LINKING THE INTERCONNECTEDNESS AND INNOVATIVENESS OF GLOBAL VALUE CHAINS

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Abstract

There is a strong conceptual link between the structure of Global Value Chains (GVCs) and innovativeness. However, evidence of the link has largely been limited to the study of GVCs in industries that are purported to be innovative, and the studies have largely been at the level of an individual firm or product. This sampling bias and level of analysis creates a lack of an objective measure of innovativeness which would enable generalisation to other firms in a given industry and with which to perform inter-industry comparison. This chapter extends the typology of Global Value Architectures (GVA) by Wixted and Bliemel to use the same trade data to quantify the structures of 22 industry complexes via a measure of significant sourcing pathways per economy (SPE). We use the SPE results to rank the industries according to their level of interconnectedness and then reveal how this measure of trade complex structure correlates to well-established innovation measures based on R&D intensity, alliancing, and modularity. These correlations suggest that measures of trade in GVCs are complementary to these innovativeness measures. We thus propose that these innovativeness measures can be replaced by ours, as it is a more objective, replicable and thus reliable measures of innovativeness which also explicitly accounts for the dispersion of innovation across regions thereby representing the aggregate structure of all GVCs of a given industry.

Keywords

Inter-industry trade
Inter-country input-output (ICIO) modelling
Industry complexes
Global value architectures
Innovativeness measures

Introduction

In a globally connected business environment, the mantra for many is to innovate or die. Barring the existence of favourable and monopolistic trade agreements, tariffs or embargos, if your company does not source and produce the most innovative products or services or does not use the most innovative efficient and effective production processes, then it will only be a matter of time until your business fails. Advances in telecommunication, transportation (incl. containerization), and international trade agreements can work for or against anyone. The aggressiveness by which firms focus on producing and distributing innovative products applies across almost all industries. For manufacturing-based firms, and increasingly for service-based firms, this push to innovative and distribute globally has resulted in two primary strategies: specialisation and systems integration (Hobday, Davies & Prencipe 2005).

These two interrelated strategies create an inherent link between innovation and trade as indicted by DeBresson over 20 years ago. But what do they look like when played out at the level of an industry? What can we deduce about innovativeness from analysing the trade data of multiple industries at a global scale? Is it possible to create an objective measure to benchmark the relative level of innovativeness for any given industry? Can this measure be used to benchmark innovativeness across industries?

In this chapter we explore how a structural measure of industry complexes relates to measures of innovation. As in the previous chapter, trade complexes are defined as the trade network structure of a particular industry incorporating all source inputs but disaggregated by each source country. Trade complexes thus include more than a given industry, and include inter- and intra-industry trade. In essence, they reveal the global distribution of production. We then correlate our measure against the best established indicators of innovativeness.

Our analysis consistently reveals a relationship between the global distribution of production and multiple indicators of innovativeness across 22 manufacturing industries, our proposed measure of trade intensity to other industry classifications and indices. The measure derived here reveals rankings across industries that are strikingly similar to rankings based on the OECD's R&D intensity, modularity (Rosenkopf & Schilling 2007), and Pavitt's (1984) taxonomy. Such rankings are useful when exploring under-researched industries, and when making comparisons about each industry's relative trade intensity and innovativeness. Based on our findings, we discuss what our measures of the global distribution of production tell us about the relative innovativeness of industries suggest implications for innovation studies.

Literature Review

Global Value Chains (GVCs) have been studied from a plethora of perspectives and their empirical analysis continues apace. The different methodologies reflect the different interests of researchers. For instance, the World Bank (2017) is interested in economic development and impact. Nielsen (2018) represents an interest in firm-level data on business involvement in international trade. To address the above questions about investigating a relationship between structural patterns of trade in GVCs and degrees of innovativeness of that GVC or industry, we are more closely aligned with network-based studies. Recent network studies include Cingolani et al. (2018) which represents a stream of work analysing complete global trade networks at the 'industry' level. Similarly, Criscuolo and Timmis (2018) examine centrality and peripheries in networks. Both of these are nearest to our own interests (see Wixted and Bliemel this volume). Despite this rise in quantitative network analysis of GVCs, there remains little empirical work that links GVCs to innovation indices beyond case studies (see De Marchi et al. 2018) or early exploratory analysis (see Wixted 2009).

As articulated more elaborately in the companion chapter (Wixted & Bliemel this volume), the lack of empirical studies that objectively compare the network structure of GVCs across industries is likely to be an artefact of the lack of research at the meso-level. The meso-level includes inter-industry and inter-country trade that simultaneously reflects how individual firm's GVCs are structured (i.e., micro-level analysis), while also reflecting the globally aggregated structure of trade (i.e., macro-level analysis). Such aggregations of trade across national borders are clearly useful for national trade policy. However, the trade-off of macro-level analysis is that it can obscure the ability to identify the sourcing pathways of specific components from supplier industries or firms, which is important to consider for managers and academics interested in the broader phenomenon of trade and innovation.

Other literatures related to studying the relationship between the global distribution of production and innovation include the innovation system literature (e.g., Lundvall 1992; Cooke 2001) and technological innovation systems (e.g., Markard & Truffer 2008; Bergek et al. 2008). Many of these are geographical bounded studies of the interplay of organisations that foster innovation. In that sense, such studies do not reveal the inter-regional structure of the system or GVC that produces the innovation. Nor do they explore the degree of innovativeness of whatever is being produced. By definition, innovation systems are assumed to produce something with a requisite level of innovativeness, or else they would be a broader category of production systems with less emphasis on innovation.

An important concept in innovation systems research is its emphasis on the separability of components and activities within a system or region (e.g., von Hippel 1990 or Carlsson 2006). We draw on this concept, noting that is has rarely been extended to the level of inter-regional trade (aka the meso-level). Only a handful of studies approach a meso-level to include comparison of multiple global industries without geographic distinction (e.g., Rosenkopf & Schilling 2007).The separability or modularity of components and sub-components that are sourced via GVCs is a core attribute of many modern globally distributed value chains.

Systems of trade and innovation

In this study, we employ a meso-level at which we can being to disentangle global trade into *what* products are traded, *where* the production occurs and *with whom* trade occurs (as also advocated by Ernst 2002 and Luo et al. 2012), regardless of the degree of innovativeness. The 'who' and 'where' aspects are incorporated in some innovation studies at the meso-level (e.g., industry or cluster, as in Bathelt, Malmberg & Maskell's 2004 suggested framework).

