On Production Networks[*]

- work in progress -

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1 Introduction

Viewing the economy as - in modern terms - a network, traces back to the ideas of Quesnay (1758) with his *Tableau économique* or the concept of Sir William Petty recognizing a *circular flow of production interdependencies* in the British economy in the mid-seventeenth century (Miller and Blair, 2009). However, it was the seminal work of Leontief (1936) who paved the way for what is called *Input-Output Analysis* today and is used for general economic, technological change, regional and interregional analysis and beyond (Rose and Miernyk, 1989).

This small review paper aims to give an brief overview about the most relevant literature on production networks in recent years, from an theoretical as well as empirical perspective. Therefore Figure 1 provides a brief overview of buzzwords, capturing more fine grained strands of literature. As can be seen, even though all topics relate to production networks, its application is rather vast.

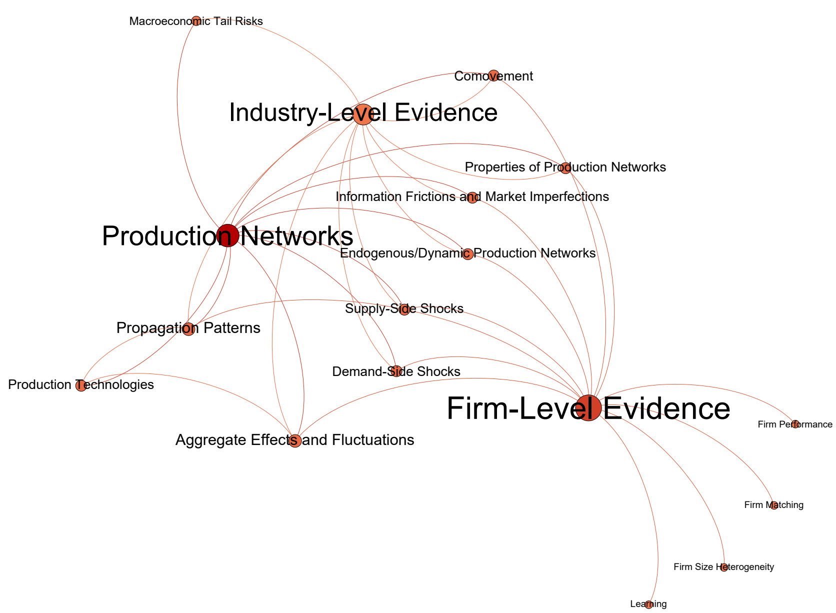

Figure 1: **Strands of literature on production networks.** Network visualization.

It becomes apparent that especially the examined path, upstream to input-supplying entities or downstream to customer entities as well as the level of "granularity" (Industry- or Firm-Level) play a vigilant role in every strand of literature relating to production networks. Therefore, the upcoming

[*] In this review this term may also refer to input-output networks, customer-supplier networks, production interlinkages or networks relating to value chain interdependencies.

sections provide a brief overview about the literature, especially relying on literature categorizations of Savoie (2017), Carvalho and Tahbaz-Salehi (2018), and Bernard et al. (2019).

2 Properties of Production Networks

There are well-documented stylized facts about industry- and firm-level production networks. Industry-level networks are sparely connected, they are dominated by a small number of hubs, and the networks average path length distance is short and the diameter small. The latter has come to be known as the small-world property. Moreover, the production networks exhibit a highly skewed distribution and its sectoral centralities can be well approximated by a Pareto distribution as documented by Carvalho (2014); Acemoglu et al. (2012) and also in my master thesis (Hempfing, 2017).

Carvalho et al. (2016) and Bernard et al. (2019) provide several salient characteristics of firm level production networks for Japan and Belgium. As industry-level networks firm-level networks exhibit extensive heterogeneity in the role of firm as input-suppliers. In contrast to industry-level data, the in-degree distributions are also very skewed and follow a Pareto distribution. That this apples for both, in- and out-degree distributions, has also been shown by Arata and Mundt (2019). Moreover, larger firms (by sales or employees) tend to have a larger number of buyers and suppliers. Finally, the geographical distance seems to be an important determinant in firm-to-firm link formation.

3 Suppy- and Demand-Side Shocks in Production Networks

Carvalho and Tahbaz-Salehi (2018) start introduce the theoretical perspectives on production networks with a static baseline model of the multi-sector general equilibrium model of Long Jr and Plosser (1983), while introducing several of the topics introduces in Figure 1 step-by-step. To achieve an understanding for supply-side productivity shocks in production networks, they introduce a model in which each product can be either consumed by the (representaive) household or used as intermediate input for production. The (representative) firms in each industry employ Cobb-Douglas production technologies with constant returns. Thus, the competitive equilibrium consists of a collection of prices and quantities that (i) the household maximizes her utility, (ii) the firm maximizes its profits while taking prices and wages as given and (iii) all markets clear.

