Identifying macroeconomic shocks using firm-level data: Material shortages in the German manufacturing sector *

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This version: February 10, 2025

Abstract

We leverage micro-data for identification of macro shocks in time series settings. We exploit firm-level forecast errors on prices and production along with information on production impediments to construct a shock series capturing input material constraints. Our approach allows to separately identify periods of tightening and easing material supply shocks. We find that both types of shocks have different implications for economic activity: tightening shocks instantaneously push prices up whereas an easing of material constraints instantaneously boosts production and triggers a more sluggish response of prices. Decomposing the instrument into its individual components allows to contrast the response to input material shocks to any other generic supply shock. We also show that the construction of the instrument is robust to variations in the underlying identification assumptions at the micro-level.

Keywords: material shortages, micro data, firm expectations, sign restrictions, inflation

JEL-Classification: C32, C36, E31, E32

Preliminary draft

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We wish to thank Simona Giglioli, Sarah Zubairy, Diego Känzig, Isabel Gödl-Hanisch and participants at various ifo institute seminars, the 1st Tor Vergata PhD conference in economics, the 5th joint BoC-ECB-NY Fed Conference on Expectations Surveys, Central Banks and the Economy, the 2nd Women in Central Banking Workshop, the 37th CIRET Conference and the 14th ifo Conference on Macroeconomics and Survey Data for helpful comments and suggestions.

1. Introduction

Identifying and quantifying the repercussions of macroeconomic shocks is not an easy task. Recently, supply chain disruptions put strains on many economies, yet it took time to understand what this meant for affected economies given these disruptions occurred during times of elevated economic distress. Our paper suggests to use firm-level data to construct a shock series capturing the purely exogenous part of these disruptions and meant to identify unexpected input material shortages in the German manufacturing sector. By tracking firm-level forecast errors on prices and production along with information on production impediments over time, our approach isolates disruptions directly attributable to material shortages from broader economic disturbances. The underlying idea is that the larger the share of forecast errors due to unexpected material input constraints, the higher the likelihood that supply chain induced disruptions at the firm-level spread to the broader economy.

The Germany manufacturing sector provides a suitable setting for studying these effects. In 2022, manufacturing accounted for 20.2% of Germany's value added, well above the EU average of 16.6%[1]. On average, according to the ifo business survey, every second firm experiences material shortages in any given quarter. With its heavy reliance on imported intermediate goods and raw materials, it is vulnerable to supply chain disruptions.

We find that input material shocks exert inflationary pressure on producer and commodity prices. Industrial production and GDP initially decline in response to the shock but recover swiftly. To mitigate these disruptions, firms reduce their inventories, yet their investment behavior remains largely unchanged. Monetary policy reacts with a lag of three to four quarters, with the central bank policy rate thereafter rising gradually by approximately ten basis points per quarter. The effects of input material shocks are evident across different manufacturing sectors, although their magnitude varies. Constructing the shock series relies on several firm-level assumptions. However, relaxing some of these assumptions does not alter our main results. Additionally, we asses to what extent responses to an input material shock differ from responses to a generic supply shock. Our results emphasize the importance of properly accounting for the demand component in the shock series to avoid mixing endogenous network effects with the exogenous part of the shock. Reassuringly, our results are robust across different modeling choices, holding under both a proxy VAR setting and local projections. We extend our methodology to identify periods of easing input material shocks, which have smaller and opposite effects to tightening shocks. While they instantaneously boost industrial production and GDP, prices only decline with a delay. Given suitable microdata, our identification approach extends to other contexts, too.

[1] https://www.destatis.de/Europa/DE/Thema/Industrie-Handel-Dienstleistungen/Industrie.html

Methodologically, our work contributes to the literature on identification in time-series settings using external instruments and exogenous shock series. This approach is widely used to identify monetary policy shocks (Miranda-Agrippino and Ricco, 2023; Stock and Watson, 2018; Gertler and Karadi, 2015; Mertens and Ravn, 2013; Stock and Watson, 2012) but also applied to global oil markets (Känzig, 2021) or climate change (Bilal and Känzig, 2024). These authors commonly exploit high frequency or granular data to extract shocks and rely on Cholesky decompositions, sign restrictions, or narrative restrictions on impulse responses for identification. We complement this literature by demonstrating the value of firm-level survey data for identification. We are not the first to leverage granular firm-level data for identification. Bachmann *et al.* (2013) analyze firm-level expectations to construct proxies for time-varying business uncertainty and estimate the impact of uncertainty on economic activity. Bachmann and Zorn (2020) use responses to an investment survey among German manufacturing firms to identify aggregate demand and aggregate technology shocks. Other studies investigating the link between firm-level expectations and macroeconomic shocks are (Balleer and Noeller, 2023; Born *et al.*, 2024; Enders *et al.*, 2022). Lenza and Savoia (2024) include firm revenues in a VAR setting to show how revenue-heterogeneity across firms affects standard macroeconomic aggregates across euro area countries. Gabaix and Koijen (2024) introduce the concept of granular instrumental variables for causal inference. The instruments extract idiosyncratic shocks to large economic players. The resulting variation is used to infer about developments at higher levels of aggregation.

Our empirical application focuses on the macroeconomic consequences of supply chain disruptions, which we also refer to as input material constraints. The body of literature examining the risks and benefits of global value chain participation has expanded significantly, particularly in the wake of the COVID-19 pandemic. One strand of the literature focuses on new supply constraint indices to capture early signals of supply chain tightening (Bai *et al.*, 2024; Burriel *et al.*, 2023; Benigno *et al.*, 2022). Another strand approaches the link between supply disruptions and macroeconomic aggregates through structural time series models. Using VAR frameworks with sign and/or narrative restrictions, these studies commonly find negative effects of supply chain shocks on output and prices (Bai *et al.*, 2024; Celasun *et al.*, 2022; Finck and Tillmann, 2022; Kilian *et al.*, 2021). The related literature on supply chain linkages stresses the risk of micro-level shocks accumulating into global macro threats. During the heights of the Covid pandemic, halts in firms' production processes or the confinement of workers in ports led to a series of supply chain disruptions. These bottlenecks contributed to a surge in global import prices (Khalil and Weber, 2022). Our empirical application adds to this literature by investigating the relationship between supply chain constraints, production developments and producer price inflation in Germany.

2. Data

We provide more information on the data entering our VAR in section (3.3). Here, we instead introduce the firm-level data retrieved from the ifo Business Survey. To measure (endogenous) supply chain distortions, we use the share of firms indicating that their production is currently impeded by a lack of material, as published by the ifo Institute. Firms included in this measure are not restricted to face material constraints only, but may potentially also report other obstacles to production. Our identification strategy, in turn, aims at extracting the unexpected, idiosyncratic component of this series.

Other popular measures of global supply chain disruptions include the Global Supply Chain Pressure Index (GSCPI, Benigno *et al.*, 2022) or the Average Port Congestion Index developed by Bai *et al.* (2024). The ifo supply chain measure and the GSCPI generally exhibit similar dynamics with a high degree of correlation (0.63, compare Appendix B.2). We hence also present results based on alternative measures of supply chain stress.

In the following, we provide more details on the ifo Business Survey in the manufacturing sector and on the relevant variables for constructing the instrument. We then outline our identification strategy and the construction of the instrument.

The ifo Business Survey in the Manufacturing Sector We construct an external instrument based on firm-level data from the ifo Business Survey in the Manufacturing Industry (from now on ifo survey), that has been conducted regularly since 1949. Participation is voluntary and firms do not receive any monetary compensation[2]. The respondent is usually a member of the company's senior management. Sauer and Wohlrabe (2019) document that 85% of respondents are indeed CEOs or department heads. The response rate for the ifo survey is typically high; approximately two-thirds of the firms initially contacted in mid-2021 participated in at least two survey rounds (Born *et al.*, 2024). High response rates persist also after the initial contact, the survey maintains an average monthly response rate of 82% (Enders *et al.*, 2022). The survey data is available at the firm level with firms being classified into the subsector level according to the ISIC Rev. 4 classification. The survey represents firms across all manufacturing sectors except the Manufacturers of Other Transport Equipment (C30) and Installation, Maintenance and Repair of Machinery and Equipment (C33). Table (B7) in Appendix B.3 provides an overview of the exact definition of manufacturing subsectors covered in our analysis. Note that survey data for industries C10, C11 and C12 (Food, Bevarages and Tobacco) and C13, C14 and C15 (Textiles, Wearing Apparel, Leather and Related Products) is only inquired as an aggregate.

Every month, between 2000 and 5000 manufacturing firms participate in the ifo survey, responding to a broad range of mostly qualitative questions on developments within their sector. Many of these questions are asked at a monthly frequency, others are queried only

[2] The non-monetary compensation consists of receiving sectoral and aggregate results of the survey.

once per quarter. We focus on questions eliciting information about firms' price and production expectations, their actual realizations, potential production impediments, and firm-level demand developments.

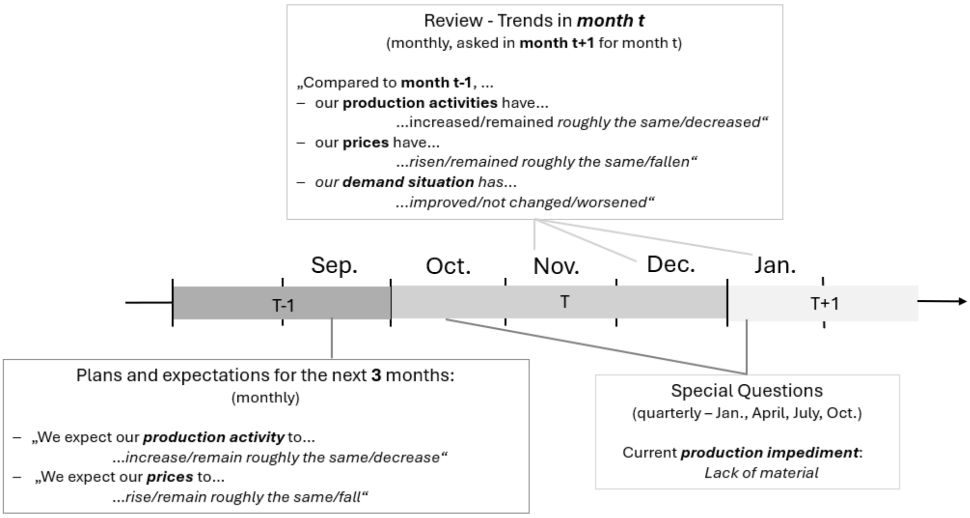
Relevant ifo survey data in our application The core of our identification strategy is firm-level information about potential production impediments, in particular about material shortages. The ifo survey inquires information about potential production obstacles in the first month of every quarter. Obstacles are then further defined as financial constraints, demand or labor shortages, or lack of materials. Concretely, the question reads:

> *"Our domestic production is currently constrained by...*
>
> *...too few orders/insufficient technical capacity/difficulties of financing/**lack of raw material or pre-materials**/lack of skilled employees/lack of low-skilled employees/difficulties of financing/other."*

Balleer and Noeller (2023) study the answering behavior of firms to this question in detail. They document the share of firms reporting material shortages to be pro-cyclical. Additionally, they emphasize that variations in responses are more pronounced within industries than across different industries. Their findings also suggest that material constraints are not persistent at the firm level.