To explore the relationship between the geographic distribution of production ('where' and 'who') for each industry ('what') and the degree of innovativeness (of the 'what') we look to logic provided by DeBresson (e.g, 1996). DeBresson conducted hundreds of interviews and collected thousands of surveys at the firm level on innovation and indicates a correlation between domestic trade. His analysis included multiple industries *and* their trade, albeit *within* a given region (e.g., DeBresson 1996; DeBresson & Xioping 1996). While his work is at a different level of analysis that GVCs, we are inspired by DeBresson's (1996) tome, which uses innovation input-output tables of a number of countries including the Italian economy; covering thousands of Italian manufacturers across 29 industries, and reveals a high correlation (0.836) between domestic trade patterns and innovation. DeBresson offers an output-oriented explanation for the correlation: Ceteris paribus, more innovative products will be in greater demand than less innovative ones:

> "[The] innovative output of one supplier industry will likely be used in greater proportion by a [downstream] industry that consumes more of that supplier's [innovative] output" (DeBresson 1996, p. 115).

While, this correlation is certainly interesting, DeBresson's work focussed only on individual economic regions with limited ranking across industries. For example, he provides a ranking of the top 10 industries according to innovative output and number of domestic suppliers, but specific to Italy (e.g., Table 7.3 in DeBresson 1996, p. 112). As such, he does not provide a complete scale or ranking across industries at a global scale.

DeBresson's work with Xioping includes some comparison across countries, such as his scatter plot of multiple industries for three economies (Italy, China, and France) which contrasts the number of domestic economic linkages against innovation frequency or innovative product sales (depending on the data availability - see Figure 6, in DeBresson & Xioping 1996, p. 196). Their analysis again reveals a correlation between domestic trade and innovativeness, for which they offer an additional explanation to the aforementioned one, which is a pre-cursor to the systems integration strategy we know today (Hobday et al. 2005):

> "The most plausible explanation for the above relationship between economic linkages and innovative activity is a simple one, the more varied the enterprise's information network is, the more likely it is to combine production factors in a new way for new uses. Innovation, as Schumpeter stressed, requires first and foremost new combinations. [..] If the entrepreneur is in contact with a variety of potential input suppliers, he has more opportunities to innovate. Conversely, if he has a variety of potential market outlets for his products, he has greater possibilities for innovative variation" (DeBresson & Xioping 1996, p. 197).

This input-oriented explanation is at the firm level and offers complementary logic to DeBresson's (1996) output-oriented explanation: Having more linkages enables more innovative combinations of inputs. This holds under the assumption of a matching increase in absorptive capacity since the absorptive capacity of a firm determines its ability to make use of the new information it receives. If the information inflows increase beyond the firm's absorptive capacity, then the firm will still not do any better.

While these correlations between trade and innovativeness are intriguing, the limited number of countries and variation across the countries leaves the reader with puzzle pieces rather than a complete picture. For example, in their research '*economic linkages'* were between organizations, and not at a global level. And, their measure of innovativeness incorporates the subjectivity of the managers responding to their interviews and surveys. Researchers are left to wonder, are these patterns generalizable to more countries and more industries? How robust are these pattern using less subjective data? Beyond a likelihood of producing something innovative, how is the degree of innovativeness related to these patterns of sourcing?

Measures of trade and innovation intensity

Scattered through the literature are various attempts at operationalizing industry attributes in terms of the skill, task or modularity intensiveness of industry products. For example, Minondo and Requena-Silvente (2013) employ a measure of skill-intensity based on the number of occupations related to ISIC 4 digit industry codes as a proxy for product complexity.

While these measures are good at capturing what occurs within an industry, they don't necessarily capture the interconnections across industries and regions, and thus only cast some light onto the question of how industries are interconnected and concentrated at a global level. Vice-versa, analysis of trade data (like ours) directly captures the latter, but only indirectly captures the bigger picture of innovation complexity. The merits (and scope for future research) of *inter*-industry and *inter*-country trade data analysis are also aptly summarized by Panagariya and Bagaria (2013): *"A complementary explanation for the concentration in trade is in terms of international specialisation in the production of components that has been made possible by the fragmentation of previously vertically integrated production processes. A country may specialise in the exports of a few final products that it assembles using the components that it imports. This will produce some concentration in both exports and imports."* (p. 1179).

To explore how the distribution of global production may be related to the degree of innovativeness across industries, we draw on three indices and categorizations of innovation intensity and complexity: (i) the OECD's (1997) R&D intensity, (ii) measures based on alliancing and modularization (Rosenkopf & Schilling 2007), and (iii) Pavitt's classic sectoral taxonomy (1984). The OECD measure and Pavitt's taxonomy are well established in the literature as indicators of innovativeness. The measures by Rosenkopf and Schilling remain contested as explained in greater detail below, but provide another emerging benchmark of innovativeness across multiple industries.

Methodology and analysis

In this section, we explain how we build on an earlier typology of Global Value Architectures (Wixted and Bliemel, this volume) to quantify the intensity of the interconnections of each industry, as an indicator of innovation complexity. By innovation complexity, we mean the degree to which the production of goods by an industry are dependent on a large number of highly interdependent inputs. We then also benchmark our measure against other industry level measures related to innovation.

The method follows three general steps:

1. We start with the same data, method and inter-country input-output (ICIO) model as Wixted (2009) and Wixted and Bliemel (this volume) by which significant sourcing pathways were isolated for each of 22 industry complexes.
2. The trade structure of each industry complex is operationalised as a trade link intensity measure, which is a count of the significant pathways per industry, normalised by the number of economies that have significant trade pathways in that industry complex.
3. The league table of trade intensity across all industries is then compared to the aforementioned benchmarks of innovativeness measures (e.g. OECD, Pavitt and Rosenkopf & Schilling).

Step 1: Isolation of significant sourcing pathways

This step is comprised of the two steps in our other chapter, including the construction of the 'Wixted model' from the OECD input-output data, from which we isolate only the significant sourcing pathways per economy across all 22 manufacturing industries in the 1995 and 2000 OECD input-output tables. Our measure is based on 'significant' trade links that account for at least 10 per cent of the imported value (foreign value-added) of an industry *in a particular country* – cumulatively forming the trade complex. The isolated relationships reveal the structure of the trade complex (see Wixted & Bliemel, this volume, for graphics) and emphasize the core portion of the value-add structure of trade. They should *not* be interpreted as representing *net volumes* or *scale* of trade. Our measure provides a new perspective on the patterns of global sourcing and should not be confused with long running existing debates on *net* trade.