They summarize the input-output linkages $A = [a_{ij}]$ between various industries as the input-output matrix $\Omega = [\omega_{ij}]$ with input expenditures as a fraction of sales. This implies that A is an element-wise non-negative matrix with row sums to unity, which guarantees that the spectral radius of A is also less than unity. They define the equilibrium vector of log relative prices in terms of industry-level shocks and the economy's production networks as the *Leontief inverse*. As the spectral radius is less than 1, the Leontief inverse always exists and is element-wise nonnegative which also imples that the Leontief inverse can be expressed as the infinite sum of the powers of the input-output matrix A (G.W. Stewart, 1998). This implies that the Leontief inverse measures the importance of industry j as a direct and indirect input-supplier to industry i in the economy. Thus, ℓ_{ij} covers all possible directed walks that connects industry j and i over the network.

Returning to the equilibrium characterization they show that in this model theoretic specification the log output of an industry i may depend on the Leontief inverse entry ℓ_{ij} and the productivity shocks ϵ_j of industries $j \neq i$. Moreover, the Leontief inverse can be used to identify the resulting propagation patterns and as a shock to industry j effects i's output, ℓ_{ij} in this model only captures "downstream" effects from one industry to its customers. The absense of "upstream" effects is a consequence of the (i) Cobb-Douglas preferences and technologies, (ii) a single factor of production and (iii) constant returns to scale.

To show that demand-side shocks may lead to patterns that are different from those of supply-side productivity shocks, Carvalho and Tahbaz-Salehi (2018) follow Acemoglu et al. (2015) and modify their model by assuming that the government purchases an exogenously given quantity g_i of good i; this modifies the market-clearing condition. By this, changes in government spending correspond to demand-side shocks affecting industries differentially. Solving for the economy's competitive equilibrium, they show that demand side shocks do not impact relative prices and contrasting the findings on supply-side shocks, demand-side shocks propagate upstream from one industry to its direct and indirect suppliers via ℓ_{ji}. Yet, however, in this setting supply-side shocks are "turned off" and the economy is perfectly competitive which a single factor of production and Cobb-Douglas technologies and preferences.

4 Propagation Patterns

With their paper, Acemoglu et al. (2015) provide a first pass at testing the propagation mechanism described by the model above at the industry level. Thereby they are decomposing the output growth of an industry i into an own effect, resulting from the industry i's own productivity shock, and a network effect characterized by a weighted average of shocks hitting i's direct and indirect suppliers (downstream) and customers (upstream). Their empirical exploration emphasizes that downstream network effects of productivity shocks are economically and statistically significant and that upstream effect of productivity shocks are much smaller economically and its statistical significance is not robust to alternative output measures. However, when incorporating government spending into the empirical model, to construct a demand-side shock, the results indicate significant upstream - rather than downstream - network effects that dominate the industry's own effect.

In the same vain, but to a early stage of research, Acemoglu et al. (2012) survey if such propagation mechanisms of shocks can translate idiosyncratic microeconomic shocks into significant fluctuations at the aggregate level, which stands in stark contrast to the diversification argument of Lucas (1977). They find that sufficient heterogeneity in various industries' roles as input-suppliers can lead to significantly higher levels of aggregate volatility and thus that microeconomic shocks can generate sizable aggregate fluctuations when the economy's production network consists of industries with widely disparate centralities.

Similarly, but from a firm level and without the network perspective in mind, this discussion is also at the heart of Gabaix (2011) which postulates that at the presence of significant firm size heterogeneity at the micro level, the incompressible "grains" of economic activity matter for the behavior of macroeconomic aggregates. One pillar of Gabaix (2011) is *Hulten's theorem*, which is also used by Carvalho and Gabaix (2013) to investigate whether changes in the economy's microeconomic composition can account for the "great moderation" and its unraveling in major world economies. Yet, Hulten's theorem may not hold in inefficient economies, which will be discussed in the upcoming section. More importantly for this review, there is a growing strand of literature which uses more fine grained data across a host of different countries to document the propagation of shocks in production networks at the firm level.