In addition to production impediments, the ifo survey offers a broad range of (qualitative) information on firms' performance. For our analysis, we focus on data related to price, production, and demand developments. Specifically, we compare firms' expectations for future prices and production with their actual realizations. Figure (1) visualizes the frequency with which the questions relevant to our analysis are posed, along with the corresponding time horizon. The exact wording of these questions can be found in Appendix B.4.

Figure 1: Timing of relevant survey questions



Notes: The graph visualizes the timing and the horizon under consideration for different questions in the ifo survey, crucial in our identification strategy.

The ifo survey queries information on prices, production and demand on a monthly basis, but the time horizons vary depending on the type of question. While expectations in month t are elicited with respect to developments over the next three months, realizations reported in month t reflect performance in the previous month, $t-1$, relative to the month before that, $t-2$. As previously mentioned, information on production impediments is gathered once per quarter (in January, April, July and October). To align the monthly data with the quarterly nature of the production impediment question, we aggregate answers accordingly. Section (3) provides more details. The qualitative nature of the questions reduces measurement errors, yet complicates quantitative assessments (Born *et al.*, 2024).

2.1. What dampens industrial production?

Before turning to the main analysis, we briefly present stylized facts on self-reported production impediments across German manufacturing firms. Next to informing about firms' production environment over time, they motivate the construction of our instrument.

Table (1) provides summary statistics on self-reported production impediments, where the last column shows the average number of impediments reported by firms across sectors and time. On average, a firm reports 0.56 impediments per quarter. Interestingly, this number is quite stable across sectors and time. The remaining columns examine the extent to which firms report to be exclusively affected by one of the possible production impediments over time [3]. We therefore group impediments into three broader groups: Financial, demand, and production-side related constraints. Financial constraints appear to matter predominantly

[3]As before, the question also presents as possible impediment "lack of low-skilled employees". This answer, however, was only introduced in 2020, hence we decided decided to abstract from it in the following.

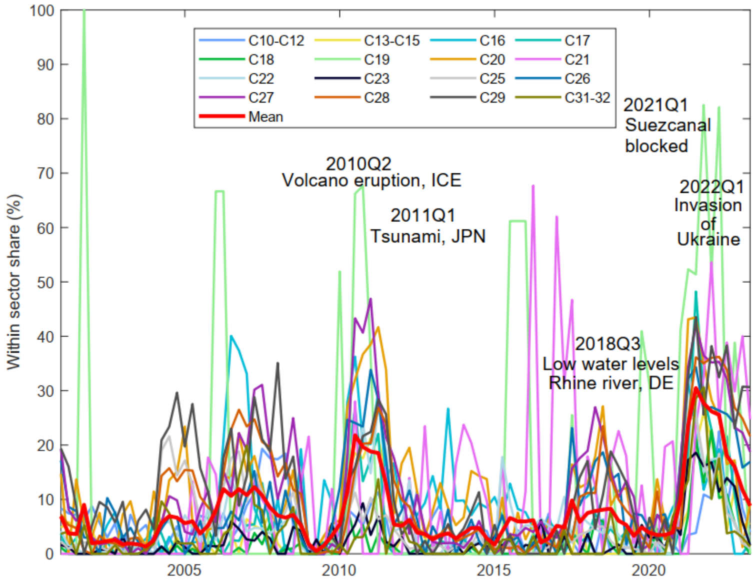
for firms involved in the publishing, printing, and media industry, as well as for those working with cokery, mineral oil, fissile, and fertile materials. Note, however, that overall the share of firms solely affected by financial constraints is low. Spikes were observed around the Great Recession and the sovereign debt crises. Historically, a significant share of firms reports order shortages. This is particularly true for firms in the chemical industry and the automotive sector. During the Great Recession, the Global Financial Crisis and the early onset of the Covid-19 pandemic, the proportion of firms within a sector (exclusively) reporting demand shortages has been particularly high, averaging at around 50%. On the other hand, a lack of skilled labor is only rarely the only constraint on production. A few firms report insufficient production capacity as the sole reason for low production. Since 2010, this tends to co-move with the share of firms (uniquely) reporting order shortages. Figure (2) focuses on material shortages and shows the share of firms within a sector that reports to be solely constrained by a lack of material. In addition, we mark major events with the potential to trigger disruptions in global supply chains. Two observations stand out. First, the majority of firms reporting material constraints at any point in time are firms operating in sectors whose production relies heavily on intermediate materials or capital goods, such as, e.g., the vehicle (C29) or machinery sector (C28). Second, the peaks of this series correspond well with (global) disruptive events. For instance, we observe a high share of firms in the vehicle manufacturing sector reporting material lacks around a major Tsunami in Japan (2011). We also observe a rapid increase in firms reporting material shortages following the disruptions arising due to the Covid pandemic or the blockade of the Suez canal. The answers on material impediments tend to be negatively correlated with the answers regarding orders. This observation warrants some discussion on the relevance of demand effects when introducing the external instrument below.

Table 1: Summary statistics for various production impediments by sector

	Skilled worker imp.			Order imp.			Financial imp.			Capacity imp.			Nbr. of imp.		
Sector	∅	Min.	Max.	∅	Min.	Max.	∅	Min.	Max.	∅	Min.	Max.	∅	Min.	Max.
C10-C12	0.07	0.00	0.30	0.42	0.00	0.83	0.01	0.00	0.06	0.03	0.00	0.10	0.54	0.31	1.21
C13-C15	0.08	0.00	0.33	0.40	0.01	0.80	0.02	0.00	0.06	0.03	0.00	0.11	0.62	0.39	1.19
C16	0.07	0.00	0.37	0.37	0.02	0.89	0.01	0.00	0.08	0.05	0.00	0.17	0.47	0.17	1.15
C17	0.04	0.00	0.22	0.57	0.03	0.88	0.01	0.00	0.07	0.01	0.00	0.07	0.65	0.30	1.39
C18	0.08	0.00	0.40	0.36	0.07	0.63	0.02	0.00	0.16	0.04	0.00	0.12	0.46	0.24	1.03
C19	0.05	0.00	0.37	0.51	0.06	0.77	0.02	0.00	0.12	0.01	0.00	0.15	0.51	0.25	1.21
C20	0.06	0.00	0.35	0.43	0.04	0.84	0.01	0.00	0.09	0.03	0.00	0.12	0.62	0.34	0.99
C21	0.06	0.00	0.21	0.48	0.00	0.84	0.02	0.00	0.10	0.06	0.00	0.27	0.47	0.21	1.09
C22	0.05	0.00	0.25	0.60	0.02	0.88	0.01	0.00	0.06	0.01	0.00	0.09	0.64	0.36	1.51
C23	0.04	0.00	0.19	0.42	0.00	0.81	0.01	0.00	0.07	0.01	0.00	0.09	0.54	0.27	1.14
C25	0.07	0.00	0.37	0.42	0.00	0.91	0.01	0.00	0.08	0.02	0.00	0.12	0.52	0.18	1.40
C26	0.05	0.00	0.26	0.50	0.03	0.82	0.02	0.00	0.08	0.03	0.00	0.09	0.66	0.30	1.36
C27	0.06	0.00	0.29	0.52	0.02	0.84	0.02	0.00	0.09	0.03	0.00	0.09	0.55	0.23	1.27
C28	0.07	0.00	0.36	0.39	0.00	0.86	0.02	0.00	0.10	0.05	0.00	0.14	0.57	0.29	1.23
C29	0.06	0.00	0.35	0.55	0.01	0.91	0.01	0.00	0.05	0.02	0.00	0.08	0.48	0.24	1.07
C31-32	0.07	0.00	0.34	0.45	0.02	0.82	0.01	0.00	0.08	0.03	0.00	0.10	0.57	0.30	1.25
Mean	0.06			0.47			0.02			0.03			0.56		

Notes: The Table shows the average, minimum and maximum share of firms across time (by sector) reporting one of the listed production impediments as their unique impediment to production.

Figure 2: Share of firms reporting a lack of material as unique impediment



Notes: The graph shows the sectoral shares of firms reporting a lack of material as sole production constraint .

3. Methodology

3.1. Identification based on firm-level data

Identification in VAR applications is regularly achieved via Cholesky ordering, sign restrictions, narrative restrictions, long run restrictions or instrumental variable (proxy VAR) approaches. Our work adds to the latter by showing that firm-level information provides itself useful to identify a macroeconomic shock.

The firm-level data based instrument Identification is based on a comparison of firm-level forecast errors with respect to price and production developments across two groups: Firms reporting material shortages against firms not affected by any production impediment. For both groups, we impose sign restrictions on their forecast errors on price and production developments that are in line with the general notion of a supply shock. Coupled with additional information on obstacles to production and demand developments, we identify firms that have been unexpectedly hit by a material supply shock, i.e. their forecast error is uniquely attributable to a material supply shock.

Constructing the shock series To begin with, we single-out firms potentially hit by any generic supply shock, usually characterized by an increase in prices and a decrease in production. To relate this to the firm-level information, we follow Born *et al.* (2024) and Bachmann *et al.* (2013) and construct firm-level forecast errors as

$$x^i_Q - \mathbb{E}^i_{T-Q}\{x^i_Q\} = \begin{cases} 0 & \text{if signs of } x^i_Q, \mathbb{E}^i_{Q-1}\{x^i_Q\} \text{ coincide} \\ 1 & \text{else} \qquad \forall x, i. \end{cases} \tag{1}$$

occurring whenever firm's expectations about price and production developments differ from their realizations.