Step 2: Normalisation of trade intensity per economy

The second step is to count the total number of significant sourcing pathway and normalise it by the number of economies available in the model, repeated for each of the 22 industries. This normalization results in a measure of significant sourcing pathways per economy (or SPE for short) that reflects the level of complexity and interconnectedness of each industry complex. The averaging to a per-economy basis accommodates industries for which the raw data by OECD did not include the full matrix of countries. For instance, for Non-ferrous metals, Pharmaceuticals, Aerospace and Transportation equipment the fewer than 10 economies were available in OECD's 2000 dataset, so the dataset for 1995 was used for these industries, with 12, 13, 13 and 17 economies, respectively. This approach can also accommodate ICIO models of different dimensions, such as ones based on the World Input-Output Database (WIOD)[1] which has a different number of countries and industries.

Each economy's transaction intensity or SPE value is also directly analogous to the average in-degree centrality measure used in social network analysis. To explore robustness of this measure across time and datasets, we compare the SPE measures based on OECD data against SPE measures using WIOD data (Timmer et al. 2012). While the WIOD data offers more recent data and more countries it manages this partly by amalgamating important industry categories, thereby obfuscating critical differences across some industries. For example, the two electronics industries and 'precision and optical equipment' in the OECD data are treated as one 'electrical and optical equipment' industry in the WIOD data. Similarly, WIOD does not separate pharmaceuticals from the broader chemicals classification. Furthermore, the WIOD categorization for 'Basic and Fabricated Metals' incorporates two OECD industries, as does WIOD's 'Machinery nec' industry. Mapping the vehicular industries across the two databases is particularly problematic because OECD's distinction between 'motor vehicles,' 'aerospace,' railroad equipment and transport nec. and 'shipbuilding' are treated as a single unified category in WIOD.

Such trade-offs maximise geographic coverage yet miss important industry differences. Nonetheless, we have repeated our analysis using WIOD data for 2008 as an additional robustness check and have not found any major differences in the results. Table 1 summarizes the SPE levels for all the manufacturing industries in the Wixted model (ranked by SPE) and the WIOD model, both using the 10% threshold for 'significance' of pathways.

Table 1: Significant sourcing pathways per economy (SPE) by industry complex and model

Wixted model / OECD industry name	SPE	WIOD model / industry name	SPE
Iron and steel	0.82	Basic Metals and Fabricated Metal	1.38
Coke, refined petroleum products and nuclear fuel	0.82	Coke, Refined Petroleum and Nuclear Fuel	0.97
Other non-metallic mineral products	0.95	Other Non-Metallic Mineral	1.25
Food products, beverages and tobacco	0.95	Food, Beverages and Tobacco	1.33
Wood and products of wood and cork	1.00	Wood and Products of Wood and Cork	1.28
Pulp, paper, paper products, printing and publishing	1.00	Pulp, Paper, Paper , Printing and Publishing	1.53
Chemicals excluding pharmaceuticals (Industrial & other)	1.00	Chemicals and Chemical Products (including Pharmaceuticals)	1.53
Textiles, textile products, leather and footwear	1.00	Average for (1) Textiles and Textile Products, and (2) Leather, Leather and Footwear	1.64
Fabricated metal products, except machinery and equip	1.05	Basic Metals and Fabricated Metal	1.38
Non-ferrous metals	1.08	Basic Metals and Fabricated Metal	1.38

[1] WIOD is the World Input Output Database, which was developed by an international consortium funded by the European Commission and released in May 2012 at http://www.wiod.org/. In comparison to the 1.2m cells in our model, the WIOD database contains ((35x35) x (41) x 41 = approximately 2.1m cells.

Manufacturing nec; including Furniture	1.09	Manufacturing, Nec; Recycling	1.63
Rubber and plastics products	1.23	Rubber and Plastics	1.70
Building & repairing of ships and boats	1.36	(not distinguishable from other vehicular industries)	-
Motor vehicles, trailers and semi-trailers	1.36	(not distinguishable from other vehicular industries)	-
Medical, precision and optical instruments	1.41	Electrical and Optical Equipment	1.78
Machinery and equip nec (aka industrial machinery)	1.41	Machinery, Nec	1.48
Electrical machinery and apparatus, nec	1.45	Machinery, Nec	1.48
Railroad equipment & transport equip nec	1.53	Transport Equipment	1.60
Radio, television and communication equipment	1.57	Electrical and Optical Equipment	1.78
Pharmaceuticals	1.69	(integrated into Chemicals and Chemical Products)	n/a
Office, accounting and computing machinery	1.77	Electrical and Optical Equipment	1.78
Aircraft and spacecraft	1.85	(not distinguishable from other vehicular industries)	-

Overall, the WIOD data show the same general sequence of industries in terms of SPE. In addition to the differences between models (i.e., industry classifications and regions), the overall increase in SPEs in the WIOD data reflects the increased levels of globalization in 2008 versus the OECD data from 2000 (see also Figure 3 in Los, Timmer & de Vries 2015 for a trend analysis).

Step 3: Comparison of SPE and innovativeness

The third step is to examine the relationship between trade intensity and indices of innovation. The purpose of this step is to explore whether an index based on trade link intensity is representative of the relative 'innovativeness' of industries. Innovativeness is typically perceived as something that is primarily based on knowledge or its manifestation as a technology or product. As such, knowledge and technology are related to the products and to their production, but remain distinct concepts. We acknowledge that linking innovativeness and trade might appear to confuse the knowledge and technologies embedded in products with the production of those products. However, the global organisation of production remains conceptually distinct from the level of technology and knowledge innovativeness in the products being produced. These are separate but related key features of global value chains and studying their relationship is the motivation for this study.

As revealed in the earlier analysis and GVA typology by Wixted and Bliemel (this volume), there are significant differences across industries in terms of how interconnected various regions are, and how interconnected the three 'worlds' are (Europe Asia, and the Americas). Some of these trade relations are governed by (i) natural resource constraints or endowments of each country and (ii) industry or firm specific trade agreements. When qualitatively comparing the exo-nets against the global factories, a theme of low- versus high-tech products emerges. This is in part due to the cost-to-value curve of shipping raw materials vs. high-tech goods; commodity ores and metals often compete on cost to the purchaser and are sourced due to geographic proximity and delivery speed (for metals), while computer components compete on value for the purchaser and are often sourced from around the globe. More importantly, the degree to which an industry's trade complex is interconnected is a factor of the technological composition of the industry's products. High-tech products are usually not just a single high-tech component; they are complex assemblies of *multiple* high-tech components (Dedrick, Kraemer and Linden, 2009; Ali-Yrkkö et al., 2011).

