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Multidimensional Connectivity

Benefits, Risks, and Policy Implications for Europe and Central Asia

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Abstract

International connections through trade, foreign direct investment, migration, the Internet, and other channels are critical for the transmission of knowledge and growth and form macroeconomic linkages. But how much knowledge is transmitted to a country is not only the result of the overall level of connectivity, but also to whom a country is connected, as well as how these connections complement each other. For example, being well-connected to an economy with wide-reaching global connections is likely to be a stronger conduit for knowledge transfers than being connected to an isolated economy. Likewise, connections are likely to complement each other. For example, ecommerce is often seen as a benefit of Internet connectivity, but without transport connectivity, ecommerce may not amount to much. This wider definition of connectivity, referred to as multidimensional connectivity, is broadened and explored in this study as it applies to Europe and Central Asia. Focusing on countries from the Europe and Central Asia region, the paper shows that multidimensional connectivity is an economically and statistically important determinant of future economic growth. The paper further discusses the potential risks and transfer of shocks that can result from cross-country economic connectivity. Furthermore, it provides some examples of how policy tools can be designed to leverage the benefits of connectivity channels and mitigate their risks.

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Multidimensional Connectivity: Benefits, Risks, and Policy Implications for Europe and Central Asia[1]

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1. Introduction

Increased trade and financial relations together with various macroeconomic variables, such as exchange rates, interest rates, and equity prices, have resulted in increased economic linkages among countries. This has been further expedited by the growing global integration, and the cross-border flow of trade, migration, technologies and knowledge. As such macroeconomic linkages increase, the debate has grown regarding the benefits and risks that result from such cross-border linkages, or connectivity.

Investigating the role of connectivity across countries and across different economic activities has resulted in three main findings. First, regional connections through trade, FDI, migration, telecommunications and other channels over the past two decades have risen more rapidly than ECA's connections outside the region, in part reflecting policies geared to increasing regional integration and the rising importance of regional value chains. However, countries in ECA that are linked to strong globally-connected ECA countries, for example Germany or Great Britain, may nevertheless have experienced substantial increases in global connectivity as well. Among connectivity channels, ECA's intraregional trade links are stronger than FDI links, while airline connections and labor market integration have increased sharply among European countries. Second, network connectivity measures for trade, FDI, migration, information and communication technology, airline flights and portfolio flows are all positively related to growth, and each is associated with higher growth over and above the influence of standard growth determinants. However, not all channels play an equally important role. Trade connectivity is perhaps the most important and is related to overall growth and the income growth of the bottom 40 percent of the income distribution. Increasing linkages in each form of connectivity are associated with higher growth, but at a decreasing rate, suggesting that a balanced connectivity profile along all dimensions of connectivity is more important than a large increase in one channel only. The growth impact of multidimensional connectivity is higher than the impact of each of the individual network indices, suggesting that overall connectivity is more important than each of the individual channels separately. Thus, policies to promote connectivity across trade, migration and FDI are likely more beneficial than focusing on enhancing only one channel, and reducing connectivity in one dimension may reduce the impact of growth from other channels. Third, greater international connectivity can increase a country's exposure to international shocks, but may also mitigate shocks by enabling a country to increase its reliance on other links in its network. Both countries with low and high levels of connectivity tend to be more resilient to shocks in the global network, the first because of the limited number of partners that may become a source of shocks, the second because well-diversified connections may provide alternative sources of, for example, finance or export demand. By contrast, countries in the "middle" of the connectivity spectrum, that is, those that are highly dependent on a few well-connected countries, appear to be most susceptible to shocks that originate from, or affect, these countries.

Globalization often means different things to different people. For some, it is the large number of imported goods seen on store shelves. To others it is a social phenomenon that includes everyday exposure to a wide variety of cultures, peoples, foods, products, and spoken languages. In major cities throughout Europe and Central Asia (ECA) the change is perhaps most apparent, while in smaller towns or villages it may be less so. In Central Europe the look and feel of major cities is very different now than before the transition to market economies in the early 1990s. But even in the small towns in Western Europe, integration brought by the European Union and greater global connectivity has changed the look and feel of everyday life and economic opportunities. Regardless of where one is physically located, or how one observes globalization, the interconnectedness of the world is increasingly touching us either directly by the people we encounter or indirectly through the items we purchase or foreign firms that employ us.

Since the early 1990s, the ECA countries have been radically transformed, as borders were opened and many hurdles impeding cross-border connectivity were lowered. The move towards the common market in the European Union and the fall of the Iron Curtain had impacts well beyond trade – including positive impacts on income and income distribution. This trend towards income convergence with developed countries occurred despite intermittent external shocks, suggesting, in turn, that economic connectivity to regional and global markets has likely been an important driver of growth and improved standards of living. Since 2008/09, the global financial crisis, deepening geo-political tensions, the refugee influx and sharp commodity price fluctuations have posed new challenges for the region, pointing, *inter alia*, to the need to more fully understand the role that economic connectivity can play in preserving economic growth and incomes in times of political and economic flux.

ECA's international economic bilateral connections with other countries and regions has expanded sharply over the past three decades, owing to greater global integration driven by lowering of costs to economic transactions, the breakup of the Soviet Union, and increasing integration within, and expansion of, the European Union. Enhanced international connectivity generally has been associated with growth, through the transmission of technologies across borders. This transmission is most effective when deep connections exist across different channels, and when countries are connected to other, well-connected countries. This paper discusses the multidimensional character of connectivity. It assesses the impact of improved connectivity on income and income distribution, and it addresses the question of whether the region is optimally connected to other economic poles in the world.

Much of the empirical work done to date has recognized the importance of openness for economic growth, including through trade, foreign direct investment (FDI), the internet (information, communications, and technology—ICT), migration, and other forms of connectivity (Dollar, 1992, Sachs and Warner, 1995, Ben-David, 1993, Edwards, 1998, Frankel and Romer, 1999, and Javorcik and Smarzynska, 2004, among others). While there are many nuances to the empirical findings, and questions remain regarding causality between outcomes and policies (Rodriguez and Rodrik, 2000), the association appears to be strong and intuitively appealing. Technologies embodied in goods, investments, and people are likely to be transmitted across borders, as long as the source and host countries are open and have the capacity to absorb these innovations. In other words, in addition to the gains from specialization that openness brings through each layer of connectivity, knowledge spillovers are also likely created. This leads not only to one-time increases in output, but also, in the context of endogenous growth theory, long-term increases in economic growth as the cost of acquiring new knowledge falls with an increasing stock of knowledge (Helpman, 2004; Romer, 1990).

To date, economic research has only examined one dimension at a time of partner connectivity and the relationship to economic growth. One main area of research has focused on macroeconomic linkages resulting from exchange rates, following the Mundell–Fleming model, which discusses how being an open-economy or incorporated into the global economy, means that a country has to adopt a strategic choice making behavior in handling volatilities of its macroeconomic variables especially the exchange rates (Fleming, 1962; Mundell, 1961, 1963). Furthermore, some research has focused on the link between monetary policies and interest rates across different countries (see for example Kung, 2015). Empirical research is available on the relationship between various types of trade and economic growth, FDI and growth, the internet and growth, and migration and growth (Alfaro 2004; Borensztein 1998; Mountford 1997; Czernich 2011). More recent work has focused on using a global vector autoregressive model on different measures of macroeconomic linkages, to identify channels of shock transmissions (Hassan et al., 2017). But empirical and theoretical work has yet to examine how the *interplay* between these various layers of connectivity complement each other. For example, internet connectivity has various direct avenues for influencing economic growth, including providing individuals the ability to quickly research products available in foreign countries, take online courses, and transact in services remotely, as well as serving as the backbone to facilitate greater deepening of cross-border global supply chains. E-commerce has been greatly enhanced by the availability of broadband internet. Nonetheless, without transport connectivity through roads, rail, shipping, and air transport, the effects of broadband connectivity as a channel to stimulate growth via e-commerce would be greatly diminished.

More telling regarding the interplay between various forms of connectivity, is the role of migration and international travel, be it for permanent migration, foreign study, or tourism. While Gould (1994) first identified the complementary relationship between migration and trade between the home and host countries of migrants, subsequent research has also identified migration's importance in influencing FDI and its direct influence on growth through knowledge transfers (Onodera 2008). Consequently, migration may not only be important for growth by directly transferring knowledge between the host and home countries, but also by facilitating knowledge embodied in trade and FDI flows through bridging market information gaps.

This paper finds that being connected to well-connected countries matters for economic growth, but there is complementarity in the various types of connections that enhances growth as well. Countries can benefit from: (i) multiple types of economic links (such as trade, investment, migration, modern telecommunications, and transport) that underpin the movement of technologies and ideas; but also, (ii) the quality of connections in terms of knowledge spillovers and the indirect connections made through partners that are well connected. These are both aspects of inter-connectedness that affect growth and growth spillovers.

2. Trends in Economic Connectivity

A fundamental prerequisite for identifying the complementarity between various forms of connectivity is the ability to identify the specific country links in the connectivity chain. For example, matching migration and trade flows between country partners is essential to identify the complementarity between migration and trade in enhancing economic growth. Knowing the size of overall trade and migration flows for a country is not sufficient to identify that trade from specific countries is facilitated by migration from those same countries.

Mapping these direct connections between countries also brings to light the potential importance of indirect connections. While two similar countries may have the same number and size of connections, they may be connected to very different countries. Being connected to "well-connected" countries may provide greater opportunities for knowledge transfers from partners of partner countries (Duernecker, Meyer, and Vega-Redondo, 2014). For example, a dollar of trade between Algeria and Germany may provide greater knowledge spillovers than a dollar of trade between Algeria and Morocco, because Germany is much more connected to the global economy and is likely to be a source of advanced knowledge as well as a conduit for technology and knowledge from other countries it is connected to.

The importance of direct and indirect connections between countries, as well as the complementarity between various types of connections for knowledge transfers and economic growth, lends itself to the use of *multilayer network analysis*. Network analysis is simply a tool to study the direct and indirect connections between countries. Multilayer networks (Kivela et al., 2014) go beyond the notion of a single, one dimensional isolated network, and provide a description of the interactions between various types of connections (layers) in a larger network.

Economic links facilitate trade and the transfer of factors of production (capital, labor, etc.) and therefore impact the overall level of production. However, these links are also likely to facilitate the flow of ideas and innovation, and, hence, long-run growth. But the strength of information flows is likely different for different economic connections. For example, the knowledge spillovers associated with merchandise trade are likely centered around the information embodied in the products traded (knowledge spillovers related to trade in processed food, for example, may be different from those related to trade in semiconductors).[2] FDI links are associated with a transfer of managerial, organizational, and corporate governance expertise. And migration flows can facilitate the transfer of knowledge directly, but also support less tangible cultural exchange, increase exposure to foreign languages, and bridge gaps in trust in business dealings that cannot always be narrowed through explicit contracting, particularly with differences in governance and legal systems.

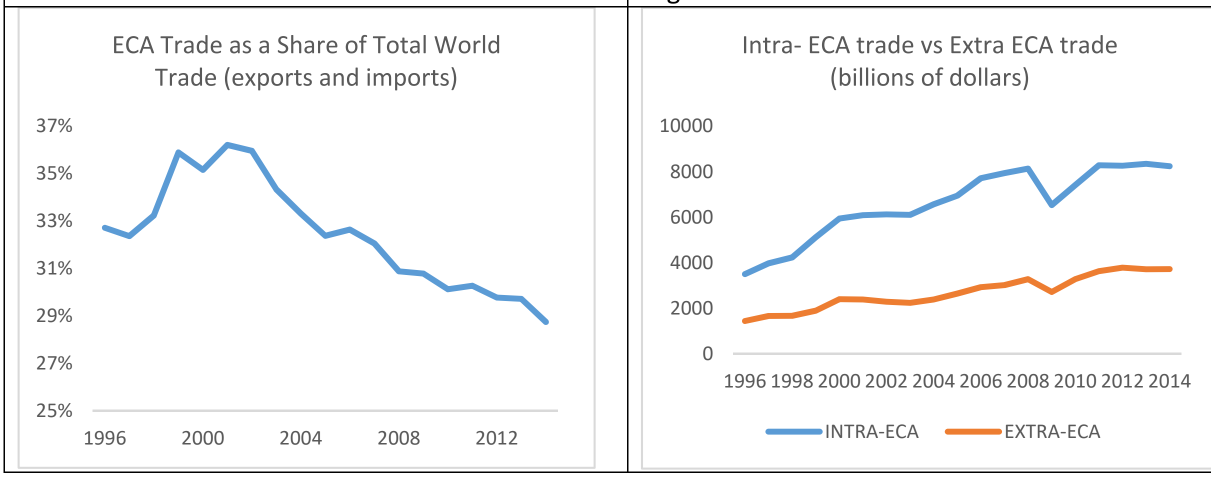
As mentioned above, country and regional connectivity has typically been viewed as the size of trade relative to GDP or global trade. ECA's share of global trade has declined since the early 2000s (figure 1a). Moreover, although intra-regional and extra-regional trade have grown, intra-regional trade has grown more rapidly (figure 1b). Increased trade within ECA may reflect greater cooperation across institutional and regulatory dimensions with important implications for regional integration and convergence. Similar aggregate measures of connectivity (total FDI, migration, telecommunications, etc.) suggest that while regional integration has increased substantially, growth of global connections may not have kept up.

