D3.4 – Methodology for economic impact assessment of supply chain disruptions

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Executive Summary

The COVID-19 pandemic is a global health crisis and has caused devastating casualties worldwide. To reduce the spread of COVID-19, worldwide governments have implemented numerous intervention policies. Undoubtedly, these policies have minimized the total number of deaths due to the pandemic. However, some of these restrictive policies have discouraged economic activities in countries where these restrictions are enforced. Additionally, they have created spillover effects on other countries. Therefore, policymakers are keen on understanding how the COVID-19 shock is amplified and propagated through an economy.

This deliverable (D3.4) develops a methodology to estimate the economic impact of the COVID-19 shock. It investigates how the COVID-19 shock is propagated through a network of global supplier-customer relationships, capturing interdependencies between suppliers and customers along the supply chain, allowing us to estimate the cascading effects of the COVID-19 shock. The methodology is built on a difference-in-differences approach which compares economic activities over time between suppliers or customers (treatment group) affected by COVID-19-induced supply chain disruptions and suppliers or customers (control group) that are not impacted by disruption. This methodology enables us to examine whether and to what extent changes in economic activities are due to disruptions in a firm's suppliers, disruptions in a firm's customers, or interruptions to a firm due to government intervention policies. Specifically, scenarios such as full workplace closures are used as a proxy for COVID-19-induced supply chain disruptions.

This deliverable examines all publicly traded companies with headquarters in the European Union from the first quarter of 2019 to the third quarter of 2021. The univariate results indicate a robust demand for COVID-19-related goods (including medical devices, personal protective equipment, pharmaceuticals, as well as soaps and cleaning compound) since the COVID-19 outbreak. Firms producing COVID-19-related goods experienced positive sales growth in nearly every quarter in 2020. To cater to the robust demand of COVID-19 related goods, firms appear to increase output based on existing production capabilities rather than building new plants or facilities immediately because investment growth declined mildly in the first three quarters of 2020.

The difference-in-differences results show that full workplace closures are a binding constraint on sales growth for firms producing COVID-19 related goods. A firm's sales growth declines significantly by over 10 percentage points when the firm is affected by full workplace closures in the current quarter and quarter (t-2). These declines are enormous considering the strong demand for COVID-19 related goods worldwide. In contrast, a firm's sales growth is unresponsive when the firm's suppliers are affected by full workplace closures.

Similarly, the difference-in-differences results also suggest that full workplace closures restrict investment growth for firms producing COVID-19 related goods. A firm's investment growth increases markedly by one-fold when one of the firm's suppliers is affected by full workplace closures in the quarter (t-3). This increase is delayed by three quarters, suggesting firms might face huge uncertainties about the severity and duration of the COVID-19 shock during the early stage of the pandemic. Therefore, it may take months for companies to act and invest as they realize that the COVID-19 shock is ongoing, at least in the coming years. In addition, the difference-in-differences results indicate that for firms producing COVID-19 related goods, supplier growth remains unchanged when the firm's suppliers are affected by full workplace closures in the current quarter and the prior quarter. Given

the overwhelming demand for COVID-19-related goods, this result is intriguing but consistent with the widespread export restrictions of COVID-19-related goods during the early stage of the pandemic. However, the number of suppliers drops when one of the firm's suppliers is affected by full workplace closures in quarters (t-2) and (t-4). This result suggests that firms reduce the number of suppliers several quarters after full workplace closures have disrupted their pre-existing supply chain relationships. This result also implies that firms may rely more on in-house production as they invest aggressively three quarters after one of its suppliers is affected by full workplace closures.

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List of acronyms

Abbreviation / acronym	Description
COVID-19	Novel Coronavirus Disease
CRI	Associazione della Croce Rossa Italiana
EU	European Union
HAN	Hanken School of Economics
HERoS	Health Emergency Response in Interconnected Systems
HOPE	Project HOPE – The People to People Health Foundation
NGO	Non-Governmental Organization
OU	The Open University
PCPM	Polish Center for International Aid
PPE	Personal protective equipment
SQU	Squadron
TUD	Delft University of Technology

1. Introduction

The Coronavirus Disease (COVID-19) pandemic has emerged as an unprecedented health crisis worldwide and heavily disrupted global supply chains. All the involved actors of the chain (buyers, distributors, suppliers, service providers, producers, etc.) have been affected differently. The severity of the impact depends on the relationship and closeness of the suppliers, e.g., local vs. global suppliers, tier1 vs. tier2 suppliers. (Paul, Moktadir & Ahsan, 2021; Xiong et al. 2021).

In our previous deliverable (D3.1), we focused on the gaps in medical supply chains and made recommendations on securing the medical supplies to respond to pandemics. Medical supply chains in the first wave of COVID-19 (March to September 2020) were disrupted by consumer behaviour, capacity limitations and legislations or the lack of it. These disruptions led to shortages of personal protective equipment (PPE) and respiratory ventilators, among other essential items, and had a direct impact on the pricing and the quality of those items. In addition, the policies that governments implemented to fight the pandemic, such as lockdowns and export bans, had a negative impact on the availability of those items and the economic output.

The objective of D3.4 is to develop a methodology to capture the economic impact of the COVID-19 outbreak and the interdependencies between industries and sectors and cascades through global supply chains. In D3.4, we measure the economic impact of the supply chain disruption based on different economic indicators (sales growth, investment growth, stock return, and buyer-supplier relationship). The report highlighted the disruption of medical goods, particularly personal protective equipment. The report has been prepared according to the difference-in-differences approach, which compares sales growth or investment growth over time between suppliers affected by COVID-19 induced supply chain disruptions (treatment group) and suppliers that were not affected (control group). Our initial sample starts from all publicly traded companies headquartered in the European Union from the CompuStat Global database in the first quarter of 2019. Our sample is constructed from six databases. Data on supply chain relationships are obtained from the FactSet Revere database. Data on COVID-19 are extracted from Johns Hopkins University Centre for Systems Science and Engineering. Data on government interventions are fetched from the Oxford COVID-19 Government Response Tracker (OxCGRT) project (Hale et al., 2021). Stock market and financial data are obtained from CompuStat Global and CompuStat North America. Lastly, data on economic characteristics are gathered from the World Bank's World Development Indicators.

The structure of D3.4 is as follows. Section 2 presents the literature review related to the economic impact of supply chain disruption. In section 3, the supply chain cascades are discussed. Section 4 describes the methodology to measure the economic impact. In section 5, conclusions and future research are highlighted.

2. Literature review

Previous literature on the economic impact of the COVID-19 pandemic covered different economic performance indicators such as international trade, investment, capital flow, GDP, etc. (Himanshu, Mushir & Suryavanshi, 2021). There are different approaches for evaluating economic performance at the national and international levels (macro). At the macro level, several indicators such as the stock market (Mazur, Dang & Vega, 2021; Baker et al., 2020), investment (Singh, 2020; Himanshu, Mushir & Suryavanshi, 2021), consumption (Chen, Qian & Wen, 2021; Cohen, 2020), and the labour market (Radulescu et al., 2021; Sakshaug et al., 2020; Campello, Kankanhalli & Muthukrishnan, 2020) can be assessed.

The consequences of supply chain disruptions on the economy have been studied by supply chain researchers and economists. For example, Al-Mansour & Al-Ajmi (2020) focused on the economic and management implications of supply chain disruptions, while other scholars have assessed the impact of earthquakes (Tokui, Kawasaki & Miyagawa, 2017). Some other scholars have analysed both the negative and positive effects of disruptions (Ibn-Mohammed et al., 2021).

The impact of the COVID-19 pandemic on the global economic environment is evident, as reflected in many economic studies (OECD, 2020). Before the COVID-19 pandemic, most of the trade barriers were removed as part of international trade facilitation, trade agreements, international trade policy etc. (UNCTAD, 2022). However, after the pandemic had been declared, several border control and import/export restrictions were imposed by various countries (AMID, 2021). The restrictions limited the cross-border movement of peoples, goods, and vehicles in more than 90 countries in the first quarter of 2020 (Ibn-Mohammed, 2021). This control obstructed transportation, which is a cornerstone of the supply chain because it facilitates the physical movement of products and materials. Such restrictions directly impact world trade (Weiss et al., 2021). WTO (2020) statistics show a decline in world trade volume by 13- 32%. In addition, the IMF report indicates that the economies of developed countries will face ongoing economic challenges until now due to supply shortages (Goel, Saunoris & Goel, 2020).

The COVID-19 pandemic casts a negative shadow on economic growth across Europe due to measures taken by states to control the COVID-19 outbreak (Ahoniemi & Koskinen, 2021). According to economic reports in (October 2020), global economic growth declined at a rate ranging between - 4.5% and - 6.0% in 2020. However, 2021 witnessed a partial recovery of + 2.5% to + 5.2% (International Monetary Fund, 2021). The GDP of the EU in the first quarter of 2020 has registered a 4.4% decline for most EU states except for four states that registered positive growth: Romania, Bulgaria, Ireland, and Sweden (Soava et al., 2021). The second quarter witnessed a further decline of 11.8%, while the third quarter showed limited recovery despite the 0.7 decline in the fourth quarter registered (Euro statistics agency, 2020). In the fourth and third quarters of 2021, EU GDP had grown 4.1% and 2.2%, respectively; however, in the first quarter contracted by 0.1% (World Trade Statistical Review, 2021). In the end, the COVID-19 pandemic led to a decline in world trade by an annual rate of 9.2% (Weiss et al., 2020). For example, some European Union countries have been more negatively affected than others; most countries were negatively affected, while Romania, Iceland, and Ireland achieved positive economic growth due to multi-national companies' investment (Gopinath, 2020).

In several ways, the global economy (e.g., international trade, investments MNCs) has been negatively affected by the COVID-19 pandemic (Oravský, Tóth & Bánociová, 2020). from a business profit point of view, the profitability of many sectors (e.g., banks) has shown negative growth in 2020 as a spillover of business disruption (Ahoniemi & Koskinen, 2021). Furthermore, the effect of supply chain disruption appears on suppliers' performance amid the COVID-19 pandemic, e.g., delaying the buyer orders, cancelled contracts, or postponed (e.g., raw materials, supplies) (Chen, Wang. & Wu, 2021; Baldwin & di Mauro, 2020).

Supply chain shock on both sides, supply, and demand would lead to recession and thus affect the demand for labour, and then spread across the economy (Elgin, Basbug & Yalaman, 2020). There are two types of shocks, supply shocks, and demand shocks. Where shocks are caused by specific conditions or risks (environmental conditions, epidemics, or shocks related to legislation such as taxes, etc.), in turn, these risks cause supply and demand fluctuations (Yılmaz & Özayturk, 2021). If the shock causes an increase in supply, that is a positive shock, while the shock that causes a decrease in the supply is considered a negative shock. For example, the demand shock in Europe came out as a consequence of business closures in the first wave of COVID-19, border restrictions and barriers, COVID-19 testing, and quarantine requirements (Yılmaz & Özayturk, 2021). All these measures led to decreased productivity and supply shortage. In addition, the consumption of many products decreased, accompanied by higher risks and costs (McKibbin & Fernando, 2020).

The COVID-19 shock has had an overall effect on global supply (Maital and Barzani, 2020). However, the measures taken due to the COVID-19 pandemic were more related to demand and thus potentially impacted the global economic recession (Yılmaz & Özayturk, 2021). A cross-sectorial statistics show a decrease in demand in the EU, e.g., the demand for cars decreased by 25.70% in July 2020 (Boranova et al. 2022). The oil demand is negatively affected due to travel restrictions because the aviation sector represent 60% of oil demand. The above argument, figures, and evidence reveal the impact of the COVID-19 pandemic on different economic dimensions (Deloitte, 2020).

The following sections discusses the thematic area of economic impact of the COVID-19 pandemic.

2.1. The impact of the COVID-19 pandemic on sales

The COVID-19 pandemic has shattered expectations in the speed of business closures due to restrictions imposed by local authorities or federal governments (Bloom, Fletcher & Yeh. 2021; Hoeft, 2021; Sharma, Rangarajan & Paesbrugghe, 2020). Several surveys and statistics indicate the impact of the COVID-19 pandemic on sales across many sectors. E.g., results of a survey conducted in November 2020 revealed that European SMEs experience a 20% sales decrease in sales (Digitally Driven, 2021). De Vet et al., (2021) estimated an overall decline in sales revenue across European industry sectors by 31% compared to 2019. The drop in sales due to COVID-19 varies between countries and times, pandemic stage (early stage, peak time), closure procedures and the seriousness of the closure (Chronopoulos, Lukas & Wilson, 2020).

Furthermore, the decline in sales also varies depending on the business type. The impact of the COVID-19 pandemic in Europe on various sectors was as follows.

- Healthcare: In the first wave, the COVID-19 pandemic negatively hit the healthcare system's performance, as the demand for hospital services was curbed to spare capacity for COVID-19 cases (Infosys BPM, 2021). The pharmaceutical sector in the EU witnessed a 12% drop in retail trade by March 2020 due to supply chain disruptions (Eurostat, 2021). The industry gained a 12% growth in sales in September 2020. According to Eurostat (2021), demand is expected to continue growing in 2021-2022.

- Digital industry: The digital industry experienced tiny drops compared to other sectors (e.g., leisure) during the first wave of COVID-19. In 2020, Q3 computer demand growth reached 4.6%, and software demand growth was 4%. In 2021 digital industry is started recovery, which is estimated to achieve 30% growth compared to 2020 (IDC, 2020).
- Textiles & apparel industry: In the EU, the textile and apparel industry experienced 18.8% drops in retail sales in Q1 2020. The textile industry in the EU started to recover from Q3 2020 onward when retailers' sales increased by 62% compared to Q2. It is expected to return to the pre-crisis situation in 2023, while turnover in 2021 increased by 15% (De Vet et al. 2021).
- EU Construction Industry: The impact on the construction industry is diverse since COVID-19 restrictions and business closures vary from one country to another. The pandemic affected workforces directly and indirectly. Effects of lockdowns on industries also differed across countries. In some countries, such as Germany, it was possible to continue working during COVID-19, while working was not allowed in France, Spain, and Slovakia. The drop in the construction industry during the first six months was small. The sector's performance started to stabilize from November 2020, and the sector grew in 2021. The growth of the sector is expected to reach 3.4% in 2022 (Euroconstruct, 2020).
- Chemical industry: Europe was the second-largest Chemical producer in 2020. The EU Chemical Industry has 499 billion euros of world sales (Cefic, 2022). The negative effect of COVID-19 on sales has been investigated by a few authors (e.g., Bloom, Fletcher & Yeh. 2021; Fairlie 2020).

The findings of these studies support the negative impact of the COVID-19 pandemic on sales. However, the negative impact is realized in every business sector (Bloom, Fletcher & Yeh. 2021). According to Bloom, Fletcher & Yeh. (2021), fully online businesses experienced less drop in sales than fully or partially offline businesses.