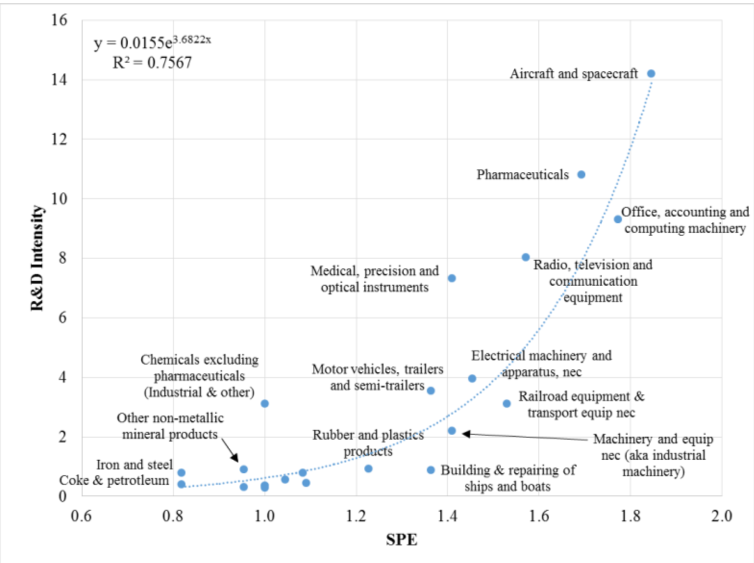
All of the above arguments, include DeBressons explanations suggests a correlation between trade and innovativeness. There are, however, also arguments and evidence to the contrary. For instance, recent work by Piccardi and Tajoli (2018) on the complexity of products and the centralisation of their export networks finds that more complex products actually have more centralised networks. The key difference between the research in this chapter and theirs is whether the trade is imports or exports. As noted in their conclusions: "even if global value chains increase connectivity by generating many [sourcing] trade links between countries exchanging parts and inputs, the complex goods resulting from this organization are eventually exported by the final assembler, giving rise to a centralized structure of [export] trade" (ibid., p. 10).

To quantitatively explore whether SPE can be used as an index of innovativeness across industries, we benchmark three indices and categorizations of innovation intensity and complexity: (i) the OECD's R&D intensity, (ii) measures based on alliancing and modularization (Rosenkopf & Schilling 2007), and (iii) Pavitt's classic sectoral taxonomy (1984).

SPE versus R&D intensity

Our first benchmarking of the SPE measure is against R&D intensity. As part of their bi-annual Science, Technology and Industry Scoreboard, the OECD (the same source as our data) provides an R&D intensity measure of manufacturing industries.[2] This measure has long been held to be a useful index of innovativeness when assuming that firms invest their own resources into their own innovations. While the number of industries is insufficient to derive a statistically significant correlation, the SPE measure does appear to increase with R&D intensity[3], as shown in Figure 1.

Figure 1: Significant trade pathways per economy (SPE) versus R&D intensity



[2] http://dx.doi.org/10.1787/sti_scoreboard-2013-en We use the 2000 data to correspond to our ICIO model.
[3] This might look to some readers as an echo of Vernon's (1979, 1992) theory of technology and trade, even though his work was based volumes of exports and imports not the patterns of value-add linkages.

It has long been observed that there is a relationship between innovativeness and *volume* of *exports*, wherein innovating economies export to emerging economies until it becomes more cost effective for the innovation to be produced elsewhere (Nelson and Vorman 1977; Krugman 1979). Here we are concerned with a slightly different hypothesis, that the innovativeness of an industry is related to the *structure* of the *imports* required to produce the innovation. The null hypothesis is that there is no mathematical relationship linking (sourcing) trade and innovativeness. Based on the above visualisation, this is easily rejected, with an indication that there is at least a linear fit (R^2 = 73.38).

Furthermore, we observe that an exponential relationship slightly improves the fit (R^2 = 75.67). The exponential relationship suggests that there may be limits to how globally interconnected an industry can be. R&D intensity may increase well above 10%, but one can only have so many significant sourcing relationships with before running out of countries. Also visible in Figure 1, is that a number of trade complexes have a similar number of SPEs but have differing levels of R&D. Aerospace is a prime example with similarly high levels of SPE to other industries, but disproportionately high levels of R&D intensity.

The curve in Figure 1 echoes DeBresson's comments that more innovative outputs from one industry are more likely to be inputs to multiple other industries (DeBresson 1996). There are of course exceptions to this pattern, such as shipbuilding, which has disproportionately more trade significant sourcing pathways for such a low R&D intensity industry. OECD data shows that patenting is increasing at a slower pace in the maritime industry than in the economy more generally (Corbett et al., 2016) although the difference between different subsectors is substantial with defence shipbuilding showing an R&D spend of some 10% of turnover (Bekkers et al. 2009). Variation from the curve simply acknowledges that trade linkages may be driven by factors other than innovation (e.g., trade agreements, tariffs, strategic relationships, cost-to-value of shipping commodities, etc.).

SPE versus modularization and alliancing

Amador and Cabral (2016) present the argument that "Technology is a key driver of GVCs [and] makes it possible that parts and components produced in factories in different parts of the world perfectly combine in sophisticated final products" (Amador & Cabral, 2016, p. 280). Despite this argument, their survey of measures of global value chains does not return to the topic of parts being shipped and traded globally. Blyde (2014) and Amador and di Mauro (2015) also avoid discussions of modular/modularity based GVCs. We can only speculate that their omission of modularity-based measures is because such measurement is problematic. Aside, it may be interesting to note that changing production technologies can impact sourcing pathways. An example is GE's Advanced Turboprop (ATP) where the engine design team reduced 855 separate parts down to just 12 and as a result, more than a third of the engine is 3D-printed with the associated reduction of the supply chain.[4] See also the case study associated with this chapter for a closer look at the modularisation in Aerospace, associated vulnerabilities to GVC disruption and the impact of disintermediating sources by 3D-printing.

Modularity has its roots in 'near-decomposability' (Simon 1962), and is the concept that larger systems can be broken down into multiple interrelated components or modules that can be "mixed and matched" (Baldwin & Clark 1997). The implication is that modularization enables faster

[4] https://www.ge.com/reports/mad-props-3d-printed-airplane-engine-will-run-year/

iteration of variations of the whole, and can lead to greater performance and accelerated product innovation, because firms can “rapidly respond to altered business conditions by recombining diverse divisional resources and product-market domains” (Galunic & Eisenhardt, 2001, p. 1244). In other words, modularization is linked to innovation via Schumpeterian innovation through recombination of modules, consistent with the proposition put forward by DeBresson and Xioping (1996). Adoption of modularisation as a strategy to increase the diversity of modules and their combinations can occur in many ways, ranging from open markets providing the modules, to modules being collaboratively produced with suppliers (e.g., Song, Ming & Wang 2012), through to modules being developed in-house and then outsourced to strategic suppliers while maintaining full control over IP (e.g., Chanaron 2001).