Expectations on production and price developments for the upcoming three months of firm i, $\mathbb{E}^i_{Q-1}\{x^i_Q\}$[4], are elicited on a monthly basis. Throughout this text, Q refers to quarterly measures, whereas t marks monthly variables. x^i denotes qualitative firm-level information on either price or production developments. For our baseline instrument, firms' responses in the last month t of quarter $Q-1$ hence indicate their expected production (price) development for quarter Q. Every month, firms further indicate realized production and price developments for the previous month. While the questions on expected developments provide

[4]As expectations are asked every month for the upcoming three months, to underline their monthly nature, it would be more appropriate to denote the expectations as $\mathbb{E}^i_t\{x^i_{t+3,t}\}$. As we however only rely on the expectation given in the last quarter of a month and hence referring to the upcoming quarter, we use the quarterly notation.

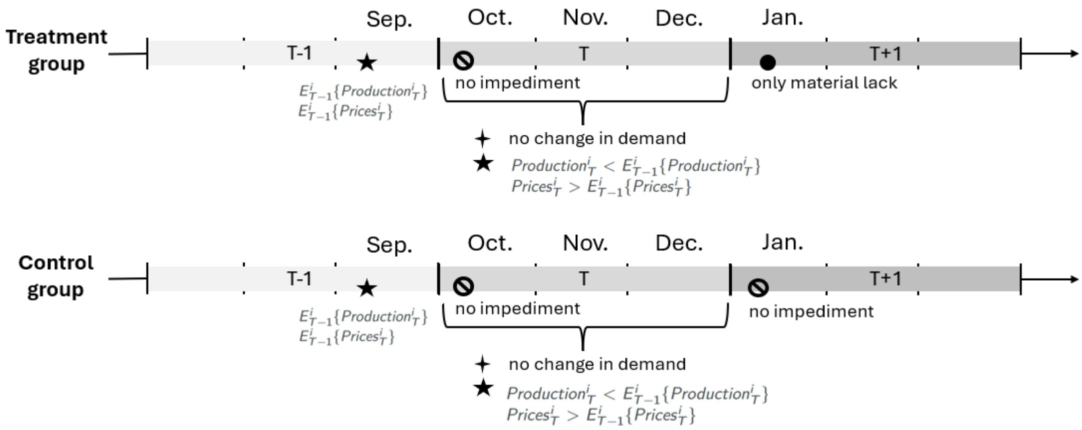
a natural candidate to align with the quarterly information about production impediments, we need to aggregate the monthly information on firms' actual price and production realizations to the quarterly frequency. We start by re-coding monthly realizations x_t^i such that $x_t^i \in \{-1, 0, 1\}$, depending on whether production (prices) *declined, did not change,* or *increased.* And proceed by taking the sum of the three monthly values over the corresponding quarter: $x_Q^i = \sum_{k=0}^{2} x_{t+k}^i$. We interpret a positive value of x_Q^i as an increase, a negative one as an overall decrease, and 0 as no change in prices (production) during that quarter. We recognize that the aggregation mechanism chosen does not allow to account for the magnitude of changes. Hence, a sequence consisting of no change followed by an increase and ultimately a decrease would amount to unchanged production (prices) over the quarter — although the decrease might quantitatively exceed the previous increase or vice versa.

Next, to distinguish this generic supply shock from a material supply shock, our shock of interest, we add information on self-reported production impediments. We characterize an unexpected material supply shock as a situation in which a lack of material is not a concern for firms when stating their production (price) expectations for the upcoming quarter but becomes a concern only after responding to the survey. We hence implicitly assume that firms who report material impediments at the same time when providing information on their expectations, have (to a large extent) already been constrained during the past month(s) — the odds of a sudden material impediment arising exactly at the time of answering the ifo survey should be rather small.

Apart from material shortages due to supply chain disruptions, firms could potentially also report material constraints in response to a positive demand shock. To control for the latter, we additionally use monthly (qualitative) firm-level data about demand developments and construct an auxiliary quarterly variable on firms' demand situation, similar in construction to the quarterly measure on production and price developments. We only consider firms to be hit by an unexpected supply-side driven input material supply shock if their demand situation remained unchanged during the quarter.

We then combine the information on forecast errors regarding prices and production, on production impediments and demand developments to flag a firm in our sample as hit by a material input shock if i) price and production expectations for quarter Q were better than actual realizations, ii) at the beginning of quarter Q, when stating expectations, the firm does not indicate any production impediments but reports material shortage as a unique production impediment in quarter $Q + 1$, and iii) the firm does not report a change to demand during quarter Q. Note that in the context of prices, expectations are considered better than realizations if expected prices were lower than realized prices, whereas in the context of production, expectations are considered too optimistic if realized production falls short off expected production, compare Table (2).

Figure 3: Timing of survey answers and firm level constraints for identification of a tightening material supply chain shock



Notes: Panel visualizes the identification of a material input supply shock at the firm-level. The upper graph shows constraints for firms hit by such a shock, the lower graph refers to the control group of firms that is not affected by such a shock. The visualization generalizes to any generic quarter.

Table 2: Forecast error restrictions to identify a generic negative supply shock

	Production (IP)	*Prices (PPI)*
Sign restriction	$\mathbb{E}^i_{Q-1}\{IP^i_Q\} > IP^i_Q$	$\mathbb{E}^i_{Q-1}\{PPI^i_Q\} < PPI^i_Q$

The final shock series is then constructed following multiple steps. Figure (3) visualizes our identification approach. We start by defining treatment and control groups.

Step 1: Flag all firms that satisfy conditions on generic supply shock and material impediment in line with a *tightening* material input shock and do not report changes to demand. We call this group treatment group T. We proceed to define an associated control group of firms that only differs from its treated counterpart in that firms neither indicate any production constraints in quarter Q nor in quarter $Q+1$.

Step 2: Next, we aggregate the information from *Step 1* at the manufacturing sub-sector level. For each sector, we calculate the share of firms satisfying the conditions for the treatment and control group relative to those that only satisfy the impediment constraint. We weight individual firms with their headcount to acknowledge that firm size may matter for the spread of bottlenecks

$$sh_{t,j,s|\bar{d}} = \frac{weighted\ \#firms\ sign\ \&\ impediment\ (j)\ satisfied}{weighted\ \#firms\ impediment(j)\ satisfied} \tag{2}$$
$$\forall j \in (mat, noimp),\ s \in manufacturing\ sector.$$

Step 3: Aggregate the sector level series for the treatment and control group up to the manufacturing level. Aggregate series are the weighted sum of sector-level shares, where the share in gross value added of total manufacturing serves as weights.

$$sh_{t,j|\bar{d}} = \sum_{s=1}^{N} sh_{t,j,s|\bar{d}} \frac{GVA_{Y,s}}{GVA_Y} \quad \forall j \in (mat, noimp), \tag{3}$$

with s denoting the manufacturing sector, GVA_Y is gross value added in the manufacturing sector for year Y and $\bar{d}$ indicates an unchanged demand situation at the firm level. $j = mat$ denotes the condition on material constraints in line with a tightening of material availability, while $j = noimp$ refers to the conditions on production impediments for firms not affected by any production constraint.

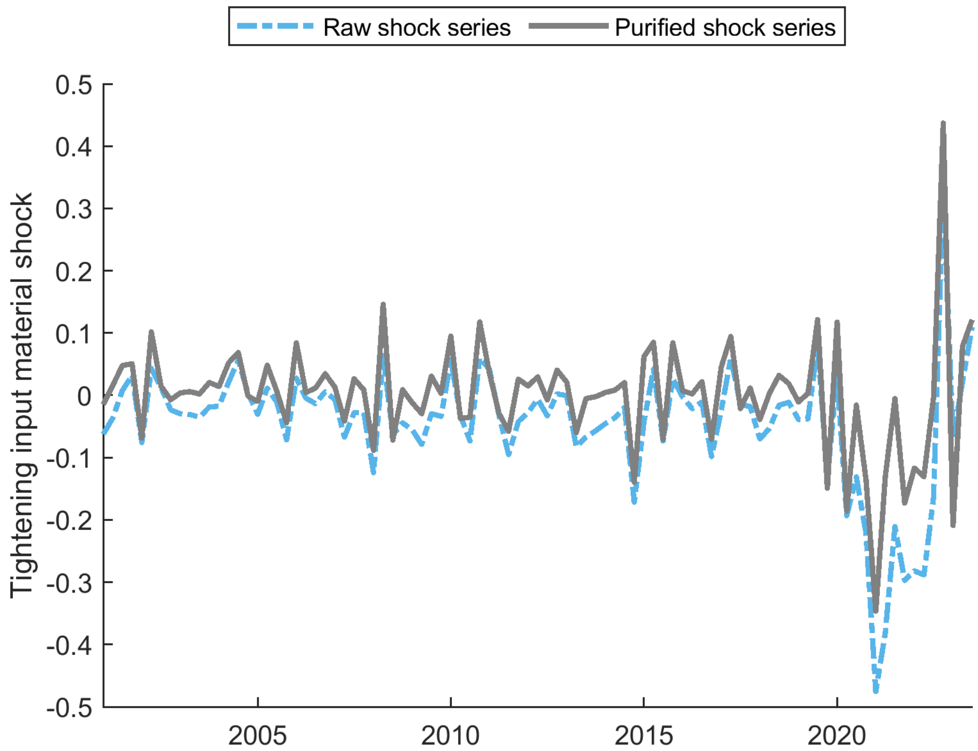
Step 4: The aggregate exogenous shock series iv_t is given as the difference between treatment and control group.

$$iv_t = sh_{t,mat|\bar{d}} - sh_{t,noimp|\bar{d}} \tag{4}$$

We validate the shock series by running some common sanity checks. At best, the shock series is neither serially correlated nor predictable to fit the notion of an exogenous and unexpected event. We cannot rule out that the series exhibits some degree of serial correlation at conventional levels of significance. We follow Miranda-Agrippino and Ricco (2023) and purify the shock series of its auto-correlated component by running an auxiliary regression of the shock series on its own lags and use the residual of this regression as the final shock series. This series shows no signs of serial correlation. Next, we run a set of Granger causality tests on the purified shock series to ensure its not correlated with potential macro variables showing significant swings during times of material constraints. These economic variables include the stock of finished goods, GDP, investment, CPI inflation, a commodity price index, the EUR-USD and EUR-CNY exchange rates and the ECB short-term interest rate. We find evidence that GDP and commodity prices Granger cause our shock series depending on the stringency of the significance levels. We therefore include these series in the VAR setting to account for potential cross-correlations. Appendix (A.2) provides the corresponding figures and statistics.

