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USING EQUITY MARKET REACTIONS AND NETWORK ANALYSIS TO INFER GLOBAL SUPPLY CHAIN INTERDEPENDENCIES

Key points

- *The COVID-19 pandemic has exposed the vulnerabilities of "just-in-time" international supply chains and is set to further accelerate transformations of international production networks. However, global supply chains are highly convoluted and very little is known about how they are linked together at the firm level, making it difficult to assess where the dependencies lie.*

- *Using firm-level data on customer-supplier relationships from over 170 economies, and leveraging the geographically-contained nature of the early outbreak in Mainland China as an exogenous shock to global supply chains, we study the equity price responses of Mainland China-linked companies to news of virus-induced lockdowns, to assess whether markets priced in the associated supply chain propagation effects.*

- *Our findings reveal that the stock prices of firms with Mainland ties significantly underperformed other firms in a short window following news of the lockdowns, highlighting the economic significance of global production network linkages as a mechanism for propagating the coronavirus shock. The extent of underperformance, in turn, depends on the relative positioning in the supply chain (as upstream suppliers or downstream consumers vis-à-vis virus-affected firms in Mainland China), as well as the closeness of connections to the Mainland (network distance).*

- *Diving further into the industry breakdowns reveals that Mainland China-linked firms in cyclical industries (e.g. energy, raw materials, equipment), and those with prominent global segmentation of production, exhibited significantly greater equity price declines. And speaking to the public health nature of the COVID-19 shock, firms upstream to Mainland China in the pharmaceuticals industry outperformed, while downstream players yielded more negative stock returns.*

- *Then, to gain a more holistic view of the inter-regional dependencies of global supply chains, we use network analysis tools to create graphical depictions of the firm linkages in the highly globalised auto and Information Technology (IT) industries. Our graphs reveal complex and extensive network structures – with firms in Asia, the US, and Europe all exerting significant influence – which suggest that efforts to reshore auto and IT supply chains could face substantial difficulties. This becomes especially clear when compared to the textiles industry, which features much simpler supply chains comprised overwhelmingly of firms from one region.*

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I. INTRODUCTION

The outbreak of the COVID-19 virus has wreaked havoc across the globe, and exposed the vulnerabilities of "just-in-time" international supply chains that rely on a complex network of globally-connected firms performing disparate and specialised tasks, many of which, if disrupted, could threaten to throw off the functioning of the entire production process. This was laid bare in the early stages of COVID-19's outbreak when Mainland China's lockdown measures since late January soon resulted in signs of supply chain disruptions across a wide range of industries and economies abroad[1], bringing to light the extent of the world's reliance on international supply chains, and prompting a broad reassessment of the costs and benefits of this globally-segmented production approach, including initiatives in several advanced economies (AEs) to reshore their supply chains[2].

Although foreign outsourcing has long been practiced and is widely adopted, firms engaged in such behaviour are typically immersed in lengthy and winding supply chains, making it costly and difficult to track their indirect exposures; firms, let alone their governments, are often oblivious to the linkages they may have further up or down their supply chains beyond the direct relationships. Likewise, due to data limitations on supply chain linkages at a more granular level, research assessing global value chains (GVCs) and their implications often fails to capture these hidden firm dependencies that can span across multiple industries and geographical locations. Studies mainly rely on enterprise surveys, international trade statistics, or industry-level input-output (IO) models, none of which can simultaneously shed light on the role of firm heterogeneities and on inter-industry and inter-country linkages.[3] However, as the outbreak of COVID-19 has brought supply-chain vulnerabilities back to the forefront, *accounting for these often*

[1] A report by corporate data and analytics firm Dun & Bradstreet found that at least 51,000 companies around the world have one or more direct or Tier 1 suppliers in the initially most virus-ravaged provinces of Mainland China and at least five million companies have one or more Tier 2 suppliers there; for details, see: https://www.dnb.com/content/dam/english/economic-and-industry-insight/DNB_Business_Impact_of_the_Coronavirus_US.pdf.

[2] See, for example: https://www.nytimes.com/2020/05/11/opinion/coronavirus-jobs-offshoring.html, https://www.reuters.com/article/us-health-coronavirus-germany-pharmaceut/germany-would-like-to-localize-supply-chains-nationalization-possible-minister-says-idUSKBN2101BH.

[3] See a discussion by Fortanier et al. (2019) comparing the different approaches.

overlooked indirect exposures has become critical in order to assess the extent of global production interconnectedness and where the vulnerabilities lie.

In this study, we attempt to address these issues by mapping global production networks using data on bilateral customer-supplier relationships, and by studying equity price responses to news of lockdown measures to contain COVID-19. We first use stock price movements to infer supply chain dependencies on Mainland China, the first economy that reported a surge in local COVID-19 cases. This allows us to investigate the propagation effect of the virus shock on Mainland China through international production networks from the perspective of stock market investors using an event study framework. Provided that financial markets are efficient, events affecting firms' expected profitability will be immediately reflected in their stock prices, allowing us to infer the supply chain propagation effect from the heterogeneous response of firms' asset prices, depending on their exposure to the virus-disrupted companies. The fact that early cases of domestic virus outbreaks in Mainland China were generally perceived to be contained within national borders, allows us to identify the impact transmitted to other economies through supply chain connections. As it later became increasingly apparent that the virus would become a global pandemic, however, the *direct effects* of local virus outbreaks and containment efforts on asset prices likely overshadowed the impacts originating from overseas factory shutdowns.

Estimates from our event study analysis reveal that foreign firms' supply chain linkages to Mainland China shaped their stock price reactions to the country's virus-induced lockdown measures. Firms with Mainland Chinese customer and supplier ties significantly underperformed other firms following news of major developments relating to the outbreak, with investors pricing in disruptions to firms both upstream and downstream, as well as firms both directly and indirectly linked, to the virus-stricken companies. Diving further into the sub-sector breakdowns of these firms, our findings show that Mainland China-linked firms in industries that provide the raw materials and equipment for manufacturing processes exhibited significantly greater equity price declines, as did firms in industries with prominent

globally-segmented production – notably information technology (IT) and automobiles. Suppliers in the Energy and Aerospace & Defense industries also yielded more negative returns, consistent with Mainland China's role as the world's largest importer of oil and gas and its path to becoming the biggest aviation market in the next few years. Furthermore, firms in the pharmaceuticals industry yielded opposing stock market movements depending on whether they are positioned upstream or downstream to a Mainland Chinese firm, with upstream suppliers outperforming and downstream customers underperforming, reflecting the unique public health nature of the shock.

Then, to gain insight into the broad patterns of inter-regional dependencies of global supply chains, we use network analysis tools to create detailed graphical depictions of the firm linkages in the highly globalised auto and IT industries. These network visualisations show extensive and complex interconnections that likely served as an important propagation mechanism for supply chain shocks such as COVID-19, and highlight the pervasive role that Asian firms play in the auto and IT production networks, alongside US and European firms. Furthermore, when compared to the relatively simple network structure of the textiles and apparel industry – another key sector where Asia plays a major role, the highly convoluted and geographically dispersed nature of the auto and IT production networks suggests that AE-led supply chain relocation efforts in these two industries will face substantial difficulties, while reconfigurations of textile supply chains may be a comparatively easier task.

The rest of this paper is organised as follows: Section II reviews the relevant literature and highlights our contribution, Section III describes the data, Section IV outlines the equity returns model and our findings, Section V showcases the network analysis visualisations and outlines the implications for supply chain reshoring, and Section VI concludes.

II. LITERATURE REVIEW

Our work builds upon a growing body of literature that emphasises the role of microeconomic IO linkages in the propagation and amplification of shocks. Whether granular shocks can drive aggregate fluctuations remains an open question in macroeconomics, with the traditional view, initially proposed by Lucas (1977), long being that firm-level fluctuations average out in aggregate based on a diversification argument[4]. However, several recent studies have argued that the presence of interconnections between different firms and sectors act as an important propagation mechanism of idiosyncratic shocks throughout the economy. For example, Acemoglu et al. (2012), Barrot and Sauvagnat (2016), and Carvalho et al. (2016) outline theoretical frameworks that provide a systematic quantification of the role of IO linkages by explicitly taking into account these inter-firm and inter-sectoral dependencies[5]; their work forms the basis of a number of recent empirical analyses finding substantial evidence of production network propagation effects, including ours.