2.2. The impact of the COVID-19 pandemic on investment

COVID-19-related measures such as social distancing and business closures have impacted the economics of many countries in different ways and dimensions, particularly with respect to export, demand, and consumption. In an uncertain situation such as the COVID-19, profit might decline due to uncertainty (Shen et al. 2020; Zeng et al. 2016). Instability in the global business climate may stall market growth (Gilal et al. 2020). The new economic environment created by the COVID-19 pandemic is incomparable to any economic environment before (Sadiq et al. 2021; Cheema, Faff & Szulczuk, 2020). The comparison of the impact of the financial crisis in 2008 and the COVID-19 pandemic in 2020 on the service sector revealed that the impact of COVID-19 on the service sector was far more than in 2008 (De Vet et al. 2021; Casquilho-Martins & Belchior-Rocha, 2022; Jaworek, Karaszewski & Kuczmarska, 2020). By definition, investments include buying assets or spending on valuable businesses that are expected to generate revenue or different values (De Vet et al. 2021). The COVID-19 pandemic changed investment management as well as the decisions and behaviours of the investors (Casquilho-Martins & Belchior-Rocha, 2022). Globally, investment inflow fell by 42% in 2020 compared to 2019. In 2021, the global inflow investment witnessed a rebound up to 77% from 2020's figures (UNCTAD, 2022). Europe experienced an inflow of USD 4 billion in investment in 2020 compared to 2019 (UNCTAD, 2021). However, in 2021, Europe had recuperation in inflow investment by 80% from 2020's figures. Similarly, on the 3rd of March 2020, the interest witnessed a decline of 1% (Jackson et al. 2021). Due to the COVID-19 pandemic, the business environment became more unsteady and unpredictable; future investors were struggling with investment decisions (Gurbaxani & Gupte, 2021). The supply and demand shock caused by the COVID-19 pandemic led to direct and significant effects on the financial and credit markets, as borrowers experienced challenges related to investment risks (Rizvi, 2020).

The COVID-19 pandemic has significantly impacted the capital markets due to the credit risks of retail customers of banks and businesses (Jiang et al., 2021). The European Banking Authority indicates that 30% of loans have been deferred, and the credit risk has grown (Ahoniemi & Koskinen, 2021). Furthermore, non-performing loans of small and medium-sized service sector companies have increased in Q4 of 2020. In 2021, the non-performing loans in Q1, Q2, and Q3 represented 2.54%, 2.32%, and 2.17%, respectively (European Central Bank, 2021). Again, because of the COVID-19 disruption, internal business activities such as the internal supply chain and other operations associated with production and sales encountered severe difficulties (Jiang et al., 2021). According to Jiang et al., (2021), the high level of uncertainty caused by the COVID-19 pandemic weakened the ability of companies to obtain the income necessary to meet outstanding debts. The spillover effects of postponing loan repayment and extending financial measures may lead to investment stagnation (Financial stability Board, 2021). The total or partial business closures can be negatively associated with a lack of investment as investors are under uncertainty, a decrease in labour availability due to (social distance), and weak supportive logistics service at the peak of the COVID-19 outbreak (Durach, Wiengarten & Choi, 2020). There is evidence that some European countries faced a severe investment decline (France, Belgium), more than others (Germany, Netherland in the quarter four 2020 (Andersen et al. 2021).

Going through several previous experiences, such as the financial crisis of 2008 and many others, investors have become more vigilant to avoid the adverse effects of a crisis such as the COVID-19 pandemic (Financial Stability Board, 2020). As a result, safer portfolio investment strategies have been extensively implemented to avoid losses and achieve returns during crisis times (Singh et al. 2020). In times of uncertainty, companies' enthusiasm for investment does not necessarily decrease, but they seek to find strategies that reduce the effects of uncertainty and risks (Koepke, 2018).

2.3. The impact of the COVID-19 pandemic on the stock market

The stock market is one of the most vulnerable markets and is susceptible to countless factors (Nieto & Rubio. 2022). The stock market witnessed one of the most significant losses due to the COVID-19 shock. In March 2020, the Dow Jones industrial average decreased by 26% (Mazur, Dang & Vega, 2021). According to Olufadewa et al. (2020), global stock markets lost $24 billion. The performance analysis of EU industries showed a variation in terms of the impact of the COVID-19 pandemic since March 2020. The most hit industries were travel and leisure because they heavily depend on human interactions. In contrast, electronics, pharmaceuticals, and health services performed well during the COVID-19 pandemic (De Vet et al. 2021) . On Black Monday (March 9, 2020), companies in the energy sector, particularly crude petroleum, lost 60% of the market value in a single day. This decline was a short-term decline but revealed the extent of the impact of COVID-19 on the stock market (Mazur, Dang & Vega, 2021). More evidence from listed companies in the S&P 1500 showed a negative relationship between the monthly stock return and the daily stock return during March 2020 (Mazur, Dang & Vega, 2021). Several research findings indicate that the COVID-19 pandemic caused a negative impact on the stock market (Ambros et al., 2020; Mishra et al., 2020) and fluctuation of stock prices (Zhang et al. 2020; Bora & Basistha, 2021; Baker et al. 2020. Although it remains to be seen how the overall impact of the COVID-19 pandemic will be on the stock market when the pandemic is over, it can be stated that the stock markets in many countries have experienced a decrease since January 2020 (Ramelli & Wagner, 2020).

2.4. The impact of the COVID-19 pandemic on buyer-supplier relationships

The core of the supply chain is the networking and reciprocal relationship between the chain actors (Lu et al., 2018). Any business activity needs to be backboned by a good relationship with suppliers (Choi et al., 2002). This relationship (buyer-supplier) can be classified into different types, such as arm's length relationships, cooperation, collaboration, partnerships, and strategic alliances (O'Toole & Donaldson, 2002; Tangpong et al., 2015; Christopher and Jüttner, 2000).

Arm's length is a transactional inter-organizational relationship that relies on auctions or a specific spot of transactions (Skjøtt-Larsen, Kotzab & Grieger, 2003). In this relationship, the contracts specify the transaction details to prevent independent decisions. Arm's length is characterized by the lack of information sharing and investments in the relationship by the partners (Lambert and Cooper, 2000). Although the arm's length relationship is critiqued for its focus on cost, it is appropriate for situations when multiple supply options are available (Ferrer et al., 2010).

In a cooperative relationship between buyer and supplier, both buyer and supplier work jointly by sharing resources and solving problems to achieve common goals (Choi et al., 2002). The collaborative relationship, by its nature, is a long-term relationship compared to a competitive relationship (Tangpong et al., 2015). This relationship requires a structure of close working that guarantees trust and commitment in the relationship and unifies the partners' vision (Ferrer et al., 2010). The relationship depends on the common goals between the partners and the aspects of synergy. The s-buyer-supplier collaborative relationship can be classified into supplier-led collaboration and buyer-led collaboration. Supplier-led collaboration is characterized by the buying company being more dependent on the supplier, while in buyer-led collaboration, the supplier company is more dependent on the buyer (Tangpong et al., 2015).

A strategic alliance is defined as a long-term relationship between a buyer company and supplier company, where both parties show mutual trust and commitment to information exchange and risk-sharing (Skjøtt-Larsen, Kotzab. & Grieger, 2003). Today, businesses rely on the interdependence of a vast network of partners, including suppliers, to achieve business goals and continuity (González, Rodríguez-Sánchez. & Pelechano, 2021). When the environment is uncertain and unstable, trust and close relationships with suppliers could support the partners' performance (Hoyt, Huq, 2000). Supply chains are complex in network architecture and require a high level of synergy and mutual commitment; therefore, managing the relationship with suppliers require resources, especially during pandemics (Nunes, Park & Paiva. 2021). Many large and multinational companies have been affected by supply chain disruptions because they have supply facilities in different areas across the globe where these facilities were under COVID-19 restrictions (Lee et al., 2020). The effects on companies varied due to the nature of demand for each product, but overall supply chains operations have been slowed down by COVID-19 restrictions (Linton and Vakil, 2020). In line with that, 62% of companies experienced a delay in receiving goods, 53% were not able to get information from suppliers in China during first and second waves of COVID-19 in 2020 (Magableh, 2021).

In many countries, governments have imposed restrictions such as complete or partial closures which restricted the movement of people by public transportation to slow down the spread of COVID-19

(Burgos & Ivanov,2021). Thus, restrictions created bottlenecks in shipments and delivery at the ports, docks, etc. Therefore, suppliers could not fulfil their commitments to customers (Ivanov and Das, 2020). COVID-19 has tested the relationships between supply chain actors. Actors may find some suppliers non-performing but finding alternative suppliers are challenging and may take much time (House, 2021). Therefore, the solution lies in encouraging and assisting existing suppliers and showing sympathy (Durach, Wiengarten & Choi, 2020).

2.5. COVID-19-related goods

Due to the COVID-19 pandemic, the demand for medical supplies, particularly personal protective equipment (PPE), skyrocketed (Hu, 2022). Buyers experienced a shortage of supply of personal protective equipment due to stock shortages, business lockdown, and imposed restrictions (Meier & Pinto, 2020). At the beginning of the pandemic (first wave), personal protective equipment was one of the first measures to combat COVID-19. Several countries started to reserve personal protective equipment for local use, which limited the trade of PPEs (Fu, McMahon and Xue, 2020). In an era of high dependence on international exchange, no single country can produce all medical supplies (Gereffi, 2020). Accordingly, there are main leading producers and exporters of personal protective equipment. UN Comtrade (2020) reported that China was the biggest exporter of masks, 44% in 2018, followed by the US with 7% and Germany with 6%. In addition, 50% of medical PPEs come from (Germany, U.S, Switzerland, China and Ireland). In March 2020, estimates indicated that the world's demand for personal protection equipment would multiply ten times due to COVID-19 (Gereffi, 2020). Before the COVID-19 pandemic, the demand for medical PPE had regular products mix (e.g., gloves, masks) as dominant items, but after the outbreak, the products mix of medical PPE has been shifted to face mask dominancy which represents 40% in 2021 while it was 5% in 2019 (IFC, 2021). In 2020, the supply of PPE chartered by China dominated 20% of the market share, followed by Malaysia and Germany (19.4 and 14.1%) (Garcia-Santaolalla, de Klerk & Mendez, 2021). By 2022, the demand for PPE is expected to drop because of a decrease in consumer and non-healthcare demands. By 2023, the demand is expected to return to its normal trend due to the protective measures imposed by countries (IFC, 2021). For example, USA confiscated personal protective equipment bound to Germany in April 2020 (Minondo, 2021). Some countries took sudden measures during the peak of the pandemic (march to June 2020), such as restrictions on transportation movement and border closures at the same time as global demand for personal protective equipment was increasing. According to Evenett (2020), the situation became paradoxical. The Global Trade Alert team accounted for 459 measures imposed by countries on medical supplies, food products and other goods.

Protective measures took various forms, such as banning the selling and shipping of personal protective equipment, export quotas, export licenses, keeping a percentage for local needs, and maintaining a minimum level of stock (Forini, Hoekman & Yildirim, 2020). Export and import policy interventions significantly led to unexpected severe supply chain disruption for PPEs (Farrell & Newman, 2020).

Table 1 summarises the areas of impact of the COVID-19 pandemic.

Table 1: Areas of impact of the COVID-19 pandemic

Author	Impact area	Objective	Methodology	Findings

Sales				
Romano, et al (2021).	Sales	to characterize the impact of the COVID-19 on outpatient medicines' sales and shortages.	time-trend analysis	The pandemic resulted in an increase in medicines' demand and reported shortages during the early stage of the outbreak.
Panzone, Larcom & She, (2021)	Sales	measure the impact of the COVID-19 shock on sales of UK food retailers and restaurants	Econometric model	in the period March–August 2020, COVID-19 restrictions accounted for a £4 billion increase in sales for food retailers, and £4 billion in non-store retailers
Rangarajan, (2021).	Sales	explore how firms have responded to these interconnected changes during the COVID-19	qualitative	the value-adding contributions of an adaptive and hybrid sales force
Davis & Gomez, (2021)	Sales	identify the drivers of customer satisfaction (CS) and sales performance	survey	four main CS factors: Staff Interactions, Wine Tasting, COVID-19 Precautions and Ambience that play a significant role in overall CS
Fairlie & Fossen, (2021)	Sales	analysis of losses in sales among the universe of businesses in California	Event analysis	sales losses were largest in businesses affected by mandatory lockdowns such as accommodations, which lost 91%, whereas online sales grew by 180%.
Stock Market				
Prabheesh, Padhan & Gargal (2020)	Stock market	Test the relationship between stock market and the return of oil price	DCC-GARCH	The relationship between oil prices and stock prices supported by the COVID-19 pandemic
Al-Awadi et al. (2020)	Stock market	To evaluate the outcomes of Stock market	Panel Regression	Significant impact of rising
Gil-Alana and Claudio-Quir, (2020)	Stock market	Impact on Asian Stock markets	Fractal Integration	Transitory effect on Japan
Phan and Narayan (2020)	Stock market	To measure the Stock market reaction to real time	Event Analysis	Market overreacts to unexpected news related to the COVID-19 pandemic
Ofori-Boateng, et al. (2021).	stock returns	Examining the impact of the COVID-19	quantitative, time series and deductive in nature	The COVID-19 pandemic has led to wide variations in the market increasing the risk of investments.

		pandemic on the stock returns		
Yong & Laing, (2021)	Stock market	examine the reaction of U.S. stock market to the new declaration of WHO	event study	imports and exports are Significant and negatively associated with standardized cumulative abnormal returns in the short run
Investment				
Tecău et al (2020).	heavy work investment	the influence of the COVID-19 pandemic on heavy work investment	survey	there were decreases in work investment during the pandemic
Yoshino, Taghizadeh-Hesary & Otsuka (2021).	optimal portfolio	investigated the optimal portfolio investment scheme by considering the SDGs		The global recession and investors are less interested in environmental factors or SDG indicators
Jiang et al. (2021).	firm investment	The impact of the COVID-19 pandemic on Chinese business investment	score matching method and difference-in-differences estimation	The COVID-19 pandemic in China had a negative impact on Chinese listed firm
Fu, Alleyne & Mu. (2021)	FDI	How the COVID-19 pandemic affected home and host countries' FDI margins		FDI was affected by its domestic pandemic control
Sohail, Husssain & Qurashi, (2020).	on investment decision of individual	the impact of the COVID-19 pandemic on investment decision of individual	Semi-structured interviews	The impact of the COVID-19 pandemic on individual investor's investment decisions
Buyers-suppliers				
Chowdhury, et al 2021)	supply chain	reviews existing research on the COVID-19 pandemic in supply chain disciplines	Systematic review	most studies have focused on supply chains for high-demand essential goods and healthcare products, while low-demand items and SMEs have been largely ignored
Pereira, Silva & Hendry, (2021).	suppliers	investigate the impact of the COVID-19 pandemic on supply chain (SC) sustainability learning.	scenarios	Social sustainability was observed to be the main priority by suppliers facing this unprecedented outbreak,

Anner (2021)	Buyer-Supplier's relationship	Investigates "Power relations in global supply chains and the unequal distribution of costs during crises	Survey, a time-line analysis, and trade data analysis	buyers indeed pushed many of the costs of the COVID-19 pandemic down onto suppliers.
Nunes, Park & Paiva, (2021)	supplier crisis response strategies	investigates supply chain leaders' initiatives to support their partners in the early stages of the COVID-19 pandemic	Exploratory& scenarios	supplier crisis response strategies have positive effects on both supplier satisfaction and commitment

3. Cascades in the supply chain

Throughout this deliverable, we have already stressed the importance of cascading effects**,** whereby the non-pharmaceutical interventions such as lock-downs, export and travel bans quickly led to a sharp decline of mobility, electricity usage and economic activity (Chen et al., 2020; Demürguc-Kunt et al., 2020) and severe business disruptions which, in turn, created severe disruptions of globalized supply chains (Guan et al., 2020) along with a rapid decline of productivity and GDP (Jena et al., 2021). Further, the interventions also led to an increasing volatility on the labour market (Su et al., 2021), leading to an increase of gender inequality (Reichelt et al., 2021), higher unemployment and a decline in purchasing power (Almeida et al., 2021). Only policies aimed at protecting those most hit by the crisis, either through discretionary measures (e.g., income subsidies), or automatic stabilization (e.g., unemployment benefits or lower taxes paid because of job loss and/or decrease in market incomes), could partly reduce the toll (Almeida et al., 2021). As earlier in this deliverable, we here specifically focus on the cascading effects related to the PPE supply chains. Based on the interviews that were conducted for the D3.1, we developed a causal loop diagram to highlight the interdependencies and feedback loops that we identified in the response to COVID-19 (see Figure 1.).