Modularization may be operationalized in three ways: in terms of product (i) components, (ii) organizational units, or (iii) the production-related activities these units perform. An example of how products and their production are simultaneously modularized within a larger system can be found in GE’s multimodal production plant in Puna, India. This manufacturing plant can deploy the same 1,500 employees and footprint to pivot cleanly from production of jet engines and locomotive technology to wind turbines and water treatment equipment as demand changes (Toner et al. 2015). Another rule of thumb for how much to modularise and how to bundle components into modules or submodules is that the number of modules is approximately the square root of the number of components in the systems (Lean Management Institute 2012 in Qiao, Efatmaneshnik, Ryan & Shoval 2017).

While differences exist in some settings, these three forms of modularization are generally correlated (Sanchez & Mahoney 1996; Brusoni & Prencipe 2001; MacCormack, Baldwin & Rusnak 2012). Despite these nuances between different forms of modularity, the core premise remains the same: modularization creates transactions across firm boundaries (Baldwin 2008; Luo et al. 2012), thus further cementing a relationship between innovation and trade.

Despite several advances in modularity research, the “biggest challenge in empirical research on modularity is quantifying modularity” (Cebon, Hauptman & Shekhar 2008, p. 382). Instead of benchmarking against a modularity measure per se, we compare our index against measures provided by Rosenkopf and Schilling (2007), including their Innovation Activity Separability (IAS) variable and their small world quotient of strategic alliances within an industry, both of which are proxies for modularity. For the IAS variable, their intention was that it “captures the degree to which the industry is considered to be characterized by innovation activities that can be separated across multiple firms (as, for example, when the industry is characterized by interfirm product modularity” (2007, p. 193). However, their IAS measure includes three limitations. Firstly, it is not a conventional scale (i.e., Likert style), but based on votes in a survey in which “respondents were asked to nominate the 10 industries with the highest level” (ibid., p. 193). While their voting process may reveal the rank of each industry by modularity, it may not accurately reflect their relative level of modularity. Secondly, the IAS measure is based on subjective nominations requested from of a ‘set of 13 scholars’, for which it remains questionable how many scholars responded to their request and how much each scholar was an expert across all industries. Thirdly, the voting criteria contained a blend of (i) IAS and (ii) product modularity, despite their article’s emphasis on IAS. Despite these limitations, we believe their measures provide reasonable safeguards against biases and subjectivity and cover a broad range of industries to provide another useful robustness check against which to benchmark or calibrate our SPE-based index.

The small world quotient is the degree to which the network is clustered and has longer path lengths in comparison to a random network graph of the same size (Watts & Strogatz, 1998). Rosekopf and Schilling (2007) create a small world quotient based on strategic alliance data and thus less subjective than their IAS measure. It represents the degree to which the aggregate strategic alliance pattern of all firms in a given industry represents one interconnected 'world' or whether the industry is fragmented into many smaller and lessor interconnected clusters. This measure is conceptually analogous to our notion of a global factory, but does not include weightings of each relationship or geographic specificity. Plots of SPE versus the IAS measure (Figure 2) and small-world quotient (Figure 3) indicate the degree to which SPE is correlated with their measures. In absence of a more sophisticated theory linking trade and innovativeness, we default to a linear relationship, with the null hypothesis being 'no relationship'. Overall, both graphs lend further evidence towards a relationship between the global distribution of production and innovativeness.

Figure 2: Significant trade pathways per economy (SPE) versus Innovation Activity Separability (IAS)

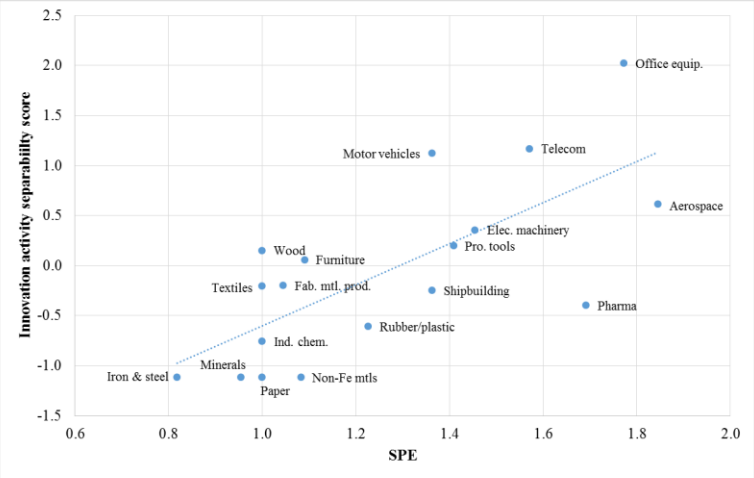


Figure 3: Significant trade pathways per economy (SPE) versus small-world quotient

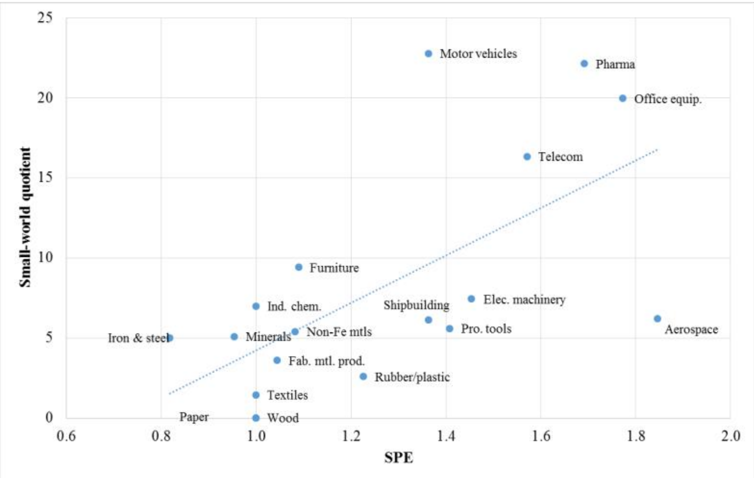
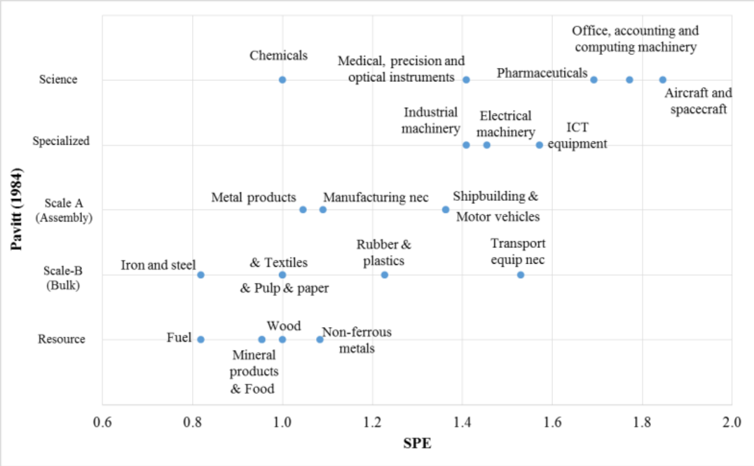