Figure (4) shows the quarterly shock series. Noticeably, the tightening shock series captures disruptive events triggering material shortages following major (natural) events and disasters but also accentuates the extent to which the build-up in supply chain disruptions and lack of material is to a great extent endogenously driven or eventually outweighed by overall uncertainty mirroring in high shares of forecast errors.

Figure 4: Series of tightening input material shock



Notes: Blue line shows the raw shock series of a tightening input material shock according to equation (4). The grey line plots the purified shock series retrieved as the residual of a regression of the shock series on its own lags.

3.2. Discussion of the external instrument

The ultimate goal of our paper is to present an approach that allows to quantify the extent to which supply chain constraints (or any shock related to material constraints) affect output and prices, where identification is based on an exogenous shock series constructed based on firm level-information on material input shocks. In the following, we discuss its exogeneity and provide supporting evidence on its relevance from a statistical perspective as well as results from sanity checks on the properties of the shock series.

A material or supply chain shock is similar in nature to any other supply shock: it is likely to affect prices and output in opposite directions. Simply imposing sign restrictions on the forecast error at the firm level, in line with the notion of any generic supply shock, hence does not unambiguously identify the shock we are looking for. We therefore impose additional constraints based on self-reported production impediments in order to attribute forecast errors to unexpected material input shocks. By imposing constraints on two consecutive answers for the question on production impediments, we hope to capture anticipation effects at the firm-level regarding production (price) expectations to the best possible extent. By construction, no firm will enter the shock series in two consecutive quarters. The shock series measure the excess share of firms whose forecast error is largely due to unexpected material input constraints. Importantly, this series disregards firms that already adjusted their expectations in anticipation of such a shock. At least to the extent that at the point of stating expectations production impediments were not yet a point of concern. Admittedly, we cannot rule out that a firm was not yet aware of the potential that material may be constrained over the next quarter, but even if not stating this explicitly, a firm may probably account for this in its price and production expectations. As a result, our measure of the firm-level forecast error would properly assign "no error" or "error" with the caveat that we simply could not differentiate the magnitude of being wrong due to the qualitative nature of our survey information. The normalization implied by equation (2) accounts for a potentially unequal distribution of firms facing a material supply shock across time and sectors. The definition of a control group addresses two additional concerns related to the exogeneity of the instrument. First, it is unlikely that firms will always get their expectations right, hence some firms always commit a forecast error. Second, alternative economy-wide shocks can cause firms' expectations to diverge from realizations. These may be shocks that are difficult to control for at the firm-level because they affect sectors as a whole: Among others, fiscal or monetary policy interventions, but also any other idiosyncratic shock that could invalidate identification. To remove their potential influence from the shock series, we introduce the control group. This rests on the assumption that these economy-wide shocks affect all firms equally and that firms in the treatment group do not differ structurally from those in the control group. If true, our shock series effectively captures the excess portion of forecast errors due to unexpected material input shocks. Furthermore, we address concerns regarding the endogenous build-up of material constraints due to an increase in demand by conditioning firms not to face changes in their demand situation.

Another concern may arise whether the endogenous build-up of constraints along the production network invalidates identification. Although identification is based on firm-level data, we cannot discriminate between first-, second-, or higher-round effects. However, we argue that the inability to account for endogenous network effects is not a major concern for our identification strategy. What matters is that firms do not expect the material supply shock at the time they report expectations. Yet, it does not matter whether the following shock then arises as a result of a purely exogenous event, such as a natural disaster, or as a result of an endogenous build-up of resource constraints across firms. That is, a firm may face an unexpected material shortage not only because it is directly affected by a disastrous event, but also because at least one of its suppliers is affected, but the firm did not expect this event to affect its own production. Given this holds true, we should be able to quantify the aggregate effect of these shocks on the economy.

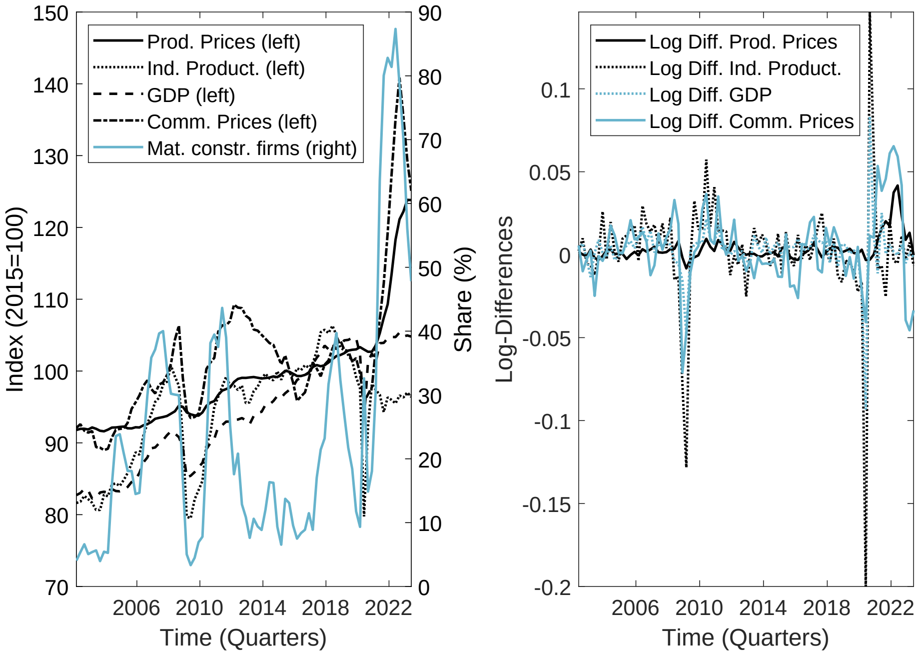
Beyond exogeneity, the shock series should be closely enough related to the shock of interest, i.e. it is necessary to assess the strength of the external instruments. We follow Montiel Olea *et al.* (2021) and calculate the F-statistic from regressing the residual of the supply chain measure (ifo survey on material constraints) constructed from the first stage of the VAR onto our instrument. According to the literature, a relevant instrument should exhibit a corresponding F-statistic of at least 10. Anticipating part of the results here, column (3) of Table (A2) shows the F statistics for the tightening material supply shock. The Table also presents the F-statistic for a battery of robustness analyses and alternative shock series specifications that we present further below. The strength of the instrument varies slightly across the exact specifications of the VAR, yet for our baseline, the results suggest that the instrument should perform satisfactorily from a purely statistical point of view. In addition, Table A3 in Appendix B provides the average number of firms observed in each of the four groups identified to build the proxy.

3.3. Estimation

Our baseline analysis relies on a five variable Bayesian proxy VAR, akin to Stock and Watson (2012) and Mertens and Ravn (2013). Our main specification includes industrial production, the producer price index, GDP, a commodity price index and as endogenous measure of input material constraints the share of firms reporting material constrained as obtained from the ifo survey. Table (B6) in Apendix (B) provides information on the exact series and their sources. We construct "pseudo" series for both industrial production and the producer price index to mimic the availability of manufacturing sectors in the ifo Business Survey. The "pseudo" series isolate developments in the sectors represented in the firm-level data. We do so by aggregating the manufacturing branches represented in the ifo survey weighted according to their share in value added[5]. Our data spans the period between 2002Q1 and 2023Q4. The analysis is conducted on a quarterly basis as certain data necessary for constructing the instrument are available only at this lower frequency. Production and producer prices are aggregated into quarterly measures by means of averaging across the monthly observations. Industrial production, producer prices, GDP and the commodity price index enter the model in log differences. The left panel in Figure 5 depicts the raw series for industrial production, the producer price index, GDP, the commodity price index and the share of material constrained firms. The right panel shows the series as they enter the VAR.

[5]Our robustness checks show that results do not hinge on the inclusion of the "pseudo" series but also hold when using the official industrial production and producer price index in the manufacturing sector.

Figure 5: Time series entering the (baseline) VAR



Notes: Figure shows the evolution of the main macro variables entering the VAR . Left graph shows the untransformed variables, the right graph shows them as they enter the VAR in log differences.

The response of production and prices to a tightening input material supply shock is identified based on an instrument designed to extract the purely exogenous part of this variable. The crucial assumption underlying this identification procedure is the relevance and exogeneity of the instrument. We can only hope to recover the response to a supply chain shock if the instrument is solely correlated to the shock of interest and unrelated to any other shock in the system.

Starting point for our analysis is a regular reduced-form VAR(p) model given by

$$\mathbf{y}_t = \mathbf{c} + \sum_{i=1}^{p} \mathbf{B}_p \mathbf{y}_{t-i} + \mathbf{u}_t, \tag{5}$$

where p denotes the lag length, $\mathbf{c}$ is an $n \times 1$ vector of constants, $\mathbf{y}_t$ is an $n \times 1$ vector of endogenous variables and $\mathbf{u}_t$ is the $n \times 1$ vector of reduced-form innovations. As usual, we assume that the reduced-form errors are linearly related to the structural errors such that

$$\mathbf{u}_t = \mathbf{\Phi} \nu_t, \tag{6}$$

where $\mathbf{\Phi}$ denotes the impact matrix and ν_t is an $n \times 1$ vector containing the structural shocks we are after. By definition, the structural shocks are mutually uncorrelated, i.e. $Var(\nu_t) = \Omega$ is diagonal and $Var(\mathbf{u}_t) = \mathbf{\Sigma} = \mathbf{\Phi\Omega\Phi}'$.