While past studies find evidence that greater trade openness and integration improves growth, these aggregate measures of integration may obscure the underlying bilateral connections and the importance of partner country connections. In other words, while ECA's intra-regional connectivity may be growing faster in the aggregate than extra-regional connectivity, it is difficult to determine how well ECA countries are connecting to other ECA countries that are well connected globally. ECA global connectivity may actually be increasing for the average ECA country, if countries in ECA are linking to strong globally connected ECA countries. The following section examines the pattern of connections between countries and how countries are connected to the broader network of countries. Subsequently, the section uses this wider network of connectivity information to analyze types of connectivity, how the various layers of connectivity interact, and how connectivity might be associated with economic growth and shared prosperity.

[2] See Hidalgo, C. and Hausmann, R., 2009.

Figure 1: Trends in intra-regional trade in the ECA

a. ECA's share of global trade has been falling	b. Intra-regional trade growing faster than extra-regional trade



Source: Author's calculations based on UNCTAD and World Bank Development Indicators

While there are potentially hundreds of ways countries can connect with varying implications for the transfer of ideas, this paper focuses on six types of economic connections: trade, FDI, migration, information and communication technologies (ICT), air transport and portfolio financial flows. A summary of the data used is provided in Table 1. While other forms of connectivity may also be important for how knowledge transfers between countries and for economic growth, these data are the only ones available on a global and country to country basis. Subsequent sections will drill down into additional layers of connectivity (for example, land transport in ECA) as well as unique aspects of the layers of connectivity. This paper takes a broad macro view of the many layers of connectivity as a means to observe general trends in the strength of connections, how ECA countries are connected to each other and the rest of the world, and how these connections influence growth.

Table 1. Data used for measuring economic connectivity, including the data sources and sample period.

Indicator Name	Description	Coverage
FDI	Total bilateral FDI stocks. Source: OECD	2002-2013
Trade	Bilateral total trade flows for manufacturing goods. Source: UNCTAD	2000-2015
Migration	Total migration stocks. Source: Individual Countries' Census Data, OECD and World Bank estimates (See Artuc et. al 2017)	2000 and 2010

ICT	Proxy for ICT flows. Estimated by combining bilateral duration of phone conversations and the bandwidth capacity between countries. Source: Derived from TeleGeography data.	2003-2011
Airlines	Estimated bilateral number of flights (end destination) Source: ICAO	2002-2012
Portfolio Flows	Total bilateral portfolio flows. Source: BIS, Consolidated Banking Statistics (CBS)	2000-2014

As an initial overview of ECA connectivity in the global context, we show graphically how countries in ECA and the rest of the world are connected in each layer of connectivity. We show data for the initial year and the last period available to see how connectivity in a particular dimension has changed over time. In Figures 2 to 7, ECA countries are highlighted in shades of blue, and the rest of the world is shown in shades of orange. The size of each country-node is proportional to the size of its total connectivity in each layer of connectivity described. Outward arrows point to the two strongest bilateral partners. The methodology for plotting the countries attempts to show clearly the connections between countries in the global network of countries.[3] The largest country-nodes are pulled to the outer boundaries of the graph, but the pull is counterbalanced by the number and strength of connections with partner countries. Consequently, country-nodes will tend to be grouped together if they share common connections with well-connected countries.

Trade

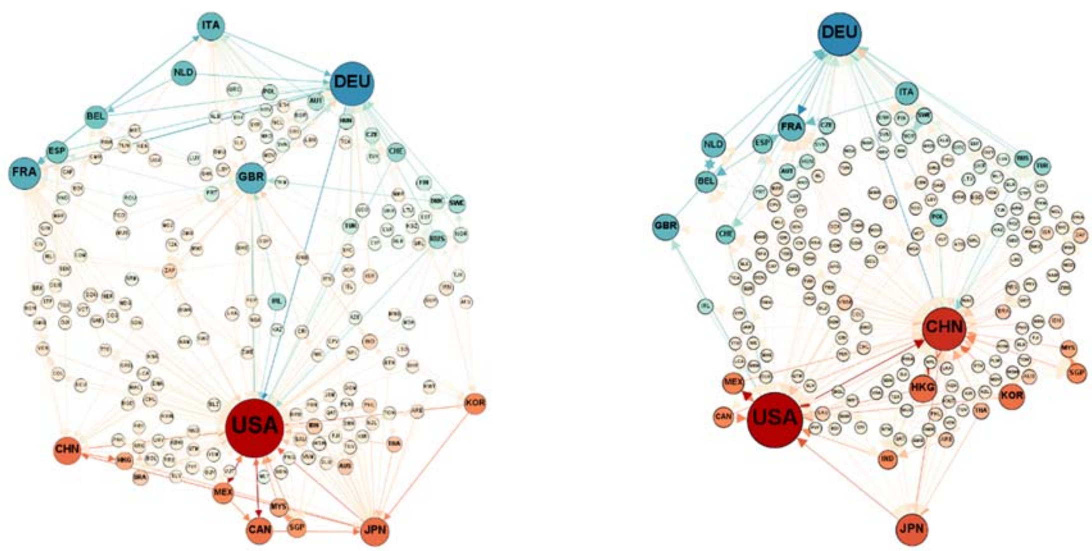
Figure 2 is based on trade of manufactured goods between all the countries in the world in 2000 and 2014. The size of each country-node reflects the total volume of trade (exports and imports) for each country, and the two outward arrows are pointed to each country's two top export destinations. One of the most dramatic developments in global trade has been the emergence of China (CHN) since 2000, which has not only grown to one of the three largest traders, along with the United States (USA) and Germany (DEU), but also is pulled toward the center of the graph, with numerous connections to regional hubs in Europe, the Americas and Asia. ECA's relative dominance in trade has declined, along with other regions, as China and other Asian countries' share of global trade has increased. Interestingly, however, ECA country-nodes are much closer to each other in recent years than in the past, reflecting the higher degree of regional integration and value chain development in Europe. Germany is the primary hub for ECA's manufacturing

[3] Country node placement utilizes the Barnes-Hut algorithm (http://arborjs.org/docs/barnes-hut). The algorithm attempts to place large country nodes closer to the edges of the graph as a means to more clearly show their numerous connections to smaller country nodes. The repulsion of the country nodes away from the center of the graph is proportional to their size. The repulsion away from the center of the graph is counterbalanced by the attraction forces due to how strongly each pair of countries are connected to each other. Once the forces of repulsion and attraction on the country nodes have been defined, the behavior of the entire graph under these forces may then be simulated as if it were a physical system. In such a simulation, the forces are applied to the country nodes, pulling them closer together or pushing them further apart. This is repeated iteratively until the system comes to a mechanical equilibrium state; i.e., their relative positions do not change from one iteration to the next. The positions of the country nodes in this equilibrium generate the graphical depiction of the network.

integration. Great Britain (GBR) is pulled equally between Europe and the United States, and, hence, is located almost equidistant between these two poles.

Figure 2: Exports of manufactured goods.
The size of each country-node reflects the total volume of trade. Each node has two outgoing links, which point to the two top export partners of the country.

2000 **2014**



Source: Author's calculations based on *UNCTAD data.* ECA countries are shown shades of blue

Foreign Direct Investment (FDI)

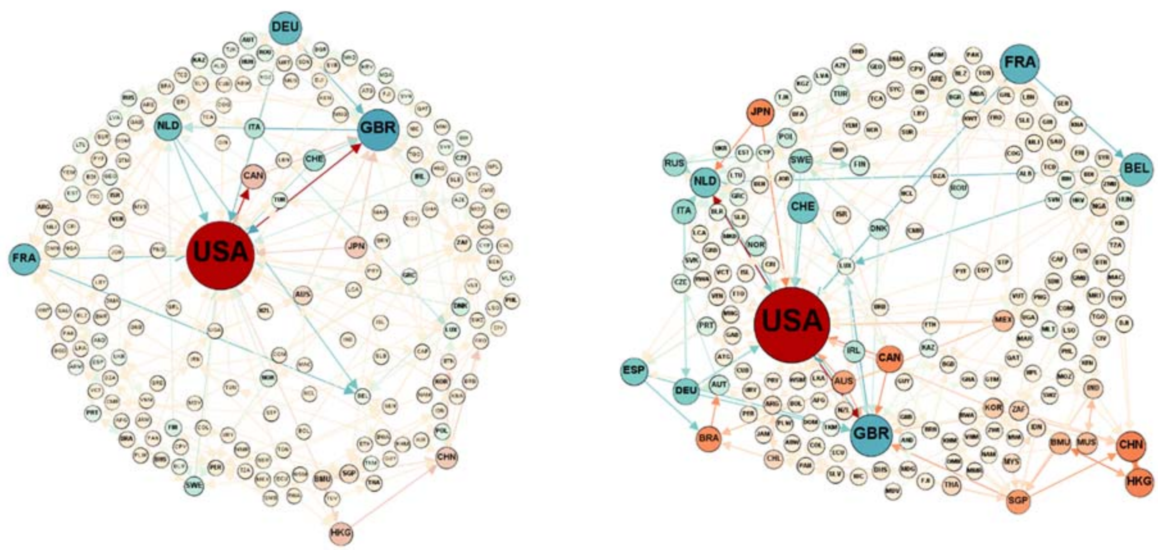
Figure 3 is based on total stocks of foreign direct investment (inward and outward) for all the countries in the world. Each country-node shows two outward arrows that are pointed to each country's two top FDI destinations. Unlike the international trade network, global FDI remains dominated by the developed countries in Europe and the United States, although developing countries have seen some modest increase. Much FDI moves between countries of similar levels of development, with relatively modest investments going from developed to developing countries and vice versa. China and the rest of Asia were the beneficiaries of significant incoming investment flows between 2000 and 2012. China, on the other hand, has focused its outgoing investments toward the United States and neighboring countries.

For ECA, the distribution of FDI is also less regionally focused than trade. FDI appears to be connected to language and historical colonial linkages (for example francophone African countries largely share in FDI flows with France and Belgium) as well as driven by corporate acquisitions for technology, transport, access to markets, and natural resource endowments. Financial centers (e.g., Great Britain and Switzerland) have also become increasingly important for attracting FDI. Interestingly, compared to trade, Germany's and China's participation in global FDI is small, but while China's share has grown, Germany's relative FDI stocks have fallen. Nonetheless, ECA's overall participation in global FDI increased from 2002 to 2012, and has become more equally distributed as Spain (ESP), Belgium (BEL), the Russian Federation (RUS), and Sweden (SWE) have seen relative increases.

Figure 3: Foreign Direct Investment.
The size of the country-node reflects the total FDI stocks (incoming and outgoing) of the country. Each country has two outgoing links that point to the two main FDI destinations for each country

2012

2002



Source: Author's calculations based on *OECD and FDI Markets data.* ECA countries are shown shades of blue

International Migration

Perhaps more than any other connectivity layer, international migration is dominated by the United States, which is the main recipient of migrants in the world (figure 4). Although the importance of China in this network increased between 2000 and 2010, China's migration connectivity in the global network is significantly lower than its other connections. Russia is a particularly large center of migration in ECA, but this is primarily a legacy of the breakup of the Soviet Union. Individuals who were born in former Soviet Republics living in Russia are classified as foreign born, although at the time of birth they were nationals of the same country as Russian natives. Nonetheless, Russia remains an important destination for migrants from Central Asian countries, such as Tajikistan (TJK) and Uzbekistan (UZB). Remittance flows generated by these migrant workers living in Russia account for a substantial share of income for many Central Asia economies (in some cases, over 30%, see section 5).