Naturally, the raise of infections during the COVID-19 pandemic (centre) led to increasing demand for PPE, while the supply decreased (left side of Figure 1). As there were in many cases limited safety stocks, decision-makers across the world rushed to order PPE. Given the shortages of PPE, and the pressure from health care providers and the population alike, we observed herding behaviour and panic buying. While typically, this is a well-known behaviour of consumers (e.g., Zheng et al., 2021), we could observe here that also strategic decision-making followed the same behavioural patterns, driven by the urgent need to respond. At the same time, because of the urgency of the situation, there was limited time to control and check orders. The combination of panic buying and a lack of worldwide standards for PPE led to low-quality and high-cost orders. The travel and transport bans further exacerbated the situation, causing further delays.

In sum, the very measures that were designed to protect public health systems during Covid19 in this case created a series of **cascading effects** that led to delays, high cost, and lower quality of PPE – the latter witnessed by the PPE-scandals in several European countries[1] .

[1] E.g., NL https://www.theguardian.com/world/2021/jun/08/dutch-to-investigate-business-trios-100m-facemask-deal, Germany https://www.aerzteblatt.de/nachrichten/126824/Urteile-zu-FFP2-Maskenbestellungen-Bund-soll-Millionen-zahlen

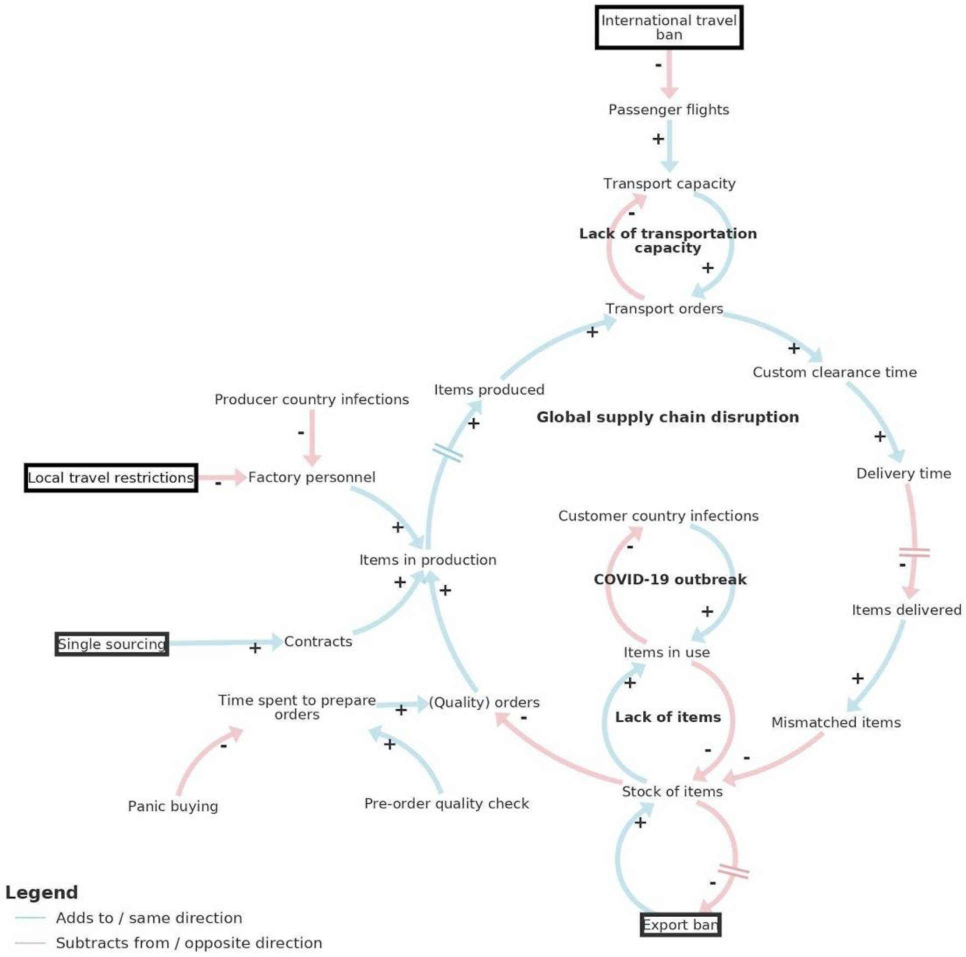

Figure 1 : Causal Loop diagram of PPE supply chain disruptions during COVID-19.

This example demonstrates that isolated approaches trying to manage only one aspect of the supply chain, always fall short, as they fail to address the many feedback loops. In addition, the time delays in detecting the rise of infections further delay response – even though several authors confirmed that *early* interventions were both most effective and better for the economy (Demürguc-Kunt et al., 2020). For COVID-19, data on positive virus tests and hospital or ICU admissions are only available weeks after the actual infections and only present a small portion of infections. This is not atypical for epidemics: in the West-African Ebola Outbreak in 2014, decision-makers indicated they knew "*too little, too late*" (Comes et al., 2015), resulting in delayed and ineffective response.

4. Measuring the economic impact of supply chain disruptions caused by the COVID-19 pandemic

This deliverable develops a methodology for capturing the economic impact of COVID-19 induced supply chain disruptions, the interdependencies between industries and sectors, and cascades through global supply chains.

4.1. The economic impact of the COVID-19 pandemic

The COVID-19 outbreak started in Wuhan, China on December 31, 2019. As COVID-19 cases increased rapidly and significantly, China imposed an unprecedented lockdown in Wuhan and other cities in Hubei on January 23, 2020. The Wuhan lockdown was stringent including mandatory closures of workplaces, schools, public transportation, cancellation of public events, and prohibition of internal movement and international travel. Similar lockdown and containment policies were quickly implemented in other Asian economies, e.g., Hong Kong on January 28; Macao on February 3; South Korea on February 24; and Japan on February 25.

In the European Union, Italy is the first country to implement workplace closure policies. Considering the rapidly growing COVID-19 cases, Italy closed all essential workplaces in the North starting on February 22. This closure was severe and lasted for 71 consecutive days. Similar closure restrictions were also imposed in other EU countries. However, stringency of closure restrictions differs substantially across countries. For example, Denmark, Finland, Greece, Hungary, and Sweden closed only selected workplaces (hereafter as "selective workplace closure"). In contrast, Ireland required closing of all essential workplaces (hereafter as "full workplace closure") in every quarter of 2020; whilst Italy and France implemented full workplace closures in three quarters of 2020.

Stringency of workplace closures also differs widely across time within a country. Out of all EU countries, Sweden has the least stringent workplace closure policies. On March 16, Sweden issued a recommendation for workplace closure (hereafter as "recommend workplace closure”). Recommend workplace closure is the least restrictive form of workplace closure because firms are not required to close production. This policy was sticky and lasted for 283 consecutive days in 2020 until Sweden implemented selective workplace closure policy on November 23. Nevertheless, Sweden has never implemented full workplace closure since the COVID-19 outbreak.

Workplace closures disrupted firm production in the affected region because it forced firms to shut down production. We use the Wuhan lockdown to demonstrate the damaging effects on supply chain relationships. Wuhan is a major manufacturing city producing nearly 10% of automobiles for domestic customers and supplying auto parts for overseas automobile companies. The lockdown led to shortages in auto parts and disrupted automobile production worldwide, especially for companies which rely heavily on imports from Wuhan. Shortages in auto parts forced Hyundai and Kia to temporarily shut down production in South Korea; as well as Nissan and Honda to scale back production in Japan. During the period from January 23 to March 20 when plants were mandated to shut down in the Hubei Province, share prices of Hyundai and Kia declined by 45%; whilst those of Nissan and Honda by 37% and 25%, respectively.

4.2. Research methodology

The COVID-19 pandemic has detrimental effects on world economic growth. In 2020, GDP growth dropped by 3.4 percentage points in the U.S. and by 6.4 percentage points in the European Union region (International Monetary Fund, 2022). However, these impacts differ widely across EU countries. In 2020, GDP growth dropped by 10.8% in Spain and by 8.9% in Italy, compared to a drop of 2.4 percentage points on average in the Nordic region including Denmark, Iceland, Norway, and Sweden.

Although declines in GDP growth differ markedly across countries and highly correlated with the severity of COVID-19 situations, it is unclear how the COVID-19 shock is amplified and propagated through the economy. For example, restrictive government intervention policies might force companies to shut down production, thereby lowering economic growth of a country. Alternatively, the COVID-19 shock might create spillover effects via firm-level linkages. Supply chain disruptions arising from domestic or foreign intervention policies might amplify the COVID-19 shock and propagate through a network of global supplier-customer relationships and ultimately lowering its economic activities. Therefore, policy makers are interested to understand the mechanism in which the COVID-19 shock is amplified and propagated through the economy.

Prior studies also investigated the relevance of sectoral linkages as a propagation mechanism which shocks hitting sectors create ripple effects and cause aggregate economy-wide fluctuation. However, extant studies offer mixed empirical evidence on its importance (Long and Plosser, 1983; Acemoglu et al., 2016). Additionally, the COVID-19 shock might propagate through a network of supplier-customer linkages. Empirically, whether firm-level linkages are an important propagation mechanism is unclear and an underexplored question because reliable data on firm-level linkages are typically unavailable.

This deliverable fills this void and uses FactSet Revere database to identify firm-level supplier-customer relationships. This database provides data for researchers to examine whether and to what extent sizable drops in economic growth are due to COVID-19-induced disruptions of supplier-customer linkages or other factors, e.g., government intervention policies.

To disentangle these competing mechanisms, we use accounting and stock data to quantify the economic impact of the COVID-19-induced disruptions of supplier-customer relationships. Our proxies of economic impact include a firm's sales growth and stock return which are widely used in the macroeconomics literature (e.g., Barrot and Sauvagnat, 2016; and Carvalho et al., 2021). Our research methodology is a difference-in-differences approach which compares sales growth and investment growth over time between suppliers affected by COVID-19-induced supply chain disruptions (treatment group) and suppliers that are not (control group).

For simplicity and without loss of generality, let us assume that firm XYZ has two competing suppliers, S1 and S2. Assume also that S1 and S2 do not have any economic ties other than their relationship with their customer (XYZ). We first analyse the response of XYZ when S1 is affected by a COVID-19-induced supply chain disruption. Next, we analyse the response of S2, a competing supplier which is not affected by the disruption. In each case, we contrast these effects with characteristics that capture the cost of substituting S1 with S2. In other words, common shocks which affect suppliers (S1 and S2) will be cancelled out in our difference-in-differences setting. This characteristic is desirable in our case because the COVID-19 pandemic is a common shock and led to a drop in demand for nearly every firm within a country. To pin down whether the decrease in economic activity is driven by COVID-19-induced supply chain disruptions (rather than domestic intervention policies), any common decrease in economic activity (which are unrelated to supply chain disruptions) will be cancelled out in our difference-in-differences setting.

4.2.1. Identifying COVID-19-induced supply chain disruptions through full workplace closures

We use full workplace closures as events to identify COVID-19-induced disruptions to suppliers' output. The full workplace closure event occurs if workplace closure requirement is imposed exogenously on a supplier where its headquarter is located. Precisely, full workplace closures refer to closing (or work from home) for all-but-essential workplaces, e.g., grocery stores, doctors.

Our definition of full workplace closures is motivated by two reasons. First, it is a binding constraint on suppliers and can significantly reduce suppliers' output. Full workplace closures disrupt suppliers' output in the restricted region as they force factories to shut down (or reduce) production. They also produce ripple effects and reduce output of suppliers' downstream customers and firms along the supply chain. Therefore, full workplace closures should raise suppliers' production cost. Second, as the pandemic is ongoing, less stringent form of workplace closures (e.g., recommend workplace closure or selective workplace closure) have remained effective in many countries since COVID-19 was declared as the pandemic in March 2020. In contrast, stringency of full workplace closures differs significantly across times within a country. Such across-time variations in stringency in workplace closures allow us to accurately detect the true effect of full workplace closures (induced by COVID-19 situations) on suppliers' output.

However, there are five major shortcomings of our identification strategy which can undermine the effectiveness of full workplace closures to serve as a binding constraint to reduce suppliers' output. First, suppliers have plants and establishments in regions outside their headquarters. Second, our measure of full workplace closures is primitive because it is measured on a quarterly basis. More specifically, full workplace closure occurs in a country during a quarter if full workplace closure restriction is imposed for only one day in the country during the given quarter. Third, due to data limitation, full workplace closures are measured at the country-level rather than at a finer level, e.g., state- or county-level. As stringency of full workplace closures differs markedly across regions within the same country and distribution of a firm's headquarter location vary widely across regions within a country, our measure may not capture the true effect of full workplace closures on suppliers' output.[2] Fourth, full workplace closure events could be anticipated by market participants such as suppliers, customers, and the stock market. Therefore, suppliers (or customers) might react before the full workplace closure event, e.g., stocking up on inventories and raw materials, or shifting supply-chain relationships to other regions in anticipation of such closures. Fifth, full workplace closures and other containment policies (e.g., social distancing, school closures, and internal movement restrictions) could be implemented simultaneously in a country. Therefore, the estimated effect on full workplace closures may be confounded by other containment policies.

These shortcomings are valid and introduce measurement errors to our measure of full workplace closures. However, these measurement errors are likely to bias our estimates towards zero, i.e., full

[2] https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/documents/briefingnote/wcms_767028.pdf

workplace closures have no material effect on a firm's output as well as output of its suppliers and customers along the supply chain.

Table 1 reports quarterly average percentage of EU countries with full workplace closures in a given quarter. Full workplace closures were widespread in the EU, but these averages differ significantly across quarters. Out of the 27 EU countries, 63% of them had full workplace closure policies in the first quarter of 2021 and nearly 50% of them had such restrictions in the first two quarters of 2020. In contrast, only 3.7% of these countries had full workplace closures during the summer, i.e., the third quarter of 2020 and 2021.

Table 2 reports quarterly average percentage of days with full workplace closures for EU countries with such closures in a given quarter. Full workplace closures refer to closing (or work from home) for all-but-essential workplaces for one day in a given quarter.

These averages differ moderately across time ranging from 14 days in the first quarter of 2020 to 44 days in the third quarter of 2020.[3] To investigate the severity of full workplace closure restrictions across EU countries, Figure 1 displays the percentage of days with full workplace closures for each EU country during the COVID-19 pandemic from January 1, 2020, to September 30, 2021. As indicated clearly in Figure 1, full workplace closures differ substantially across EU countries. Out of the 27 EU nations, three countries (including Finland, Romania, and Sweden) had never imposed full workplace closures during this period. In contrast, two countries (including Italy and Ireland) had implemented full workplace closures for about 40% of the time during the same time period.

Table 2: Quarterly average percentage of EU countries with full workplace closures

Time	Percentage of EU countries with workplace closures
2020Q1	48.15 %
2020Q2	51.85 %
2020Q3	3.70 %
2020Q4	40.74 %
2021Q1	62.96 %
2021Q2	40.74 %
2021Q3	3.70 %
2021Q4	22.22 %

The next table (Table 3) reports quarterly average percentage of days with full workplace closures in EU countries. The average is computed by dividing the sum of the total number of days with full workplace closures in a quarter by the number of EU countries with workplace closures in the same quarter. Full workplace closures refer to closing (or work from home) for all-but-essential workplaces for one day (or more) in a given quarter.

[3] These estimates are computed as follows: 14 days (=0.1547*91) and 44 days (=0.47.83*92).