Barrot and Sauvagnat (2016) investigate the propagation of firm-specific shocks by combining data on the timing and location of major natural disasters in the U.S. with information on supplier-customer linkages of publicly-listed firms. They focus on "local" propagation patterns from a firm to its immediate suppliers and customers by regressing changes in quarterly sales of firms on a variable capturing whether the firm's direct suppliers were located in a county hit by a natural disaster in a recent quarter. They find that exposures to the natural disaster results in a two to three percentage point drop in sales growth of the disrupted firm's direct customers. Boehm et al. (2019) are investigating, at the corporate level, the cross-border transmission of supply chain disruptions caused by the 2011 Great East Japan earthquake. Combining reduced-form evidence with structural estimates of production elasticities, they show that the US subsidiaries of Japanese multinationals have experienced a output decline in production of about one-for-one in response to the decline in imports. This result shows that the short-term elasticity of substitution between imported and domestic inputs is close to zero.

While Barrot and Sauvagnat (2016) and Boehm et al. (2019) focus on evidence of shock propagation from firms to its direct suppliers or customers, Carvalho et al. (2016) investigates impacts on the aggregate economy also taking more distant, indirect-connected, firms into account. They find a significant post-earthquake impact on the sales growth rates of firms with direct suppliers and also firms' indirect customers. The evidence on indirect propagation effects, coupled with the "small world" nature of the production network described above, suggests that local disturbances can have non- trivial aggregate consequences. Carvalho et al. (2016) also focus on a generalization of the baseline model by replacing the Cobb-Douglas production function by a nested constant elasticity of substitution (CES) structure. This can lead to richer patterns of shock propagation over input-output linkages. The results of Carvalho et al. (2016) are extended by Baqaee and Farhi (2018b) to a general class of economies with heterogenous agents, arbitrary nested CES production structures, and multiple factors of production.

Understanding shocks propagate in production networks is a fast-expanding strand of literature. For example, Demir et al. (2017) study the propagation and amplification of financial shocks by liquidity-constrained firms. Carvalho et al. (2018) document that an increase in demand expands innovation efforts for both final demand producers and their upstream suppliers through recursive market size effects. Similar to Pasten et al. (2016), Ozdagli and Weber (2017) study the importance of production networks for the transmission of macroeconomic shocks using the stock market reaction to monetary policy shocks as an object of investigation. Their results suggest that production networks are an important mechanism for transmitting aggregate shocks to the real economy. Fujii (2016) investigates shock propagation in granular networks while Lee (2019) investigates the transmission of domestic and external shocks through input-output networks. Quispe (2017) and Bouakez et al. (2018) empirically evaluates the (international) transmission of government purchase shocks through production networks and Su (2017) analyses what he calls the "reflection channel" of shocks in production networks. This list can be extended, however, the literature on shock propagation is not limited to production networks but is also relevant for banking and financial networks, for example Feng et al. (2014); Bardoscia et al. (2015) or Mitchener and Richardson (2018). Yet, also the transmission channels of financial shocks in globalized production networks is sometimes examined, as for example in Escaith and Gonguet (2011).

5 Market Imperfection

Carvalho and Tahbaz-Salehi (2018) illustrate that equilibrium efficiency and the envelope theorem[1] lie at the heart of Hulten's theorem. However, when the original allocation is efficient, any aggregate effect is second order due to the resource reallocation channel and thus can be ignored in a first order approximation. Baqaee and Farhi (2018a) explore the role of such nonlinearities by extending Hulten's theorem including second-order effects of microeconomic shocks on aggregate output and document that, while Hulten's theorem is a statement about the shocks first-order effect, the production network of an economy can manifest itself through significant non-linear effects that are captured by the terms of higher order. Building on these theoretical results, we propose in our current working paper a parsimonious model for the continuous adjustment of sales shares by productivity shocks between observation periods which can be readily operationalized with available data (Hempfing et al., 2018).

Nevertheless, this in fact means that one also has to consider models for inefficient or imperfect economies which are not perfectly competitive and where input-output choice distortions, away from efficient levels, exist. There theoretical considerations are adopted in, amongst others, Jones (2013), Fadinger and Ghiglino (2015), Bigio and La'O (2016), Baqaee and Farhi (2017), Caliendo et al. (2017), Grassi (2017), and Liu (2018). Jones (2013) shows that the misallocation of resources at the micro level can aggregate up to look like differences in total factor productivity. Using tools from network theory, Fadinger and Ghiglino (2015) investigate how the input-output structure interacts with productivities and taxes in the determination of aggregate income. Bigio and La'O (2016) study how an economy's production structure determines the response of aggregate output and employment to sectoral financial shocks. Liu (2018) investigates why many developing countries adopt industrial policies that favor selected sectors. He finds that the distortion in sectoral size is a nonparametric sufficient statistic for the social value of promoting a specific sector. Caliendo et al. (2017) and Baqaee and Farhi (2017) investigate the interaction between distortions and productivities while Baqaee and Farhi

[1]The theorem describes how the optimum value of the objective function of a parameterized optimization problem behaves when the parameters are changed.