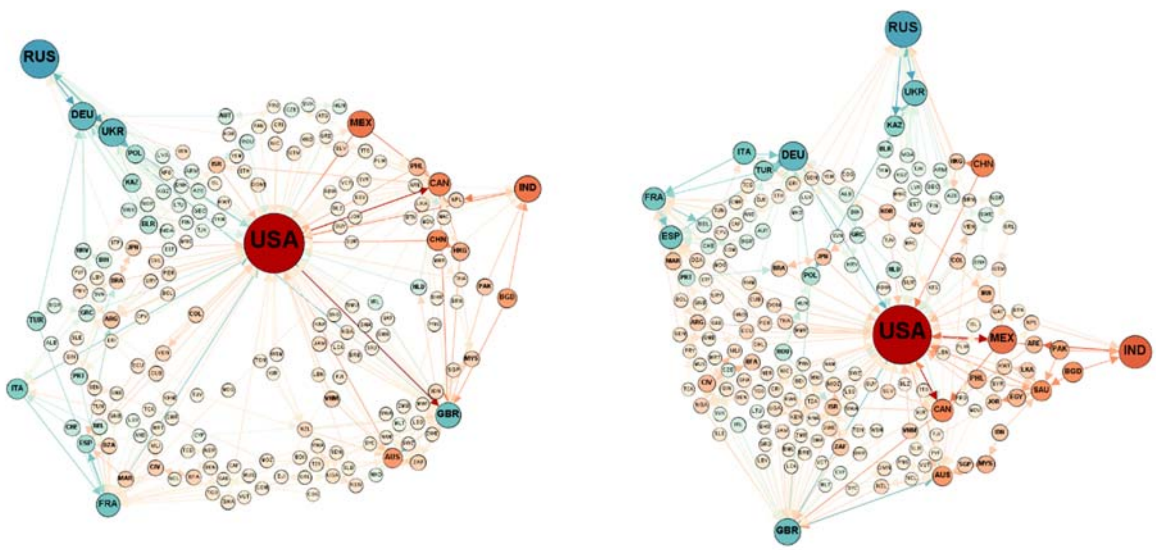
The share of immigrant populations among European countries appears to have increased from 2000 to 2010. The region is more integrated in its labor market, as evidenced by the somewhat higher clustering of European countries in the last year, reflecting easing of immigration rules in the EU under the Schengen Agreement. It is interesting to note that Germany was a large recipient of migration flows from Russia and other Communist bloc countries during the first decade after the breakup of the Soviet Union; however, in the figure for 2010 Germany is pulled much closer to the center of EU countries. Likewise, Poland after joining the EU has closer migration linkages to Germany and Great Britain, compared to its connections to Russia and the United States.

In general, migration flows are strongly influenced by language similarities (e.g., Romanians living in Italy and Spain), proximity (e.g., US, Canada, and Mexico), and historical colonial ties (e.g., France and North Africa; Great Britain and Zimbabwe).

Figure 4: Migration.
The size of each country-node represents the total number of foreign-born individuals residing in the country plus the total number of native-born citizens living outside the country. Each country-node has two outgoing links which represent the two main largest emigration destinations of each country

2010

2000



Source: Author’s calculations based on *OECD data.* ECA countries are shown shades of blue

Passenger Airline Connectivity

The bilateral airline connectivity shown in figure 5 represents not simply the number of flights between countries, but the origin and final destination of passengers, which requires information on passenger itineraries. Oftentimes passengers utilize hubs and transfer to other flights and airlines before reaching their destination, which, without data on itineraries, can overweight hubs as being the final passenger destination and underweight countries that connect to the global network of countries through hubs. These data were painstakingly estimated by the International Civil Aviation Organization, using flight and itinerary information to build a data set for passenger flight origins and final destinations. However, despite these efforts, private flights are not always included in available data and hubs may still be over represented as the final destination for air passengers.

What appears from the data is that, similar to the migration network, the links among European countries increased substantially between 2000 and 2012 as shown by the increased clustering of ECA countries in the later period. Moreover, ECA high-income countries, particularly Germany, Great Britain, France, Spain, Italy, and Turkey, have increased in importance in airline passenger origin and destination countries.

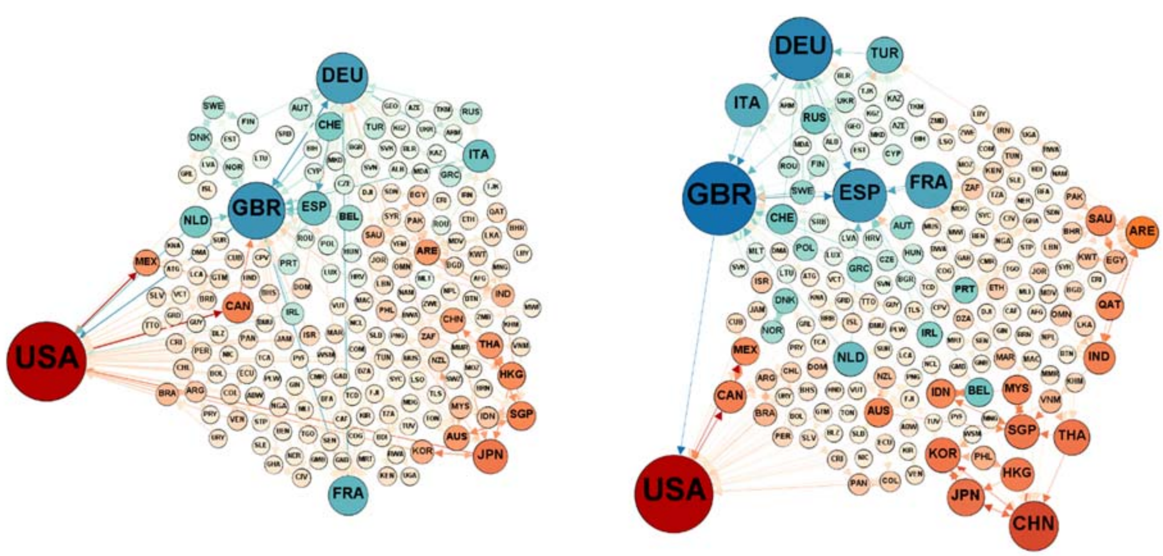
Since 2007, Europe's direct connectivity gains within the region have been driven by regional integration policies and the subsequent expansion of regional short-haul Low Cost Carriers (LCCs). Meanwhile, Full Service Carriers (FSCs) have seen their regional direct connectivity drop with the greater competition. LCCs now account for nearly a third of Europe's direct connectivity and are focused on linking airports within the intra-European market. The lion's share of Europe's direct connectivity to other world regions is still held by FSCs.

Outside ECA, rapid economic development made China an attractive destination for international flyers; China overtook Japan's role as the top airline flight destination in Asia in 2012. The development of popular Middle East Gulf carriers (e.g., Qatar and Emirate Airlines) may indicate a country bias in the data due to their importance as regional hubs, but it is also reasonable that they are attracting greater final destination air traffic due to broader investments to diversify their economies away from oil.

Figure 5: Airline connectivity.
The size of each country-node represents the estimated total number of air passengers. Each country-node has two outgoing links which point the two largest passenger flight destination countries.

2012

2000



Source: Author's calculations based on IACO data. ECA countries are shown shades of blue

International Internet and Communications Technology

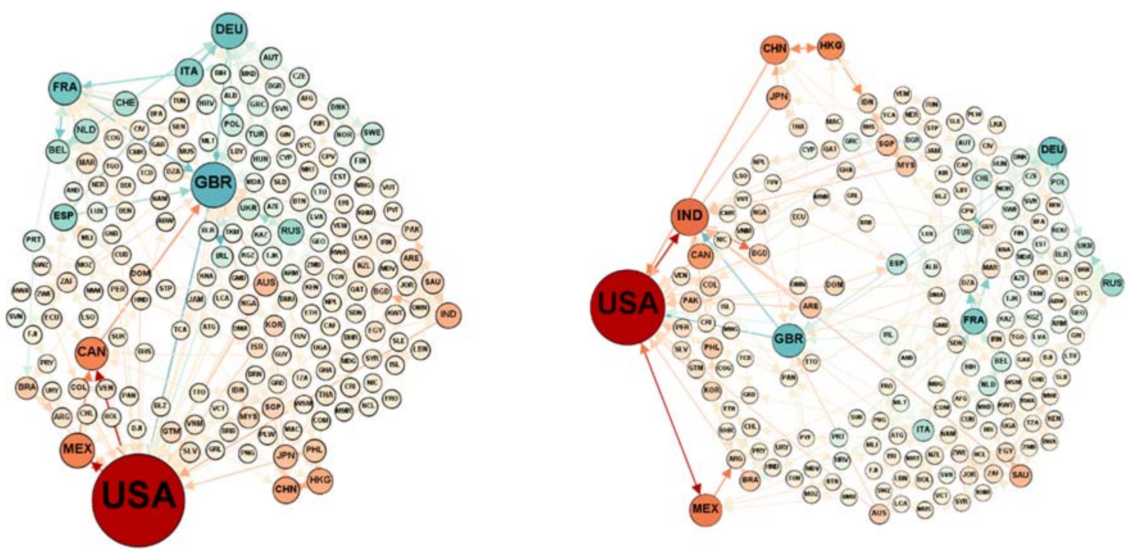
The International ICT global flows network is shown in figure 6. The data were constructed by using total country internet bandwidth (bilateral country data were not available) and allocating bilateral traffic in proportion to bilateral telephone calls for each country. ICT flows appear to be clustered in three groups:

Europe, North America and Asia. The United States and Great Britain are the major hubs in this network, with a notable increase in the importance of India in 2010 due to the back-office outsourcing of service jobs and call centers. It should be noted, however, that the data on the network in the latter period are not as complete as in the early period and should be interpreted skeptically. Nonetheless, intuitive regional patterns persist with connections driven by language, supply-chain linkages, and economic activity.

Figure 6: Internet and Communication Technologies.
Each country-node represents the combined value of the estimated incoming and outgoing ICT communication. Each country-node has two outgoing links that point to the two main outgoing communication partners for each country.

2010

2002



Source: Author's calculations based on and TeleGeography data. ECA countries are shown shades of blue

Portfolio Financial Flows

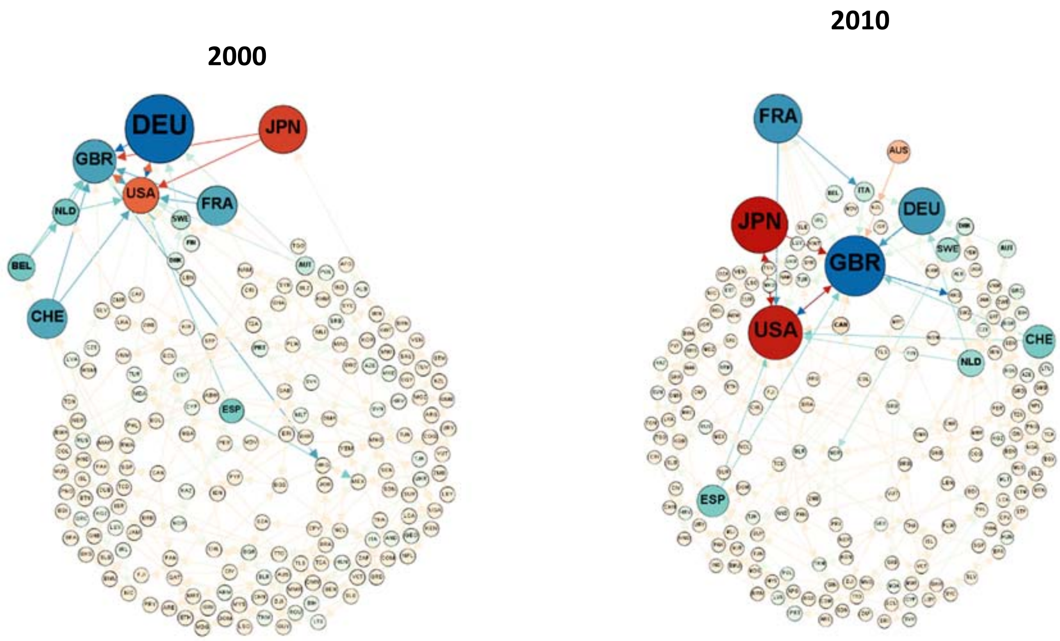
The portfolio financial flows are derived from the BIS Consolidated Banking Statistics (CBS).[4] The CBS capture the worldwide consolidated positions of internationally active banking groups headquartered in the BIS reporting countries. Portfolio financial flows appear to be driven by the largest financial centers, without a strong relationship to underlying trade or other economic relationships (figure 7). The six top centers include Germany, Great Britain, Japan, France, the United States, and Switzerland. Some relationships are economically intuitive, with many ECA countries having at least one top portfolio flow connection in the ECA region and the second in the United States. In 2010 Spain's two top connections included Germany and the United States, reflecting integration within ECA and outside, while in 2000 it was Mexico and the United States. In other words, ECA ties became relatively stronger. Nonetheless, even

[4] https://www.bis.org/statistics/consstats.htm

within ECA, because of the agglomeration benefits of financial sectors, and the practice of many companies to issue portfolio financial bond or equity instruments in well-established markets where market size and transparency help to stimulate supply and demand, financial flows do not particularly match the level of real economic relationships. The concentration of portfolio flows centered in a few country-nodes, however, provides some insight into how vulnerable portfolio flows may be to shocks in the central nodes.