Empirical papers studying the supply-chain transmission effect at the firm level often make use of localised natural disasters as an exogenous shock that affects a subset of firms connected to other firms through IO linkages. *The majority of these studies, however, focus on the propagation within country borders, or between a few select economies*. For example: leveraging the 2011 earthquake in Japan, Boehm, Flaaen and Pandalai-Nayar (2014) find evidence of cross-country supply chain shock transmission by studying the output loss of US affiliates of Japanese multinationals, while Carvalho et al. (2016) document the supply chain disruption within Japan propagated from firms in close proximity to the earthquake locale; similarly, looking at major natural disasters in the US over the past 30 years, Barrot and Sauvagnat (2016) show that affected suppliers impose substantial output losses on their domestic customers. One exception is Kashiwagi, Matous and Todo (2018), who use data from a sample of global firms to compare the intra-national and international propagation effects of the US's Hurricane Sandy disaster to firms' direct and indirect customers and suppliers. Their study, however, looks only at the

[4] See Lucas (1977) for details.
[5] See Carvalho and Tahbaz-Salehi (2019) for a more comprehensive review of the theoretical literature.

"two-step" customers / suppliers (i.e. a customer's customer or a supplier's supplier) when assessing firms' indirect exposure to disaster-area firms; on the other hand, *our work incorporates higher degree indirect linkages*, sometimes spanning more than 10 firm connections, to take into account the often lengthy and complex supply chain networks characteristic of globalised industries. Indeed, our findings suggest significant international transmission effects, contrary to their work where they find only evidence of within-country transmission.

Within the corporate finance literature, our work also contributes to the growing strand of research that studies the effects of supply chain linkages on asset pricing. For example, Ramirez (2017) extends standard asset pricing models to take into account how idiosyncratic shocks propagate along firm networks in the US and captures dynamics of the cross section of stock returns, while Grant and Yung (2019) evaluate the importance of upstream versus downstream exposures of US firms to shocks from each direction by studying equity returns, finding that the former (shocks propagating downstream from suppliers to customers) is greater than the latter; and leveraging the US-China trade war, Huang et al. (2018) and Zhang (2019) find that supply chain exposure to Mainland Chinese companies of US and Asian firms, respectively, magnified their negative equity returns surrounding dates of significant escalations in trade tensions.

Our study also adds to the branch of the supply chain literature that leverages network analysis techniques to examine how firm and sectoral interactions affect economic outcomes and the transmission of shocks. For example: Kim (2015) applies a social network analysis approach to analyse the structure of the South Korean automotive industry, Nuss et al. (2016) assess supply chain risk by mapping the production networks of five technology platforms that use a variety of potentially critical metals, Korniyenko, Pinat and Dew (2017) examine the supply fragility of individual traded goods to determine countries' supply shock vulnerability using network analysis metrics, and Inoue and Todo (2017) use data on Japanese firm interactions to show that production network structures play an important role in transmitting the impact from natural disasters. Studies at a more granular level tend to focus on a few select economies or industries / product platforms due to data

limitations[6]; *to the best of our knowledge, our study is the first to combine data on firm-level supply chain linkages at a global scale and across multiple sectors with network analysis visualisation techniques to examine the geographical interdependencies.*

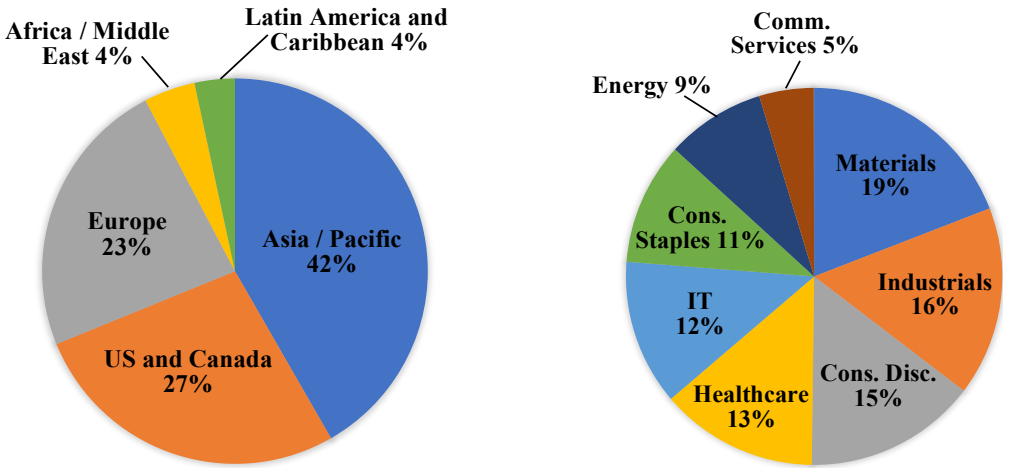
Finally, our work contributes to the burgeoning body of research on the economic and financial market impacts of COVID-19 propagated through supply chains. For example: using quantitative models of world production and trade, Bonadio et al. (2020) and Guan et al. (2020) show that the transmission of foreign lockdowns through supply chains magnifies the losses beyond the direct effects of the pandemic; Hassan, Hollander and Tahoun (2020) develop text-based measures of corporate exposure to the virus outbreak (including supply chain exposure) for a global sample of firms based on earnings-call transcripts, finding that they explain firms' stock market responses; and Ramelli and Wagner (2020) study the cross-section of US firms' stock price reactions to COVID-19, finding that firms more exposed to trade with Mainland China underperformed. Most similar to our work is Ding et al. (2020), who use a global sample of firms and data on customer-supplier relationships to assess the cross-firm stock price reactions to the pandemic as a function of firms' supply chain exposure (and other corporate characteristics), finding that firms with greater exposure saw more negative returns. However, Ding et al. (2020) only consider the direct supplier and customer relationships, whereas our study also looks at indirect linkages, finding that these "hidden" connections are an important mechanism for supply chain propagation; *we believe that our study is the first to examine both the direct and indirect supply chain effects of the pandemic on stock prices using firm-level data.*

[6] The combination of network analysis techniques with firm-level business relationships has been applied at a global scale in other strands of literature, such as banking; e.g. Chan-Lau (2010) and Minoiu and Reyes (2011) use network analysis tools to study global banking interconnectedness and its implications for systemic risk.

III. DATA

Data on inter-firm customer and supplier relationships and firm financial variables were taken from S&P's Capital IQ (CIQ) database[7], which provides a snapshot of inter-firm linkages declared within the last two years. Our sample consists of all publicly-traded and private firms in the "Manufacturing", "Mining" and "Agriculture, Forestry and Fishing" SIC industry classifications[8] *that have declared a "supplier" and / or "customer" linkage with another firm in the last two years* as of end-February, 2020. This amounts to 35,940 companies covering eight of the eleven Global Industry Classification Standard (GICS) sectors[9] in over 170 economies[10] (see Chart 1), and more than 120,000 bilateral customer-supplier relationships declared among them.

Chart 1: Breakdown of firms by region and GICS sector



Notes: "Cons. Staples" = Consumer Staples; "Cons. Disc." = Consumer Discretionary, "Comm. Services" = "Communication Services".

[7] According to CIQ, it covers 99% of the global market capitalisation in terms of publicly traded companies.
[8] While the default industry classification used by CIQ is GICS, it provides a mapping system to SIC primary industry categorisation which allows a simpler identification of "supply-chain-related" industries; we exclude other SIC industry classifications to avoid capturing firms performing non-supply-chain-related activities. For other purposes, however, we use the CIQ default industry classification - GICS.
[9] Firms in the Financials, Utilities, and Real Estate GICS sectors are excluded; the GICS-SIC mapping process captures some Communication Services firms as manufacturing firms-for example, firms in movies and entertainment that produce entertainment equipment. For a detailed sector breakdown, see: https://www.spglobal.com/marketintelligence/en/documents/112727-gics-mapbook_2018_v3_letter_digitalspreads.pdf.
[10] Represents the economy / country in which the firm's headquarters / primary offices are located. Headquarters can be the subsidiary of a firm in another country (e.g. Mainland China-headquartered firms may include US multinational subsidiary firms in the Mainland). We use this specification instead of the country of the ultimate parent company as our purpose is to illustrate foreign supply chain exposures on a locational basis.