Figure 4: Significant trade pathways per economy (SPE) grouped by Pavitt (1984)



In comparison to the other benchmarks, Pavitt's initial work is based on one country for innovations between 1945 and 1979. So, it unsurprising that it is only a *good* fit, and not a perfect fit. However, *that it is a fit at all is important*.

Discussion

By focussing on only the significant sourcing pathways, we make a methodological contribution: quantifying the structure of industry complexes and GVCs by calculating the significant sourcing pathways per economy (SPE). This methodological contribution forms the foundation for direct quantitative comparison of industries' structures (e.g., how much % more globally networked is industry X vs industry Y?) and for subsequent analysis of innovativeness across industries. As a robustness check, we repeat our analysis using WIOD data. While their model includes more regions, it is less granular about industries. Nonetheless, we find the SPE index is generally consistent across datasets.

Perhaps the most significant contribution is the benchmarking of the SPE measure against the various innovation indices and categories, supporting our proposition that it can be a reliable and objective proxy for innovativeness across industries. The three comparisons of (inter- and intra-industry) sourcing pathway intensity lend consistent support that industries which have a higher proportion of international value-add to supplies from a larger number of source countries also tend to be industries with greater levels of innovativeness. This consistent pattern is despite there being significant differences between these three benchmark measures. Some measures are more directly related to innovation (R&D intensity), and others are incidental to innovation and knowledge (alliancing). Some measures are based on objective data (R&D intensity, alliancing), while others are based on expert's knowledge (IAS, Pavitt). Predominantly, these measures and classifications are based on what happens *within* an industry. The only one that is somewhat inclusive of inter-industry relations is the small world quotient of strategic alliances. Our comparisons of SPE against these benchmarks reinforce that there can be no perfect index that captures the multidimensionality of product complexity. Further, research is required to compare these metrics to the Product Complexity Index developed by Urbanic and ElMaraghy (2003, 2006) at the plant level and the Product Complexity Index (PCI) developed by Hausmann et al. (2012) at the level of global trade. However, the support for a link between trade pathways and innovation is consistent across all three benchmarks. We thus argue that the SPE measure appears to be a reliable and objective proxy measure for innovation complexity in a global era. Furthermore, we believe it can be used across time to analyse changes at the industry and global levels.

Empirical implications

Because of the similarities between SPE and the three measures of innovativeness, we believe that the rank order of industries according to SPE in Table 1 provides a guide to measure the innovativeness of each industry in a way that is more objective than the three benchmarks used. To guide and simplify our discussion of the empirical implications of this relationship, we frame the discussion using each of the three archetypes of Global Value Architecture – global factory, fusion and exo-net (see also the previous chapter by Wixted & Bliemel for a more elaborate explanation of the typology). Using this categorisation, we explore how the different indices' arguments are aligned within each category.

We acknowledge that some industries do not neatly follow this categorisation because they deviate from the curves shown in the above figures. For example for the R&D intensity benchmark shown in Figure 1, Chemicals (industrial and other) along with Medical and Optical Instruments stand out as being off the curve. Meanwhile, for both the Innovation Activity Separability and small world quotient benchmarking shown in Figures 2 and 3, Aerospace and Pharmaceuticals do not follow the general pattern. Finally, for the benchmarking against Pavitt's taxonomy, shown in Figure 4, one of the more obvious variants is Chemicals. Pavitt classified it as science-based, later the OECD suggests it is scale-based; more precisely bulk scale based. Over time, as new production methods are introduced, products that were previously scale-based may become less dependent on scale, as with the introduction of flow chemistry. This means that the categorisation may change over time. It could be argued that the classification challenges relating to Chemicals can be explained by considering whether the innovation is related to the production process, as with scale-based petrochemicals or whether the innovation is related to the chemical itself, as with science-based pharmaceutical molecules.

Pharmaceuticals are also a peculiar industry, with their own tariff-free structure (i.e., the Uruguay Round) and extreme emphasis on R&D and high value per unit, with relatively few raw ingredients and intermediate goods, where imports and exports are predominantly finished goods. As noted by Kiriyama (2011), "More than 70% of the exports to [high-income countries] are finished goods [and finished goods] exports to [low- and middle-income countries] occupy more than half of such exports. A major exception is China, over 70% of whose exports are intermediate goods" (p. 24). At any rate, these deviations from the generalised pattern provide interesting areas for a future research agenda.

Despite these variations, our analysis and plots above suggest that the classifications are consistently mapped onto the three global value architectures as follows in Table 2. The first column is the GVA type and the second column reflects the quantitative measure and range according to OECD and Rosenkopf and Schilling (2007). Pavitt's categorisation is added as a third column because is it not a quantifiable measure and reveals how his five industry classes map onto the three GVA types.

Table 2: Innovation characteristics of Global Value Architectures (GVA)

GVA	Innovation measure	Pavitt's categorisation
Global Factory	High R&D intensity High/Medium IAS Spider web / hybrid alliance network structure	Science based (except chemicals in Pavitt's original)
Fusion	Medium R&D intensity Medium and High IAS Hybrid alliance network structure	Specialised supplier Scale A - assembly
Exo-nets	Low R&D intensity Low IAS Disconnected alliance network structure	Scale B – bulk materials Supplier dominated / resource intensive

Global Factories (aerospace, radio, television and communication equipment, office, accounting and computing machinery) are characterized by high SPE levels and high R&D intensity. The investment in R&D related knowledge and coordination in this industry is evident at the level of product architectures (Boeing 787 or smartphones / tablets) and at the level of individual components (e.g., screens or chips). These each require a considerable amount of investment in both knowledge creation and innovation development. Higher orders of specialization open up opportunities for knowledge sharing within alliances as well as international trade of the specialized components. As products become more knowledge intensive and complex there are greater opportunities for a division of labour, including innovation activities, and systems integration (Hobday et al. 2005). Such higher levels of complexity and interconnections are also observed in Minondo and Requena-Silvente's (2013) analysis of occupational complexity, wherein aerospace, electronics, precision instruments and pharmaceuticals are at the top of their list. The last two of these are high in our fusion category.