Figure 7: Portfolio Financial flows.

Each country-node represents the combined value of portfolio inflows and outflows. Each country-node has two outgoing links that point to the two main recipients of portfolio financial flows for each country.



Source: Author’s calculations based on Bank of International Settlements Consolidated Banking Statistics. ECA countries are shown shades of blue

In summary, Europe’s integration policies have had a positive impact on internal European connectivity through most economic relationships, especially in trade, migration, and air passenger transport, but less so in FDI, ICT and portfolio financial flows. In the early 2000s, there were strong migration patterns between the transition economies and Western Europe (particularly Russia and Germany), which then diverged into two regional blocks, one centered around Russia and the other the EU, with Germany as the primary country-node. Transitional European countries trade and migrate intensively within Europe, but are increasingly creating linkages with the rest of the world. Established (advanced) European countries have had wider global connections with the United States and Asian countries, but regional connections are deepening. Overall, ECA’s relative importance as a central node for connectivity with the rest of the world has fallen as emerging economies (especially China) are growing and account for a larger share of global economic activity. This is true for most advanced countries, including the United States, as emerging economies are increasing in economic size and wealth. Perhaps not surprisingly, airline and ICT connectivity has changed the most over the last decade due to deregulation and innovation, while portfolio financial flows have tended to be concentrated in a few dominate financial sectors that have changed only slightly.

This network analysis adds to previous and ongoing research on economic relationships and their influence on growth by not looking at one network layer independently of others, but by examining the many layers of connectivity together. Not only do individual connections matter but also their interdependence in economic relationships. Connectivity should be seen as a multidimensional concept: including trade, migration, finance, transport, communications, and other factors. Greater connectivity in one area may be a complement or substitute for connectivity in another area.

3. Connectivity and Income Growth

According to traditional economic growth models, an increase in trade, or other forms of connectivity, will have no impact on long-run income growth. The *level* of income will increase due to gains from specialization, but this will not lead to sustained increases in growth unless it has an impact on improving technological accumulation over time (i.e., the endogenous growth model, Romer, 1990). Thus, the main mechanism through which connections affect growth is via the transfer of knowledge and innovative ideas and technologies. Innovations are continuously generated globally, and they travel the world through the network of countries. Greater multidimensional connectivity increases the probability that an economy will absorb these new ideas and increase long-run growth.

The empirical strategy we use for understanding how a country's international connections and the interplay of these connections influence economic growth is three-fold. First, we simply estimate a baseline growth model that includes standard explanatory variables, including the initial GDP per capita level, schooling, size of government, inflation, quality of governance, and investment rates (see also Helliwell, 1994). Second, we include the traditional measure of connectivity, trade/GDP, that is used in the economic literature on openness. Our interest is not so much replicating previous research, but rather determining a benchmark against which to compare network effects of connectivity. Third, we develop network centrality measures for each type of connection indicator (for example, trade, FDI, etc.) based on a modified Google's PageRank algorithm (Page, 1999). This algorithm gives a higher ranking to countries that have a larger number of connections to well-connected countries as well as connections to countries with a high "intrinsic value." Intrinsic value in our context means a high propensity to generate and disseminate knowledge. We proxy this intrinsic value by the size of the country's population and GDP per capita.

We modify and expand the analysis in Duernecker, Meyer, and Vega-Redondo (2014) of the relationship between a network measure of trade and economic growth to other measures of connectivity (trade, FDI, migration, airline transport, portfolio flows, and ICT). We compare our six individual network centrality results with the relationship between traditional measures of connectivity (for example, overall trade to GDP) and growth, to determine whether network centrality measures are any better at describing long-run growth than the standard, non-network, measures. The different variables, data sources, and sample periods, are summarized in Table 2.

Table 2: Summary of the variables, data sources, and sample period used for the growth models.

Indicator Name	Description	Coverage
Initial GDP per capita	The logarithm of the initial value of GDP per capita for the growth period in question (2000-2016). Source: World Bank World Development Indicators (WDI).	2000-2016
Governance	Index of the quality of governance which takes into account corruption, the rule of law and the quality of institutions. Source: WDI.	2000-2016
Inflation	Measure of CPI change. Source: WDI.	2000-2016
Government Size	Total government expenditure as a share of GDP. Source: WDI.	2000-2016
Years of Schooling	The average number of years of schooling. Source: Barro-Lee (www.barrolee.com).	

Finally, we develop a comprehensive measure of overall network centrality, referred to as multidimensional connectivity, that combines all six types of connectivity into a single network measure. This indicator takes into consideration the complementarity of the various forms of connectivity, as described in the introduction. Multidimensional connectivity is found to be significantly related to long-run growth, and provides a better explanation of long-run growth than the individual connectivity channels. In other words, the sum is greater than the parts. As a robustness check, we develop an alternative index of network centrality, multiplex connectivity, which describes the complete network but does not impose the restriction that each layer of the network is a complement to other layers. This indicator has a similar, albeit less strong, relationship with growth than the multidimensional connectivity indicator.

3.1 Network centrality

This section introduces a measure of centrality, or influence, based on the well-known Google PageRank algorithm which was used to rank websites based on their links in the network. The algorithm was initially developed to rank websites in terms of their “importance” and “relevance” to a search query. Network analysis was a natural starting point for this problem because websites with more hyperlinks pointing at them were thought of as being of higher quality. In addition to the number of the incoming links, having more links from higher quality websites is yet another indicator of website quality. The innovation by Page (1999) consisted in modifying the popular network Eigenvector Centrality measure so that the centrality value of a website was proportional to the probability that a person clicking randomly on hyperlinks would land on that page.[5] Or more precisely, the PageRank value reflects the share of visits to the website by a random web-surfer over some period of time.

We modified the PageRank algorithm so that its initial idea – capturing the probability that a random traveler in the network will arrive at a certain node – remains in place. In the economic network discussed in this section, the connectivity index is proportional to the probability that a random economic/technological innovation will reach the country. This probability reflects the likelihood that an innovation will be transmitted to that country through each form of connectivity (trade, FDI, etc.), based on the country's links to other countries, those countries' links to other countries, and so on (the value of connections is progressively reduced by 15 percent at each link in the chain). [6] The index also reflects the intrinsic probability that each connection (country) will innovate and disseminate knowledge independently (proxied by population and GDP per capita).[7]

More formally, the centrality value Θ_i is proportional to the probability that an innovation will be transmitted to country i :

$$\Theta_i = \lambda \sum_k A_{ki}\,\Theta_k + (y_i * P_i)$$

The value A_{ki} is a function of the links between countries k and i, λ is an exogenous parameter which captures the weight of decay placed on connections (set to 0.85), y_i is GDP per capita and P_i is the population (the last two terms together equal aggregate GDP).

The intrinsic value, proxied by GDP, plays an important part in determining the value of the index. For example, even a completely isolated country has a positive probability to innovate and grow based on its domestic resources only. Our choice of proxy for the intrinsic (internal) likelihood to innovate is based on two simple considerations. First, the greater the number of people in a country, the greater the knowledge (or new ideas) that could potentially be generated. Second, we assume that higher-income countries are closer to the technological frontier and thus have a higher probability of producing new knowledge. If a country does not produce the knowledge intrinsically, it can learn from others through its connections. This mechanism is captured by the term: $\lambda \sum_k A_{ki}\,\Theta_k$.

Thus, the probability that an economy has the knowledge to innovate is a sum of the likelihood of its intrinsic innovation (proxied by GDP) and a weighted average of the connectivity of its partners where the weights (A) are a function of the connections. These weights reflect the strength of the informational link and ultimately the probability of successful transmission of ideas.

A_{ki} takes on the following set of values:

$$A_{ki} = \left\{\frac{Trade_{\,ki}}{GDP_k};\frac{FDI\ stock_{ki}}{GDP_k};\frac{Migration\ Stock_{ki}}{POP_k};\frac{ICT\ flow_{ki}}{POP_k};\frac{Flights_{ki}}{POP_k};\frac{Portfolio\ Flows_{ki}}{GDP_k}\right\}$$

[5] Eigenvector centrality is a measure of the influence of a node in a network. A high eigenvector score means that a node (country in our case) is connected to many nodes who themselves have high scores.
[6] This is the standard value of similar parameters used in most network analyses.
[7] In the original search engine applications of PageRank this value captured the likelihood that the random surfer can type the URL of the website without relying on hyperlinks to get to it.

Each connection (total bilateral trade, total FDI stocks, bilateral migration stocks, ICT, airline transport and portfolio flows) is divided by a proxy for the size of the country (GDP or population). In the original PageRank algorithm, this feature is introduced by dividing by the total number of outgoing links of the partners. Therefore, the probability of getting from website A to website B by a random web surfer decreases as the number of outgoing links in A increases (there are more sites the surfer can land). In the case at hand, the probability of an idea reaching a specific country decreases with the population of the sending country.

Similar adjustments are necessary when one considers information flows between countries along the various networks. For example, conditional on an innovation being present in country A, the probability that a single migrant from A to B will carry this idea decreases with size of the population of A. Although large countries are more likely to generate ideas domestically, they need greater flows and deeper links in order to transmit those ideas to their partners. In this paper, it is argued that this measure is a good proxy for the probability of growth-relevant knowledge generation by each country (either through learning from its connections or developing knowledge domestically).

3.2 Network Centrality Measures and Growth

In this section, we estimate the importance for growth of the connectivity measures described in the previous section. We first estimate a standard cross-country, long-run model over 2000-2016, where growth depends on the initial levels of GDP per capita, education, investment rate, governance, government size and inflation. We then add trade/GDP, the traditional measurement of openness, as an additional explanatory variable. Finally, we add each of our network measures of connectivity to determine whether network centrality measures are any better at describing long-run growth than the standard, not-network, measure.

Two adjustments are required to the network connectivity measures described above before including them in the model. First, we scale the value by population to account for the fact that more populous countries are expected to depend less on being connected to the rest of the world for innovations and growth than smaller countries, which, due to their size, naturally rely more on connectivity (e.g., China vs. Singapore). This has the effect of transforming connectivity into per capita terms. Second, because the network connectivity measure includes the country's own level of GDP per capita (as well as GDP per capita of partner countries), we subtract the country's own level of GDP per capita from the connectivity measure because it is already included as an explanatory variable in describing country growth. This, in effect, eliminates double counting. The intrinsic value of partner countries' GDP per capita is still included in the network connectivity measure.

The estimation of the relationship between growth and the variables typically used in the empirical literature (and included here) faces several key challenges. Perhaps the most difficult concerns *endogeneity,* often reflecting reverse causality, or the influence of the dependent variable (growth) on some of the independent variables (e.g. government size). Our main goal is to measure the contribution of our network connectivity measures to growth, after controlling for other variables (inflation, etc.) thought important to growth. However, both our connectivity measures and these other variables may themselves be determined, in part, by growth (they may not be *exogenous*, as assumed in our estimation procedure). Thus, most researchers using cross sections are only able to capture partial correlations instead of causality.