Sources: CIQ and staff calculations.

Before going any further, it is important to point out some of the limitations of the CIQ data on business relationships. First, firm's reported connections may represent only a portion of their total customers and suppliers, as companies are typically not obligated to disclose them all (the SEC mandates that issuers disclose all customers representing 10% or more of their revenue[11], for example). To account for this, we follow Carvalho et al. (2016) by augmenting each firm's list of suppliers (customers) with the reports of other companies that declare the firm as their customer (supplier), although this may not be able to capture all the unreported suppliers and customers. Second, the data is simply a binary variable representing the existence of a relationship, but does not provide the nominal value of each linkage nor the details of the transaction (such as what types of goods or services were exchanged). Such data, even if available from other sources is notoriously sparse, especially on a global scale.

IV. ASSESSING THE SUPPLY CHAIN PROPAGATION EFFECT OF THE COVID-19 OUTBREAK IN MAINLAND CHINA THROUGH A STOCK MARKET LENS

As Mainland China was the first country to report a surge in local COVID-19 cases, we exploit its outbreak as an exogenous shock to foreign firms relying on global supply chains to assess the propagation effect of the virus disruption through production networks. While other major manufacturing economies, such as Korea and Germany, also subsequently experienced domestic virus surges, their outbreaks occurred alongside those in several other countries, prompting widespread sell-offs of risk assets amid increasing realisation that COVID-19 would become a global health crisis. For this reason, we choose to focus on Mainland China's case, as its early outbreak was generally perceived to be contained within national borders, allowing a cleaner identification of the propagation effect to foreign firms through global supply chains.[12]

[11] See: https://www.sec.gov/rules/final/33-7620.txt.

[12] We do, however, conduct similar analyses for Korea-linked firms following news of its outbreak. Results are available upon request.

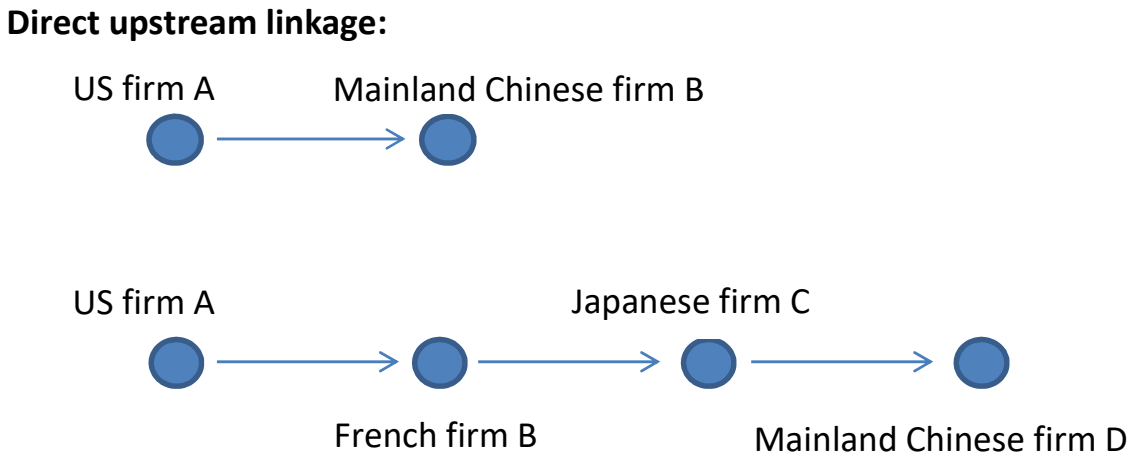
More specifically, we map international supply chain exposures to Mainland China, and use these measures of supply chain dependence to study the heterogeneous response of firms' asset prices to news of Mainland China's lockdown measures, depending on firms' exposure to Mainland companies. Provided that financial markets are efficient, events affecting firms' expected profitability will be immediately reflected in their stock prices, allowing us to infer the supply chain propagation impact from equity price fluctuations in a small window surrounding the events.

Mapping supply chain exposures to Mainland China:

To construct measures of Mainland China supply chain exposure, we first exclude from our sample firms headquartered in the Mainland, and then form dummy variables representing network distances of the remaining firms to Mainland companies using those firms' declared business relationships, differentiating between upstream (supplier) and downstream (customer) positions[13]. For instance, a firm that declares a customer (supplier) in Mainland China is deemed an upstream (downstream) supplier (customer) to the Mainland with one degree of separation, i.e. this firm is *directly* upstream (downstream) to a Mainland Chinese firm. For *indirect* linkages with higher degrees of separation, we connect firms to customers and suppliers in the Mainland through multiple layers of bilateral relationships; see Chart 2 below for an illustrative example. It is important to note that we are neither trying to measure a firm's position in, nor the length of, the overall value chain of a product or sector; rather, we are measuring a firm's position, and the length of the supply chain, *relative to a firm in Mainland China in the same production network*.

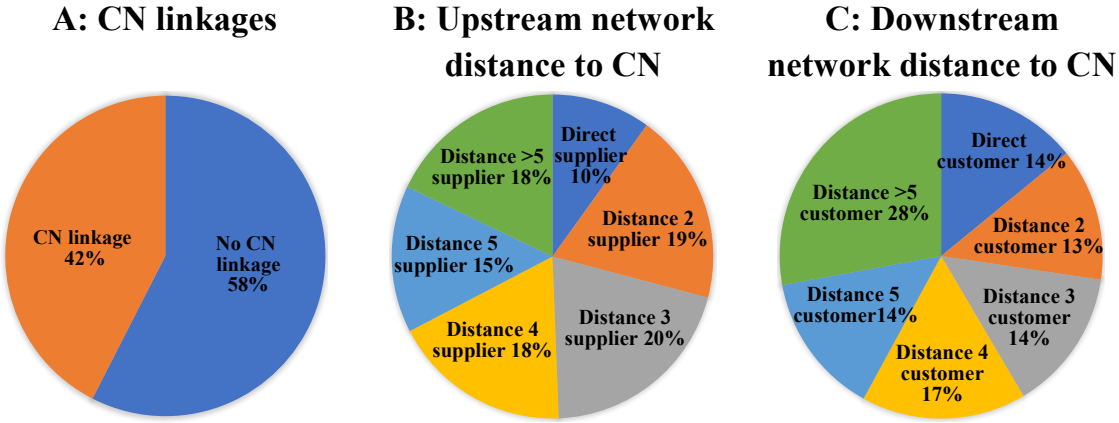
[13] This differentiation is not exclusive – there are firms with both upstream and downstream exposures to Mainland China, which represent around 20% of all Mainland-linked firms.

Chart 2: Illustrative example - direct and indirect upstream exposure of a US firm to a Mainland Chinese firm



This mapping exercise reveals that nearly half (42%) of the non-Mainland manufacturing firms in our sample have direct or indirect supply chain linkages to Mainland China (Chart 3A), underscoring the geographical interconnectedness of production networks and the Mainland's outsized role in global manufacturing. Furthermore, the majority of Mainland China-linked firms are exposed to the country through *indirect* linkages, often with multiple degrees of separation (Charts 3B and 3C), demonstrating the complexity of GVCs and the importance of looking beyond the immediate inter-firm business ties when assessing production network exposures.

Chart 3: Supply chain linkages with Mainland China ('CN'), among non-Mainland firms



Sources: CIQ and staff calculations.

Stock market event study – methodology

Leveraging the exogenous and initially localised nature of the COVID-19 shock in Mainland China, and our measures of supply chain exposures outlined in the previous sub-section, we examine whether firms with supply chain ties to companies headquartered in Mainland China exhibited significantly lower equity returns following news of virus-induced lockdowns in the country. For this estimation, we exclude non-listed companies from our firm sample and add back publicly-listed firms in the other SIC industries (e.g. Wholesale Trade, Services etc.) to provide an empirical benchmark for our estimates.[14] We choose to focus on firms' equity price movements, which capture the expected impact of virus-induced disruptions on firms' future earnings, rather than their actual performance (e.g. sales, profitability, etc.) as the latter is of quarterly frequency and reflects the cumulative effect of multiple events; as surges in virus cases started to emerge all over the world starting in late February and COVID-19 was declared a global pandemic in early March, the impact of supply chain disruptions on first-quarter firm financials will be confounded by the direct effects of domestic virus outbreaks.