In regards to Pavitt's taxonomy, there is an important distinction to make regarding knowledge sources versus more tangible sources. In Pavitt's taxonomy science-based firms relied on internal knowledge sources and knowledge gained through collaboration with universities. While this remains true for individual firms, the organisation of the trade complexes reveals that bringing innovative products to market requires 'global factories' that source tangible inputs from well beyond the firm's boundaries. Our result may be interpreted as another manifestation of the trend for R&D intensive firms to focus their resources on R&D and marketing while outsourcing and offshoring labour-intensive activities (i.e., manufacturing). This trend is visualized in the 'smile curve' (Baldwin & Evenett 2015; Office of the Chief Economist 2018). Labour intensity in manufacturing is continuously declining (Tregenna 2008) and in the period 1985-2014 there has been a shift of manufacturing from labour-intensive to skill-intensive activities in developed countries (Wood 2017).

Fusion architectures (Railroad equipment & transport equip nec, Motor vehicles, trailers and semi-trailers, Electrical machinery and apparatus, nec, Pharmaceuticals, Building & repairing of ships and boats, Medical, precision and optical instruments) are characterized by mid-range SPE levels which reflect their structure comprising two moderately interconnected worlds. In comparison to Global Factories, this reflects regionalization of the production, as perhaps influenced by trade policies specific to that industry or the relatively high cost of shipping modules around the world. For example, the cost of shipping $1m of microchips is much lower than the cost of shipping $1m of railroad equipment.

This group of industries is a 'mixed bag' of science-based, specialised suppliers and the scale-based auto industry. However, these industries have relatively similar (medium) levels of R&D intensity. This group includes specialised high value contract jobs of custom shipbuilding and repairs and lower value contract jobs of mass produced railroad equipment. While traditional studies of the Medical, precision and optical instruments ‘industry’ emphasise the geography of the innovators, it may be a fusion trade complex due to the *inter-industry* links with electronics industries. The mix of industries in this category suggests that each has its own particular dynamics – that integrate it more into the global economy than the exo-nets but less than the global factories – across all the dimensions of R&D, alliance building and innovation generally.

Notably, the motor vehicles industry is in this category and is not a global factory. This suggests that the complexity of the motor vehicle industry may be actually be lower than it is perceived to be (c.f. high IAS scores). Some of the differences between perceptions versus the reality of modularisation and complexity in the automotive industry come down to whether only the tier 1 suppliers modules are considered, or also the tier 2 and 3 submodules and components, as the latter have been shown to have higher PCI scores than the finished vehicles (extracted from the observatory of economic complexity https://atlas.media.mit.edu/en/rankings/product/hs07/?year_range=2011-2016). This discrepancy makes it a peculiar case study, thus reinforcing the high level of attention it has received in academic literature, particularly the global value chains literature. Despite the modest levels of trade links, the strategic alliances in this industry are densely interconnected and the tiers of suppliers and the application of modularity in this industry have been extensively analysed (cf. Cabigiosu, Zirpoli & Camuffo 2013).

Similarly, the pharmaceuticals industry has received considerable attention over a very long time by innovation scholars. Our SPE indicator ranks pharmaceutical higher than perhaps might be expected for the production of this kind of product. Nevertheless, it has fewer trade links than would be suggested by other measures of innovation (R&D intensity, alliance measures and Minondo and Requena-Silvente 2013). The process to get a drug approved across jurisdictions can be long and complicated, involving prolonged research, licensing and distribution royalty payments, multi-site clinical trials and data exchange, and complex partnership agreements related to patenting costs, marketing and production costs. While trade in the intermediate components to a particular drug are relatively low (Foreign Value Add), our trade link indicator is not excessively out of step with the other innovation metrics and suggests that the trade routes for pharmaceuticals are more complicated than expected. It might also be possible that the raw data for the I-O tables picked up the service element (such as R&D and licencing).

Exo-nets are characterized by low levels of R&D intensity, low IAS, disconnected alliance networks and activities that Pavitt/OECD associate with bulk production, ‘supplier dominated’ and resource based industries. In these industries the innovation is done by the tier one suppliers and then migrates into the resource extraction industry. This is mostly a push innovation rather than pull innovation. These industries are at the little-studied end of the innovation spectrum. That is not to say they are uninteresting (cf. Hirsch-Kreinsen 2008 and Hirsch-Kreinsen & Jacobson 2008). Their study remains focused on the creation of innovation and the sources of knowledge, but usually does not extend to global production systems. There is fertile territory to explore the policy connections between global innovation and trade complexes, especially the potential for specific structures around productivity competitiveness. It is possible that the low SPE levels are more related to the sequential flow of goods in these industries than to a lack of developing and emerging economies in the Wixted ICIO model (replication using WIOD’s data also had lower SPE levels than other industries).

Methodological implications

The empirical contributions have methodological and practical implications. Methodologically, trade statistics that appear as rows in a table or lines on a map can be easily misunderstood. While they appear to represent an *average* industry or firm in a given country, that mindset is mistaken; *aggregates* are not representative of *averages*. As seen in our selection of significant sourcing pathways per economy and with many other economic phenomena, power laws apply (Andriani & McKelvey 2007). Bernard, Jensen and Schott (2009) suggests 90% of imports and exports with the US are accounted for by just the top 5 per cent of U.S. firms; i.e., aggregates are more representative of industry 'outliers' than industry averages. A similar argument can be made for the geography of production. Parilla and Berube's (2013) analysis shows that production within North America is not evenly distributed. Instead, out of all cities in North America (Canada, Mexico and USA) there are just 19 automotive, 16 electronics and 14 aerospace city-based clusters which produce more than $100m in value. While we cannot interpolate our data to reveal city-to-city or firm-to-firm connections, the scale-free nature of trade gives us the confidence to assume that the significant links presented here can be understood as being representative of connections between these top-trading firms in their respective cities.

