1.2	1369.1	1299.6	901.0
	DIV	43	–	18	74	89	604	573	505
	FANI-Rate	0.374	0.000	0.530	0.323	0.169	0.051	0.044	0.016
	Co-Inv Rate	0.146	0.000	0.268	0.195	0.038	0.015	0.019	0.007
	NAFI-Rate	0.141	1.000	0.075	0.057	0.036	0.029	0.068	0.009
1995	Population(m)	162.3	148.4	960.5	1204.9	42.1	373.1	266.3	125.4
	GDP (b$)	1401.0	879.0	596.6	1473.5	232.7	11986.7	10377.9	5063.8
	Frontier (TN)	87.5	309.3	41.1	107.4	124.2	35140.6	28500.4	13396.5
	B.-Frontier	2594.4	10463.9	1281.5	8742.1	285.4	41139.7	22618.6	282837.7
	HTKI	3.7	24.7	0.8	15.8	6.6	2818.4	3479.0	2266.9
	DIV	117	237	47	144	128	608	580	551
	FANI-Rate	0.257	0.318	0.500	0.163	0.336	0.075	0.055	0.034
	Co-Inv Rate	0.118	0.155	0.345	0.121	0.090	0.029	0.039	0.015
	NAFI-Rate	0.026	0.043	0.036	0.022	0.078	0.044	0.092	0.023
2005	Population(m)	186.9	143.5	1144.1	1303.7	48.8	388.5	295.5	127.8
	GDP (b$)	1774.8	1281.3	1107.2	3551.1	322.2	15091.1	14513.4	5672.3
	Frontier (TN)	395.7	809.3	1185.1	3822.2	435.1	69941.0	60052.2	36462.1
	B.-Frontier	3578.9	21888.9	−446.9	81010.8	−26.6	28651.8	13779.2	265687.4
	HTKI	19.5	93.7	106.6	1475.1	32.6	7515.4	9566.7	6300.3
	DIV	244	322	262	465	240	615	611	565
	FANI-Rate	0.206	0.291	0.240	0.204	0.103	0.098	0.097	0.027
	Co-Inv Rate	0.112	0.169	0.134	0.113	0.053	0.048	0.062	0.013
	NAFI-Rate	0.033	0.040	0.038	0.049	0.030	0.076	0.112	0.032
2015	Population(m)	206.0	144.1	1309.1	1371.2	55.3	404.9	321.0	127.1
	GDP (b$)	2331.9	1631.8	2293.1	8862.6	418.4	16454.7	16768.2	5979.7
	Frontier (TN)	714.7	1022.5	2729.7	34218.5	296.8	73063.4	59839.6	48582.6
	B.-Frontier[a]	1171.3	25542.4	−95.0	576408.9	−283.1	26693.2	3433.5	156961.2
	HTKI[a]	42.8	140.2	289.3	5579.2	31.9	6502.0	9511.9	6471.6
	DIV	337	338	398	559	218	616	594	569
	FANI-Rate	0.224	0.257	0.431	0.102	0.144	0.097	0.091	0.018
	Co-Inv Rate	0.114	0.114	0.179	0.027	0.082	0.053	0.069	0.009
	NAFI-Rate	0.041	0.031	0.031	0.037	0.050	0.087	0.117	0.029

[a] Data for 2013.

Table A3
RTA Indices for the period 2007–2015 and changes in the RTA Indices compared to the period 1989–1997.[a]