Using a firm fixed-effects panel specification, we run a baseline regression of firms' daily stock returns on their respective market returns[15], a set of firm controls, quarter dummies, and key regressors that capture the virus impact on Mainland China propagated to non-Mainland firms through international production networks; notably, we include an interaction term between a virus dummy variable ($Virus_t$) for dates of significant virus developments in Mainland China and a supply chain dummy variable that take the value of one if a firm has a linkage to a Mainland Chinese firm somewhere along its supply chain (CN_link_i):

[14] See Chart A1 in the appendix for the regional and GICS sector breakdown of the new sample, along with the new share of firms with Mainland China linkages. Note that for the network visualisations in Section V below, we revert back to the original sample.

[15] Data on firms' daily stock prices were taken from CIQ while market benchmark indices were taken from Bloomberg.

$$\Delta Equity\_Price_{i,t} = \alpha_i + \beta_1 \Delta Benchmark\_Price_{i,t} + \beta_2 Log(Market\_Cap_{i,t-1}) + \beta_3 PTB_{i,t-1} + \beta_4 ROA_{i,t} + \beta_5 LEV_{i,t} + \sum_{j=1}^{3} \beta_{j+5} Quarter_t^{j+1} + \beta_9 Virus_t + \beta_{10} Virus_t \times CN\_link_i + \varepsilon_{i,t} \quad (1)$$

Where α_i is the firm fixed effect, and $\Delta Equity\_Price_{i,t}$ and $\Delta Benchmark\_Price_{i,t}$ represent the daily change in firm i's last sale price and benchmark index price, respectively, between time t and t-1 in percentage terms. We control for the benchmark index to capture firms' abnormal equity return in excess of broad market movements reflecting firms' idiosyncratic responses to the supply chain disruption shock through our exposure measures. Similarly, we also control for several financial variables that could affect the fundamental value of the firm – market capitalisation ($Market\_Cap_{i,t-1}$), price-to-book-value ratio ($PTB_{i,t-1}$)[16], return on assets ($ROA_{i,t}$), and the leverage ratio ($LEV_{i,t}$) – following the literature on asset pricing[17], to account for stock price movements based on firm fundamentals that are not driven by news of the virus developments. Our sample runs from January 1, 2019 to April 17, 2020. Firms headquartered in Mainland China are excluded to capture only the effect propagated to other economies through supply chains, and the virus dummy ($Virus_t$) takes the value of one on January 22 and 23 when the Hubei authorities announced a lockdown of the city of Wuhan, and January 27 when a nationwide extension of the lunar new year holiday was imposed[18].

[16] Taking the level variables that vary daily at day t-1, as we are looking at the change in equity prices of firm i between day t-1 and t.

[17] E.g. Zhang (2019), Huang et al. (2018), and Wagner, Zeckhauser, and Ziegler (2017).

[18] We use both the 22 and the 23 of January for the Wuhan lockdown event because the announcement was made at 2:37AM China standard time on January 23, meaning it reached some parts of the world on January 22 when markets were still open (e.g. the announcement came at 2:37PM New York Time, before the New York Stock Exchange closed at 4PM); see: https://twitter.com/ChinaDaily/status/1220052882596286465, http://en.hubei.gov.cn/news/newslist/202001/t20200123_2014475.shtml, and http://english.www.gov.cn/policies/latestreleases/202001/27/content_WS5e2e34e4c6d019625c603f9b.html

Stock market event study – results

Table 1, column 1 presents the results from our baseline regression, specified in equation (1), that estimates the extent to which stock price movements reflect firms' heterogeneous exposure to the COVID-19 shock in Mainland China through their supply chain linkages. The coefficient on the key interaction term between the virus and supply chain dummies is negative and significant, with Mainland China-linked firms exhibiting a 0.4 percentage point (p.p.) larger stock price decline compared to firms without Mainland supply chain ties, following announcements of lockdowns in late January. This suggests that global production networks were perceived to be an economically important mechanism for propagating the coronavirus shock. Contrary to Kashiwagi et al. (2018), who find no evidence of supply chain propagation beyond US borders when studying the effects of Hurricane Sandy, our findings suggest that the international channel could be substantial. As their work focuses on the effect of a US shock and only considers indirect exposures for up to two degrees of separation, our results highlight that the global propagation effects could vary depending on the source country of the shock (e.g. depending on an economy's role in global GVCs) and the importance of taking into account more extensive supply chain connections.

Furthermore, by breaking down firms' Mainland China linkages by their supply chain position, we see in column 2 of Table 1 that exposures in both the upstream and downstream directions are statistically significant, consistent with findings from Carvalho et al. (2016)[19]. However, in contrast to their work and others, where the intensity of upstream propagation from customers to their suppliers is found to be more muted than its downstream counterpart and sometimes insignificant[20], our findings show that investors priced in an important upstream propagation impact, in addition to the downstream effects. Firms upstream to one or more Mainland Chinese firms exhibited stock price declines of 0.35 p.p. more than

[19] Note that the breakdown of upstream and downstream exposures is not exclusive; however, our results are robust to using the exclusive upstream and downstream measures, and are available upon request.

[20] E.g. Grant and Yung (2019) find that upstream exposures (shocks to a firm's suppliers) of US firms are more important for explaining firms' idiosyncratic equity responses than downstream exposures. Similarly, Carvalho et al. (2016) also find a larger downstream propagation effect, explained by a substitution and output effect generating downstream propagation that is absent in generating propagation effects in the opposite direction; see their paper for details.

firms without such linkages, compared to stock price declines of 0.28 p.p. more for firms downstream to the Mainland.

This could potentially be explained by the unparalleled role Mainland China plays in global manufacturing both as a major supplier and buyer in the supply chain; just as the country's early virus outbreak led to supply disruptions in other economies relying on crucial inputs supplied *by* Mainland China, it also dealt a shock to foreign firms providing inputs *to* Mainland China, which is an important buyer of raw materials and industrial supplies, such fuels and metals, for example. Indeed, Mainland China was the world's top importer of both mineral fuels and ores and metals in 2018. Similar to our results, Ding et al. (2020)'s analysis of stock price reactions to COVID-19 as a function of supply chain exposure also finds evidence of a larger equity price decline for firms exposed to the virus outbreak in foreign countries *through their customers*, compared to supplier exposure.[21]

Table 1: Firm equity returns and Mainland China supply chain linkages

Dependent Variable: Firm return (%)	**(1)**	**(2)**
Market return (%)	0.810***	0.810***
	(0.004)	(0.004)
Log(market capitalisation)	-0.830***	-0.830***
	(0.016)	(0.016)
Price-to-book ratio	-0.008***	-0.008***
	(0.002)	(0.002)
ROA (%)	0.002***	0.002***
	(0.0004)	(0.0004)
Leverage ratio	-0.182***	-0.183***
	(0.033)	(0.033)
Virus lockdown dummy	0.034*	0.037**
	(0.019)	(0.019)
Virus lockdown dummy * the following linkage dummy variables:		
Mainland China linkage	-0.395***	
	(0.039)	
Upstream linkage		-0.349***
		(0.048)
Downstream linkage		-0.280***

[21] See Table 3 in Ding et al. (2020).

		(0.050)
Observations	4,795,389	4,795,389
Number of firms	15,577	15,577
R-squared	0.127	0.127

Notes: *** p<0.01, ** p<0.05, * p<0.1; robust standard errors in parentheses; quarterly dummies and constant are not shown. "Virus lockdown dummy" takes the value of 1 on January 22, 23, and 27. Excludes firms headquartered in Mainland China.