Our identification strategy attempts to reduce problems from endogeneity, although it does not eliminate them. First, we calculate the right-hand side variables by taking the earliest observation available in the data at the start of the growth period. This of course does not correct all potential endogeneity problems, but it is indicative of a lack of reverse causality. Second, our measures of connectivity build on direct and indirect links for the various types of connectivity in the global network, and countries are only able to impact direct links and not indirect ones. By taking into consideration higher order indirect links, our connectivity measures are at least to some extent exogenous, or unaffected by growth of the country being measured. Moreover, for robustness we also included geographic distance between countries as a separate layer of connectivity to account for geographic proximity that may affect growth and the strength of connectivity channels simultaneously.[8] For a deeper treatment of endogenous relationships in economic growth we refer the reader to the rich literature (see, Frankel and Romer, 1999; Rodriquez and Rodrik, 2000; Helpman, 2008; Beck, 2008; Feyrer (2009) and Panizza, 2013).

This kind of estimation also may suffer from the existence of unobserved country effects (which are potentially correlated with the independent variables used in the empirical model). Furthermore, most variables are measured with considerable error. Since developing countries represent a large fraction of our sample, results depend on the reliability of the data. Hence, measurement error can be a source for inconsistent coefficient estimates.

We examine the growth effects of connectivity along each network layer separately (trade, FDI, migration, ICT, airlines connectivity and portfolio flows) in Table 3.

Table 3. Connectivity effects on overall income growth

The dependent variable in each model is the annualized income growth (%) between 2000-2016. All right-hand-side variables are transformed in logs and we take the first available observation for the growth period. There are 111 countries for which we are able to estimate each version of the model. The connectivity variables /PageRank are normalized using the standard normal distribution. Therefore, the size of the coefficient represents the growth impact of one standard deviation change. All model specifications include an intercept, which is not reported in the table.

	1	2	3	4	5	6	7	8
GDP per capita $_{t=0}$	-0.91***	-1.10***	-1.31***	-1.29***	-1.15***	-1.06***	-1.11***	-1.11**
Years of schooling $_{t=0}$	2.46***	2.4***	1.7***	1.87***	1.60***	2.06***	1.99***	2.04***
Government size $_{t=0}$	-9.24**	-8.64**	-5.81	-5.24	-4.91	-5.44	-5.21	-5.79
Inflation $_{t=0}$	1.02	0.99	2.92	2.75	2.54	2.1	1.82	1.73
Governance $_{t=0}$	1.18	2.13	1.2	0.99	1.04	1.43	1.32	1.63*
Investment Rate $_{t=0}$	0.160**	0.170***	0.190***	0.21***	0.20***	0.20***	0.20***	0.20***
Baseline Standard Connectivity model								
Trade/GDP $_{t=0}$		0.28						
Network Effects (PageRank)								

[8] Including a layer of network connectivity that was determined solely by geographic (capital to capital) distance between countries was not a significant determinate of growth, nor did it change the empirical results related to our empirical inferences related to the multidimensional connectivity index described below.

Trade Connectivity per capita $_{t=0}$			0.61***					
FDI Connectivity per capita $_{t=0}$				0.59***				
Migration Connectivity per capita $_{t=0}$					0.34*			
ICT Connectivity per capita $_{t=0}$						0.12		
Portfolio Flows per capita $_{t=0}$							0.17	
Airline Connectivity per capita $_{t=0}$								0.19*
Adj-R^2	0.54	0.53	0.59	0.58	0.56	0.54	0.55	0.56

Table 2. Network effects on overall income growth

The dependent variable in each model is the annualized income growth (%) between 2000-2016. All right-hand-side variables are transformed in logs and we take the first available observation for the growth period. There are 86 countries for which we are able to estimate each version of the model. The connectivity variables /PageRank are normalized using the standard normal distribution. Therefore the size of the coefficient represents the growth impact of one standard deviation change.

	1	2	3	4	5	6
GDP per capita-t0	-1.31***	-1.29***	-1.15***	-1.06***	-1.11***	-1.11**
Years of schooling-t0	1.7***	1.87***	1.60***	2.06***	1.99***	2.04***
Government size-t0	-5.81	-5.24	-4.91	-5.44	-5.21	-5.79
Inflation-t0	2.92	2.75	2.54	2.1	1.82	1.73
Governance-t0	1.2	0.99	1.04	1.43	1.32	1.63*
Investment Rate - t0	0.19	0.21	0.20	0.20	0.20	0.20

	0***	***	***	***	***	***
Network Effects (PageRank)						
Trade Connectivity per capita-t0	0.61***					
FDI Connectivity per capita-t0		0.59***				
Migration Connectivity per capita-t0			0.34*			
ICT Connectivity per capita-t0				0.12		
Portfolio Flows - t0					0.17	
Airline Connectivity						0.19*
Adj-R2	0.59	0.58	0.56	0.54	0.55	0.56

Note: All coefficients are estimated with ordinary least squares regression. ***,**,* represent significance levels at 99%, 95% and 90% respectively.

Compared to the base model and the standard measure of openness (trade/GDP), nearly every network connectivity measure manages to increase the explanatory power (Adj-R^2) of the standard growth equation, although not every network layer is statistically significant at the minimum 10 percent level. Deeper integration along each individual dimension is associated with stronger per capita GDP growth over the subsequent 16-year period. Unlike the traditional measure of openness and connectivity (trade/GDP), the PageRank-based index, which was designed to capture the knowledge spillovers from connections, is associated with higher long-term growth in the case of international trade, FDI, migration and airline connectivity. A one standard deviation increase in the trade connectivity of a country is associated with more than half a percentage point (0.6%) higher annual economic growth over the long term. The effect of FDI connectivity is similar (0.59%), and the effects of migration and airline connectivity markedly lower (0.34% and 0.19% respectively).

Connectivity can also boost shared prosperity. Economic channels by which the poor and bottom 40 percent may directly benefit from greater connectivity include improved access to finance and markets, changes in the return to capital and/or labor, exposure to technology and better governance, and changes in the relative prices of goods and services. Trade, for example, may enhance resource allocation across countries leading to improved opportunities for asset use by the bottom 40 percent of the income distribution (B40). Investment flows may generate new returns for the B40. As production becomes more competitive, the poor may also experience a mix of welfare gains and losses from relative price changes. Migration may open new opportunities, but also has implications for the labor market. Connectivity influences commerce and investment, but it also is a means to transfer ideas, technology, and institutional arrangements, which are all potential sources for spillovers to growth and may indirectly influence shared prosperity.

Table 4 summarizes the estimated impact of connectivity on the income growth of the poorest 40 percent of the income distribution in each country. Trade connectivity has the largest impact. In fact, the knowledge spillover effects from trade appear to be more important for the bottom 40 than for the top 60. However, the other measures of connectivity do not appear to play a statistically significant role in bottom 40 growth.

Table 4. Connectivity effects on Bottom 40 income growth

The dependent variable in each model is the annualized bottom 40 income growth (%) between 2000-2016. All right-hand-side variables are transformed in logs and we take the first available observation for the growth period. There are 88 countries for which we are able to estimate each version of the model. The connectivity variables /PageRank are normalized using the standard normal distribution. Therefore, the size of the coefficient represents the growth impact of one standard deviation change. All model specifications include an intercept, which is not reported in the table.

	1	2	3	4	5	6	7	8
GDP per capita $_{t=0}$	-0.77**	-0.69*	-1.19***	-1.08***	-0.69***	-0.71*	-0.75**	-1.77***
Years of schooling $_{t=0}$	2.1***	2.1***	2.32***	2.39***	2.15***	1.91**	2.65***	2.51***
Government size $_{t=0}$	-7.37	-7.38	-3.61	-9.05	-10.38	-6.4	-8.05	-5.72
Inflation $_{t=0}$	2.61	2.62	5.69	6.21	5.08	5.23	4.01	0.96
Governance $_{t=0}$	1.13	1.14	-0.74	0.75	1.37	1.5	2.18	0.3
Investment Rate $_{t=0}$	0.09*	0.08*	0.08*	0.13**	0.09*	0.12**	0.09*	0.09*
Baseline Standard Connectivity model								
Trade/GDP $_{t=0}$		0.02						
Network Effects (PageRank)								
Trade Connectivity per capita $_{t=0}$			1.49**					
FDI Connectivity per capita $_{t=0}$				0.8				
Migration Connectivity per capita $_{t=0}$					0.18			
ICT Connectivity per capita $_{t=0}$						0.21		

Portfolio Flows per capita $_{t=0}$							-0.13	
Airline Connectivity per capita$_{t=0}$								0.11
Adj-R^2	0.24	0.24	0.28	0.26	0.25	0.23	0.23	0.23

Note: All coefficients are estimated with ordinary least squares regression. ***,**,* represent significance levels at 99%, 95% and 90% respectively.

3.3 Multidimensional Connectivity: Interplay of network connections and growth

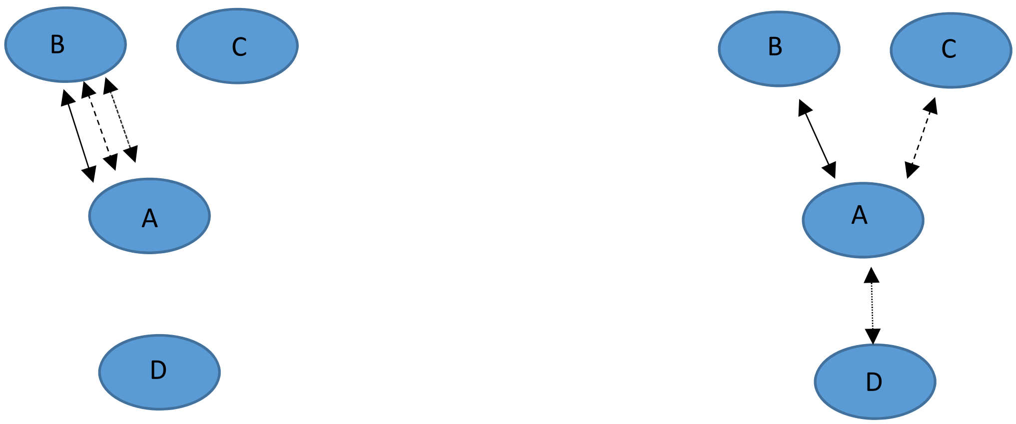
In this section, we develop two unique methods for combining each individual network layer (trade, FDI, migration, ICT, airline transport and portfolio flows) into a single total network measure of connectivity to address the complementarity between connectivity measures and their relationship to growth. Indeed, there appears to be a strong correlation between all measures of connectivity, with perhaps the exception of portfolio financial flows (Table 5). FDI and trade are the most correlated across connectivity layers, airline transport and migration less so, while portfolio flows is highly idiosyncratic. Intuitively, interplay between various forms of connectivity can be seen most clearly in migration and international travel. Much research has found that migration and trade tend to be complements (greater migration between two countries is associated with greater trade between them), and subsequent research has also identified migration's importance in influencing FDI and its direct influence on growth through knowledge transfers (see, for example, Gould 1994, Onodera 2008, and others). Thus, people to people contact may be important for growth by directly transferring knowledge between the host and home countries, as well as indirectly by facilitating knowledge embodied in trade and FDI flows through bridging market information gaps.

Table 5: Correlation between connectivity layers is high, except for portfolio financial flows

	Trade	FDI	Migration	ICT	Airline	Portfolio Flows
Trade	1					
FDI	0.9295*	1				
Migration	0.7173*	0.7092*	1			
ICT	0.7107*	0.7882*	0.6789*	1		
Airline	0.8515*	0.9090*	0.6200*	0.8348*	1	
Portfolio Flows	0.2560*	0.2751*	0.2624*	0.2286*	0.2697*	1

The six network connectivity measures could be aggregated in a simple, ad hoc way (for example, taking averages of the network centrality measures). However, this is likely to result in a loss of important information and would not account for the interaction of various network layers and their effect on economic growth. For example, vastly different bilateral connectivity patterns in each dimension can result in similar average values. This is schematically described in Figure 8. In the left and right panels of the figure, country A has the same centrality index calculated using simple averages of modified PageRank centrality across three types of networks, represented by the three types of arrows (line, dash and dot). It is clear however, that the patterns of connections and the overall network for country A is vastly different between the two cases. It is easy to show that using aggregation at the country level, the modified PageRank produces a higher centrality for country A in the case on the right compared to the one on the left.

Figure 8: Two examples of network connectivity and the modified PageRank of county A.