Identification via external instrument To recover the impact of an input material shock, we use the newly introduced instrument as a proxy for the structural shock. We denote the instrument with x_t. A valid instrument needs to be correlated with the shock of interest (relevance condition (7)) but has to be uncorrelated to all other shocks (exogeneity condition (8))

$$\mathbb{E}[x_t \nu_{1,t}] \neq 0 \tag{7}$$

$$\mathbb{E}[x_t \nu'_{-1,t}] = \mathbf{0}, \tag{8}$$

where $\nu_{1,t}$ denotes the (structural) supply chain shock and $\nu_{-1,t}$ collects all other shocks. Given these two assumptions hold, to identify the structural shock we can write

$$\mathbb{E}[x_t \mathbf{u}'_t] = \Phi\mathbb{E}[x_t \nu'_{\mathbf{t}}] = (\phi_{\mathbf{1}} \quad \mathbf{\Phi_{-1}}) \begin{pmatrix} \mathbb{E}[x_t \nu_{1,t}] \\ \mathbb{E}[x_t \nu'_{-1,t}] \end{pmatrix} = \phi_1 \alpha, \tag{9}$$

stating that ϕ_1 is identified up to scale. Further,

$$\mathbb{E}[x_t \mathbf{u}'_t] = \begin{pmatrix} \mathbb{E}[x_t u_{1,t}] \\ \mathbb{E}[x_t \mathbf{u}'_{-1,t}] \end{pmatrix} = \begin{pmatrix} s_{1,1}\alpha \\ \mathbf{s}_{-1,1}\alpha \end{pmatrix}, \tag{10}$$

such that

$$\frac{\mathbf{s}_{-1,1}}{s_{1,1}} = \frac{\mathbb{E}[x_t \mathbf{u}'_{-1,t}]}{\mathbb{E}[x_t u_{1,t}]}, \tag{11}$$

given that $\mathbb{E}[x_t u_{1,t}] \neq 0$. Intuitively, equation (10) resembles the well known IV estimator and serves as departure for the two stage regression procedure, where u_1 is first regressed onto the instrument x and in a second step, $\mathbf{u}_{-1}$ is regressed upon the fitted values $\hat{u}_1$, that reflect the exogenous part of the reduced form innovation explained by the proxy. Our implementation for estimation is akin to Miranda-Agrippino and Ricco (2017).

To estimate the reduced form VAR, our baseline estimation we use a Minnesota prior on the parameters and two lags, as suggested by the Akaike-Information criterion.

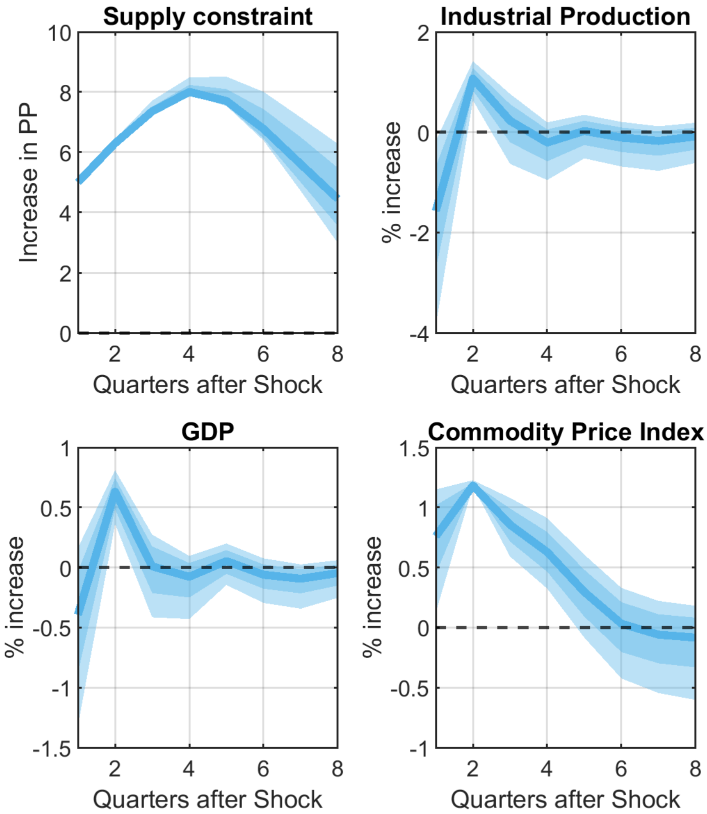
4. The effect of material constraints on prices and production

Figure (7a) shows the impulse response of all variables to the identified input material shock based on the proxy VAR. All responses are normalized to an increase in the share of firms reporting material constraints by five percentage points. This is close to the historic quarterly increase in firms reporting material constraints and about one fifth of the magnitude observed during the heights of supply chain disruptions following the Covid period. The response on all variables but the ECB short-term rate is measured in percentage changes. The latter is reported in basis point changes.

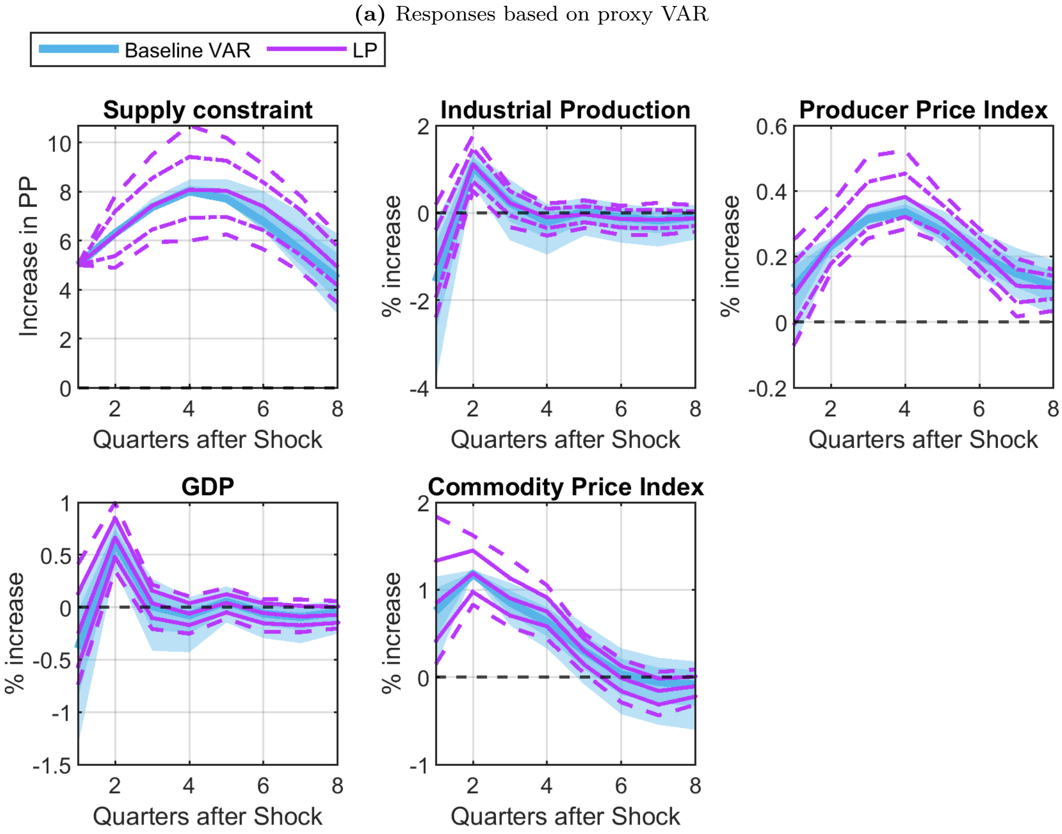
An unanticipated decline in the availability of input materials results in an immediate surge in producer prices. The surge in producer prices resulting from a negative surprise in material availability persists for an extended period and reaches its peak approximately four quarters after the onset of the shock. The subsequent decline in producer price inflation only happens gradually and stays significant throughout the entire horizon under consideration. Similarly, commodity prices increase in response to an input material shock. The increase on impact is about six times larger than the one on producer prices, yet, it reaches its peak already after two quarter and thereafter, the increase in commodity prices already starts declining and becomes insignificant after five quarters. Industrial production, in turn, only reacts with a delay and recovers from the shock within a few quarters. The response of GDP looks similar to the latter but unsurprisingly, the magnitudes of the effect are smaller.

Our modeling approach assumes that a VAR is an appropriate choice to model the underlying dynamics. As an alternative, we run local projections in the spirit of Miranda-Agrippino and Ricco (2017) and verify that our results are not driven by the underlying dynamics modeled in a VAR. Figure (7b) supports our baseline results. Qualitatively, impulse responses from both the VAR and the local projections are similar. In terms of magnitude, at least the median response from the local projection always falls within the confidence bands obtained from the VAR estimation.