We next examine whether varying network distance relative to the virus-stricken firms yields differing stock market reactions. Results outlined in Table 2, column 1, show that both direct and indirect supply chain channels were important for explaining firms' idiosyncratic equity responses, with upstream firms directly and indirectly linked to Mainland Chinese companies seeing 0.56 and 0.28 p.p., respectively, lower stock returns than other firms, and downstream firms seeing 0.37 and 0.23 p.p., respectively, lower stock returns. Also, consistent with the GVC literature finding that propagation effects are attenuated as the shock travels over the supply chain, results in column 2 presenting a breakdown of the indirect linkages into network distances of up to four degrees of separation, show that the negative equity price response of Mainland China-linked firms generally diminishes in magnitude and significance the further away the firm is to a Mainland company in the production network.

Table 2: Firm equity returns and Mainland China supply chain linkages, network distance

Dependent Variable: Firm return (%)	**(1)**	**(2)**
Market return (%)	0.810***	0.810***
	(0.004)	(0.004)
Log(market capitalisation)	-0.830***	-0.830***
	(0.016)	(0.016)
Price-to-book ratio	-0.008***	-0.008***
	(0.002)	(0.002)
ROA (%)	0.002***	0.002***
	(0.0004)	(0.0004)
Leverage ratio	-0.183***	-0.183***
	(0.033)	(0.033)
Virus lockdown dummy	0.034*	0.028
	(0.019)	(0.019)

Virus lockdown dummy * the following linkage dummy variables:		
Direct upstream linkage	-0.555***	-0.541***
	(0.091)	(0.090)
Indirect upstream linkage	-0.282***	
	(0.052)	
Indirect upstream linkage, distance 2		-0.232***
		(0.071)
Indirect upstream linkage, distance 3		-0.334***
		(0.099)
Indirect upstream linkage, distance 4		-0.226**
		(0.114)
Direct downstream linkage	-0.373***	-0.384***
	(0.083)	(0.083)
Indirect downstream linkage	-0.225***	
	(0.057)	
Indirect downstream linkage, distance 2		-0.303***
		(0.077)
Indirect downstream linkage, distance 3		-0.225*
		(0.115)
Indirect downstream linkage, distance 4		-0.170
		(0.123)
Observations	4,795,389	4,795,389
Number of firms	15,577	15,577
R-squared	0.127	0.127

Notes: *** p<0.01, ** p<0.05, * p<0.1; robust standard errors in parentheses; quarterly dummies and constant are not shown. "Virus lockdown dummy" takes the value of 1 on January 22, 23, and 27. Excludes firms headquartered in Mainland China. The number X at the end of "Indirect up(down)stream linkage, distance X" represents the degree of separation to one of more Mainland Chinese firms.

To better understand the driving forces behind these supply chain propagation effects, we dive further into the industry-level stock price reactions using three-way dummy variable interactions, with the results presented in Table 3. Column 1 shows our findings from a regression of firm equity returns on the interaction between dummy variables for the virus lockdown event, the industry classification, and whether a firm has a Mainland linkage, regardless of the supply chain position. We can see that Mainland China-linked firms in industries providing the raw materials and equipment needed for other manufacturing sectors to function exhibited significantly greater equity price declines in response to Mainland China's

lockdown measures, with Materials and Capital Goods firms seeing negative stock returns of 0.25 p.p. and 0.15 p.p, respectively, relative to other firms. Furthermore, markets also priced in significant supply chain propagation effects of the virus shock in the technology and energy sectors - firms of which underperformed by 0.67 p.p. and 0.38 p.p., respectively, and the Consumer Durables industry – firms of which underperformed by 0.58 p.p.

Columns 2 and 3 present the results from a regression where the Mainland China linkage dummy in the virus event and industry interaction is further broken down into its respective upstream and downstream positions.[22] Consistent with Mainland China's outsized role in global manufacturing, we can see that upstream suppliers of raw materials and manufacturing equipment to the Mainland are the ones driving the Materials and Capital Goods industry results in column 1. Similarly, upstream suppliers to Mainland China were the underperformers in the Energy sector, as factory shutdowns in the world's biggest importer of oil and gas weighed on their stock prices. Materials firms downstream to Mainland China also exhibited more negative returns, as the Mainland is also a prominent player in the production and sourcing of raw materials. For example, Mainland China was the world's top producer and exporter of steel in 2018[23], and is the sole source or a primary supplier for a number of widely used and specialised metals, including rare earths[24]. In the Consumer Durables industry, however, neither upstream nor downstream firms to Mainland China yielded significant equity price responses to the lockdown measures, suggesting supply-chain position relative to a Mainland firm was not deemed an important determinant of the firm's exposure beyond simply having a Mainland linkage.

In the IT sector, firms both upstream and downstream to Mainland China exhibited larger stock prices declines (of 0.54 p.p and 0.45 p.p, respectively) following news of the country's virus-induced lockdowns, reflecting the highly globalised nature of the industry's supply chains and the Mainland's key role in them.

[22] Columns 2 and 3 present results from *a single regression*; coefficients for the upstream and downstream linkage interactions are presented in separate columns (2 and 3, respectively) for ease of comparison.
[23] See: https://www.worldsteel.org/en/dam/jcr:96d7a585-e6b2-4d63-b943-4cd9ab621a91/World%2520Steel%2520in%2520Figures%25202019.pdf.
[24] See: https://www.hsdl.org/?abstract&did=817145.

The tech sector, along with the auto industry, is often cited as being at the forefront of international economic integration, with trade in intermediate goods in the electronics and autos sectors dominating world trade in manufactured intermediate goods (a proxy for GVC participation)[25]. Indeed, downstream firms relying on Mainland Chinese suppliers in the auto industry also underperformed, by 0.3 p.p.. Combined with Mainland China's dominant role in global manufacturing, it comes as no surprise that the internationally-integrated IT and auto supply chains acted as an important propagation channel of the COVID-19 shock in the Mainland.

Breaking down the industry interactions by supply chain position also reveals that aerospace and defense firms supplying to Mainland China saw more negative stock returns (by 0.66 p.p.) in the event window. This comes as no surprise, as the country is a major market for commercial aircrafts and is expected to overtake the US as the world's largest aviation market by 2024; in 2018, Mainland China was the US's single largest export market for aerospace and defense exports, and the country houses the local assembly plants of several large overseas aerospace companies such as Boeing and Airbus[26]. Interestingly, the sign of stock price reactions of firms in the pharmaceuticals, biotech, and life sciences industry with Mainland Chinese ties differs depending on the supply chain position, speaking to the nature of the shock and underscoring the importance of differentiating between upstream and downstream exposures. As Mainland China was in the midst of a virus outbreak and in need of medical supplies to treat COVID-19, pharmaceutical firms supplying to the Mainland (directly or indirectly) outperformed, with positive stock returns of 0.58 p.p.; on the other hand, pharmaceuticals firms downstream to Mainland China yielded significantly more *negative* stock returns, as virus-induced factory shutdowns in the Mainland combined with its role as the world's largest supplier of active pharmaceutical ingredients likely led to shortages in overseas production[27].

[25] See Sturgeon and Memedovic (2010).
[26] See: https://www.iata.org/en/about/worldwide/asia_pacific/Asia-Pacific-20-Year-Forecast/, https://www.aia-aerospace.org/research-center/statistics/industry-data/foreign-trade/, https://www.airframer.com/news_story.html?release=68763, and https://www.airbus.com/newsroom/news/en/2018/09/airbus--china-assembly-facility-marks-10-years-of-quality-manufa.html.
[27] See: https://www.ft.com/content/38991820-8fc7-11e8-b639-7680cedcc421.