NACE code	NACE description	Brazil RTA Index 2007–2015	Brazil Change 1989–1997	Russia RTA Index 2007–2015	Russia Change 1989–1997	India RTA Index 2007–2015	India Change 1989–1997	China RTA Index 2007–2015	China Change 1989–1997	South Africa RTA Index 2007–2015	South Africa Change 1989–1997
10	Manufacture of Food Products	2.17	0.92	1.18	0.18	1.25	0.10	0.66	−0.87	1.62	−0.14
11	Manufacture of Beverages	2.84	−1.16	2.96	0.61	1.22	−1.06	0.61	−1.76	3.17	1.59
12	Manufacture of Tobacco Products	1.38	0.64	1.25	0.41	0.26	0.26	3.83	−2.10	2.77	−0.08
13	Manufacture of Textiles	1.25	0.53	0.33	0.13	1.14	0.74	0.68	0.03	0.82	0.15
14	Manufacture of Wearing Apparel	1.77	1.01	1.28	0.22	0.35	0.35	0.92	−1.90	3.13	2.41
15	Manufacture of Leather and Related Products	2.72	0.66	1.18	−0.33	0.17	−1.39	0.78	−1.39	1.81	1.81
16	Manufacture of Wood and of Products of Wood and Cork, Except Furniture; Manufacture of Articles of Straw and Plaiting Materials	1.05	1.05	1.14	−0.85	0.07	−3.16	0.62	−2.37	0.38	−4.41
17	Manufacture of Paper and Paper Products	1.58	−0.22	1.40	0.87	0.57	−0.28	0.61	−0.81	1.14	−0.94
18	Printing and reproduction of recorded media	0.83	0.05	1.84	0.70	0.32	0.25	0.30	−0.69	0.42	−0.62
19	Manufacture of Coke and Refined Petroleum Products	2.52	0.62	2.65	−0.85	2.51	−5.83	0.58	−4.27	4.40	2.92
20	Manufacture of chemicals and chemical products	1.60	0.69	0.99	−0.01	1.54	−0.36	0.56	−0.30	1.07	0.06
21	Manufacture of Basic Pharmaceutical Products and Pharmaceutical Preparations	1.26	0.65	1.21	0.36	3.56	−0.88	0.73	−0.69	0.83	0.21
22	Manufacture of Rubber and Plastic Products	1.05	0.29	0.53	0.10	0.38	−0.13	0.36	−0.34	0.66	0.10
23	Manufacture of Other Non-Metallic Mineral Products	0.94	0.24	0.80	−0.55	0.54	−0.08	0.55	−0.56	0.86	−0.68
24	Manufacture of Basic Metals	1.76	0.16	2.01	−0.91	0.53	−0.03	0.76	−0.88	3.23	0.98
25	Manufacture of fabricated metal products, except machinery and equipment	0.82	−0.10	1.42	−0.05	0.42	0.00	0.55	−0.34	2.05	0.45
26	Manufacture of computer, electronic and optical products	0.41	0.02	0.91	−0.01	0.90	0.34	1.72	1.05	0.47	−0.04
27	Manufacture of electrical equipment	0.91	−0.42	0.68	0.05	0.50	0.09	1.10	−0.28	0.82	−0.19
28	Manufacture of machineryand equipment	1.20	0.01	1.08	0.04	0.66	0.22	0.69	−0.21	1.17	0.11
29	Manufacture of motor vehicles, trailers and semi-trailer	0.99	−0.13	0.58	−0.29	0.55	0.12	0.33	−0.85	0.69	−0.10
30	Manufacture of Other Transport Equipment	1.53	−0.49	1.91	−1.39	0.47	0.22	0.67	−1.04	1.64	−0.12
31	Manufacture of Furniture	1.85	0.58	0.83	0.77	0.29	0.29	0.78	0.28	2.72	−0.36
32	Other Manufacturing	1.35	−0.83	1.08	0.02	0.57	0.23	0.59	−0.64	1.41	−0.18
42	Civil engineering	2.80	−1.06	1.64	−0.62	0.83	0.83	0.90	0.90	3.07	1.85
43	Specialised Construction Activities	1.90	0.69	1.76	1.27	0.37	0.12	0.81	−0.65	3.09	−0.71
62	Computer Programming, Consultancy and Related Activities	0.95	−0.21	1.38	0.51	2.86	2.12	0.80	−0.03	3.51	1.55

Note:
[a] Due to missing data for Russia between 1980 and 1986, we choose 1989–1997 as a period for comparing RTA Indices with the period 2007–2015.

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