Figure 6: Impulse responses to a tightening input material shock



(a) Responses based on proxy VAR



(b) Responses based on Local Projection

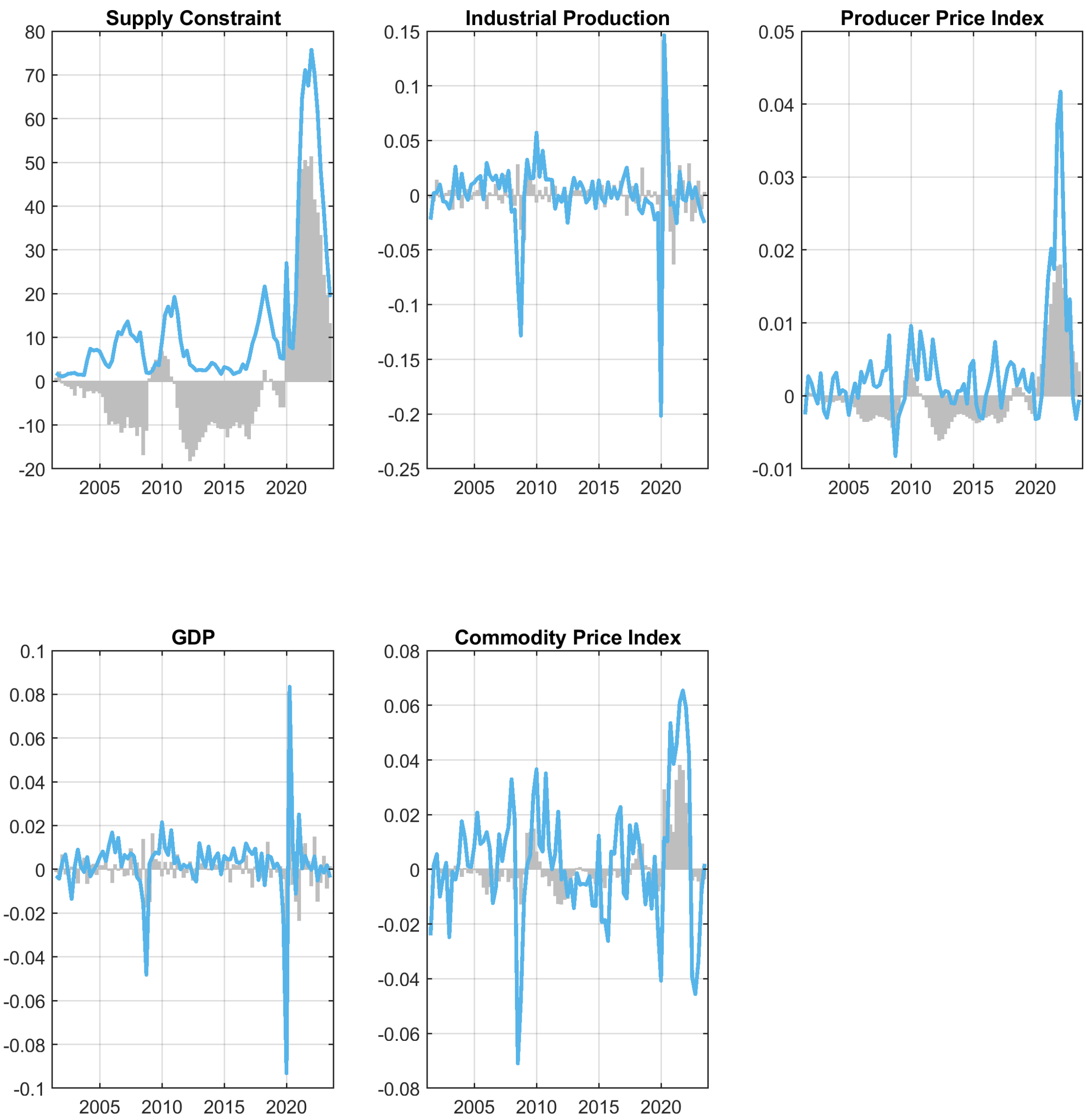
Notes: Impulse responses to an identified tightening input material shock, normalized to a five percentage point increase in the balance of firms affected by material shortages. Identification based on the IV presented in the main text. The endogenous supply chain constraint is measured by the share of firms reporting material lack as production impediment. Top panel shows the impulse responses based on a proxy VAR estimation, where blue shaded areas show the 90% and 68% confidence bands. Bottom panel shows the impulse responses based on local projections. Solid purple line denotes the median response. Dashed and dotted lines represent the 90% and 68% confidence bands.

We close the discussion of our baseline results by comparing results based on our suggested identification approach to identification approaches commonly used in the literature, i.e. sign restrictions potentially enriched with narrative restrictions (Bai *et al.*, 2024; Finck *et al.*, 2024; Khalil and Weber, 2022; Kilian *et al.*, 2021). For the sign restricted approach we impose that in response to an input material shock, the share of firms reporting material constraints increases, industrial production declines and producer prices increase on impact. Figure (A1) in Appendix (A.1) shows the results. Results based on our suggested instrument are more precisely estimated than those using the sign-restricted alternative. The dynamics across both sets of impulse responses, however, are similar although magnitudes slightly differ. In particular, the effect on producer prices is more pronounced and more persistent based on the proxy VAR as is the effect on Commodity prices.

4.1. Historical importance of input material shocks

To what extent did input material shocks influence historical economic fluctuations? Figure (8) shows the historical contribution of input material shocks to fluctuations in the variables entering our baseline VAR specification. Pure input material shocks contributed positively to an increase in firms reporting material constraints in the early 2010s and after the onset of the Covid period, while for other periods, the decomposition suggests that dynamics were mostly endogenously driven. In turn, industrial production and GDP do not appear to be structurally driven by these shocks. Although we can attribute a small share of quarter-to-quarter fluctuations, particularly in the early 2010s and in the post-Covid period, to input material supply shocks. Fluctuations in the producer price index and the commodity price index, in turn, seem to be stronger affected by these shocks. Again we note the positive contribution to the build-up in producer prices in the early 2010s and the strong impact of these shocks to producer price increases since 2020. The commodity price index shows an even stronger positive correlation with the input material shock contribution. Although the shock historically explains a small fraction of commodity price inflation, we can clearly see how increases and decreases are affected by these shocks. Input material shocks, on the other hand, contributed significantly to the rise in commodity prices in the early 2020s but their importance already declined towards the end of our sample.

Figure 8: Historical importance of tightening input material shocks



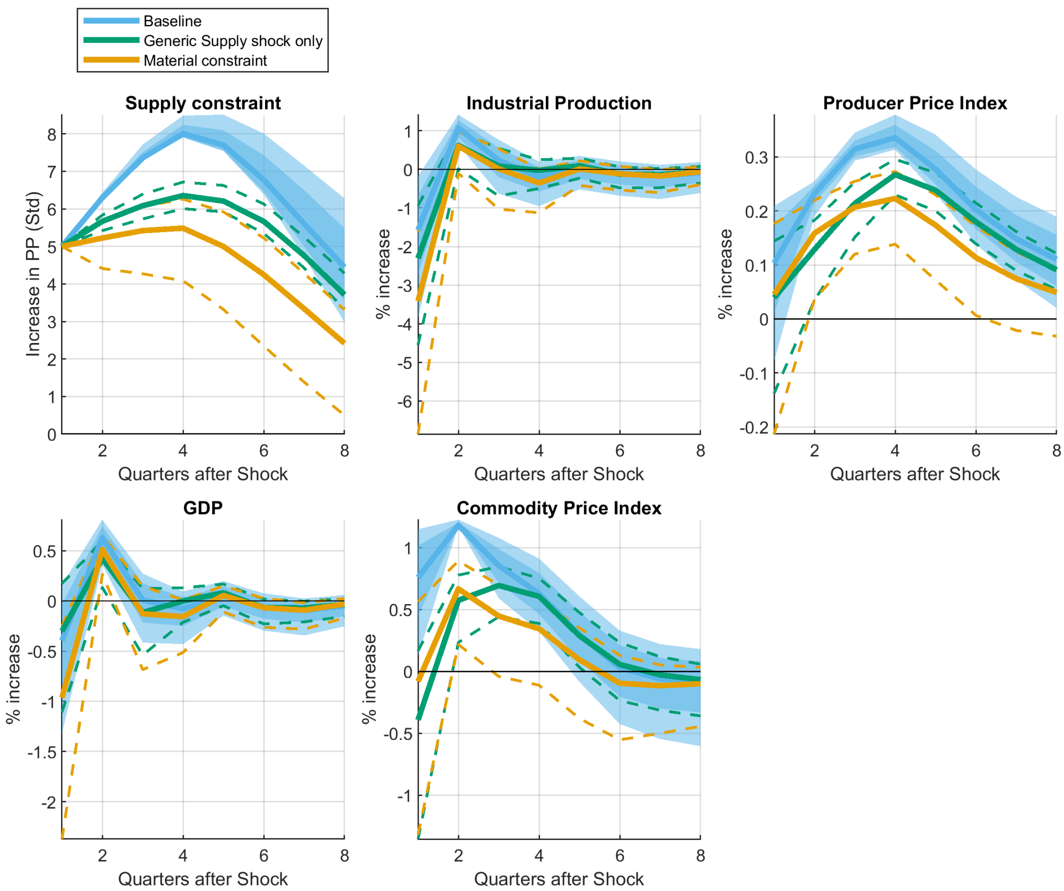
Notes: Graph shows the historical decomposition of the input material supply shock of the main variables in our baseline VAR specification. Blue lines show the evolution of the variables as they enter the VAR. Grey bars indicate the historical contribution of the tightening input material shock.

4.2. Decomposing the instrument

The instrument consists of two components - the generic supply shock (including the condition on unchanged demand) and the impediment constraint. The generic supply shock should represent the average response of prices and production to any generic supply shock, whereas the impediment constraint alone represents the average effect from missing material for production due to any reason. How does the input material shock compare to shocks due to one of the components alone? From a statistical perspective, all partial shock series contain relevant information (Table (A2)). Yet, the interpretation of the shocks is not as clear as before as the individual responses represent average effects only. For the impediment condition, the response to supply-side and demand-side developments may be mixed.

Figure (9) shows the impulse responses to the partial shock series along with the baseline results. Unsurprisingly, we see the biggest difference in the response of the endogenous supply constraint measure. Industrial production reacts more strongly to average supply-side shocks than to a pure material input shocks. Industrial production declines most in response to an average material input shock, which may be driven by the combination of demand and supply-side factors that make up the average effect. These differences vanish quickly after the onset of the shock. A similar pattern appears in the response of GDP to the individual shock components. The effect on producer and commodity prices, in turn, is strongest for our identified shock although the dynamics themselves are robust in response to each individual shock series.

Figure 9: Decomposition of the instrument

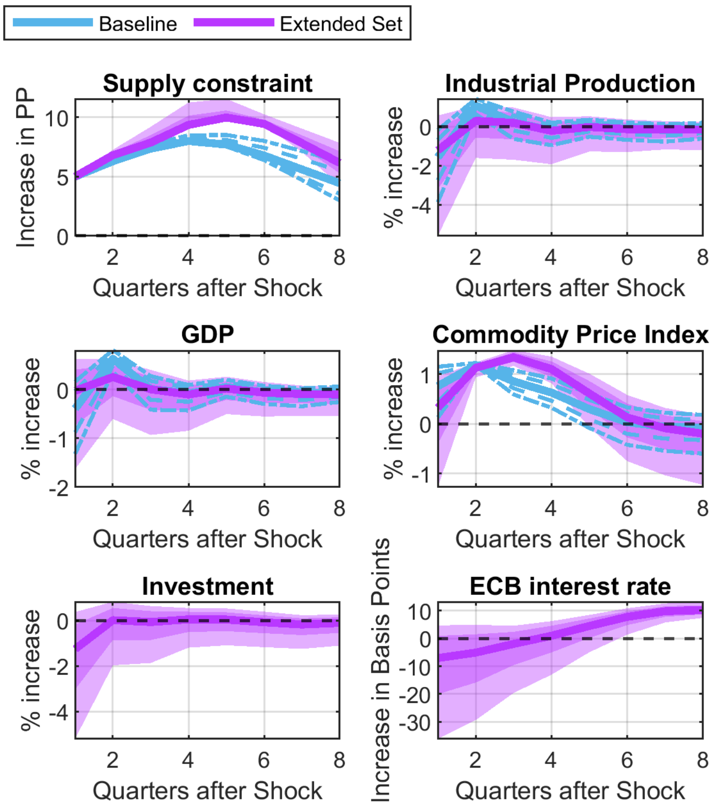


Notes: Graph shows the impulse responses to an identified tightening supply chain shock, normalized to a five basis point increase in the balance of firms affected by material shortages. Along with the responses from decomposing the instrument into its (average) supply shock and (average) missing material component. All other identifying assumptions remain unchanged and as explained in the text. The endogenous supply chain constraint is measured by the share of firms reporting material lack as production impediment. Blue shaded areas show the 90% and 68% confidence bands for the baseline result. Dashed lines report the 68% confidence bands on the effects of the partial shock series.