We therefore adopt a somewhat more intuitively appealing procedure for aggregating the connectivity measures. This includes calculating the weighted multiplicative average of the separate connectivity measures. The equation is:

$$I_{ki} = x_{ki}^{\alpha} f_{ki}^{\beta} m_{ki}^{\gamma} i_{ki}^{\delta} a_{ki}^{\nu} p_{ki}^{\eta}.$$

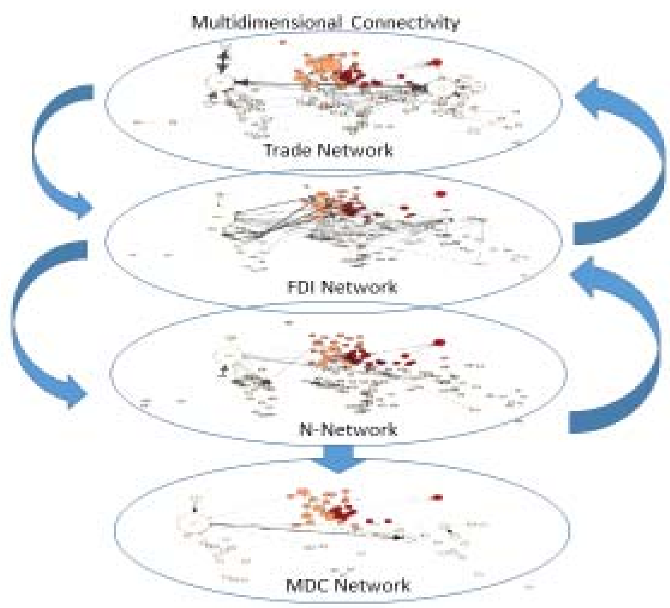
where I_{ki} is the network information function and $\alpha, \beta, \gamma, \delta, \nu, \eta$ are the estimated weights for each connectivity layer. The weights are calculated using the maximum likelihood procedure where the objective function was to maximize the goodness of fit of the growth equation (adjusted R-squared).

Essentially, the six networks are collapsed into one network where each bilateral link is a function of each of the layers, as shown in Figure 9. The functional form used has several desirable features that have been well documented in other economic contexts. First, it imposes decreasing returns to scale, that is, having a large amount of one type of connection provides the country with decreasing informational returns. After some initial (low) threshold, an increase in connectivity will have less than a one-to-one increase in informational exchange. Second, this functional form allows imperfect substitutability of the channels in terms of transmitting growth-relevant information. That is, a balanced increase in connectivity along each dimension would have a stronger impact on the bilateral informational link than a rapid increase in the connectivity along one layer only. It is very likely that these different channels complement each other in terms of the information they transmit. For example, a foreign investor is likely to be more successful in transferring know-how in the host country if there already are deep links through migration and trade that can complement the information flows embedded in FDI.

Furthermore, the estimated weights on each of the network layers can be interpreted as the efficiency/importance of each channel in transmitting information that facilitates long term income growth. Each country's aggregate connectivity index, representing the likelihood of a country adopting an innovation, is then calculated in a similar fashion as used in calculating the individual connectivity indices. That is, the aggregate index of connectivity is summed across partner countries and added to the likelihood of the country generating an innovation independently (represented by GDP). The functional form being:

$$\Theta_i^{\mu} = \lambda \sum_k I_{ki}\, \Theta_k^{\mu} + (y_i * P_i)$$

Figure 9: Multidimensional Connectivity (MDC) Network



The impact of multidimensional centrality on growth and the indicator's component weights for each network layer are estimated simultaneously using a maximum likelihood procedure. The estimated weights for each layer of the multinational connectivity indicator, and the indicator's impact on growth are shown in Table 6. The growth impact of the multidimensional connectivity indicator is higher than each of the individual network indices (shown in Table 2). A one standard deviation increase in the multidimensional connectivity indicator is associated with 0.67% higher annualized growth. These results suggest that the overall connectivity profile of the country (one that combines all network layers) is more important than each of the individual layers separately. Moreover, in the combined network, trade has the highest importance, followed by FDI, and then migration. Neither ICT, airline transport, nor portfolio flows add additional information above these three connectivity channels. By contrast, the multidimensional measure does not add new information above the single network measure of trade connectivity in explaining changes in the growth of the incomes of the bottom 40 percent of the distribution.

Table. 6 Multidimensional Connectivity

The dependent variable in each model is annual income growth (%). All right-hand-side variables are transformed in logs. The PageRank coefficient is standardized to represent the effect of a change of one standard deviation.

	Overall Growth	B40 Growth
Multidimensional Connectivity Impact	0.67***	1.49***
Efficiency Exponents/Weights of Connectivity Channels		
Trade Channel Efficiency	0.532	1
FDI Channel Efficiency	0.37	0
Migration Channel Efficiency	0.1	0
ICT Channel Efficiency	0	0
Airline Channel Efficiency	0	0
Portfolio Flows	0	0
Adj-R^2	0.61	0.28

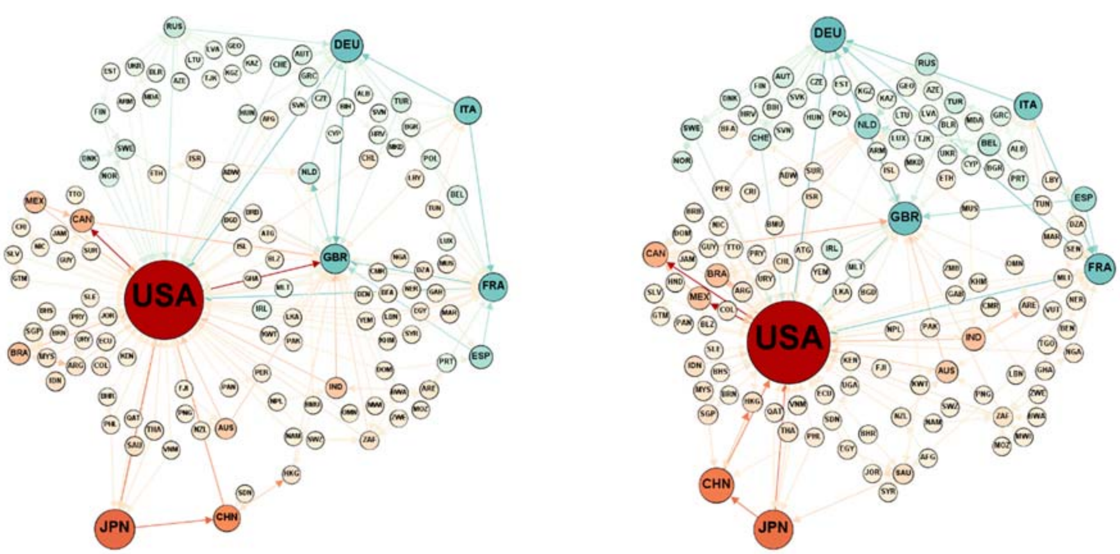
Note: ***,**,* represent significance levels at 99%, 95% and 90% respectively in an OLS regression. The values of the exponent parameters (efficiency exponents/weights) α,β,γ and δ were estimated using the maximum likelihood procedure where the objective function was to maximize the goodness of fit measure (adjusted R-squared)

Figure 10 is based on the values of each country's multidimensional connectivity index in the overall growth model. As the figure indicates, multidimensional connectivity shows a much stronger cohesion between ECA countries than any single network connection and these connections grew from 2000 to 2014. Of all the ECA countries, Great Britain shows the strongest overall linkages within ECA and non-ECA countries. In contrast, Germany is the strongest overall connector between ECA countries, but has few strong links outside of ECA. Interestingly, while China has increased network linkages with the world, it is much smaller and less connected compared to only the trade network as indicated in Figure 1; as a result, its importance to the global network is about the same as Germany's, but less than Japan's.

Figure 10: Multidimensional Network Connectivity.

The size of the node represents the multidimensional connectivity index of each country. Each node has two outgoing links which point to the strongest two connections in the multidimensional network according to the overall growth model, column 1, in Table 4.

2000 **2014**



Note: ECA countries are shown shades of blue

In terms of overall levels in ECA sub-regional multidimensional connectivity (Table 5), Northern, Southern, and Western Europe have the highest global ranking; Central Europe, Russia and Turkey have medium levels of global connectivity; while Eastern Europe, the Western Balkans, the South Caucasus, and Central Asia have the lowest levels of overall connectivity. Not surprisingly, absolute levels of connectivity are associated with higher levels of development.

Table 7: Multidimensional Connectivity varies by ECA-subregion, with the highest connectivity in the western part of the region, and lowest connectivity in the eastern part of the region

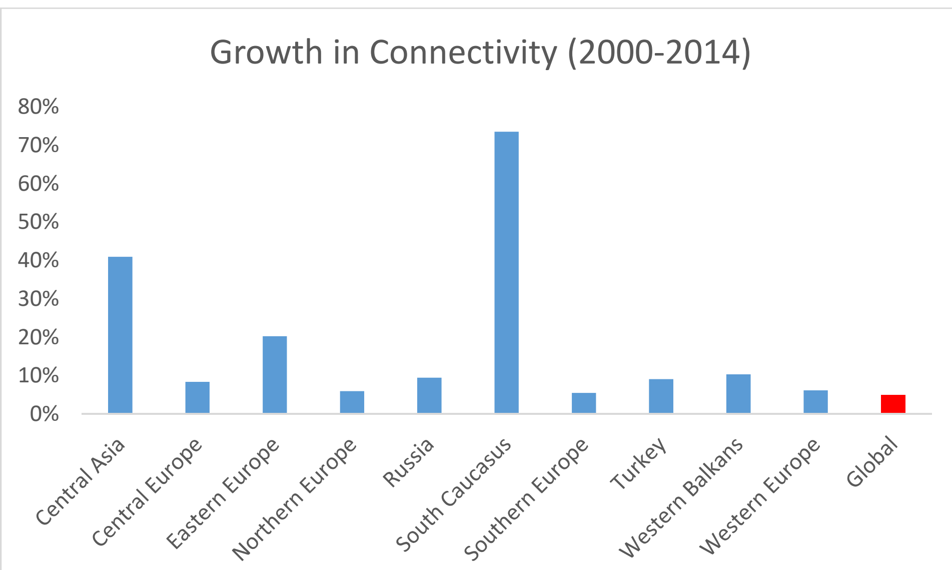
ECA Sub-regions	Multidimensional connectivity	Trade	FDI	Migration	ICT	Airline	Portfolio flows
Global ranking, from the best to worst in combined connectivity (lower is better)							
High connectivity							
Western Europe	8	8	8	18	9	11	26
Northern Europe	20	18	23	35	28	18	27
of which Baltics	*30*	*27*	*34*	*46*	*46*	*27*	*20*
Southern Europe	20	24	19	24	22	20	22
Medium Connectivity							
Central Europe	50	49	51	56	55	55	57
Russian Federation	56	53	55	58	62	71	39
Turkey	57	49	65	42	54	60	76

Low Connectivity							
Eastern Europe	71	72	73	65	82	86	91
Western Balkans	74	73	78	40	61	67	84
Central Asia	76	80	79	51	87	83	91
South Caucasus	80	83	70	58	83	77	59

Source: Own calculations. Note: Subregional indicators are median values of subregion's countries.

Interestingly, although Central Asia and the South Caucasus rank relatively low on overall connectivity, they have also seen the greatest improvement from 2000 to 2014 (Figure 11). The South Caucasus has seen connectivity increase by nearly 75 percent, while Central Asia has seen connectivity increase by over 40 percent. Eastern Europe and Western Balkans, although also starting from relatively low levels, have not seen as rapid an increase, with connectivity increasing only 20 and 10 percent, respectively. The key challenge for these regions is to find ways to improve balanced connectivity, particularly easing constraints and facilitating trade, FDI, airline, and ICT connectivity. For the ECA region as a whole, connectivity has improved more than global connectivity, reflecting the integration process of the EU as well as strides taken in transition economies.

Figure 11: ECA's connectivity has grown, but there are wide variations across subregions



Source: Own calculations. Subregional and global indicators are median regional averages.

The analysis of multidimensional connectivity and its relationship to economic growth can be useful in evaluating where countries can benefit the most in terms of reducing barriers to entry and facilitating linkages with well-connected countries. It can also help identify which connections are likely to have the largest impact on growth. For example, in China's case, while the trade network is strong, the migration and FDI networks are weak in comparison. Likewise, taking the case of Kazakhstan, increasing FDI in Bulgaria would bring a higher increase in multidimensional connectivity than increasing FDI in Poland, despite Poland's greater overall connectivity. This is due to the higher complementarity of Kazakhstan's FDI to other pre-existing connections with Bulgaria compared to Poland.