Table 3: Firm equity returns and Mainland China supply chain linkages, industry interactions

Dependent Variable: Firm return (%)	**(1)**	**(2)**	**(3)**
Market return (%)	0.809***	0.809***	0.809***
	(0.004)	(0.004)	(0.004)
Log(market capitalisation)	-0.829***	-0.829***	-0.829***
	(0.016)	(0.016)	(0.016)
Price-to-book ratio	-0.008***	-0.008***	-0.008***
	(0.002)	(0.002)	(0.002)
ROA (%)	0.002***	0.002***	0.002***
	(0.0004)	(0.0004)	(0.0004)
Leverage ratio	-0.182***	-0.182***	-0.182***
	(0.033)	(0.033)	(0.033)
Virus lockdown dummy	0.091***	0.091***	0.091***
	(0.024)	(0.024)	(0.024)
Virus lockdown dummy * the following GICS sub-sectors:			
Aerospace & Defense	0.648	0.537	0.537
	(0.418)	(0.366)	(0.366)
Automobiles & Components	-0.320	-0.164	-0.164
	(0.205)	(0.164)	(0.164)
Capital Goods ex.	-0.121**	-0.111**	-0.111**
Aerospace & Defense	(0.050)	(0.049)	(0.049)
Consumer Durables	0.102	0.068	0.068
	(0.105)	(0.107)	(0.107)
Consumer Staples	0.051	0.035	0.035
	(0.067)	(0.0663)	(0.0663)
Energy	-0.705***	-0.697***	-0.697***
	(0.105)	(0.100)	(0.100)
Health Care Equipment	0.297*	0.329**	0.329**
	(0.160)	(0.157)	(0.157)
Materials	-0.094	-0.076	-0.076
	(0.067)	(0.065)	(0.065)
Pharmaceuticals,	0.176	0.157	0.157
Biotechnology & Life	(0.128)	(0.124)	(0.124)
Sciences			

Technology Hardware, Semiconductors, and Related Equipment	-0.417*** (0.096)	-0.416*** (0.092)	-0.416*** (0.092)
Textiles, Apparel & Luxury Goods	0.096 (0.180)	0.038 (0.176)	0.038 (0.176)
Virus lockdown dummy * the following linkage dummy variables (in columns) * the following GICS sub-sectors (in rows):			
	Mainland linkage	Upstream linkage	Downstream linkage
Aerospace & Defense	-0.619 (0.439)	-0.664* (0.370)	0.302 (0.240)
Automobiles & Components	0.116 (0.220)	0.096 (0.168)	-0.296** (0.151)
Capital Goods ex. Aerospace & Defense	-0.154* (0.084)	-0.194** (0.098)	-0.117 (0.114)
Consumer Durables	-0.576*** (0.223)	-0.446 (0.365)	-0.372 (0.248)
Consumer Staples	0.010 (0.121)	0.181 (0.203)	0.003 (0.124)
Energy	-0.380*** (0.139)	-0.431*** (0.157)	-0.089 (0.162)
Health Care Equipment	0.141 (0.279)	0.207 (0.425)	-0.109 (0.299)
Materials	-0.251*** (0.094)	-0.223** (0.106)	-0.243** (0.109)
Pharmaceuticals, Biotechnology & Life Sciences	-0.061 (0.188)	0.583** (0.249)	-0.335* (0.195)
Technology Hardware, Semiconductors, and Related Equipment	-0.671*** (0.130)	-0.536*** (0.141)	-0.448*** (0.155)
Textiles, Apparel & Luxury Goods	-0.187 (0.286)	-0.015 (0.380)	-0.014 (0.307)

Observations	4,795,389	4,795,389	4,795,389
Number of firms	15,577	15,577	15,577
R-squared	0.127	0.127	0.127

Notes: *** p<0.01, ** p<0.05, * p<0.1; robust standard errors in parentheses; quarterly dummies and constant are not shown; excluding sector dummies for Commercial & Professional Services, Communication Services, Consumer Services, Health Care Providers & Services, IT Software and Services, Real Estate, Retailing, Transportation, and Utilities (which are used as an empirical benchmark). "Virus lockdown dummy" takes the value of 1 on January 22, 23, and 27. Excludes firms headquartered in Mainland China. Columns (2) and (3) show results from the same regression, with the Mainland China linkage dummy broken down into upstream and downstream linkages, shown in columns (2) and (3), respectively, for ease of comparison.

V. VISUALISING GLOBAL SUPPLY CHAIN INTERDEPENDENCIES IN THE AUTO, IT, AND TEXTILE INDUSTRIES USING NETWORK ANALYSIS: IMPLICATIONS FOR RESHORING

The findings from our stock market event study in the previous section confirm that investors priced in significant disruptions of the local virus outbreak in Mainland China to connected foreign firms, suggesting that global supply chain linkages acted as an important mechanism of shock transmission. In this section, we use network analysis visualisation software Gephi to create graphical depictions of these inter-firm connections in order to gain insight into the extent of complexity and interconnectedness of global manufacturing production networks and their broad inter-regional patterns. In a typical network graph, firms are depicted by *nodes*, sizes of which are proportional to a firm's importance in the overall network[28]. Declared customer-supplier relationships are represented by the *edges* between two nodes with arrows pointing from supplier to customer firms. The graphs are structured so that nodes sharing more connections are placed closer together. Also, we highlight firms in four countries (United States-"US", Mainland China-"CN", Japan-"JP", and South Korea-"KR") and two regions (Europe-"EU" and "Asia ex. CN, JP, KR") that account for the largest shares of global manufacturing output[29] by different colours; therefore, *more densely-connected industry networks with a wider spectrum of colours can be assumed to be more intimately integrated in global supply chains*. This allows us to make observations on the relative difficulty of supply chain

[28] In our graphs, a firm's importance is represented by eigenvector centrality, which measures a node's influence by taking into consideration not only the number of connections a node has, but also the centrality of the nodes it is connected to. All nodes start off equal, but as the computation progresses (and after several iterations), nodes with more edges start gaining importance, and their importance propagates out to the nodes to which they are connected. For more details, see: Hansen et al. (2019) and Golbeck (2013).

[29] See: https://www.weforum.org/agenda/2020/02/countries-manufacturing-trade-exports-economics/.

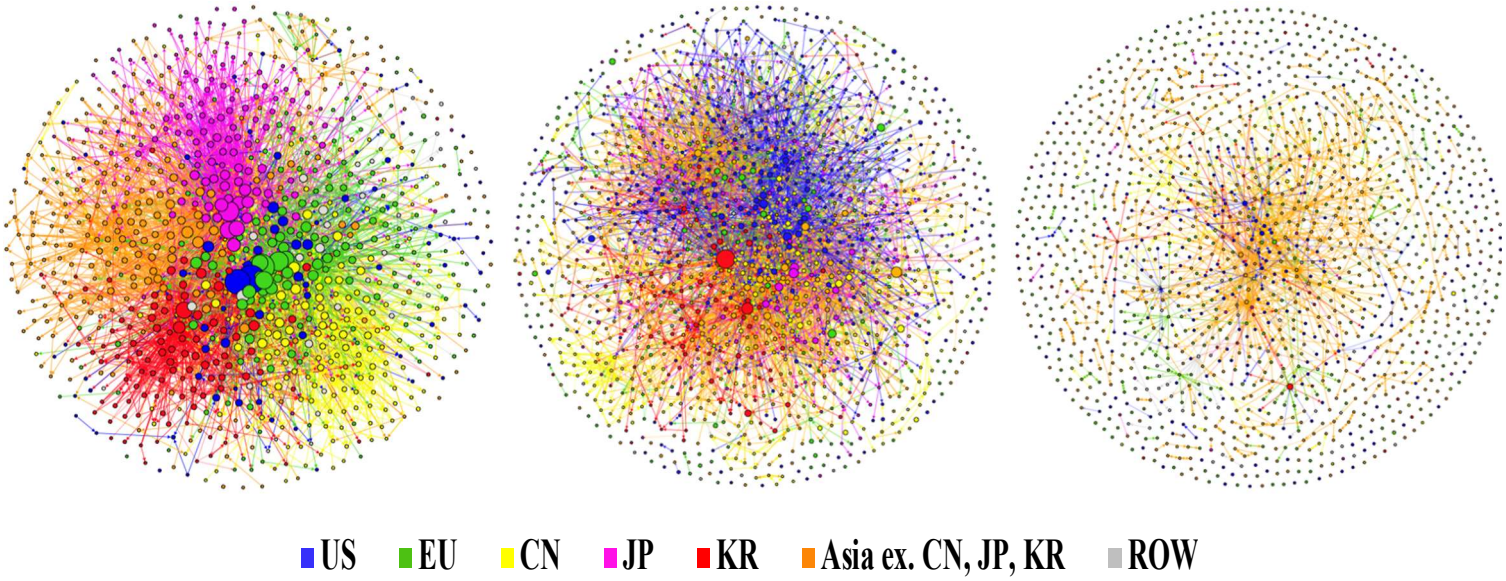
reshoring in certain industries based on network structures. That being said, it is important to keep in mind that the edges in our network graphs show only the presence of customer-supplier relationships, but not the value of transactions among the firms.