4.3. Examining the response of output and the role of interest rates

Firms may draw more heavily on their inventories and use what they have left in storage to avoid production delays when faced with material shortages. Firms may also react by adjusting their investment decisions, although it is not clear ex-ante whether firms may increase or decrease their investments. Ultimately, given the inflationary pressure of an input material shock, the central bank may need to take action and adjust its monetary policy. We hence add the ECB short-term interest rate, firm-level investment and a survey based measure of stock of inventory to our VAR (Figure (10)). The change in inventories is measured in percentage points, the response of firm-level investment is given in %-changes and the change in the ECB short-term rate is measured in basis points. The effects on the base variables are qualitatively similar, but eventually change statistically significantly in their magnitudes. Firms run down their inventories temporarily. We do not find any statistically significant effect on firm-level investment. The ECB short-term interest rate increases about a year after the onset of the shock.

Figure 10: Impulse response to a tightening input material shock



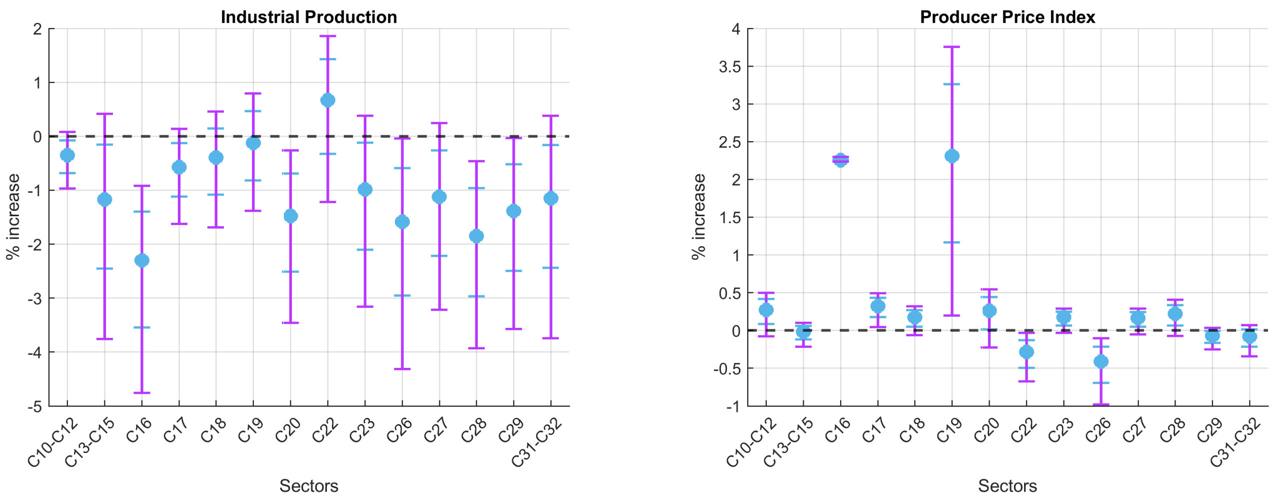
Notes: Impulse responses to an identified tightening input material shock, normalized to a five percentage point increase in the balance of firms affected by material shortages. Identification based on the IV presented in the main text. The endogenous supply chain constraint is measured by the share of firms reporting material lack as production impediment. The solid blue line repeats the median response from the baseline results (Figure (6)), the dashed lines indicate the 90% and 68% confidence bands. The purple line reports results based on a larger set of variables. Shaded purple areas show the 90% and 68% confidence bands.

4.4. Sectoral breakdown

Focusing on aggregate effects conceals sector-level heterogeneity. We re-run the analysis, whenever possible, at the manufacturing sector level. Some sectors are either too small in the number of firms represented in the survey or do not exhibit enough statistical power on the instrument to allow for a rigorous sector-level identification of the shock. Table (A4) provides an overview of sectors covered individually. Figure (11) confirms that overall, the sector-level responses mimic the contemporaneous aggregate effects. We note, however, that the magnitudes with which these shocks drive sector-level output and producer prices differ across sectors. Figure (A8) in the Appendix provides the full set of impulse responses.

When facing a tightening input material shock, output falls particularly for the manufacturers of wood and cork (C16), for manufacturers of machinery and equipment (C28) and the manufacturers of motor vehicles, trailers and semi-trailers. In contrast, the surge in prices is experienced by almost all manufacturing industries. Manufacturers of wood and cork (C16) andof coke and refined petroleum products (C19) recorded the largest price increases, while manufacturers of rubber and plastic products (C22) recorded the smallest.

Figure 11: Instantaneous response to tightening input material shock at the sector level



(a) Response of industrial production to shock

(b) Response of producer prices to shock

Notes: Immediate responses to an identified tightening supply chain shock, normalized to a five percentage point increase in the balance of firms experiencing material shortages, across sectors. Identification based on the main IV specification presented in the main text, identifying tightening and easing shocks individually. Error bands indicate 90% and 68% confidence bands.

5. Sensitivity analysis

We run a series of checks designed to verify that our results do not depend on specific assumptions on the VAR or the construction of the instrument. We group these checks into two categories: first, sensitivity checks on the instrument, with particular attention paid to the timing assumptions on the underlying questions in the questionnaire; and second, an assessment of the sensitivity of our results to changes in the specification of the overall model. We also contrast our baseline results with a naive approach that employs a variant of our instrument, which simply states the share of firms exclusively reporting material impediments as obstacle to production. Appendix (A.4) provides the full set of impulse responses for all sensitivity checks. We again standardize all results to represent the effect of an increase in the balance of firms experiencing a material shortage by five percentage points. This holds true for all specifications except the one including the GSCPI index, where results are instead standardized to an increase in the index by one unit, i.e. one standard deviation of the underlying series. The results highlight that while the model specification does not alter results too much, certain constraints on the construction of the shock series seem adequate to avoid capturing too much noise in firm responses.

Construction of the instrument The instrument is based on firm-level constraints configured to extract the unanticipated and hence exogenous part of input supply constraints. First, we consider two alternative timing assumptions in firms' responses to account for questions with only vaguely formulated time horizons: Firms are asked to provide expectations about future price and production developments "within the next three months", leaving the exact horizon open to interpretation. We therefore adjust our conditions to take the responses to the expectations questions from the first month of the quarter rather than from the last month of the previous quarter. Second, the firm-level forecast error requires that production and price expectations are better than actual realizations. We experiment with an alternative version in which either prices or production or both can perform worse than expected, removing the strict condition on the generic supply shock. To assess the importance of accounting for demand effects, we additionally provide results based on an IV that does not impose the condition of unchanged demand during a quarter but keeps all other constraints in place. Here, we also include the discussion on the results based on a naive instrument.

The naive instrument suggests that the instantaneous effect on producer prices is more pronounced, but also declines more rapidly over the specified horizon. From a statistical point of view, the naive instrument performs slightly worse than the proposed IV in terms of relevance (Table (A2)). Both observations stress that accounting for a variety of potential confounding factors is warranted. With a slight adjustment in the timing assumption of expectations, the F-statistic on the relevance condition decreases slightly (Table (A2)). Yet impulse responses are barely affected, with the exemption of the commodity price index, where a significant increase only appears after one quarter. For most variables, the median response falls within the confidence bands of the baseline results. In contrast, when the instrument is only required to deviate from its expected realization in terms of prices or production (or eventually both), the "lax" sign-restricted approach, it fails the relevance test from a statistical perspective. We interpret this finding as evidence that a clear-cut "sign-restricted supply shock" definition at the firm level is indeed necessary to satisfactorily extract the structural supply shock. Removing the demand condition from the instrument, i.e. allowing demand to change during the quarter, possibly also due to endogenous network effects across firms, attenuates the impulse responses on the endogenous input constraint measure and the producer and commodity price index. The negative effects on industrial production and GDP are accentuated on impact but qualitatively follow the dynamics of the baseline response.

Model specifications We re-estimate the model with the following modifications: First, include three lags of all variables. Second, we use an uninformative Jeffrey prior instead of a a Minnesota prior. Third, we limit the data to run only until 2020 Q1 to allow for the possibility that the effects are driven by the unprecedented supply chain constraints observed during the Covid pandemic. Finally, we use the GSCPI as an alternative endogenous measure of supply chain tightness.