Our research has two major implications for industry-level research. First, the methodology and SPE index developed here may enable further analysis of similar data in order to explore the evolution of different 'complexes.' For instance, other years of OECD data may be used to explore how these global trade complexes evolved over time, similar to Los et al. (2015), but with more qualitative texture. Such longitudinal analysis may cast some light into the impact of changes in trade agreements, trends towards outsourcing to lower wage economies, or disruptions to supply chains (including, but not limited to natural disasters and revolutionary changes in production processes and production technologies embedded in capital equipment, such as the 3D printing example above and featured in the case study associated with this chapter). This longitudinal methodological implication is not exclusive to global trade. For example, using data such as that developed by the Brookings Institution's (see Parilla & Berube 2013) one may be able to explore the evolution of complexes that are internal to countries. Such analysis would also enable comparisons between national and international patterns of trade and innovation.

Secondly, and perhaps most importantly, our empirical contributions can aid in contextualizing more detailed analysis of industry structures and dynamics, or studies that focus more on specific regions. Such future research may include virtually any inter-industry comparison (case study or quantitative), where the industry is considered to be a moderating factor. We hope that future inter-industry research can move beyond binary dummy variables and include relative measures or rankings such as the SPE-based index provided in Table 1. For context to our argument, a longstanding default index for studies of innovation, technology management and industry evolution is R&D intensity. R&D intensity is conventionally something that is driven by the internal resources of a firm or region, moderated by the industry. However, with the explosion of inter-firm and inter-regional connections, and opening of the innovation process into a system of innovation, such an internally oriented metric may be reaching the end of its utility. Similar limitations have been observed about recent decades of cluster studies, that are "excessively inward looking and [result in] an ensuing unfortunate downplay of crucial external linkages" (Maskell 2014, p. 833). Thus, based on our comparison with other innovation taxonomies and metrics, we believe our index can add more inter-industry and inter-country nuance to research on innovation intensity.

We would thus welcome further research in two distinct directions. More research explicitly combining a focus on GVCs and innovation geography along the lines of Rutherford and Holmes (2008) and Sturgeon, Van Biesebroeck, and Gereffi (2008) would be valuable. Second, cross-sectoral analysis of the innovation systems that lie behind the trade complexes / GVC structures would be very valuable. In particular, the exo-nets may lend themselves to being studied for how their structure and productivity is influenced by very specialised policy. In comparison, the complex nature of products and firms in global factories may be beyond the control of any given policy. There may also be valuable insights to be had from combining our type of GVC analysis with economic complexity analysis (for discussion around related insights from economic complexity analysis this see e.g. Reynolds et al., 2018; Roos et al. 2018).

Implications for practice and policy

As hinted in the above implications, each industry may have policies specific to it, in addition to general policies. A major challenge of policy makers is to coordinate and synchronise policies so they can have their intended consequences (Weber & Rochracher 2012). For instance, there are multiple ways to circumvent trade tariffs, including reclassification of goods to another industry (aka Tariff Engineering)5 or by routing shipments through another country (aka transshipment) (Feenstra, Lipsey & Bowen 1997). Other strategies include relocating the manufacturing into the foreign market to operate within it instead of importing into it. For instance, China encourages manufacturers to set up ship within China by imposing high trade tariffs, while simultaneously requiring them to collaborate with a domestic manufacturer, thus posing a risk of diffusion of intellectual property. Likewise, venture capital markets and R&D tax policies can influence where companies fund and conduct their R&D, separately from their manufacturing operations. Ultimately, there are many trade-related levers for policy makers to pull and coordinate to try and accrue more short- or long-term benefits in the form of import tariffs, R&D tax incentives, corporate income tax, jobs creation and personal income tax.

The challenge in coordinating multiple policies to stimulate a country's innovativeness also fits the generalisation of Ashby's (1956 & 1958) law of requisite variety which is a general principle that applies to any system, whether economic, social, mechanical or biological. It has practical relevance for systems that need to survive and grow in uncertain, turbulent environments and it is central to the design of governance systems. It has been claimed that Ashby's Law is as fundamental to the disciplines of management and economics as Newton's Laws are to physics (Senge et al. 1994). Ashby's law was derived from mathematical analysis but expressed in words it is very simple: control can only be obtained if the internal regulatory mechanism of a system is as diverse as the environment with which it interacts. The key word is 'requisite', if the control system is too complex the system will not operate efficiently; vice-versa if it lacks sufficient internal differentiation, it might not be able to cope with variable supply and demand of the variety of resources in the environment (e.g. variance and diversity in product markets, labour markets, capital markets, etc), and the system might fail entirely. An expression of this law linked to innovation policy would be that the diversity and coordination of the government policies must match the dynamics of change in the countries operating environment. This requires simultaneous consideration of policies across multiple levels of government, across a broad range of international trade partners and industries.

[5] https://www.strtrade.com/news-publications-232-301-tariff-strategies-avoid-reduce-071118.html

Limitations

This study includes several methodological limitations. While our evidence suggests that there is a connection between GVC structure and innovation via modularity theory, more theoretical and empirical research is needed to conclusively connect them. We are very aware that modularity has proven to be a difficult concept to operationalise in research and practice (see the excellent survey of the literature Campagnolo & Camuffo 2010 and Cabigiosu et al. 2013). We would hope to see a greater effort in the future to define and develop industry level modularity measures that could be used to benchmark aggregate data such as those developed in this study. We concede however, that perhaps modularity is too difficult a concept and we might need to revisit attempts at measuring complexity (see e.g. Wang & von Tunzelmann 2000).

Conclusions

In summary, we introduced a measure of trade intensity, significant sourcing pathways per economy (SPE) with which to quantitatively compare and index 22 manufacturing industries. We believe such an index or league table of industries can enable quantifiable and direct comparison of the interconnectedness of industries. For instance, this table allows us to not only say *that* one industry is more interconnected than another, but also be able to describe *relatively* how much more interconnected it is.[6] As robustness checks, we benchmark our SPE index against (i) OECD's R&D intensity, (ii) Rosenkopf and Schilling's modularization metrics (2007), and (iii) Pavitt's innovation taxonomy, and find that they reinforce the SPE measure. This supports DeBresson's hypothesised correlation between trade and innovativeness and provides further evidence that as trade pathway complexity increases so too does the underlying knowledge intensity. Such a link opens up many interesting avenues for future research and is aligned with the insights from economic complexity analysis.

While the SPE index adds support to the trade-innovativeness link, we recognise that the link is not perfect. Nor do we expect it to be. The variation of results across the SPE measure and the three benchmarks adds to the richness of methods and theoretical lenses with which researchers can analyse GVCs. In our discussion section, for each of the three Global Value Architecture archetypes, we explore industries for which the metrics diverge, and suggest new areas of research.

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[6] The average SPE using the OECD data was 1.26, whereas the average using WIOD data was 1.52. The latter data includes nearly twice as many economies, yet showed values in the same range as the former.

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