Table 3: Quarterly average percentage of days with full workplace closures

Time	Number of countries with workplace closures	Mean	Std Dev.	Min	Max
2020Q1	13	15.47 %	9.87 %	2.20 %	42.86 %
2020Q2	14	34.93 %	12.97 %	14.29 %	56.04 %
2020Q3	1	47.83 %	n.a.	47.83 %	47.83 %
2020Q4	11	29.45 %	15.66 %	7.61 %	57.61 %
2021Q1	17	40.72 %	23.25 %	5.56 %	100.00 %
2021Q2	11	31.57 %	22.79 %	4.40 %	81.32 %
2021Q3	1	17.39 %	n.a.	17.39 %	17.39 %
2021Q4	6	38.59 %	25.28 %	8.70 %	84.78 %

Figure 2 shows the percentage of days with full workplace closures during the COVID-19 pandemic from January 1, 2020, to September 30, 2021. Darker colours indicate higher percentage of days with full workplace closures. Gray indicates that no data are available. Source: Oxford COVID-19 Government Response Tracker.

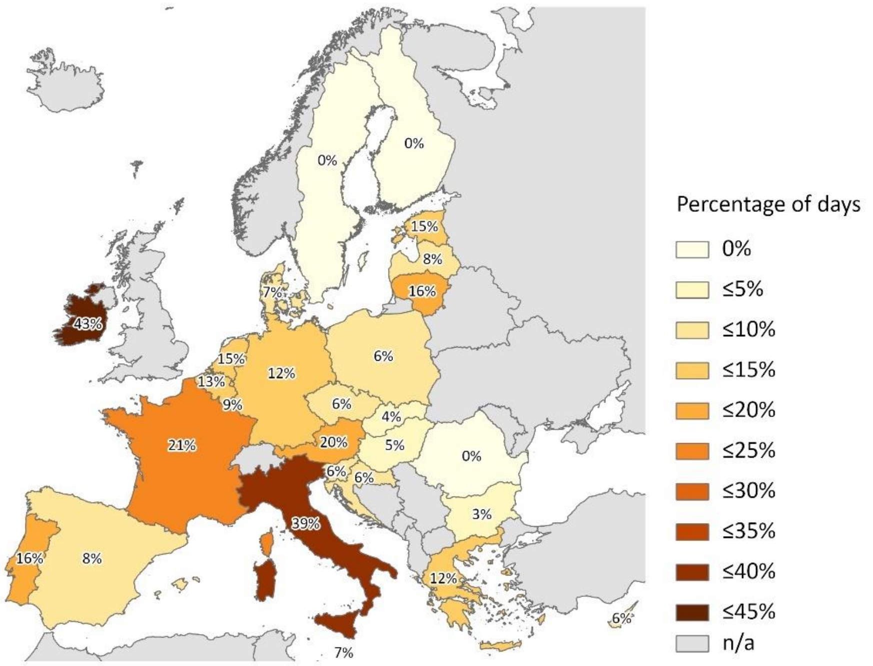

Figure 2: Full workplace closures during the COVID-19 pandemic in EU countries, 1/1/2020-30/9/2021

4.2.2. Sales growth

4.2.2.1. Baseline model

Equation (1) is the baseline model to estimate a firm's sales growth in response to the COVID-19 shock.

$$(1)\ \Delta Sales_{i,t-4,t} = \alpha_0 + \alpha_1 DisruptOneSupplier_{i,t-4} + \alpha_2 CovidDisruptFirm_{i,t-4} + X'\beta + \delta_i + \delta_{ct} + \delta_{jt} + \psi_t + \varepsilon_{it}$$

where *i*, *c*, *j,* and *t* are indexes for firm, country, industry, and time, respectively. We use sales growth as a proxy for the economic impact of the COVID-19 shock. $\Delta Sales_{i,t-4,t}$ is the sales growth between the current quarter and the same quarter in the previous year; $DisruptOneSupplier_{i,t-4}$ is a binary variable and takes the value of one if one of the firm's suppliers is affected by the COVID-19 shock in the same quarter of the previous year; $CovidDisruptFirm_{i,t-4}$ is a binary variable and takes the value of one if the firm is affected by the COVID-19 shock in the same quarter of the previous year; X′β is a vector of control variables including firm and country characteristics; and δ_i , δ_{ct}, δ_{jt} and ψ_t are fixed effects for firm, country-year, industry-year, and year-quarter, respectively.

Equation (1) estimates the effect of the COVID-19 shock to S1 on XYZ 's sales growth in a difference-in-differences framework at the firm level, where the treatment amounts to having one supplier affected by the COVID-19 shock, resulting in supply chain disruptions. As the COVID-19 pandemic is a meaningfully large and unfavourable shock, we expect that $\alpha_1 < 0$ and $\alpha_2 < 0$.

We use full workplace closures as a proxy for supply chain disruptions induced by the COVID-19 shock because such closures are triggered by the anticipated severity of COVID-19 situations. These restrictions have direct effects and disrupt a firm's output and its suppliers' output as they are mandates and force firms and their suppliers to shut down (or reduce) production if they are located in the affected regions. These restrictions might also have indirect effects and restrict movement of goods and people (including workers) in the affected regions which can severely disrupt production activities.

We use investment growth as another proxy of the economic impact of the COVID-19 chock to S1 on XYZ's output because a firm's inclination to invest is forward looking and has direct effects on the firm's output in the future. We measure investment growth ($\Delta CapExp_{i,t-4,t}$) by the capital expenditure growth between the current quarter and the same quarter in the previous year.

4.2.2.2. Control variables

To capture the severity of the COVID-19 shock, we use $Covidgr_{ct}$ to measure growth rate of COVID-19 confirmed cases in country *c* during the quarter. $Covidgr_{ct}$ is natural logarithm of one plus the cumulative total number of COVID-19 cases in quarter t minus natural logarithm of one plus the cumulative total number of COVID-19 cases in the previous quarter in country c. Alternatively, mortality rate can be used to capture the severity of the COVID-19 shock. However, growth rate of COVID-19 confirmed cases is a more desirable measure in our setting because full workplace closures are defined at a country level. Thus, they are triggered by concerns of nationwide (rather than regional) spread of the COVID-19 virus. In contrast, Basset (2020) and Iacobucci (2020) find that COVID-19 induced deaths are highly regional, which should demand a less stringent policy, e.g, selective workplace closures.

We also include lagged control variables for firm attributes including a firm's size, leverage, profitability, cash holdings, and number of suppliers. Firm size is measured by the natural logarithm of book value assets; leverage is by the ratio of long term debt to total assets (in percentage); profitability is by return on asset which is the ratio of operating income excluding depreciation expenses to total assets (in percentage); cash is by the natural logarithm of the ratio of total amount of cash and short term investments to total assets (in percentage); and number of suppliers is by the natural logarithm of one plus the number of suppliers. All control variables are measured in the same quarter of the previous year. As some variables are highly right-skewed with obvious univariate outliers, we winsorize sales growth, investment growth, supplier growth, firm size, leverage, cash, and profitability at the upper and bottom one percentile.

All regressions are estimated with fixed effects including firm, country-year, industry-year, and year-quarter using OLS with robust standard errors clustered at the firm level. The industry fixed effects are created based on the 48 industry classifications in Fama and French (1997).

4.2.2.3. Sample and Data

Our sample period includes 11 quarters spanning from the first quarter of 2019 to the third quarter of 2021. As the first COVID-19 case was confirmed by the World Health Organization on December 31, 2019, our sample period can be divided into two subsamples: Pre-pandemic sample which includes four quarters in 2019 and post-pandemic sample which includes seven quarters from the first quarter of 2020 to the third quarter of 2021.

Our sample is constructed from six databases. Data on supply chain relationships are obtained from FactSet Revere database which contains unique firm-level relationships collected from publicly disclosed documents such as periodic financial statements, corporate websites, investor presentations, and press releases. The Revere database contains a firm's network of essential relationships with suppliers, customers, competitors, and partners, regardless of whether the counterparty is a private or public company.

To demonstrate changes in a firm's supplier-customer relationships before and after the COVID-19 pandemic, Panel A (B) of Figure 2 presents Daimler AG's global supplier relationships before (after) the COVID-19 pandemic in 2019 (2021). Prior to the pandemic, Daimler AG had 46 unique global suppliers with headquarters located in 16 economies spread out across five continents. After the pandemic, the company had only 25 unique global suppliers with headquarters located in nine economies spread out across three continents.

Similarly, Panel A (B) of Figure 3 presents Daimler AG's global customer relationships before (after) the COVID-19 pandemic in 2019 (2021). Prior to the pandemic, Daimler AG had 53 unique global customers with headquarters located in 16 economies spread out across five continents. After the pandemic, the company had only 26 global customers with headquarters located in ten economies spread out across three continents concentrated mainly in the European Union region. The lines denote connections between the headquarters of Daimler AG and the location of each of its suppliers. Each node represents a supplier in the supply chain network. This figure also shows the percentage of days with required closing for all-but-essential workplaces during the COVID-19 pandemic from January 1, 2020, to September 30, 2021. Darker colours indicate higher percentage of days with full workplace closures.

Gray indicates that no data are available. Sources: FactSet Revere and Oxford COVID-19 Government Response Tracker.

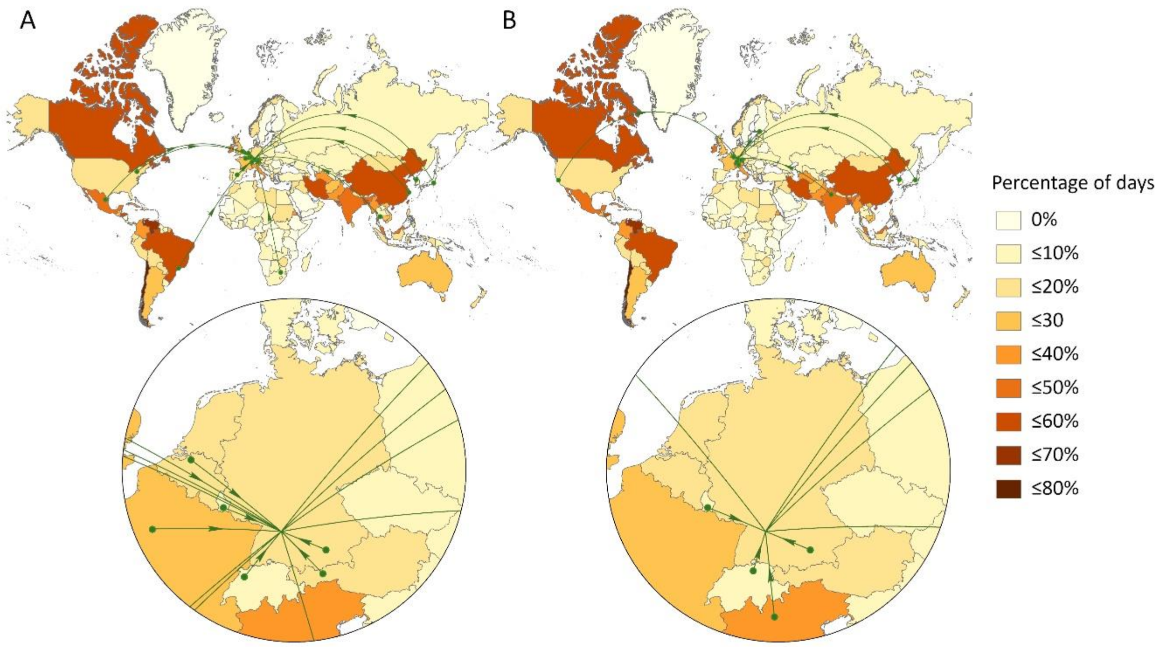

Figure 3: Global supplier relationships before and after the COVID-19 pandemic, Daimler AG

Data on COVID-19 from Johns Hopkins University Centre for Systems Science and Engineering (JHU-CSSE); data on government interventions from the Oxford COVID-19 Government Response Tracker (OxCGRT) project (Hale et al., 2021); stock market and financial data are obtained from CompuStat Global and CompuStat North America; and data on country characteristics from the World Bank's World Development Indicators.

4.2.2.4. Sample construction

Our initial sample starts from all publicly traded companies with a headquarter located in the European Union from the CompuStat Global database in the first quarter of 2019.[4] Companies are excluded if they have missing or incomplete data during our sample period. The final sample contains 18,804 firm-quarter observations containing 2,888 companies from 27 EU countries. Our sample selection is desirable because EU countries have very similar accounting rules, government regulations, information dissemination, and COVID-related intervention policies. These similarities offer a clean interpretation of our results. Additionally, EU countries are connected by land and the cost of substituting one supplier by another supplier in the EU region is deemed to be small.

Appendix 1 includes composition of our sample and Appendix 2 includes detailed descriptions of variables and data sources used in this study.

[4] Our sample excludes the United Kingdom due to Brexit.

4.2.2.5. Descriptive Statistics

Table 3 (above) reports summary statistics of major variables used in our study. In our sample, the average firm is large in size with small growth opportunities. The average firm (evaluated at the median) has a total asset of $0.81 billion euros, sales growth of 3.37%, and investment growth of -0.65%. The average firm is profitable with the median return on assets of 1.21%. For an average firm, it has 2.66 suppliers. However, a majority of our sample firms have no suppliers. Approximately 17% of our sample firms were affected by full workplace closure restrictions. Similarly, 17% of them have one supplier (or more) affected by full workplace closures. The distributions of our variables are highly right-skewed. Medians of our statistics are many times larger than their respective means except for firm profitability.

Table 4 presents quarterly average of sales growth and investment growth during our sample period. As the COVID-19 shock is unanticipated, changes in sales and investment growth in the first and second quarters of 2020 offer reliable estimates of the overall negative impact of the COVID-19 shock on firms' output. In the first quarter of 2020, sales growth declined by 3.44%, compared to a positive sales growth of 3.78% in the previous quarter. The decline in sales growth had widened to nearly 10% in the second quarter of 2020. The declines in propensity to invest were noticeable in the first two quarters of 2020. Investment growth dropped by 9.52% and 13.57% in the first quarter and the second quarter of 2020, respectively. These drops are meaningfully large and swift reflecting the severity of the COVID-19 situation and stringent government intervention policies during that period. Appendix 2 contains detailed descriptions of each variable reported in this table.

Table 4: Descriptive Statistics

	Mean	Std. Dev.	Pctl_1	Median	Pctl_99
Sales growth (t-4, t) (%)	10.12	53.51	-78.34	3.37	234.12
Investment growth (t-4, t) (%)	61.13	322.64	-94.46	-0.65	1649.34
Supplier growth (t-4, t) (%)	-2.17	39.38	-100.00	0	150.00
Total asset (t) ($billion)	14.85	144.16	0.01	0.81	226.77
Cash/asset (t) (%)	13.81	13.74	0.26	9.66	70.47
Debt/asset (t) (%)	21.51	16.77	0.15	18.56	81.62
ROA (t) (%)	0.74	3.89	-15.29	1.21	8.87
No. of suppliers (t)	2.82	8.44	0	0	39
No. of customers (t)	9.10	20.88	0	1	99
No. of COVID-19 cases (t) (mil.)	0.50	1.21	0	0	5.82
CovidDisruptFirm (t)	0.17	0.38	0	0	1
DisruptOneSupplier (t)	0.17	0.38	0	0	1
Obs.	18,804				

As our identification strategy is based on full workplace closures, we examine if there are any observable differences in firm characteristics between periods when workplaces are closed versus periods when workplaces are opened.

Table 5 provides medians of two groups based on full workplace closures. Expectedly, quarterly sales growth and investment growth declined significantly during the period when full workplace closures are enforced. Specifically, median sales growth declined by 3.22% during the period when firms were affected by full workplace closures. The drop in investment growth is even larger as median investment growth declined by 9.25% during the period when firms experienced full workplace closures. This table reports quarterly medians of sales growth and investment growth for sample EU companies. Sales growth (t-4, t) is the sales growth between the current quarter and the same quarter in the previous year, and investment growth (t-4, t) is the change in capital expenditure between the current quarter and the same quarter in the previous year.