As a robustness test of the multidimensional connectivity indicator used above, a second approach to calculating multidimensional connectivity is evaluated using the recent techniques in the study of multiplex networks, where the functional form of the relationships is unknown. These multiplex networks do not rely on collapsing the network into a single layer and do not restrict the functional form (i.e., they do not rely on the Cobb-Douglas functional form as used earlier). A benefit is that the functional form need not be assumed; the cost is that if economic theory suggests a particular relationship (i.e., complementarity between network layers), this information is not used.

Multiplex networks are observed in all types of complex systems, including economic, social, biological, infrastructure and socio-technical systems. For example, the air transportation system is a socio-technical system that exhibits many layers, all of them contributing to and essential for the overall functioning of the system. Interdependence among different layers of the air transportation system arises naturally because different airlines use the same airports. As a consequence, if an airport is closed, all the flights coming out of it (and in) stop for all the airlines. Another aspect of interdependence arises because for a flight to takeoff it needs both a crew and a plane. Similarly, banks are also connected (in often very complex ways) via their derivative positions, by overlap of portfolio composition, by joint exposure to the same creditors, etc. In other words, a multilayer network model of each system is essential to estimate the degree of resilience of the entire system to random events or attacks against some of its parts. The aim, then, would be to study potential contagion effects via multiple channels in first attempts at modeling multi-dimensional network structures. For example, a description of the financial system as a three-layer multilayer network, comprised of layers representing financial activities for funding, collateral, and asset layers, has been recently proposed by Bookstaber and Kenett (2016).

Given the surge of interest in multiplex networks, recently methodologies have been proposed to assess the centrality of nodes in multiplex, and more generally multilayer, structures. Halu et al. (2013) and Laccovacci et al. (2016) have proposed an algorithm that captures how the centrality of the nodes in a given layer of the multiplex can affect the centrality of the nodes in other layers. This effect is modeled by considering a PageRank algorithm based on the centrality of the nodes in the master layer. De Domenico et al. (2015) proposed instead to rank simultaneously nodes and layers of the multiplex network based on any previous measure of centrality stablished for single layer networks, including random walk processes that hops between nodes of the same layer and between nodes of different layers as well. The resulting centrality called "versatility" strongly awards nodes active (connected) in many layers, however the description was not intended to weight layers in any specific way.

Recently, Rahmede et al. (2017 have proposed a different approach, where they consider a random walk hopping through links of different layers with different probabilities determined by the centrality of the layers (influences). This is following the work of Sola et al. 2013)[7] where different measures for the centrality of the nodes given a set of in influences of the layers have been proposed. Rahmede et al. (2017) propose a ranking algorithm, called MultiRank, that is specified by a coupled set of equations that simultaneously determine the centrality of the nodes and the influences of the layers of a multiplex network. The MultiRank algorithm applies to any type of multiplex network including weighted and directed multiplex network structures. Very generally, this algorithm proposes an extension to the classical PageRank centrality calculation, by coupling the centrality of the node to the influence of the layer it is active in. This is done by considering the node-layer interaction as a bipartite network. Such a coupling provides new insights into the centrality of a node across different connectivity dimensions.

Similar to the measure of multidimensional connectivity described above, we consider the multilayer network of the individual flow networks. In this approach, we examine the multilayer network as a whole, and do not collapse the different flow layers one on another. Instead, we follow the approach developed by Rahmede et al. (2017) to calculate the Multiplex PageRank centrality (MPR). This approach assigns a measure of centrality to each country based on its connectivity across all the layers put together. A country's centrality is measured by assigning a score based on its connectivity in one flow defined layer, and by assigning a score to the overall importance of a given economic flow defined layer. These two scores are calculated simultaneously and are co-dependent.

Following the approach described above, we repeat the regression analysis using the same dependent and independent variables in the standard growth model, but instead use the standardized MPR centrality measure. This results in a statistically significant (albeit smaller) coefficient of the multiplex connectivity measure of 0.39 (p-value = 0.02, Adj. R^2=0.534). This alternative methodology confirms the importance of combining the multiple ways countries can connect, rather than simply focusing on one connection layer at a time, particularly for overall growth.

4. Trade-offs and Resilience to Shocks

Although the long-run effects of connectivity on growth appear to be positive, connectivity can also expose an economy to shocks and exacerbate crises. For example, Kaminsky and Reinhart (2000 and 2003) and Bae, Karolyi and Stulz (2003) show that financial sector linkages play an important role in propagating shocks. The 2005 commodity food price shock and the 2008 global financial crisis also demonstrated the cascade effects that shocks in one market can have in other markets.

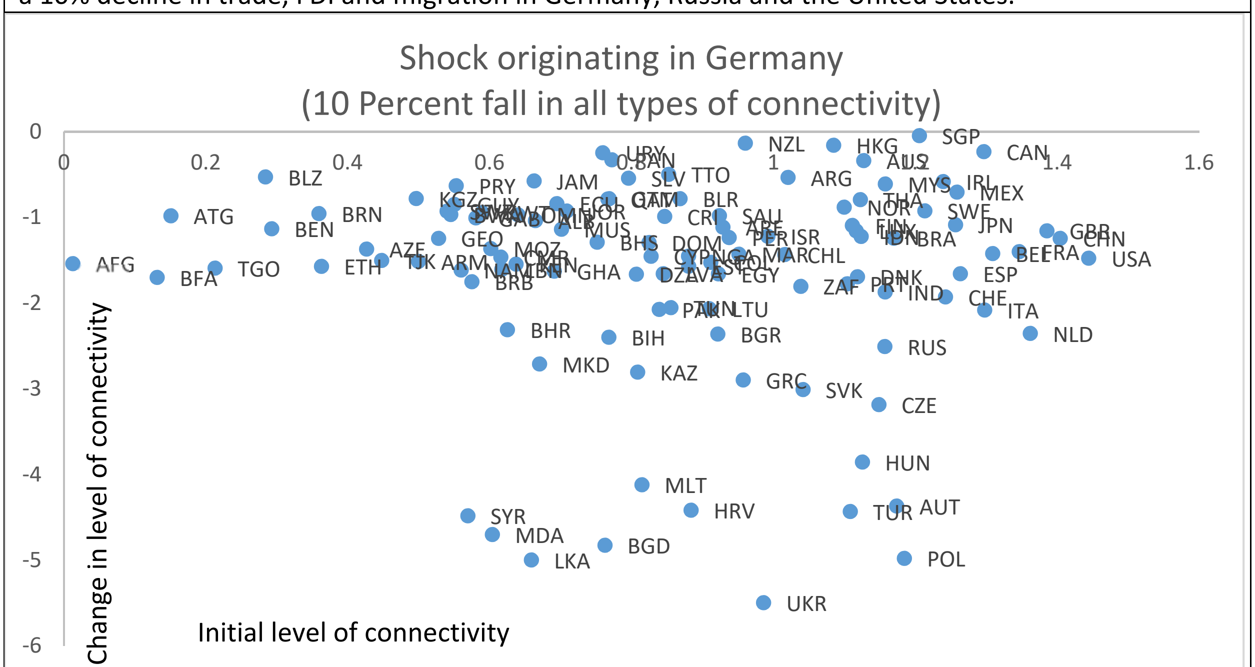
Connectivity, however, may also mitigate shocks which originate in some country-nodes in the network. For example, if a given country is well integrated in the network then a shock to one of its partners can be ameliorated by leveraging its other links to the remainder of the network.

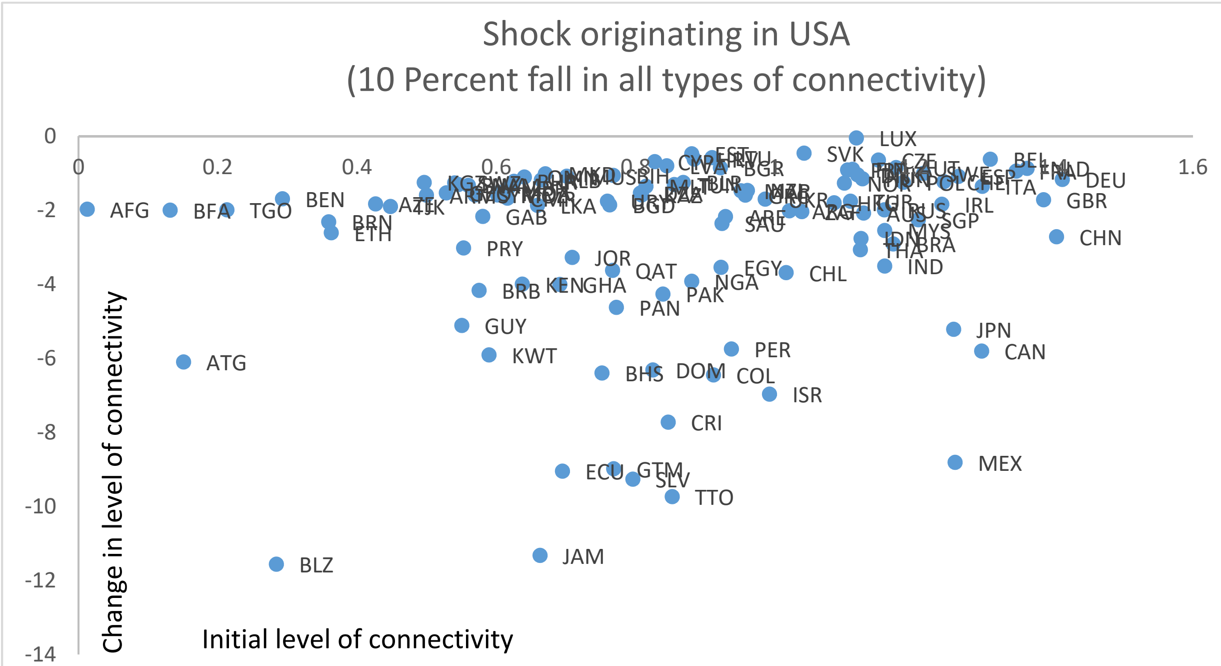
This analysis provides supporting evidence for both these phenomena. Countries with low levels of connectivity are more resilient to shocks in the global network because they have few partners and less connections that would transmit shocks. On the other hand, countries with high levels of connectivity also appear to be less affected by shocks to the network. This is likely due to well-diversified connections that can mitigate the severity of the shock. Countries in the "middle" of the connectivity spectrum appear to be most susceptible to international shocks. That is, they have low levels of diversified connectivity and are highly dependent on a few well-connected countries and connections (which boosts their overall connectivity). They are particularly susceptible to shocks affecting one of the well-connected countries where they derive access to global markets and connectivity.

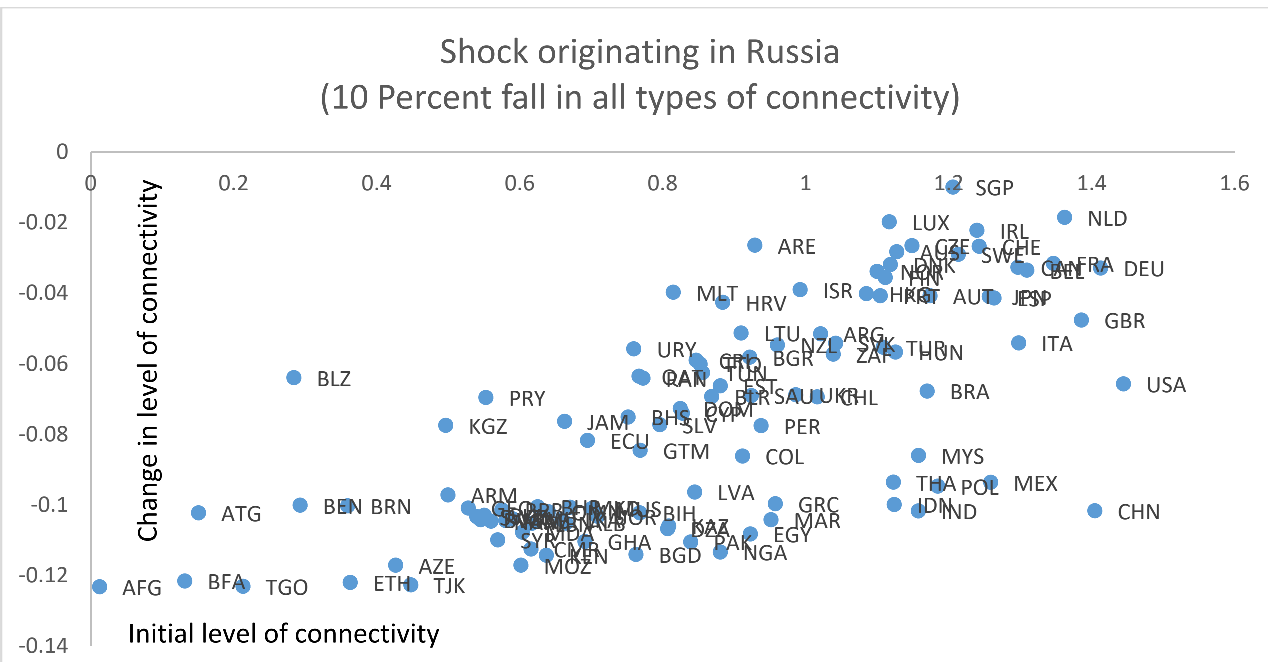
Figure 12 shows this pattern. A 10 percent simultaneous, negative shock is simulated to three connections (trade, migration and FDI) in each of three "central" and well-connected countries (Germany, USA and

Russia). The countries with the largest decline in their initial connectivity are those that are strongly connected to the country experiencing the shock and do not have strong connections to other partner countries. These countries tend to be in the middle-range of centrality and receive their connectivity through a few well-connected countries. A shock to one of these well-connected countries would do the largest damage to their global connectivity.