We focus on the automobiles and IT industries, shown in Charts 4A and 4B below, due to their prominently globalised supply chains and importance to Asia[30]; recall from section IV how estimates from our equity returns model showed that the stock prices of firms in the auto and IT industries with supply chain linkages to Mainland China significantly underperformed following headlines of its virus-induced lockdowns, suggesting that not only is the Mainland a key player in the GVCs of these two industries, but also that their globally dispersed production networks facilitated the propagation effect of the COVID-19 shock. We also compare the auto and IT network structures to that of another industry in which Asia also plays an outsized role – textiles and apparel, shown in Chart 4C below. Charts showing a bird's-eye view of cross-industry interconnections, as well as firm linkages in other key sectors are shown in Charts A2 and A3, respectively, of the appendix.

[30] Asia plays a pivotal role in the GVCs of vehicles and electronics, with East-Asia-Pacific-and-South-Asia ranking the highest of all regions in exports of intermediate goods within the two industries in 2019 according to World Bank data. Participation in auto and tech GVCs also forms an important part of the region's economy, with its exports of intermediate goods in these respective sectors representing 18.5% and 30.5% of total exports of manufactured goods. For comparison, the region's intermediate goods exports in the apparel and footwear industry, another key sector in Asia, represented 4.4% of total manufactured goods exports.

Chart 4: Country / region breakdown

A: Automobiles & Components **B: Information Technology** **C: Textiles, Apparel & Luxury Goods**



Notes: The IT sector in Chart 4B includes the "Consumer Electronics" sub-industry which is traditionally classified under the Consumer Discretionary sector of GICS. We exclude nodes with less than a certain number of edges; the cut-off points depend on the amount of firms in each sector grouping.
Sources: CIQ and staff calculations.

Chart 4 reveals the stark differences in supply chain network structures of the auto, IT, and textiles industries. From Charts 4A and 4B, we can see that auto and IT GVCs are highly convoluted and geographically dispersed, with the US (dark blue) and countries in Asia (fuchsia, yellow, red, orange) and Europe (green) all exerting significant influence in terms of the more notable nodes and the number of firms. On the other hand, textile production chains are dominated by firms from one region – Asia ex. CN, JP, KR (in orange), and exhibit much simpler organisational structures, suggesting that *supply chains in the textiles industry are relatively easy to relocate*. As clothing production is arguably less specialised, involves fewer components, and is less capital-intensive (implying potentially lower fixed costs to relocation) than the production process of car parts or smartphones, supply chains in the textile industry are more flexible, with companies frequently moving their manufacturing to low-cost locations due to the labour-intensive nature of the

industry.[31] Indeed, the textile industry in Asia has already weathered significant supply chain reconfigurations in the past few years. For example, while Mainland China remains a major player in textile and apparel GVCs, production has increasingly shifted from the country to its lower-cost Asian neighbours such as Vietnam and Bangladesh.[32]

On the other hand, the complex and geographically-dispersed production networks in the auto and IT industries, together with the capital-intensive nature of their production processes, suggest that *reshoring auto and tech supply chains would be a much more difficult task*. In the automobile production network, US carmakers are central to the auto supply chain, alongside European car companies; this is shown by the presence of large dark blue and green nodes, representing firms such as the US's Ford and General Motors and Europe's BMW and Daimler, in the middle of Chart 4A, connecting nodes from different countries / regions. This suggests that these multinational carmakers, through outsourcing their operations, play a crucial role in bridging global supply chain networks to those in Asia. Apart from that, anecdotal evidence also suggests that the foreign network linkages of multinational automakers serve foreign customers, implying limited economic rationale for these firms to relocate the entire supply chain back to the US and EU in the first place.[33] Meanwhile, in the tech industry, US and Asian firm interconnections feature prominently throughout the entire network structure.

That being said, comparing Charts 4A and 4B reveals some interesting differences in the auto and IT network structures that could potentially render the former industry relatively more resilient to supply chain reconfigurations, should major AEs press ahead with their relocation efforts in spite of the significant challenges. Auto firms from the same country / region tend to gather in bunches, implying extensive intra-country and intra-regional linkages, notably for Asian economies. Even if major US and EU automakers (the large blue and green nodes in the centre of Chart 4A) were to reduce their supply chain exposure to Mainland China,

[31] See, for example: https://think.ing.com/articles/covid-19-calls-for-more-resilient-production-chains-but-thats-easier-said-than-done/.
[32] See, for example: https://www.cnbc.com/2018/04/30/chinas-once-booming-textile-and-clothing-industry-faces-tough-times.html.
[33] See, for example: https://www.volkswagenag.com/en/sustainability/reporting/regions/china.html.

or Asia more generally, Asian automakers may continue to capitalize upon the well-established regional supply chain clusters, which are likely to remain competitive due to their economies of scale. On the other hand, the tech industry is much more dispersed geographically without a well-defined nexus of key companies; rather, many of the more important nodes formed by Asian firms in the tech industry are scattered throughout the network and exhibit significant interlinkages with US firms. This suggests that, if the US is to reshore IT production, Asian economies may not have sufficient critical mass to allow their tech industries to develop self-sustainability.

VI. CONCLUSION

The COVID-19 pandemic has brought to light the extent of regional interdependence and complexity of international production networks, and prompted government reshoring initiatives around the world. Using firm-level data on customer-supplier relationships in over 170 economies, this study maps out global supply chain dependencies on Mainland China to assess the financial market impact of the virus outbreak propagated to foreign firms through production networks, leveraging the exogenous and geographically-contained nature of the country's early virus outbreak. Our findings show that markets priced in significant disruptions to firms both upstream and downstream to the virus-stricken companies following headlines of significant virus developments, as well as to firms that are both directly and indirectly linked to companies in Mainland China, with the effect diminishing as the shock travels further along the supply chain. Sub-sector interactions also reveal that the stock prices of firms in industries that supply the raw materials and equipment to manufacturing processes, as well as industries that are well-known for having highly globalised GVCs, significantly underperformed compared to other firms. Furthermore, reflecting the unique nature of the COVID-19 shock, firms upstream to Mainland China in the pharmaceuticals industry significantly outperformed, while those downstream exhibited negative returns.

Then, to gain insight into the broad inter-regional trends of manufacturing GVCs, we created graphical depictions of the firm networks in our

sample, focusing on the automobile and IT industries due to their notoriously globalised supply chains. These visualisations reveal that auto and tech production networks are highly complex and geographically dispersed, with firms in Asia, the US, and Europe all exerting significant influence in terms of the number of firms and the more notable nodes. The industrial organisation structures exhibited in the auto and tech industries stands in sharp contrast to the textiles industry, which features simple production networks and mostly firms from one region. Combined with the more capital intensive nature of the auto and tech production processes, this suggests that reshoring car and IT supply chains could prove a much more difficult task, at least in the short term.