Table 5: Quarterly average of sales growth and investment growth

Time	Obs.	Sales growth (t-4, t) (%)	Investment growth (t-4, t) (%)
2019Q1	1713	5.82	11.06
2019Q2	1739	4.57	10.16
2019Q3	1703	4.83	7.84
2019Q4	1754	3.81	6.39
2020Q1	1805	-3.44	-9.37
2020Q2	1828	-9.86	-13.52
2020Q3	1797	-3.26	-15.3
2020Q4	1839	-1.39	-15.65
2021Q1	1745	6.7	-3.23
2021Q2	1767	18.84	3.99
2021Q3	1114	15.01	9.74

Full workplace closures lower a firm's profit but raise its cash holdings and leverage. Again, these differences are meaningfully large and statistically significant. These results are expected due to the anticipated increase in production cost from COVID-19-induced disruptions or government restrictions. Firms conserve more cash for three possible reasons. First, firms increase precautionary cash holdings due to enhanced uncertainties of business environments related to the COVID-19 shock (Sánchez and Yurdagul, 2013). Second, conserving additional cash reduces bankruptcy risks as costs of raising external capital is high during crisis periods (Duchin et al., 2010). Third, firms withhold future investment plans due to uncertainties arising from the pandemic. Firm leverage is also higher when full workplaces are enforced but this effect appears to be mechanical because the increase is initiated by a decrease in firm size, i.e., a reduction in total asset.

4.2.2.6. Regression Analysis

Table 6 presents medians of major variables of two groups based on workplace closure. The first group includes firm-quarter observations which were affected by full workplace closures in a given quarter in column (1) and the second group includes those which were not affected by full workplace closures in a given quarter in column (2). Differences in their medians are reported in column (3). The numbers in parentheses of columns (1) and (2) are standard deviations and numbers in brackers of column (3) are *p*-value. Appendix 2 contains the descriptions of all variables reported in this table. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

In Table 6, column (1) reports results from panel regression of a firm's sales growth (relative to the same quarter in the previous year) on five dummy variables indicating whether the firm is affected by full workplace closures in the current quarter and the previous four quarters. Our results indicate that sales growth drops significantly when the firm is affected by full workplace closures in the current quarter, quarter (t-2), and quarter (t-4). The estimate of CovidDisruptFirm(t) indicates that sales growth decreases by 3.51 percentage points when the firm is affected by full workplace closures in the current quarter. Given the sample mean of 10.12%, this drop is large and has economic significance. However, the estimate of CovidDisruptFirm(t-1) indicates that sales growth increases by 3 percentage points when the firm is affected by full workplace closures in the previous quarter, i.e., quarter (t-1). These results are large and unexpected and may suggest firms have inventories and existing production capabilities to react swiftly and strongly to unmet orders due to workplace closures in the previous quarter. This conjecture is reasonable because the duration of full workplace closures is short and usually less than 30 days in a given quarter.

Column (2) reports results from panel regression of a firm's sales growth on five dummy variables indicating whether one of the firm's suppliers is affected by full workplace closures in the current quarter and the previous four quarters. Our results indicate that sales growth remains unchanged when one of the firm's suppliers is affected by workplace closures.

Column (3) reports results from panel regression of a firm's sales growth on a series of dummy variables indicating whether the firm and one of the firm's suppliers are affected by full workplace closures. Our results in column (3) are qualitatively similar to those in columns (1) and (2). Overall, our results indicate that the economic impact on COVID-19 induced supply chain disruptions on a firm's sales growth is trivial. However, full workplace closures have a direct economic impact on a firm's output by reducing its sales growth.

Table 6 : Descriptive statistics by full workplace closures

	(1) Full workplace closures	(2) No full workplace closures	(3) Diff. (1) – (2)
Sales Growth (t-4,t) (%)	0.53	3.75	-3.22***
	(59.51)	(52.18)	[0.00]
CapExp Growth (t-4,t) (%)	-8.44	0.83	-9.25***
	(345.24)	(317.72)	[0.00]

Total asset (t) ($billion)	0.85	0.80	0.06
	(52.44)	(156.63)	[0.23]
Cash/asset (t) (%)	12.80	9.08	3.72***
	(14.97)	(13.38)	[0.00]
Debt/Asset (t) (%)	20.27	18.19	2.08***
	(16.86)	(16.73)	[0.00]
ROA (t) (%)	0.98	1.26	-0.28***
	(3.91)	(3.89)	[0.00]
No. of COVID-19 cases (t) (mil.)	0.80	0.00	0.80***
	(1.90)	(0.77)	[0.00]
Observations	3,240	15,564	

We perform the same set of panel regressions of a firm's investment growth (relative to the same quarter in the previous year) and report the results in Table 7. Our results in column (3) indicate that investment growth drops slightly when the firm is affected by full workplace closures in the current quarter and the previous three quarters. However, none of these estimates are statistically significant. In contrast, the estimate of DisruptOneSupplier(t-3) indicates that investment growth increases by 17.92 percentage points when one of the firm's suppliers is affected by full workplace closures in quarter (t-3). Given the sample mean of 61%, this increase is large and has economic significance. This implies that firms increase investment growth in response to COVID-19 induced supply chain disruptions.

This table presents estimates from panel regressions of a firm's sales growth relative to the same quarter in the previous year on a dummy indicated whether the firm and its suppliers is affected by full workplace closures in the current and each of the previous four quarters. All regressions include dummies for firm, year-quarter, country-year, and industry-year fixed effects. The industry fixed effects are based on 48 Fama-French industry classification. Standard errors presented in parentheses are clustered at the firm level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 7: Sales Growth

Variables	(1)	(2)	(3)
CovidDisruptFirm (t)	-3.512**		-3.655**
	(1.600)		(1.674)
CovidDisruptFirm (t-1)	3.010*		3.647*
	(1.825)		(1.904)
CovidDisruptFirm (t-2)	-4.183**		-4.787***
	(1.631)		(1.681)

CovidDisruptFirm (t-3)	1.443		1.130
	(2.081)		(2.042)
CovidDisruptFirm (t-4)	-6.577**		-5.893*
	(3.203)		(3.192)
DisruptOneSupplier (t)		-0.499	0.160
		(1.278)	(1.330)
DisruptOneSupplier (t-1)		-1.549	-2.193
		(1.712)	(1.778)
DisruptOneSupplier (t-2)		1.086	2.238
		(1.567)	(1.602)
DisruptOneSupplier (t-3)		1.210	1.500
		(1.670)	(1.634)
DisruptOneSupplier (t-4)		-3.271	-2.138
		(2.112)	(2.091)
COVID-19 growth rate (t)	0.269	0.171	0.261
	(0.250)	(0.242)	(0.248)
Log(1 + No. of suppliers) (t-4)	2.408**	2.449**	2.406**
	(0.980)	(1.008)	(1.013)
Log(total asset) (t-4)	-36.410***	-36.325***	-36.464***
	(6.549)	(6.546)	(6.547)
Log(cash/asset) (t-4)	1.527	1.554	1.520
	(1.236)	(1.235)	(1.237)
Debt/asset (t-4)	0.191**	0.190**	0.192**
	(0.094)	(0.093)	(0.093)
ROA (t-4)	-3.128***	-3.126***	-3.124***
	(0.584)	(0.584)	(0.583)
Observations	18,804	18,804	18,804
R-squared	0.146	0.145	0.146
Firm FE	Yes	Yes	Yes
Year-quarter FE	Yes	Yes	Yes
Country-year FE	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes

4.3. Cascades through supply chains

To investigate the cascading effects of COVID-19 induced supply chain disruptions, we modify Equation (1) by including not just the firm's suppliers but also its consumers along the supply chain. Equation (2) is the baseline model to capture the cascading effects as follows:

$$(2)\ \Delta Sales_{i,t-4,t} = \gamma_0 + \gamma_1 DisruptOneCustomer_{i,t-4} + \gamma_2 CovidDisruptFirm_{i,t-4} + \gamma_3 DisruptOneSupplier_{i,t-4} + X'\beta + \delta_i + \delta_{ct} + \delta_{jt} + \psi_t + \varepsilon_{it}$$

where $DisruptOneCustomer_{i,t-4}$ is a binary variable and takes the value of one if one of the firm's customers is affected by the COVID-19 shock in the same quarter of the previous year. $DisruptOneSupplier_{i,t-4}$ is a binary variable and takes the value of one if one of the firm's suppliers is affected by the COVID-19 shock in the same quarter of the previous year; $CovidDisruptFirm_{i,t-4}$ is a binary variable and takes the value of one if the firm is affected by the COVID-19 shock in the same quarter of the previous year; $X'\beta$ is a vector of control variables including firm and country characteristics; and δ_i, δ_{ct}, δ_{jt} and ψ_t are fixed effects for firm, country-year, industry-year, and year-quarter, respectively.

For simplicity and without loss of generality, we use a 2x2 example involving two suppliers and two customers in a supply chain to illustrate our setting. Suppose XYZ is an intermediate firm and has two downstream customers (C1 and C2) and two upstream suppliers (S1 and S2). Assume also that C1 and C2 do not have any economic ties other than their relationship with XYZ, the intermediate firm. We first analyse the response of XYZ when C1 is affected by a COVID-19 induced supply chain disruption. Next, we analyse the response of C2, another customer which is not affected by the disruption. In each case, we contrast these effects with characteristics that capture the cost of substituting C1 with C2. Concurrently, we also analyse the response of XYZ when S1 is affected by a COVID-19 induced supply chain disruption. Next, we analyse the response of S2, another supplier which is not affected by the disruption.

Equation (2) captures the cascading effect along the supply chain arising from disruptions to an upstream supplier or a downstream customer.

The main variable of interest in Equation (2) is $DisruptOneCustomer_{i,t-4}$. This variable captures the effect of the COVID-19 shock to one of the firm's customers (i.e., C1) on the firm's (i.e., XYZ) sales growth in a difference-in-differences framework at the firm level, where the treatment amounts to having at least one of the firm's customers is affected by the COVID-19 shock. As the COVID-19 shock is large and unfavourable, we expect that $\gamma_1 < 0$.

4.3.1.1. Regression Analysis

Next, Table 8 presents estimates from panel regressions of a firm's investment growth relative to the same quarter in the previous year on a dummy indicated whether the firm and its suppliers is affected by full workplace closures in the current and each of the previous four quarters. All regressions include dummies for firm, year-quarter, country-year, and industry-year fixed effects. The industry fixed effects are based on 48 Fama-French industry classification. Standard errors presented in parentheses are clustered at the firm level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 8: Investment Growth

Variables	(1)	(2)	(3)
CovidDisruptFirm (t)	2.592		-1.045
	(10.505)		(10.911)
CovidDisruptFirm (t-1)	2.586		-0.211
	(11.446)		(11.165)
CovidDisruptFirm (t-2)	3.334		-0.508
	(8.888)		(9.599)
CovidDisruptFirm (t-3)	-5.386		-10.871
	(8.002)		(8.348)
CovidDisruptFirm (t-4)	26.587		27.084
	(17.437)		(17.770)
DisruptOneSupplier (t)		0.158	0.384
		(8.831)	(9.255)
DisruptOneSupplier (t-1)		10.440	10.047
		(8.930)	(8.541)
DisruptOneSupplier (t-2)		8.624	8.689
		(8.450)	(9.089)
DisruptOneSupplier (t-3)		15.444*	17.918**
		(8.346)	(8.772)
DisruptOneSupplier (t-4)		-0.864	-6.357
		(15.925)	(16.198)
COVID-19 growth rate (t)	-1.887	-1.695	-1.564
	(1.957)	(1.983)	(1.977)
Log(1 + No. of suppliers) (t-4)	2.764	-0.416	-0.381
	(5.160)	(5.491)	(5.456)
Log(total asset) (t-4)	-134.717***	-135.684***	-135.632***
	(35.498)	(35.569)	(35.530)
Log(cash/asset) (t-4)	15.959**	16.200**	16.157**
	(7.268)	(7.249)	(7.259)
Debt/asset (t-4)	0.239	0.244	0.255
	(0.513)	(0.514)	(0.513)

ROA (t-4)	1.057	1.154	1.178
	(2.013)	(2.006)	(2.006)
Observations	18,777	18,777	18,777
R-squared	0.023	0.024	0.024
Firm FE	Yes	Yes	Yes
Year-quarter FE	Yes	Yes	Yes
Country-year FE	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes

In Table 8, column (1) reports results from panel regression of a firm's sales growth (relative to the same quarter in the previous year) on five dummy variables indicating whether one of the firm's customers is affected by full workplace closures in the current quarter and the previous four quarters. Our results indicate that sales growth drops when one of the firm's customers is affected by full workplace closures. The drop is noticeable in quarter (t-4). The estimate of *DisruptOneCustomer(t-4)* indicates that sales growth decreases by 4.47 percentage points when the firm's customer is affected by full workplace closures in the same quarter of the previous year. This drop is large and has economic significance.

Column (4) reports results from panel regression of a firm's sales growth on a series of dummy variables controlling for whether the firm, the firm's customers, or the firm's suppliers are affected by full workplace closures in the current quarter and the previous four quarters. Overall, our results in column (4) are qualitatively similar to those in column (1) except that the point estimate of *DisruptOneCustomer(t-4)* is not statistically significant. However, this point estimate at -3.39% percentage points is large and has economic significance given the sample mean is only 10%.

Our results in column (4) of the same Table are qualitatively similar to those in column (3) of Table 6. Overall, sales growth is not affected by whether one of the firm's suppliers is affected by full workplace closures. However, sales growth drops when the firm is affected by full workplace closures.

We also perform the same set of panel regressions of a firm's investment growth and report the results in Table 9. The results in column (4) indicate that investment growth increases significantly when the firm's customers is affected by full workplace closures in the current quarter. The estimate of *DisruptOneCustomer(t)* indicates that investment growth increases by 17.43 percentage points when one of the firm's customers is affected by full workplace closures in the current quarter. This increase is large and has economic significance. This result is also surprising because investment growth is expected to drop (rather than to rise). Future demand of goods and services from the firm's customers is expected to drop because full workplace closures (if binding) should force customer firms to shut down production. Therefore, firms should curtail investment expenses in anticipation of such a decline in future demand from their customers.

This table presents estimates from panel regressions of a firm's sales growth relative to the same quarter in the previous year on a dummy indicated whether the firm, its customers, or its suppliers is affected by full workplace closures in the current and each of the previous four quarters. All regressions include control variables in Table 6 and also the number of the firm's customers in the same quarter of the previous year, namely Log(1+no. of customers) (t-4). In addition, they also include dummies for firm, year-quarter, country-year, and industry-year fixed effects. The industry fixed effects are based on 48 Fama-French industry classification. Standard errors presented in parentheses are clustered at the firm level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 9: Sales growth with cascading effects

Variables	(1)	(2)	(3)	(4)
DisruptOneCustomer (t)	-1.296			-0.927
	(1.513)			(1.501)
DisruptOneCustomer (t-1)	-0.835			-1.285
	(1.478)			(1.531)
DisruptOneCustomer (t-2)	-1.015			-0.609
	(1.489)			(1.537)
DisruptOneCustomer (t-3)	0.173			0.301
	(1.648)			(1.795)
DisruptOneCustomer (t-4)	-4.473**			-3.385
	(2.170)			(2.252)
CovidDisruptFirm (t)		-3.512**		-2.856*
		(1.600)		(1.693)
CovidDisruptFirm (t-1)		3.010*		4.536**
		(1.825)		(2.088)
CovidDisruptFirm (t-2)		-4.183**		-4.166**
		(1.631)		(1.786)
CovidDisruptFirm (t-3)		1.443		1.483
		(2.081)		(2.261)
CovidDisruptFirm (t-4)		-6.577**		-4.091
		(3.203)		(3.332)
DisruptOneSupplier (t)			-0.499	0.275
			(1.278)	(1.337)
DisruptOneSupplier (t-1)			-1.549	-2.089
			(1.712)	(1.773)
DisruptOneSupplier (t-2)			1.086	2.216
			(1.567)	(1.571)
DisruptOneSupplier (t-3)			1.210	1.337
			(1.670)	(1.627)
DisruptOneSupplier (t-4)			-3.271	-1.874

			(2.112)	(2.073)
Observations	18,804	18,804	18,804	18,804
R-squared	0.145	0.146	0.145	0.146
Control variables	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year-quarter FE	Yes	Yes	Yes	Yes
Country-year FE	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes

Our results in column (4) of this Table are qualitatively similar to those in column (3) of Table 7. In particular, investment growth increases substantially when one of the firm's suppliers is affected by full workplace closures in quarter (t-3). In addition, investment growth appears to drop when the firm is affected by full workplace closures in the current quarter and the prior three quarters. However, investment growth increases significantly when the firm is affected by full workplace closures in the same quarter of the previous year.