Figure 12. Simulated impact on individual countries' connectivity measure (modified PageRank) from a 10% decline in trade, FDI and migration in Germany, Russia and the United States.







As Figure 12 shows, a 10% adverse shock to German trade, migration, and FDI has an important impact on most countries in the world due to the high centrality of Germany. (The left axis shows the change in connectivity and the horizontal axis shows the initial level of connectivity.) However, not surprisingly, the most affected countries are the smaller countries for which Germany is the main partner country, including countries in ECA, the Middle East, and parts of Asia. The largest decrease in connectivity, due to a 10% decline in Germany's connectivity, is in Poland, Ukraine, and Sri Lanka, followed by Bangladesh, Macedonia, Croatia, and Turkey. However, due to the importance of Germany in the ECA network, even well-connected countries like Switzerland and the Netherlands experience a significant decline in their centralities. The least affected countries are the small Latin American countries and well-connected Asian economies, like Singapore.

An adverse shock to US connectivity has an even stronger impact on most countries in the world due to the high centrality of the United States (compare the range of the left axes in all the graphs). However, not surprisingly, the most affected countries are the smaller countries for which the United States is the main partner country. The largest decrease in connectivity, due to a 10% decline in US connectivity, is in Jamaica and Belize followed by Guatemala and the Dominican Republic. Due to the importance of the United States in the international global network, even well-connected large countries like Japan, Mexico and Canada experience a significant decline in their centralities. The least affected countries are the small European countries whose main trading partners are Germany, Great Britain, or Russia. Thus, Luxembourg, Estonia, the Slovak Republic and Lithuania barely experience any decline in their overall connectivity.

A 10 percent shock originating in Russia would have a modest impact on global connectivity (left axis). The shock would most affect countries that are closely tied to Russia, such as the former Soviet Republics, which are, in general, less connected to the global economy as a whole. In other words, they are highly reliant on Russia for connectivity to the world.

This framework allows for a multitude of scenarios, including impacts to just one dimension (say trade from China), or several dimensions across a subset of countries. However, a particularly pertinent one in recent times is a shock to Great Britain’s ties to the rest of the EU, the “Brexit” scenario.

Brexit would significantly affect the connectivity of ECA countries. Table 7 shows the effect on the overall connectivity index of ECA from a 10% reduction in all flows from Great Britain to the other EU 27 countries. Even though the other EU 27 countries are those affected directly by the shock, all of ECA is impacted by Brexit due to their indirect links to Great Britain and the EU countries. Smaller, well-connected nations such as Malta, Ireland, Cyprus and Luxembourg would be the most affected countries from this assumed Brexit scenario. Alternatively, the countries in Central Asia and the Caucuses would be the least affected.

Table 8: The ECA countries most affected and least affected by Brexit (percent decrease in Multidimensional Connectivity)

Most Affected (%)		Least Affected (%)	
Great Britain	-3.46864	Georgia	-0.00105
Malta	-1.35494	Kazakhstan	-0.00109
Ireland	-1.05116	Azerbaijan	-0.00141
Cyprus	-0.76504	Armenia	-0.00153
Luxembourg	-0.70449	Tajikistan	-0.00194
Netherlands	-0.65897	Kyrgyz Rep.	-0.00234
Belgium	-0.57851	Albania	-0.00456
Sweden	-0.30127	Bulgaria	-0.00459
Spain	-0.30023	Macedonia	-0.00623
Denmark	-0.28094	Latvia	-0.00796

Different regions in ECA have different exposures to types of connectivity shocks (trade, migration, FDI). For example, Western Europe is the most exposed to shocks in other Western European economies. Table 8 shows the largest two contributors to the decline in overall connectivity of each ECA sub-region in response to a 10 percent shock in three network layers (trade, FDI, migration). Not surprisingly, the overall connectivity of Central Asia in terms of shocks to trade, FDI and migration is affected most by Russia (trade, FDI, migration), but also by China (trade and FDI), and migration (Germany). The rest of ECA appears to be more sensitive to trade shocks in other ECA countries, particularly Germany, as well as the United States. Belgium and the Netherlands have the greatest impact on overall connectivity for the ECA region due to shocks to FDI, due to their large role in trade logistics and finance. Migration shocks are transmitted to various ECA subregions via countries in close proximity, language similarities and historic ties.

Table 9: Transmission of Trade, Migration, and FDI shocks to ECA Subregions

	Largest origin countries of shocks due to a 10 percent shock in trade, FDI and Migration		
Region Affected	Trade Shock	FDI Shock	Migration Shock
Central Asia	Russian Federation/China	Russian Federation/China	Russian Federation/Germany
Central Europe	Germany/ Netherlands	Germany/Austria	Germany/Austria
Western Balkans	Italy/Germany	Austria/Hungary	Italy/Germany
South Caucasus	Turkey/United States	Russian Federation/Kazakhstan	Russian Federation/Ukraine
Eastern Europe	Russian Federation/Germany	Russian Federation/Germany	Russian Federation/Poland
Russia	Germany/United States	Germany/Switzerland	Germany/Ukraine
Turkey	Germany/Italy	Belgium/Netherlands	Germany/Netherlands
Southern Europe	Germany/France	Belgium/Netherlands	Great Britain/Poland
Northern Europe	Germany/ Netherlands	Belgium/Netherlands	Finland/Norway
Western Europe	Germany/Netherlands	Belgium/Netherlands	Italy/Great Britain

5. Example of using connectivity measures for investment decisions

Assume that a country like Kazakhstan would like to use its national sovereign wealth fund to invest USD100 million of its income from natural resources in Central Europe. Assume also that the risk-adjusted rate of return in the region has been equalized by the market. Consequently, the government decides to choose a strategic destination for its investment, which would create future knowledge spillovers and innovation transfers. Table 10 lists the potential markets and their connectivity index.

Table 10. Potential markets and their multidimensional connectivity index.

Potential Country to place Investment	Multidimensional Connectivity Index of Country
Poland	0.29
Hungary	0.27
Czech Rep.	0.26
Romania	0.25
Bulgaria	0.21
Slovenia	0.20

Not surprisingly the country with the highest connectivity index is Poland. Poland is well integrated in European GVCs, and in particular Germany's manufacturing industries. By virtue of its strong ties with the Western European economies, Poland has one of the highest overall connectivity indices in ECA, and the benefits of connecting with it are significant.

Table 11 Kazakhstan's new multidimensional connectivity index after investing $100M in each of the respective markets.

Country where Kazakh investment is placed	Kazakhstan's change in Multidimensional Connectivity (%)
Bulgaria	.00735
Poland	.00525
Czech Rep.	.00523
Hungary	.00519
Slovenia	.00515
Romania	.00510

Somewhat counter-intuitively, Kazakhstan achieves the highest connectivity increase by investing in Bulgaria and not in countries with better integration in the global network like Poland or Hungary.

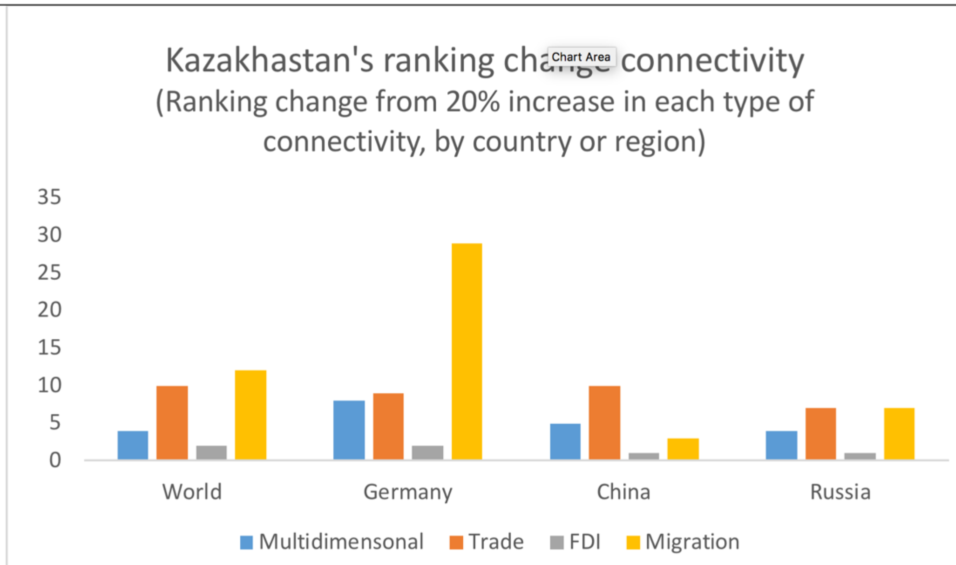
There are two reasons for this result. First, having a balanced connectivity portfolio is superior, in terms of knowledge spillovers, to being well connected only in one dimension at the expense of the others. For example, migration may bridge information between countries and stimulate other types of economic connections, such as external investment, trade, and communications linkages. Kazakhstan has relatively stronger ties to Bulgaria in terms of trade and migration but less so in terms of FDI. Therefore, increasing its FDI generates more benefits due to the complementarity of the channels.

Second, although richer countries have more knowledge than poorer ones, that knowledge is more difficult to reach. A moderate investment in a small economy can tap into a greater share of the potential of that economy than the same investment in a large one.

Choosing Bulgaria over Poland would generate over the long run 0.0021% greater economic growth. This translates into USD1.07 million higher annual income. Although this amount is negligible in terms of overall income growth, it is an additional 1.07% return on the original investment.

Examining this from another direction, Figure 13 summarizes the improvement in connectivity rank for Kazakhstan under several different scenarios. In the first scenario Kazakhstan increases each of its connections in trade, FDI and migration by 20% with every country, and improves its centrality by 4 places in the global ranking. However, if the same amount of trade, FDI and migration is focused on the bilateral connections with Germany, then the improvement in overall connectivity is 8 ranks.

Figure 13



6. Conclusion

While it has been well documented that globalization has long-term growth benefits through the technology and knowledge transferred via international connections, this is the first analysis to examine how the connections of partner countries matter for growth and how various types of connections interact with each other to influence economic growth. Economic interactions, aside from their direct benefits, also have indirect effects that can have lasting influence. Trade, migration and FDI move the flow of ideas and innovation across borders. Each of these channels individually appears to be an important source of economic growth by facilitating the transmission of knowledge. Moreover, multidimensional connectivity is more important for growth than any individual type of connectivity by itself. The whole of the connectivity network is greater than the sum of the parts. Although there is certainly some level of substitutability between the various layers, when it comes to information flows, complementary dominates. In fact, there might be a high degree of complementarity of the information flows that contribute to growth. Therefore, policies to promote balanced connectivity in many dimensions – one that focuses on trade, migration and FDI – is more beneficial than focusing on a policy to enhance only one. Indeed, reducing connectivity in one dimension may have adverse impacts on growth derived from other dimensions. Proposals to reduce migration flows, for example, may have adverse consequences for the growth-enhancing benefits of trade and FDI flows.

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