(2018b) documents how the presence of distortions can change an economy's allocative efficiency and thus the productivity shocks' propagation patterns over the network. Grassi (2017) builds a tractable multi-sector heterogeneous-firm general equilibrium model featuring oligopolistic competition and an input-output network. He shows that, by affecting price and markup, firm-level productivity shocks propagate to downstream and upstream sectors and that the structural importance of a firm is determined by the interaction of (i) the sector-level competition intensity, (ii) the firm's sector position in the network, and (iii) the firm size.

6 Dynamic Production Networks and Information Friction

Information and network formation is another strand of literature, which relates to production networks. While the literature above mainly investigates shocks and their propagation mechanism, the structure of the production network itself was invariant to these shocks. Yet, in reality the network formation may change when a industry or firm is hit. However, the complexity of direct or indirect network effects as well as the combinatorial possibilities in graph formation makes it a rather challenging theoretical field.

First model theoretical attempts are, for example, Atalay et al. (2011) which develop a statistical model where links between firms are created by preferential attachment while Carvalho and Voigtländer (2015) examine the evolution of input linkages from a network perspective, building on the friendship model of Rogers and Jackson (2007). After introducing a novel approach to information filtering Marcaccioli and Livan (2019) follow Carvalho and Voigtländer (2015) and McNerney et al. (2018) and build a simple model to predict trading relationships in the World Input-Output Dataset based on its network properties.

Oberfield (2018) develops a theory in which the network structure of production forms endogenously and shows that enormous differences in size can emerge even when differences in productivity are arbitrarily small. Thereby Oberfield (2018) overcomes the "curse of dimensionality" coined by Carvalho and Tahbaz-Salehi (2018) by (i) considering an economy consisting of a continuum of firms and (ii) restricting attention to single-input production technologies. These assumptions simplify the analysis by ensuring that equilibrium production networks with cycles fall to zero. In an alternative model, Acemoglu and Azar (2017) assume that markets are contestable, making the same menu of technologies available to a large number of firms. By this, they bypassing complex strategic considerations of how choices echo through the network. Taschereau-Dumouchel (2017) develops a firm-level model of network formation in which firms exit if they cannot meet fixed costs of production, thus creating the potential for a cascade of shutdowns that changes the shape of the production network.

In a very recent working paper Arata and Mundt (2019) use microdata of Japanese companies to analyze the topology and evolution of business partner relationships over several years and quantitatively assess the role of supplier selection mechanisms shaping network dynamics. Applying a stochastic actor-oriented model they find that topological features are a main driver of network dynamics, e.g. that the geodesic distance, relating to the small-world phenomenon, between firms and their current number of relationships are quantitatively more important than selection based on productivity.

Zou (2018) develops a quantitative trade model with an endogenous production network, where firms form linkages with each other both within and across borders, balancing the tradeoff between extra revenue brought in by downstream connections and fixed costs required to establish these relationships. Calibrating the model with data from the World Input-Output Database the model is able to replicate the actual time trend of the value added share in gross trade, as well as several cross-sectional patterns observed in the US-ROW input-output network.

Bernard and Moxnes (2018) gives an overview about the literature on firm-to-firm connections in trade and the theoretical work considering dynamic matching environments under full information or information frictions such as search frictions or learning.

7 Comovement, Aggregate Volatility and Firm Performance in Production Networks

The next question which arises when acknowledging that economies exhibit a higher level of network heterogeneity is whether this also leads to an increase in the likelihood that more industries co-move over the business cycle. Already Long Jr and Plosser (1983), Norrbin and Schlagenhauf (1990), Horvath and Verbrugge (1996), Dupor (1999), Shea (2002) and Conley and Dupor (2003) incorporated thoughts about sectoral comovement in their investigations of aggregate fluctuations.