4.4. Stock market reaction to workplace closure announcements

We also use an event study approach to measure the economic impact of full workplace closures. This approach relies on changes in stock prices to measure the economic impact of full workplace closures on firm values. Prior studies demonstrate that stock markets are informationally efficient (Fama, 1970). Stock prices aggregate market information and reflect secret or private information, e.g., fuel material used to manufacture hydrogen bomb in the early 1950s (Newhard, 2014); the company that manufactured faulty component and led to the crash of the space shuttle Challenge in 1986 (Maloney and Mulherin, 2003); whether airline crashes are caused by pilot error from 1964-1987 (Mulherin and Maloney, 1989); and political uncertainties on prospect of cross-border mergers and acquisitions (Wan and Wong, 2009) .

Stock prices reflect firms' expected future cash flows. Any material events affect stock prices because they revise the market expectations on firms' anticipated future cash flows. Changes in stock prices are forward looking, allowing us to estimate the anticipated impacts of full workplace closures on a firm's future values.

Our setting is appropriate because full workplace closures are material events as they have direct and material effects on firm output. In addition, full workplace closures, especially when it is firstly implemented in a country is likely to be an unanticipated event. Stock market reaction can accurately reflect the true economic impact of such disruptions on firms' future cash flows. Last, other measures of economic impact are likely to contain substantial noises due to multiple and concurrent government policies during the COVID-19 shock.

Our sample includes all publicly listed companies with headquarters in the EU and available from the Compustat Global databases. The event date is the first day when the stock market can react to announcements of the first full workplace closure event. For example, Italy implemented the first full workplace closing on February 22, 2022, which is a Saturday. Therefore, the event day is the following

Monday on February 24, 2022, or the first trading day when Italian shares can react to the closure news. For each firm, we use daily stock returns to measure the economic impact of full workplace closures.

Prior studies indicate that information on material events could be anticipated or leaked out prior to official announcements (Grinblatt and Wan, 2020). In addition, new information might not be fully incorporated on announcement days due to trading frictions. To capture the full impact of workplace closure events, we report stock returns in three event windows as follows: 1-day event window which is the event day, or [0] ; 2-day event window which starts from one day before the event day to the event day, or [-1,0], and 3-day event window which starts from one day before the event day to one day following the event day, or [-1,1].

Specifically, the 1-day average stock return is computed by averaging daily stock returns over all firms in a country on the event given day as follows:

(2) $\mathrm{AR}_{\mathrm{c,t}} = \frac{1}{N}\sum_{i=1}^{N} R_{i,\mathrm{c},t}$,

where $R_{i,c,t}$ is the daily return of firm i in country c on the announcement day t.

The 2-day cumulative average stock return is computed by first averaging daily stock returns over all firms in a country on the event day ($AR_{c,t}$) and on the day prior to the event day ($AR_{c,t-1}$). Next, we sum these two returns to obtain the cumulative 2-day average stock return as follows:

(2') 2-day $CAR_{c,t} = AR_{c,t} + AR_{c,t-1}$

The cumulative 3-day average stock return is computed analogously.

4.4.1.1. Empirical results

Table 10 reports stock market reaction to the first full workplace closure event in each EU country. Overall, stock prices reacted negatively to announcements of full workplace closure events. The across-country mean stock return is -0.73% on the event day. This estimate is statistically significant at the 10% level, suggesting that stock market reacted negatively upon full workplace closure announcements. As government policies could be pre-announced or leaked out, the average stock return on the event day could underestimate the fair economic impact of workplace closing on firm value. In Germany, full workplace closure was announced on December 13, 2020, which is three days before the actual implementation day.[5] Consistently with our expectations, the cumulative 2-day average stock return dropped by a larger magnitude at 0.91%.

This table presents estimates from panel regressions of a firm's investment growth relative to the same quarter in the previous year on a dummy indicated whether the firm, its customers, or its suppliers is

[5] https://www.euronews.com/2020/12/13/germany-announces-covid-19-lockdown-with-businesses-and-schools-closed-through-january-10.

affected by full workplace closures in the current and each of the previous four quarters. All regressions include control variables in Table 6 and also the number of the firm's customers in the same quarter of the previous year, namely Log(1+no. of customers) (t-4). In addition, they also include dummies for firm, year-quarter, country-year, and industry-year fixed effects. The industry fixed effects are based on 48 Fama-French industry classification. Standard errors presented in parentheses are clustered at the firm level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 10: Investment Growth with cascading effects

Variables	(1)	(2)	(3)	(4)
DisruptOneCustomer (t)	16.732*			17.435*
	(9.127)			(9.271)
DisruptOneCustomer (t-1)	5.008			5.271
	(7.557)			(8.373)
DisruptOneCustomer (t-2)	-2.697			-4.086
	(8.542)			(9.641)
DisruptOneCustomer (t-3)	0.544			0.169
	(8.026)			(8.898)
DisruptOneCustomer (t-4)	-5.871			-13.024
	(15.550)			(17.122)
CovidDisruptFirm (t)		2.592		-6.252
		(10.505)		(11.235)
CovidDisruptFirm (t-1)		2.586		-3.041
		(11.446)		(11.938)
CovidDisruptFirm (t-2)		3.334		-1.437
		(8.888)		(10.562)
CovidDisruptFirm (t-3)		-5.386		-12.252
		(8.002)		(9.368)
CovidDisruptFirm (t-4)		26.587		32.552*
		(17.437)		(18.669)
DisruptOneSupplier (t)			0.158	-0.486
			(8.831)	(9.310)
DisruptOneSupplier (t-1)			10.440	9.183
			(8.930)	(8.630)
DisruptOneSupplier (t-2)			8.624	9.540
			(8.450)	(9.148)
DisruptOneSupplier (t-3)			15.444*	17.901**

			(8.346)	(8.734)
DisruptOneSupplier (t-4)			-0.864	-4.560
			(15.925)	(16.604)
Observations	18,777	18,777	18,777	18,777
R-squared	0.024	0.023	0.024	0.024
Control variables	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year-quarter FE	Yes	Yes	Yes	Yes
Country-year FE	Yes	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes	Yes

The negative stock market reaction differs significantly across countries and meaningfully larger in countries which were among the first group of countries to implement full workplace closures. Italy is the first country to implement full workplace closure in the EU and Italian stocks declined by an average of 5.35% on the event day. Austria is the second EU country to implement such a restriction and their stocks dropped by an average of 5.71% on the event day. In sharp contrast, countries which were among the last group to implement such closures experienced a positive stock market reaction on the event day. For example, Poland is the last EU country to implement full workplace closure on March 29, 2021, more than one year since COVID-19 was declared as a pandemic. Polish stocks experienced a mild increase in value, or an average of 0.38% on the event day. The positive stock market reaction is not surprising because stock market could have fully anticipated the closure news given many countries have already adopted such policies. In addition, the positive stock market reaction could reflect the actual workplace closure restriction is less stringent than the anticipated closure, e.g., shorter in duration of the closure.

As our sample event day on workplace closing spans over one year, the stock market could have well anticipated the workplace closing event. To examine if full workplace closure events are anticipated, we modify our definition of workplace closure such that it refers to the first trading day when any types of workplace closures are implemented in a country. The first workplace closure is usually a mild restriction. To illustrate, many governments first issued recommendation (not mandates) on workplace closing in response to the COVID-19 shock. When the COVID-19 situation deteriorated, more stringent workplace closing restrictions are imposed, e.g., selective workplace closure or full workplace closure.

Table 11 reports stock market reaction to announcements of the first workplace closure in each EU country. Congruent with our expectations, stock prices reacted very negatively to announcements of the first workplace closures. The across-country mean stock return is -2.38% on the event day. The across-country cumulative 2-day average stock return dropped by a larger magnitude at 3.38%. These results are large and have economic and statistically significant. They point to the same conclusion that full workplace closures are anticipated (but partially) by the market. Therefore, our estimates are likely to be biased and underestimate the true effect of full workplace closures on firm value because firms could have anticipated full workplace closure events and reacts in advance (e.g., stock up inventories and raw materials) before governments implement such restrictions.

This table reports cumulative average stock returns on announcement days of the first full workplace closures for each EU country. Full workplace closure is the first day when a country requires closing (or work from home) of all-but-essential workplaces. The cumulative 1-day, 2-day, and 3-day average returns are average stock return on the event day (day t), cumulative average return around the event day from (day t-1 to day t), and cumulative average return around the event day from (day t-1 to day t+1), respectively. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 11: Cumulative average stock returns around first full workplace closures

		Cumulative average stock returns (%)			
Country	Event day - workplace closure	Obs.	1-day [0]	2-day [-1,0]	3-day [-1,+1]
Italy	2/24/2020	377	-5.35	-6.52	-6.18
Austria	3/16/2020	86	-5.71	-6.92	-7.63
Czech Republic	3/16/2020	18	-2.19	-1.80	-2.53
Lithuania	3/16/2020	34	-4.75	-3.16	-2.82
Luxembourg	3/16/2020	171	-2.83	-2.54	-2.67
France	3/17/2020	820	1.28	-5.99	-6.80
Belgium	3/18/2020	148	0.51	-1.79	-0.80
Portugal	3/19/2020	46	0.44	1.60	5.26
Croatia	3/20/2020	118	0.69	-0.72	-2.07
Slovenia	3/20/2020	35	0.54	-0.26	-1.38
Estonia	3/27/2020	20	-0.84	-0.85	-1.86
Ireland	3/27/2020	243	-2.11	-0.50	-0.15
Spain	3/30/2020	258	-0.34	-0.67	0.30
Cyprus	4/16/2020	83	0.43	0.70	0.71
Slovak Republic	10/22/2020	16	0.31	0.24	-0.17
Netherlands	11/4/2020	162	0.86	2.28	3.14
Bulgaria	12/15/2020	160	0.16	-0.06	0.63
Germany	12/16/2020	840	0.47	1.06	2.20
Latvia	12/21/2020	21	-1.58	0.41	5.45
Denmark	1/4/2021	190	2.06	2.06	2.54
Greece	3/1/2021	182	0.80	0.61	1.38
Hungary	3/8/2021	45	-0.87	-0.17	-0.51
Malta	3/11/2021	32	0.01	-0.15	-0.02
Poland	3/29/2021	818	0.38	1.41	1.43

	Mean	24	-0.73	-0.91	-0.52
	Standard Error	24	0.43	0.52	0.68
	T-statistics	24	-1.71*	-1.75*	-0.77

* Finland, Romania, and Sweden are excluded in the table because full workplace closures were not implemented during the COVID-19 pandemic.

4.5. Changes in supply chain relationships

To investigate whether the COVID-19 pandemic affects a firm's supply chain relationships, we modify Equation (1) to examine a firm's supplier growth in response to the COVID-19 shock.

Equation (3) is the baseline model to estimate a firm's supplier growth in response to COVID-19 induced supply chain disruptions.

$$(3)\ \Delta Suppliers_{i,t-4,t} = \phi_0 + \phi_1 DisruptOneSupplier_{i,t-4} + \phi_2 CovidDisruptFirm_{i,t-4} + X'\beta + \delta_i + \delta_{ct} + \delta_{jt} + \psi_t + \varepsilon_{it}$$

where *i*, *c*, *j,* and *t* are indexes for firm, country, industry, and time, respectively. We use supplier growth to estimate the economic impact of the COVID-19 shock. $\Delta Suppliers_{i,t-4,t}$ is the supplier growth between the current period and the same quarter in the previous year. Supplier growth is defined as zero if a firm has no supplier in quarter (t-4). To prevent this classification from introducing selection bias in our results, we include *Dummy for no supplier (t-4)* in the regression. This variable is a binary variable which takes the value of one if one of the firms has no supplier in quarter (t-4). $DisruptOneSupplier_{i,t-4}$ is a binary variable and takes the value of one if one of the firm's suppliers is affected by full workplace closures in the same quarter of the previous year; $CovidDisruptFirm_{i,t-4}$ is a binary variable and takes the value of one if the firm is affected by full workplace closures in the same quarter of the previous year; $X'\beta$ is a vector of control variables including firm and country characteristics. The δ_i , δ_{ct}, δ_{jt} and ψ_t are fixed effects for firm, country-year, industry-year, and year-quarter, respectively.

4.5.1.1. Regression Analysis

Table 12 reports cumulative average stock returns on announcement days of the first workplace closure for each EU country. The first workplace closure is the first day when a country imposes any restrictions on workplace closures including recommend workplace closure, selective workplace closure, or full workplace closure. The cumulative 1-day, 2-day, and 3-day average returns are average stock return on the event day (day t), cumulative average return around the event day from (day t-1 to day t), and cumulative average return around the event day from (day t-1 to day t+1), respectively. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

In Table 12, column (1) reports results from panel regression of a firm's supplier growth on five dummy variables indicating whether one of the firm's suppliers is affected by full workplace closures in the current quarter and the previous four quarters. Our results indicate that supplier growth increases immediately when one of the firm's suppliers is affected by full workplace closures in the current quarter. The point estimate of *DisruptOneSupplier(t)* indicates that supplier growth increases by 10 percentage points when the firm's suppliers is affected by full workplace closures in the current quarter. Given the sample mean of -2.17%, this increase is huge and has economic significance. This implies that firms reacted very quickly by adding new suppliers to mitigate risk from full workplace closures on supply chain disruptions.

Table 12: Cumulative average stock returns around first workplace closures

		Cumulative average stock returns (%)			
Country	Event day - First workplace closure	Obs.	1-day [0]	2-day [-1,0]	3-day [-1,+1]
Italy	2/24/2020	377	-5.35	-6.52	-6.18
Spain	3/9/2020	259	-3.99	-5.48	-5.89
Denmark	3/11/2020	178	-1.89	-2.49	-10.60
Austria	3/12/2020	86	20.62	18.99	18.14
Finland	3/12/2020	161	-10.33	-12.04	-11.16
Greece	3/12/2020	186	-5.42	-6.43	-5.93
Ireland	3/12/2020	243	-6.74	-7.27	-7.17
Luxembourg	3/12/2020	171	-4.78	-5.21	-4.97
Netherlands	3/12/2020	165	-8.71	-10.19	-9.96
Portugal	3/12/2020	46	-6.09	-6.38	-6.58
Romania	3/12/2020	89	-5.17	-8.13	-7.05
Belgium	3/13/2020	148	0.46	-6.07	-11.34
Bulgaria	3/13/2020	158	-1.20	-3.85	-5.36
Czech Republic	3/13/2020	18	0.41	1.84	-0.22
Latvia	3/13/2020	21	3.35	-3.00	-8.68
Malta	3/13/2020	31	-2.49	-5.78	-7.59
Slovak Republic	3/13/2020	17	-1.54	-2.03	-0.27
Croatia	3/16/2020	122	-3.47	-2.69	-2.91
Poland	3/16/2020	823	0.28	2.16	5.30
Cyprus	3/16/2020	83	-3.22	-1.68	-2.03
Hungary	3/16/2020	45	-8.71	-6.24	-6.05
Lithuania	3/16/2020	34	-4.75	-3.16	-2.82
Sweden	3/16/2020	800	-6.09	-4.07	-4.36
France	3/17/2020	820	1.28	-5.99	-6.80
Slovenia	3/20/2020	35	0.54	-0.26	-1.38
Germany	3/23/2020	846	-0.46	1.43	6.34
Estonia	3/27/2020	20	-0.84	-0.85	-1.86

	Mean	27	-2.38	-3.38	-3.98
	Standard Error	27	1.10	1.09	1.19
	T-statistics	27	-2.17**	-3.12***	-3.33***

However, our results also indicate that supplier growth drops significantly when one of the firm's suppliers is affected by full workplace closures in quarter (t-3). The point estimate of *DisruptOneSupplier(t)* indicates that supplier growth increases by 4.3 percentage points when the firm's suppliers is affected by full workplace closures in quarter (t-3). Again, this increase is large and has economic significance. As contract renegotiation is prohibitive and the COVID-19 shock affects the relative cost of using different suppliers, firms establish new supply chain relationships immediately following full workplace closures but end some pre-existing supplier chain relationships when their supplier contracts expire (Klein et al., 1978, Klein, 1996).