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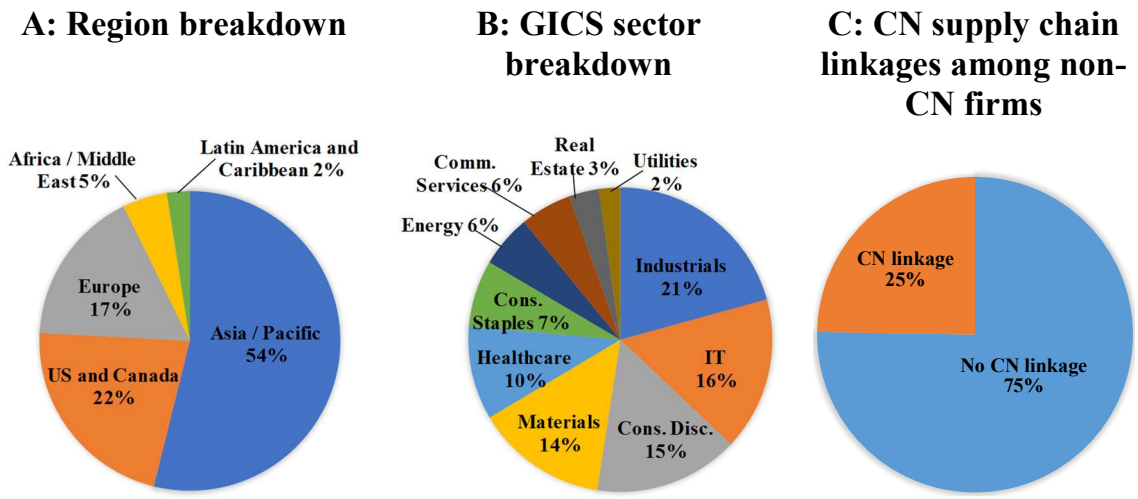
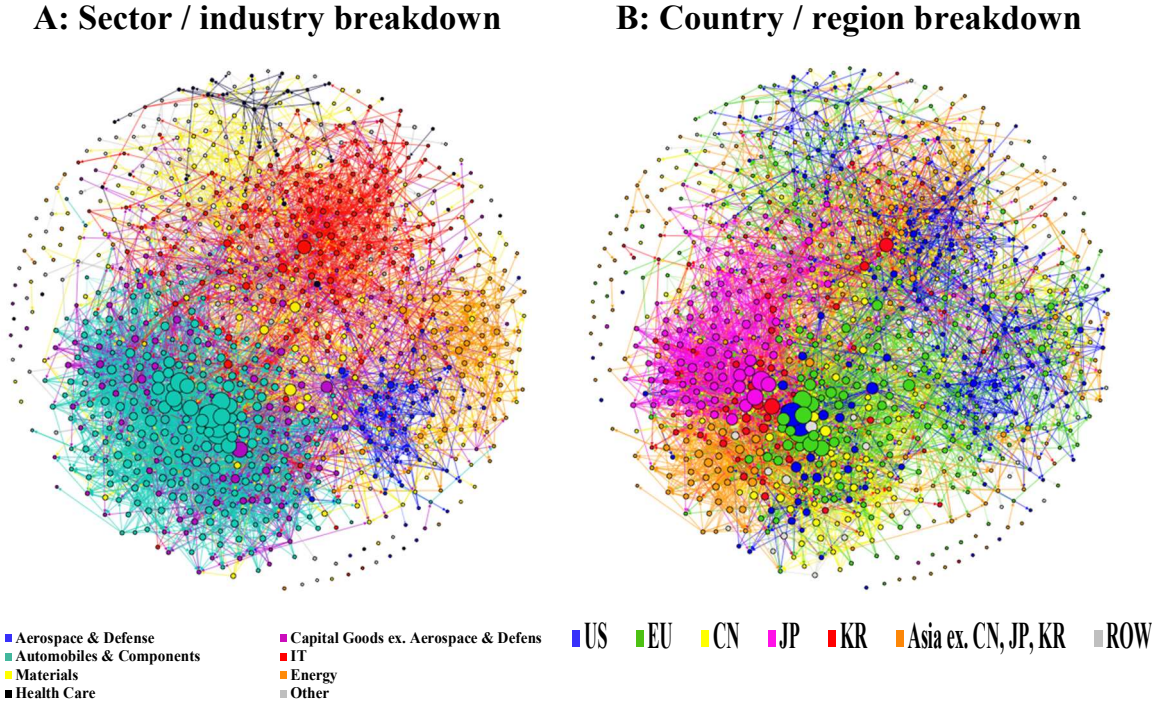
APPENDIX

Chart A1: Stock market analysis sample breakdowns



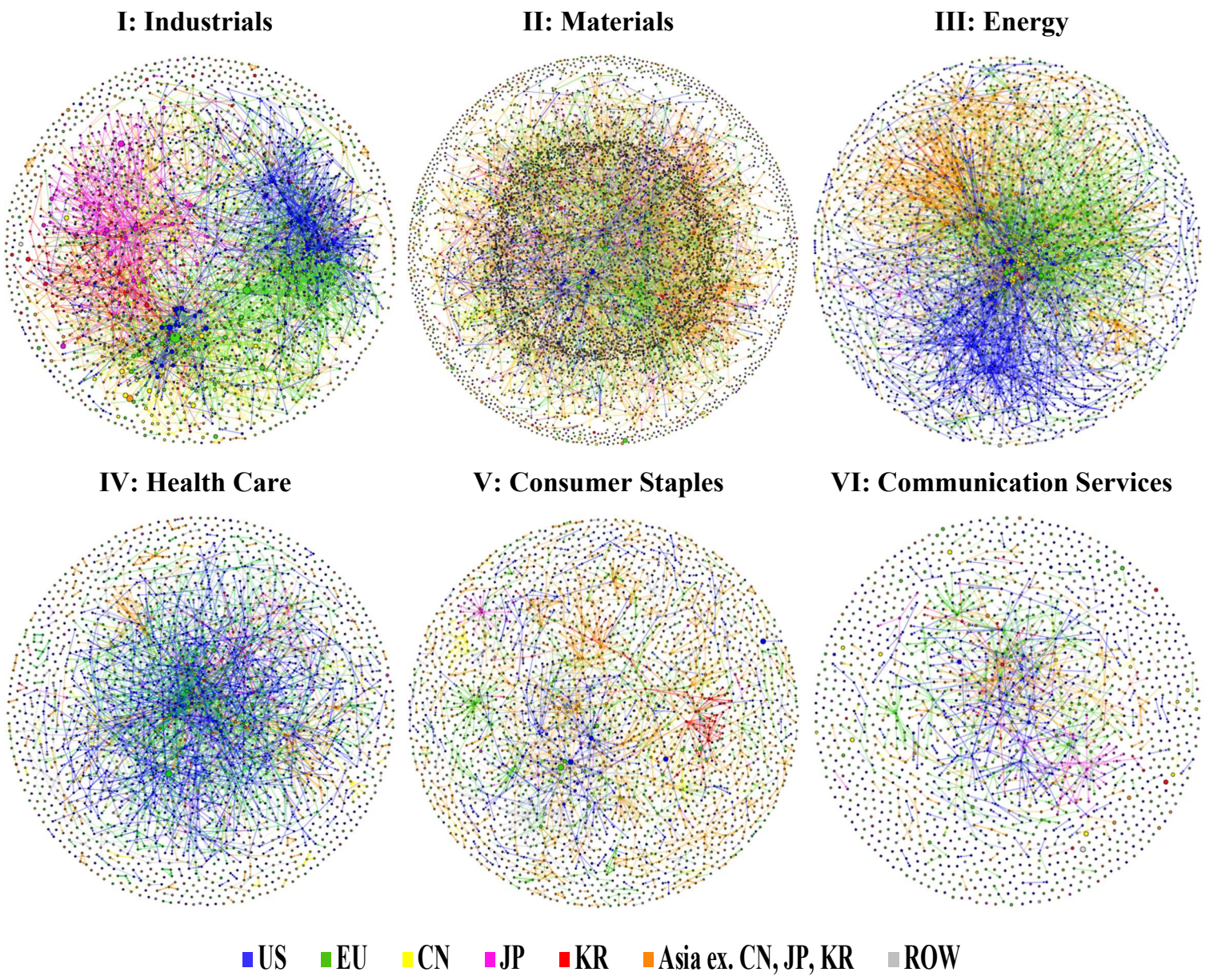
Sources: CIQ and staff calculations.

Chart A2: Global supply chain networks by sector / industry and country / region



Notes: The IT sector in red includes the "Consumer Electronics" sub-industry which is traditionally classified under the Consumer Discretionary sector of GICS. For a simpler visualisation, we exclude nodes with less than 20 edges / relationships, which explains the presence of edge-less nodes near the outer rim that are connected to excluded nodes.
Sources: CIQ and staff calculations.

Chart A3: Global supply chain networks in GICS sectors: breakdown by country / region



Notes: We exclude nodes with less than a certain number of edges; the cut-off points depend on the amount of firms in each sector grouping.
Sources: CIQ and staff calculations.