Foerster et al. (2011) uses factor analytic methods to decompose industrial production into components arising from aggregate shocks and idiosyncratic sector-specific shocks. Their results indicate that aggregate shocks continue to be the dominant source of variation in industrial production, but the importance of sectoral shocks more than doubles after the Great Moderation, which is also relevant in Carvalho and Gabaix (2013). Atalay (2017) extends the methodology of Foerster et al. (2011) to an economy with CES technologies and preferences. They conclude that concludes that 83% of the variations in aggregate output growth are attributable to idiosyncratic industry-level shocks. Di Giovanni et al. (2014), building upon Carvalho and Gabaix (2013), provide a framework to differentiate between the contribution of a "direct" (variance) and "link" (co-movement) term to aggregate volatility. Several of the studies conclude that the interplay of idiosyncratic shocks with input-output linkages can account for about two thirds of aggregate fluctuations, however not all incorporate production networks.

Magerman et al. (2016) evaluate the impact of idiosyncratic productivity shocks to individual firms on aggregate output, using unique data on firm-to-firm transactions across all economic activities in Belgium. They find that the top 100 firms contribute to 90% of the aggregate volatility generated by the model, underlining a strong granularity of the economy. Using similar data for Belgium, Tintelnot et al. (2019) estimate models of domestic production networks and international trade. They document, amongst others, that most firms that do not directly import or export still have large indirect exposure to foreign trade, especially foreign inputs. Bernard et al. (2019) uses buyer-supplier relationships in Belgium, to develp a set of stylized facts that motivate a model in which firms buy inputs from upstream suppliers and sell to downstream buyers and final demand. These stylized facts suggest that the network of buyer-supplier links is key to understanding the firm size distribution. In another attempt Bernard et al. (2018) examines the importance of buyer-supplier relationships for firm performance. Using data on Japanese firms they find that the geographic proximity plays a key role for the matching of suppliers and customers as most connections cover relatively short distances. Moreover, large, more productive companies have both more suppliers and, on average, more distant suppliers.

8 Production Networks, Growth and Others

The implications of production networks for (long-term) growth have not been in the focus of many paper recently. Still, some contributions like Jones (2013), Johnson (2015), Gualdi and Mandel (2016), Savoie (2017), Chernyshev (2018) and McNerney et al. (2018) try to account for this research gap. Johnson (2015) for example, develops a model of economic growth in which technological spillovers induce a network structure among industries. Testing a closed-economy version of the model with network data for the US from 1960 to 2005 he finds that the model explains growth in each industry and changing patterns of trade over this period better than the null model with no network effects. Chernyshev (2018) employs a framework of endogenous growth in an economy with interconnected industries, whereby sectoral productivity growth is amplified by the interconnection, and the degree of amplification grows in the strength of sectoral connections. McNerney et al. (2018) develop a simple theory that shows how the network properties of an economy can amplify the effects of technological improvements as they propagate along chains of production. By test these predictions using the World Input-Output Database they show how purely structural properties of an economy, that have nothing to do with innovation or human creativity, can exert an important influence on long-term growth.

Bosker and Westbrock (2016) develops a counterfactual approach to decompose the welfare effects of any small trade cost variation in general equilibrium models and argues that the determinants of the welfare gains from trade have fundamentally changed with the emergence of a global production network. Kikkawa and Magerman (2019) studies the implications of imperfect competition in firm-to-firm trade. They document that firms' markups increase in the average input shares among their buyers. On this they build a model where firms charge supplier-buyer specific markups, which depend on the bilateral input shares. The model suggests that reducing all markups in firm-to-firm trade by 20 percent increases welfare by 10 percent. Weisbuch and Battiston (2018) propose a parsimonious concept studying failure avalanches and their effects on production and wealth of firms. They document that a large class of models exhibit scale free distributions of production and wealth among firms and that metastable regions of high production are highly localized.

Employing techniques of complex networks analysis and Input-Output traditional tools, Gallegati et al. (2019) provide different rankings of the most "systemically important" industries involved in Brexit. Their findings suggest that Brexit would be not just a problem for the UK, but any form of Brexit could propagate affecting the global production system. Grazzini and Spelta (2015) develop an firm input-output model calibrated on empirical data and defining a fragility index that measures the ability of the system to absorb exogenous shocks. They find that the fragility of the production network has increased from 1995 to 2011. Having the labour market dimensions of global production networks in mind, Stone and Bottini (2012) examines the effects of high and low technology materials and services offshoring, and differentiating these impacts across worker skill levels. They find that high technology manufacturing has a large impact on both high and low skilled workers and that there are significant positive spillovers in the demand for services workers from this offshoring.

9 Concluding Remarks

This small literature review aimed to give a brief overview about the most relevant literature on production networks in recent time. Even though this review may not completely cover all topics related to the production networks literature I am excited to discuss ideas and promising avenues for future research arising from the literature at hand.

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