Column (2) reports results from panel regression of a firm's supplier growth on five dummy variables indicating whether the firm is affected by full workplace closures in the current quarter and the previous four quarters. Our results indicate that supplier growth remains materially similar regardless of whether the firm is affected by full workplace closures or not.

4.6. COVID-19-related goods

The COVID-19 pandemic triggered massive shortages of critical COVID-19 related goods worldwide such as surgical masks, N95 respirators, medical gloves, test kits, COVID-19 vaccines, and ventilators. In 2020, these shortages were widespread, highly publicized, triggering panic buying, and stockpiling worldwide. Expectedly, market price has surged drastically since the COVID-19 outbreak. In the United States, market prices of surgical masks and N95 respirators in April 2020 were 15-fold more than those prior to the COVID-19 outbreak. As COVID-19 related goods are absolutely critical in the COVID-19 pandemic, this section is devoted to investigating the economic impact of a targeted industry group covering COVID-19 related goods.

We apply the same methodology in Section 4.1 to estimate the economic impact of the COVID-19 shock of four industry sectors producing critical COVID-19 related goods: medical devices, personal protective equipment (PPE), pharmaceuticals, and soaps and cleaning compound. During the COVID-19 pandemic, these industries produce critical goods essential to reduce the spread of the COVID-19 virus, e.g., syringes and ventilators in the medical device industry; surgical masks and N95 respirators in the PPE industry; test kits and COVID-19 vaccines in the pharmaceutical industry; and hand sanitizers and bleach in the soaps and cleaning compound industry.

We use the North American Industry Classification System (NAICS) to define the industry sectors. The NAICS codes for the medical device industry are 334510, 334517, 339112, and 339113; those for the PPE industry are 315220, 315240, 339115, 313210, and 339113; those for the pharmaceutical industry is 3254, and those for the soaps and cleaning compound industry is 32561.[6]

[6] The medical device, pharmaceutical, as well as soap and cleaning compound industries are defined based on the United States international trade commission report on COVID-19 related goods: The U.S. industry, market,

4.6.1.1. Descriptive Statistics

Table 13 reports summary statistics of major variables used in our study for firms producing COVID-19 related goods during our sample period. This sector has experienced a robust growth in sales and investment since the COVID-19 outbreak. For an average firm producing COVID-19 related goods, the median sales growth is 7.33% which is significantly larger than 3.37% for an average firm in the full sample. Similarly, the median investment growth is 7.65% for an average firm in the COVID-19 related goods sector, compared to -0.65% for an average firm in the full sample. In addition, the average firm in the COVID-19 related goods sector has more cash holdings than that in the full sample. Other firm characteristics (evaluated at medians) are qualitatively similar between the two samples.

This table presents estimates from panel regressions of a firm's supplier growth relative to the same quarter in the previous year on a dummy indicated whether the firm and its suppliers is affected by full workplace closures in the current and each of the previous four quarters. All regressions include dummies for firm, year-quarter, country-year, and industry-year fixed effects. The industry fixed effects are based on 48 Fama-French industry classification. Standard errors presented in parentheses are clustered at the firm level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 13: Supplier Growth

Variables	(1)	(2)	(3)
DisruptOneSupplier (t)	10.039***		10.328***
	(1.487)		(1.501)
DisruptOneSupplier (t-1)	1.986*		1.923
	(1.195)		(1.238)
DisruptOneSupplier (t-2)	-0.683		-1.244
	(1.171)		(1.252)
DisruptOneSupplier (t-3)	-4.228***		-4.382***
	(1.292)		(1.355)
DisruptOneSupplier (t-4)	-0.739		-1.054
	(1.677)		(1.772)
CovidDisruptFirm (t)		-0.368	-2.048*
		(1.185)	(1.169)
CovidDisruptFirm (t-1)		1.579	0.631

trade, and supply chain challenges (December 2020). The PPE industry is defined based on United States Congressional Research Service on COVID-19 and Domestic PPE production and distribution: issues and policy options (December 7, 2020). These industries produce a wide range of products and also include products and equipment unrelated to the COVID-19 pandemic.

		(0.988)	(1.020)
CovidDisruptFirm (t-2)		1.878*	1.894*
		(1.072)	(1.139)
CovidDisruptFirm (t-3)		1.335	1.564
		(1.274)	(1.340)
CovidDisruptFirm (t-4)		2.005	2.211
		(1.669)	(1.747)
Covid-19 growth rate (t)	-0.363**	0.117	-0.233
	(0.143)	(0.154)	(0.154)
Dummy for no supplier (t-4)	-44.608***	-47.823***	-44.611***
	(1.889)	(1.836)	(1.887)
Log(1 + No. of suppliers) (t-4)	-35.349***	-35.299***	-35.383***
	(2.100)	(2.074)	(2.102)
Log(total asset) (t-4)	3.572	3.760	3.671
	(2.490)	(2.503)	(2.489)
Log(cash/asset) (t-4)	0.373	0.252	0.359
	(0.579)	(0.588)	(0.580)
Debt/asset (t-4)	-0.064	-0.064	-0.066
	(0.058)	(0.059)	(0.058)
ROA (t-4)	-0.059	-0.059	-0.055
	(0.122)	(0.123)	(0.122)
Observations	18,804	18,804	18,804
R-squared	0.271	0.265	0.271
Firm FE	Yes	Yes	Yes
Year-quarter FE	Yes	Yes	Yes
Country-year FE	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes

Table 14 present quarterly average of sales growth and investment growth for EU firms producing COVID-19 related goods during our sample period. Congruent with conventional wisdom, demand for COVID-19 related goods is strong throughout the COVID-19 pandemic. In particular, median sales growth has been consistently positive in every quarter after the COVID-19 outbreak except for the second quarter of 2020. In that quarter, the median sales growth declined slightly by 1.73%. However, this decline is justifiable because full workplace closures were first enforced in many EU countries due to the explosive growth of COVID-19 cases and shortages of critical PPE. The robust increase in demand for COVID-19 related goods is a sharp contrast to the noticeable decrease in demand for goods and services in other sectors. The results in the table show that median sales growth in the full sample is negative in every quarter of 2020. This table presents descriptive statistics of major variables used in this study for firms producing COVID-19 related goods. Appendix 2 contains detailed descriptions of all variables reported in this table.

Table 14: Descriptive Statistics: COVID-19 related goods

	Mean	Std. Dev.	Pctl_1	Median	Pctl_99
Sales growth (t-4, t) (%)	28.37	100.11	-90.84	7.33	524.87
Investment growth (t-4, t) (%)	96.14	384.55	-94.31	7.65	2083.91
Supplier growth (t-4, t) (%)	-0.62	34.74	-100	0	150
Total asset (t) ($billion)	10.25	61.77	0.01	0.45	98.04
Cash/asset (t) (%)	25.1	24.31	0.54	16.45	92.79
Debt/asset (t) (%)	22.49	20.11	0.06	19.15	87.78
ROA (t) (%)	-1.64	7.98	-36.34	0.73	9.92
No. of suppliers (t)	3.02	5.61	0	1	27
No. of customers (t)	4.68	10.2	0	1	46
No. of COVID-19 cases (t) (mil.)	0.53	1.23	0	0	5.82
CovidDisruptFirm (t)	0.2	0.4	0	0	1
DisruptOneSupplier (t)	0.24	0.43	0	0	1
Obs.	1,541				

To cater for the robust demand of COVID-19 related goods, firms appear to increase output based on existing production capabilities rather than building new plants or facilities immediately. In the first three quarters of 2020, the median investment growth is slightly negative ranging from -4.54% to -2.28%. These drops are small relative to the double-digit drops in investment growth for the average firm in the full sample. The mild drop is due to two reasons. First, capital expenditure is a long-term investment involving durable capital goods. Second, the COVID-19 shock creates huge uncertainties to business decisions because firms could not accurately predict the severity of the COVID-19 shock and also, how long this shock would last, especially in the early stage of the COVID-19 pandemic.

4.6.1.2. Regression Analysis

Table 15 reports results from panel regression of sales growth for firms producing COVID-19 related goods on a set of dummy variables indicating whether the firm and one of the firm's suppliers are affected by full workplace closures in the current quarter and in the previous four quarters. This table reports quarterly medians of sales growth and investment growth for EU companies producing COVID-19 related goods. Sales growth (t-4, t) is the sales growth between the current quarter and the same quarter in the previous year, and investment growth (t-4, t) is the change in capital expenditure between the current quarter and the same quarter in the previous year.

Table 15: Quarterly average of sales growth and investment growth: COVID-19 related goods

Time	Obs.	Sales growth (t-4, t) (%)	Investment growth (t-4, t) (%)
2019Q1	134	8.44	17.46
2019Q2	136	7.01	22.94
2019Q3	134	7.84	13.52
2019Q4	140	7.87	17.79
2020Q1	150	4.78	-4.42
2020Q2	153	-1.73	-2.84
2020Q3	148	4.28	-2.06
2020Q4	159	7.83	2.24
2021Q1	141	6.36	11.54
2021Q2	148	18.26	9.21
2021Q3	98	20.18	12.62

Our results in column (3) indicate that sales growth appears to drop when a firm's suppliers is affected by full workplace closures in the current quarter and the previous quarter but increase when one of the firm's suppliers is affected by such closures in quarters (t-2) and (t-3). However, none of the estimates of *DisruptOneSupplier* are statistically significant, even though these estimates are large and have economic significant. The drop in sales growth is 6.5 and 8.1 percentage points when one of the firm's supplier is affected by full workplace closures in the current quarter and in the prior quarter, respectively.

Our results in column (3) also indicate that full workplace closures are a binding constraint on firm output. The estimate of *CovidDisruptFirm(t-2)* indicates that sales growth declines significantly by 14.9 and 16.4 percentage points when the firm is affected by full workplace closures in the current quarter and in quarter (t-2), respectively. These declines are huge given the sharp and robust increase in demand for COVID-19 related goods.

Table 16 reports results from panel regression of investment growth for firms producing COVID-19 related goods on a set of dummy variables indicating whether the firm and one of the firm's suppliers are affected by full workplace closures in the current quarter and in the previous four quarters.

The estimate of *CovidDisruptFirm(t-3)* in column (3) indicates that a firm' investment growth declined significantly by 86% when the firm is affected by full workplace closures in quarter (t-3). This drop is huge and has economic significance and points to the same conclusion that full workplace closures create uncertainties and reduce firms' propensity to invest.

In contrast, the estimate of *DisruptOneSupplier(t-3)* in column (3) indicates that a firm's investment growth increases significantly by 103% when one of the firm's supplier is affected by full workplace closures in quarter (t-3). This increase is huge and has economic significance. The decision to delay investment activities is justifiable because firms faced huge uncertainty about the severity and duration of the pandemic during the early stage of the pandemic. Therefore, it may take months for firms to commit additional investment as they realize that the COVID-19 shock is an ongoing and persistent, at least in the coming years.

In contrast to the full sample results in Table 12, our results in column (3) of Table 16 indicate that supplier growth remains unchanged when one of the firm's suppliers is affected by full workplace closures in the current quarter and also in the prior quarter. Given the sharp and robust demand of COVID-19 related goods, this result is intriguing but consistent with the widespread export restrictions of COVID-19 related goods during the early stage of the pandemic.[7] However, supplier growth drops when one of the firm's suppliers is affected by full workplace closures in quarters (t-2) and (t-4). This result suggests that firms reduce the number of suppliers several quarters after full workplace closures disrupted the pre-existing supply chain relationship. This result also implies that firms may rely more on in-house production as they invest aggressively three quarters after the firm's suppliers are affected by full workplace closures.

This table presents estimates from panel regressions of sales growth for firms producing COVID-19 related goods on a dummy indicated whether the firm and its suppliers is affected by full workplace closures in the current and each of the previous four quarters. All regressions include dummies for firm, year-quarter, country-year, and industry-year fixed effects. The industry fixed effects are based on 48 Fama-French industry classification. Standard errors presented in parentheses are clustered at the firm level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 16: Sales Growth for firms producing COVID-19 related goods

Variables	(1)	(2)	(3)
CovidDisruptFirm (t)	-15.140		-14.919
	(11.866)		(11.542)
CovidDisruptFirm (t-1)	0.125		3.026
	(12.135)		(13.787)
CovidDisruptFirm (t-2)	-11.733		-16.410*
	(8.741)		(9.125)
CovidDisruptFirm (t-3)	1.722		1.149
	(15.980)		(15.319)
CovidDisruptFirm (t-4)	19.001		18.123
	(18.120)		(17.809)
DisruptOneSupplier (t)		-9.247	-6.492
		(8.699)	(8.428)
DisruptOneSupplier (t-1)		-7.441	-8.101
		(11.001)	(12.726)
DisruptOneSupplier (t-2)		10.782	15.202
		(9.137)	(9.710)

[7] https://www.oecd.org/coronavirus/policy-responses/the-face-mask-global-value-chain-in-the-COVID-19-outbreak-evidence-and-policy-lessons-a4df866d/.

DisruptOneSupplier (t-3)		2.209	3.249
		(11.243)	(10.082)
DisruptOneSupplier (t-4)		1.067	-1.477
		(14.701)	(13.743)
COVID-19 growth rate (t)	0.904	0.830	1.353
	(1.795)	(1.528)	(1.717)
Log(1 + No. of suppliers) (t-4)	27.147**	26.402**	26.695**
	(10.932)	(11.347)	(11.434)
Log(total asset) (t-4)	-52.254**	-53.041**	-52.806**
	(22.516)	(23.006)	(22.749)
Log(cash/asset) (t-4)	11.401*	10.743*	10.747*
	(6.372)	(6.411)	(6.495)
Debt/asset (t-4)	0.499	0.481	0.479
	(0.397)	(0.394)	(0.397)
ROA (t-4)	-4.121***	-4.057***	-4.060***
	(1.353)	(1.371)	(1.362)
Observations	1,541	1,541	1,541
R-squared	0.144	0.143	0.146
Firm FE	Yes	Yes	Yes
Year-quarter FE	Yes	Yes	Yes
Country-year FE	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes

Due to the robust demand of COVID-19 related goods, our results in column (3) indicate that supplier growth increases significantly when the firm is affected by full workplace closures. This implies that full workplace closures reflect the severity of the pandemic and also the projected demand of COVID-19 related goods. Therefore, the anticipated increase in sales motivate firms to increase supply chain relationships. All the estimates of *CovidDisruptFirm* in column (3) are consistently positive. In particular, the estimates in quarters (t-1), (t-2), and (t-4) are large and have economic significant.

Table 17 reports results from panel regression of supplier growth for firms producing COVID-19 related goods on a set of dummy variables indicating whether the firm and one of the firm's suppliers is affected by full workplace closures in the current quarter and in the previous four quarters. This table presents estimates from panel regressions of investment growth for firms producing COVID-19 related goods on a dummy indicated whether the firm and its suppliers is affected by full workplace closures in the current and each of the previous four quarters. All regressions include dummies for firm, year-quarter, country-year, and industry-year fixed effects. The industry fixed effects are based on 48 Fama-French industry classification. Standard errors presented in parentheses are clustered at the firm level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 17: Investment Growth for firms producing COVID-19 related goods

Variables	(1)	(2)	(3)
CovidDisruptFirm (t)	68.939		52.248
	(49.002)		(46.260)
CovidDisruptFirm (t-1)	-66.903		-79.830
	(48.751)		(53.740)
CovidDisruptFirm (t-2)	26.088		12.857
	(28.869)		(33.619)
CovidDisruptFirm (t-3)	-51.130		-86.129**
	(34.381)		(40.791)
CovidDisruptFirm (t-4)	139.014		91.180
	(87.170)		(88.278)
DisruptOneSupplier (t)		-17.797	-20.501
		(46.642)	(48.838)
DisruptOneSupplier (t-1)		14.949	29.733
		(47.398)	(48.925)
DisruptOneSupplier (t-2)		5.617	3.714
		(50.786)	(53.013)
DisruptOneSupplier (t-3)		90.399*	102.954**
		(47.240)	(51.507)
DisruptOneSupplier (t-4)		76.191	61.941
		(80.123)	(85.769)
COVID-19 growth rate (t)	-7.731	-0.501	-4.452
	(8.140)	(8.045)	(7.914)
Log(1 + No. of suppliers) (t-4)	38.286	20.844	19.908
	(31.963)	(35.906)	(35.545)
Log(total asset) (t-4)	-42.212	-55.011	-56.470
	(111.484)	(111.011)	(111.928)
Log(cash/asset) (t-4)	55.100**	53.505**	55.917**
	(27.084)	(25.567)	(26.352)
Debt/asset (t-4)	0.768	0.783	0.783
	(1.208)	(1.213)	(1.205)
ROA (t-4)	1.195	1.741	1.999
	(6.566)	(6.425)	(6.434)

Observations	1,537	1,537	1,537
R-squared	0.104	0.106	0.111
Firm FE	Yes	Yes	Yes
Year-quarter FE	Yes	Yes	Yes
Country-year FE	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes

Similarly, Table 18 presents estimates from panel regressions of supplier growth for firms producing COVID-19 related goods on a dummy indicated whether the firm and its suppliers is affected by full workplace closures in the current and each of the previous four quarters. All regressions include dummies for firm, year-quarter, country-year, and industry-year fixed effects. The industry fixed effects are based on 48 Fama-French industry classification. Standard errors presented in parentheses are clustered at the firm level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 18: Supplier Growth for firms producing COVID-19 related goods

Variables	(1)	(2)	(3)
DisruptOneSupplier (t)	2.357		0.866
	(3.056)		(3.106)
DisruptOneSupplier (t-1)	2.247		0.174
	(3.422)		(3.540)
DisruptOneSupplier (t-2)	-3.138		-6.269*
	(3.111)		(3.480)
DisruptOneSupplier (t-3)	1.351		-0.527
	(2.996)		(3.478)
DisruptOneSupplier (t-4)	-2.563		-8.152*
	(4.157)		(4.477)
CovidDisruptFirm (t)		1.059	2.301
		(2.923)	(3.039)
CovidDisruptFirm (t-1)		7.998***	8.634***
		(2.936)	(3.123)
CovidDisruptFirm (t-2)		5.883**	8.487**
		(2.829)	(3.280)
CovidDisruptFirm (t-3)		1.852	2.336
		(3.305)	(3.809)

CovidDisruptFirm (t-4)		9.103*	13.654**
		(5.481)	(5.781)
COVID-19 growth rate (t)	0.723	0.109	0.504
	(0.451)	(0.442)	(0.474)
Dummy for no supplier (t-4)	-39.114***	-39.050***	-38.152***
	(6.735)	(6.422)	(6.451)
Log(1 + No. of suppliers) (t-4)	-39.465***	-38.343***	-37.941***
	(6.300)	(6.483)	(6.312)
Log(total asset) (t-4)	23.604***	22.031**	24.414***
	(8.579)	(8.706)	(8.407)
Log(cash/asset) (t-4)	-0.846	-0.333	-0.847
	(2.271)	(2.282)	(2.166)
Debt/asset (t-4)	-0.207	-0.190	-0.203
	(0.142)	(0.138)	(0.138)
ROA (t-4)	-0.263	-0.253	-0.312
	(0.236)	(0.243)	(0.247)
Observations	1,541	1,541	1,541
R-squared	0.343	0.333	0.349
Firm FE	Yes	Yes	Yes
Year-quarter FE	Yes	Yes	Yes
Country-year FE	Yes	Yes	Yes
Industry-year FE	Yes	Yes	Yes

5. Conclusions

The COVID-19 pandemic is a global health crisis and has caused devastating casualties worldwide, infecting 445 million and killing nearly 6 million people. To reduce the spread of COVID-19, worldwide governments have implemented numerous intervention policies. No doubt, these policies have reduced casualties. However, they are also restrictive and discourage economic activities on countries where these restrictions are enforced. Additionally, they create spillover effects to other countries. Therefore, policy makers are keen on understanding how the COVID-19 shock is amplified and propagated through an economy.

This deliverable develops a methodology to estimate the economic impact of the COVID-19 shock. In particular, it investigates how the COVID-19 shock is propagated through a network of global supplier-customer relationships, capturing interdependencies between suppliers and customers along the supply chain. It also allows us to estimate the cascading effects of the COVID-19 shock. Our methodology is built on a difference-in-differences approach which compares economic activities over time between suppliers or customers affected by COVID-19 induced supply chain disruptions (treatment group) and suppliers or customers that are not (control group). This methodology allows us to examine whether and to what extent changes in economic activities are due to disruptions in a firm's suppliers, disruptions in a firm's customers, or disruptions to a firm due to government intervention policies.

Our research methodology is suitable to examine the economic impact of the COVID-19 shock because this shock has triggered numerous concurrent restrictions on firms and people, posing a challenge to pin down the exact propagation mechanism through an economy, e.g., firm-level linkages, sector-level linkages, or country-level linkages.

Our target group of interest is publicly traded companies in the EU region. The EU region is chosen due to its homogeneity in accounting rules, regulations, and COVID-19-related policies. This homogeneity offers a clear interpretation of our results. Our sample is biased because it includes only publicly traded companies which is a small subset of firms in an economy. However, they are the largest companies, accounting for sizable economic activities of an economy. As shocks hitting larger firms have significantly larger economic impacts than those hitting smaller firms and firm-size distribution has fat tail, the projected economic impact from our sample is a fair estimate of the overall impact of the COVID-19 shock on a real economy (Gabaix, 2011). Additionally, data on economic activities for publicly traded companies are transparent and reliable because they are reported based on a set of stringent accounting and auditing rules.

We use full workplace closures as a proxy for COVID-19 induced supply chain disruptions because they have direct effects on a firm's output by forcing companies to close or reduce production. In contrast, other intervention policies (such as school closures, restrictions on gatherings, or cancelling of social events) have indirect effects on a firm's output.

Overall, our results indicate that the COVID-19 shock has damaging impact on economic activities. In the first quarter of 2020, sales growth declined by 3.44%, compared to a positive sales growth of 3.78% in the previous quarter. The decline in sales growth had widened to nearly 10% in the second quarter of 2020. The declines in propensity to invest were even larger in the first two quarters of 2020. Investment growth dropped by 9.52% and 13.57% in the first quarter and the second quarter of 2020. These drops are large and swift reflecting the severity of the COVID-19 shock.

Our results also indicate that full workplace closures were widespread in the EU and concentrated in the first two quarters of 2020 and in the first quarter of 2021. Out of the 27 EU countries, 63% of them had full workplace closure policies in the first quarter of 2021 and nearly 50% of them had such restrictions in the first two quarters of 2020. In addition, full workplace closure restrictions differ widely within and across countries. Out of the 27 EU nations, three countries had never implemented full workplace closures during our sample period. In contrast, Italy and Ireland had implemented full workplace closures for about 40% of the time during the same time period.

Our difference-in-differences results indicate that drops in economic growth are motivated by full workplace closures, i.e, government intervention policies. Specifically, a firm’s sales growth decreases swiftly and by approximately 3 percentage points when one of the firms is affected by full workplace closures in the current quarter. In contrast, our difference-in-differences results indicate that a firm’s investment growth is unresponsive to full workplace closure restrictions, implying full workplace closure restrictions are not relevant to a firm’s propensity to invest.

In contrast to conventional wisdom, a firm's sales growth is unresponsive to whether the firm’s suppliers or the firm’s customers is affected by full workplace closures. However, our results also indicate that supplier growth increases by approximately 10 percentage points when one of the firm’s suppliers is affected by full workplace closures in the current quarter. This increase is quick and large. Taken altogether, our findings imply that pre-existing (or pre-COVID) supplier-customer relationships are robust to sustain the COVID-19 shock. It also implies that the cost of substituting one supplier by another supplier is small in the EU region because firms can adjust quickly by adding new suppliers when their suppliers are affected by full workplace closures. Overall, our difference-in-differences results point to the same direction that the cascading effects of COVID-19 induced supply chain disruptions is small.

Our results also indicate that demand for COVID-19 related goods were robust during our sample period. In particular, firms producing COVID-19 related goods experienced a positive sales growth in nearly every quarter since the COVID-19 outbreak. To cater for the robust demand of COVID-19 related goods, firms appear to increase output based on existing production capabilities rather than building new plants or facilities immediately because investment growth declined mildly in the first three quarters of 2020.

Similarly, our difference-in-differences results show that full workplace closures are a binding constraint on sales growth for firms producing COVID-19 related goods. In particular, a firm’s sales growth declines significantly by over 10 percentage points when the firm is affected by full workplace closures in the current quarter and quarter (t-2). These declines are huge considering the robust demand of COVID-19 related goods worldwide. Congruent with the results in the full sample, a firm's sales growth is unresponsive to when the firm’s suppliers are affected by full workplace closures.

Our difference-in-differences results also suggest that a firm’s investment growth increases markedly by one-fold when one of the firm’s suppliers is affected by full workplace closures in quarter (t-3). This increase is huge with a delay of three quarters. The delay in investment growth is reasonable because firms faced huge uncertainties about the severity and duration of the COVID-19 shock during the early stage of the pandemic. Therefore, it may take months for them to act and invest as firms realize that the COVID-19 shock is ongoing, at least in the coming years.

In contrast to the results in the full sample, our difference-in-differences results indicate that supplier growth remains unchanged when the firm’s suppliers is affected by full workplace closures in the current quarter and also in the prior quarter. Given the overwhelming demand of COVID-19 related goods, this result is intriguing but consistent with the widespread export restrictions of COVID-19 related goods during the early stage of the pandemic. However, supplier growth drops when one of the firm's suppliers is affected by full workplace closures in quarters (t-2) and (t-4). This result suggests that firms reduce the number of suppliers several quarters after full workplace closures disrupt the pre-existing supply chain relationship. This result also implies that firms may rely more on in-house production as they invest aggressively three quarters after the firm's suppliers are affected by full workplace closures.

Our study and methodology have several shortcomings. First, our results offer only short-term implications on a firm's responses to the COVID-19 shock. This is because the COVID-19 shock is ongoing and our sample period ends in the third quarter of 2021. In other words, our results are unable to offer intermediate- or long-term implications regarding a firm's responses to the COVID-19 shock.

Second, our sample is unrepresentative in two dimensions. It is consisted of publicly traded companies in the EU region. Thus, our results may not be applicable to non-EU economies and to private firms and smaller firms. Third, our methodology relies on the assumption that full workplace closures are a binding constraint and reduce a firm's output, and also output of its suppliers and customers. In practices, full workplace closures might not be a binding constraint. Last, our methodology focuses mainly on one probation mechanism, namely firm-level supplier-customer linkages. In real practices, the COVID-19 shock could be propagated via sector-level or country-level linkages.

To fill these gaps, future research is required to expand the scope of our analysis to other propagation mechanisms. Additional research is also required to extend the sample period to examine if our results are applicable in the intermediate- or long-term horizons. Last, characteristics and government intervention policies differ markedly across economies, future research is also required to examine if our results are applicable to non-EU economies.

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Annexes

1.1Appendix 1: Sample composition by economies

Country Name	Number of Firms
Austria	42
Belgium	72
Bulgaria	30
Cyprus	22
Czech Republic	8
Germany	406
Denmark	89
Spain	117
Estonia	12
Finland	132
France	454
Greece	88
Croatia	41
Hungary	13
Ireland	88
Italy	252
Lithuania	24
Luxembourg	46
Latvia	8
Malta	12
Netherlands	112
Poland	280
Portugal	33
Romania	37
Slovak Republic	3
Slovenia	10
Sweden	457
Total	2,888

1.2Appendix 2: Description of variables

This table contains detailed descriptions of each variable used in this study.

Variable	Definition	Data source
ΔSales$_{i,t-4,t}$*	Sales growth, growth rate of a firm's sales between the current quarter and the same quarter in the previous year.	CompuStat Global
ΔCapExp$_{i,t-4,t}$*	Investment growth, growth rate of a firm's capital expenditure between the current quarter and the same quarter in the previous year.	CompuStat Global
ΔSuppliers$_{i,t-4,t}$*	Supplier growth, growth rate of a firm's total number of suppliers between the current quarter and the same quarter in the previous year. Growth rate is set to zero if a firm has no supplier.	FactSet Revere
DisruptOneSupplier$_{i,t-4}$	A binary variable and takes the value of one if one of the firm's suppliers is affected by full workplace closures in the same quarter of the previous year.	FactSet Revere
DisruptOneCustomer$_{i,t-4}$	A binary variable and takes the value of one if one of the firm's customers is affected by full workplace closures in the same quarter of the previous year.	FactSet Revere
CovidDisruptFirm$_{i,t-4}$	A binary variable and takes the value of one if the firm is affected by full workplace closures in the same quarter of the previous year.	FactSet Revere
Covidgr$_{ct}$	COVID-19 growth rate, growth rate of the number of COVID-19 cases in a country between the current quarter and the previous quarter. It is measured as follows: log(1 + cumulative cases in the current quarter) - log(1 + cumulative cases in the previous quarter).	JHU-CSSE
Log(1+ No. of suppliers)$_{i,t-4}$	Number of suppliers, measured by natural logarithm of one plus the number of the firm's suppliers in the same quarter of the previous year.	FactSet Revere
Dummy for no suppliers$_{i,t-4}$	A binary variable and takes the value of one if the firm has no suppliers in the same quarter of the previous year.	FactSet Revere
Log(1+ No. of customers)$_{i,t-4}$	Number of customers, measured by natural logarithm of one plus the number of the firm's customers in the same quarter of the previous year.	FactSet Revere
Log(Total asset)$_{i,t-4}$*	Firm size, measured by natural logarithm of book value of total asset in the same quarter of the previous year.	CompuStat Global
Log(cash/asset)$_{i,t-4}$*	Cash holdings, measured by natural logarithm of the ratio of total amount of cash and short-term investments to total assets (in percentage) in the same quarter of the previous year.	CompuStat Global
Debt/asset$_{i,t-4}$*	Firm leverage, measured by the ratio of long-term debt to total assets (in percentage) in the same quarter of the previous year.	CompuStat Global
ROA$_{i,t-4}$*	Firm profitability or return on asset, , measured by the ratio of operating income excluding depreciation expenses to total assets (in percentage) in the same quarter of the previous year.	CompuStat Global

* We winsorize sales growth, investment growth, supplier growth, firm size, leverage, cash, and profitability at the upper and bottom one percentile.