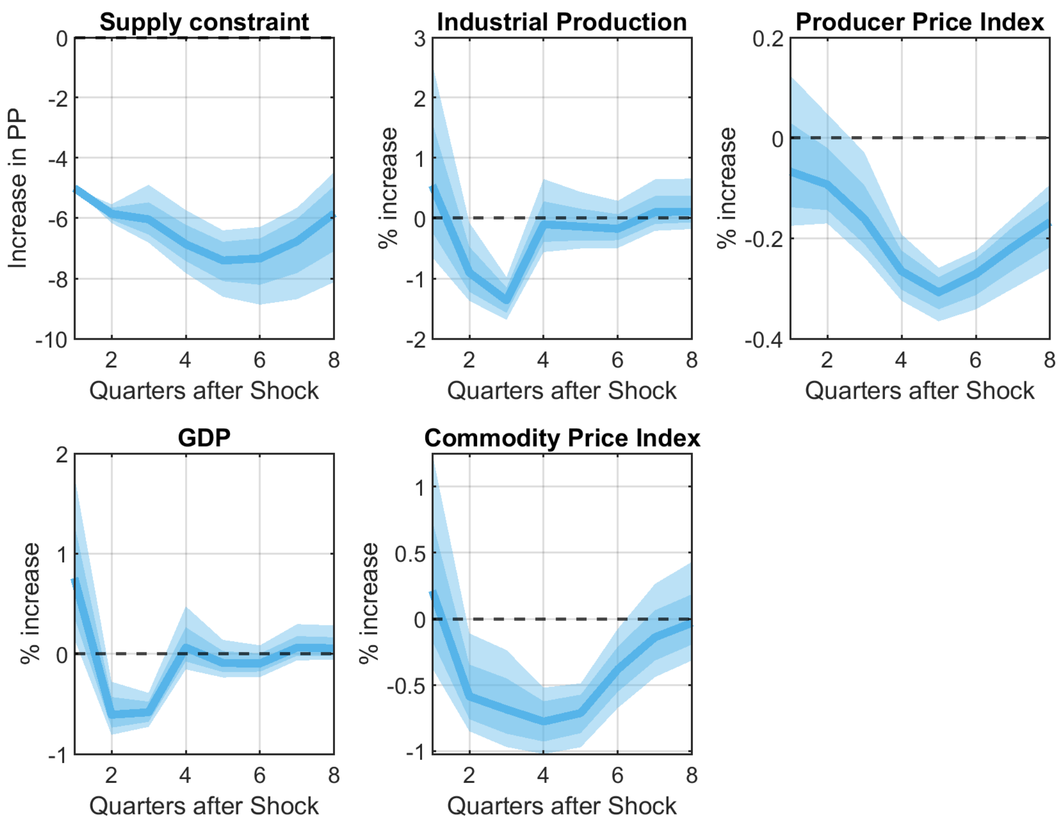
The alternative model specifications do not significantly alter our main results. Varying the lag length or changing the prior on coefficients only has a small impact on the median responses, that nonetheless fall into the confidence bands of the baseline results. The only exception is the response to commodity prices that is slightly lower on impact, yet prolonged when adding more lags. Although our proposed external instrument is similarly effective in extracting the exogenous component of the GSCPI index (tableA2), the increase in producer prices resulting from a tightening shock in supply chain pressure is, cumulatively, slightly larger than in all other specifications. Similarly, the negative impact on industrial production on impact is more pronounced. This may be due to the difficulty in perfectly reconciling the magnitude of the two endogenous series measuring supply or input material constraints. Overall, the results show similar dynamics and the qualitative differences are small. When excluding the Covid-period from our sample, the correlation between the instrument and the shock of interest, as measured by the F-statistic, slightly decreases. Noticeably, the effect on producer prices is even more persistent in this case, while the effect on commodity prices is slightly lower on impact than in the baseline but the increase keeps up for longer and tends to be higher for longer.

6. The effect of easing material constraints

Firms may not only be negatively surprised by constraints in input material availability, but may also be hit by an unexpected easing of supply tensions. Analogous to the tightening shock series, we construct a shock series capturing periods of unexpected easing of material availability. Appendix (A.5) provides details on the construction of the shock series, with section (A.2) including sanity checks on the suitability of the easing shock series. Overall, this shock series exhibits similar characteristics as its counterpart capturing unexpected tightening in input material availability. Hence, our analysis follows a similar structure as above to keep results comparable. Figure (13) shows the impulse responses to an unexpected easing shock. All results are normalized to represent a five percentage point decrease in the share of firms reporting material constraints. Historically, the average quarterly decline in the share of firms reporting material constraints is about 3 percentage points, with a maximum decline of 18 percentage points observed toward the end of 2020.

In comparison to the tightening shock, an unexpected reversal of material constraints has an instantaneous effect on industrial production and GDP whereas the producer price and commodity price index only react with a delay. Overall, the magnitudes of an easing shock are generally smaller than the ones related to the tightening shock. An unexpected reversal of material constraints has a positive, yet short-lived effect on industrial production and GDP. Compared with the tightening shock, prices react more slowly to a positive surprise in material availability. Commodity prices take one quarter until they start declining significantly. Producer prices only fall significantly two quarters after the onset of the shock.

Figure 13: Impulse response to an easing input material shock



Notes: Impulse responses to an identified easing input material shock, normalized to a five percentage point decrease in the balance of firms affected by material shortages. Identification based on the IV presented in the main text. The endogenous supply chain constraint is measured by the share of firms reporting material lack as production impediment. Shaded areas show the 90% and 68% confidence bands.

7. Discussion, Policy implications and Conclusion

We use detailed firm-level data that allows to track firms over time to identify a macro shock of interest. In our empirical application, we focus on the impact of input material shocks on economic activity in the German manufacturing sector. For identification, we combine the general notion of a supply shock with information on firms' responses to production impediments. Our empirical results highlight the negative effect on producer price and commodity price inflation as well as an adverse effect on industrial production and GDP. An easing input material shock shows opposite effects. Industrial production and GDP react almost instantaneously, whereas the effect on producer and commodity prices is much longer lived, yet only kicks in about one quarter after the shock hit the economy. The magnitudes of the effect of an easing shock are generally smaller than the ones to a tightening shock. We show that these results also hold at the sector level although we find some heterogeneity in the magnitude of the effects. We exploit the granular construction of the proxy variable to decompose the overall impact of a material shortage shock into its sub-components and show the extent to which our shock of interest differs from any generic supply shock.

Our findings underscore the inflationary risk associated with supply chain disruptions, which do not reverse quickly once these disruptions dissipate. Thus, efforts to mitigate supply chain impediments may prove beneficial to output in the long term. This is particularly true considering the stronger repercussions of negative shocks over the benefits of positive surprises. Although the individual firm is not directly subject of our analysis, results nonetheless suggest that the more firms rely on potentially international supply chains, the greater also their risk of being adversely affected once certain material becomes unavailable what may finally translate into a decline in overall economic activity. Proactively accounting for the risks associated with ever more (globally) integrated production chains is crucial not only for firms or governments, but ultimately also for monetary policy authorities that are in charge of keeping prices stable.

Given access to suitable and comprehensive firm-level data, this approach may complement established identification methods in time-series settings, such as sign-restricted and narrative approaches, by leveraging firm-level dynamics to infer the macro-level dissipation of shocks.

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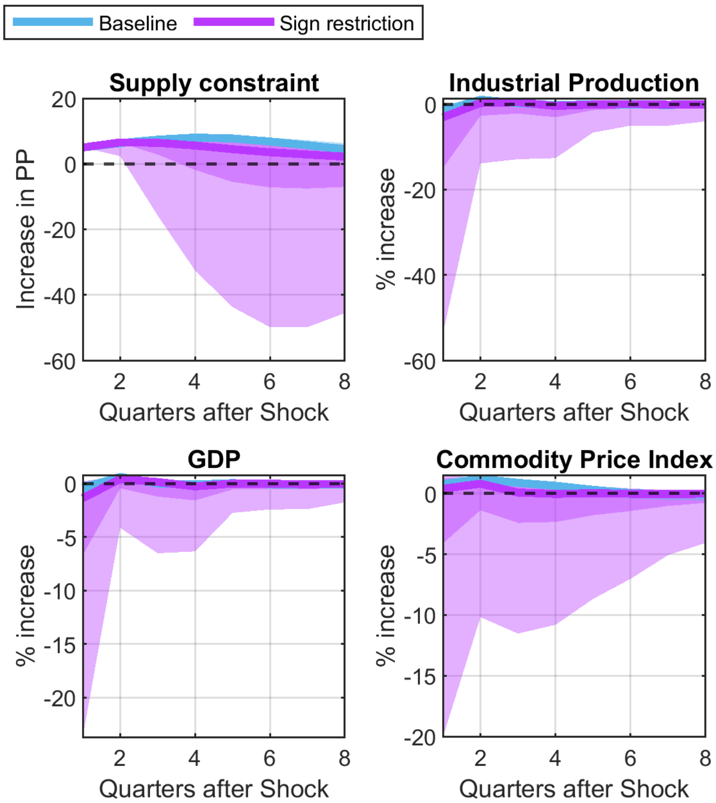
A. Appendix: Additional results

A.1. Comparing identification approaches

Figure (A1) shows impulse responses based on sign restrictions along with those from our suggested exogenous shock series.

Figure A1: Impulse response to a tightening input material shock



Notes: The graph shows the response to a tightening input material shock, standardized to a five percentage point change in the number of firms reporting material constraints. Shaded areas show the 90% and 68% confidence bands. Baseline identification refers to the set up where identification is achieved via the instrument proposed in the main text. The purple responses show the impulse responses based on a sign restricted approach where we impose the share of firms reporting material constraints and industrial production to decrease on impact, whereas prices are expected to increase on impact. The endogenous measure of input material constraints is the share of firms reporting material constraints.

A.2. Sanity checks on the shock series

At best, the shock series should not neither be serially correlated nor should it be predictable. Figure (A2) shows the autocorrelation function for the tightening shock series and its purified version. The shock series shows signs of serial correlation. We follow Miranda-Agrippino and Ricco (2023) and account for the serial component by running an auxiliary regression of the shock series on its own lags where the residuals of this regression serve as a purified shock series. Figure (A4) supports that this indeed addresses the concerns of autocorrelation. Analogously, we perform the same test on the easing shock series and again find evidence of weak serial correlation that we address similarly (Figure (A5)).

Figure A2: Serial correlation of tightening input material shock

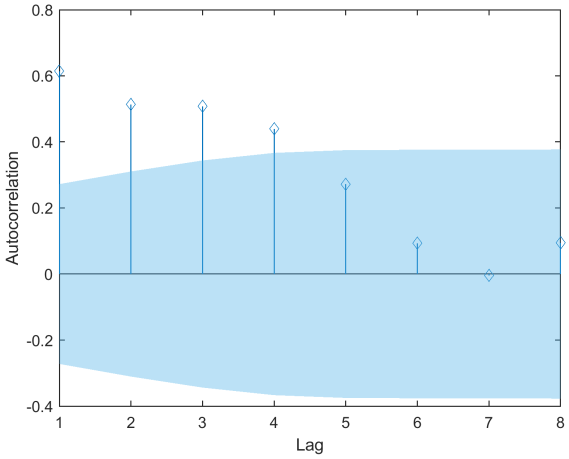


Figure A3: Tightening shock series

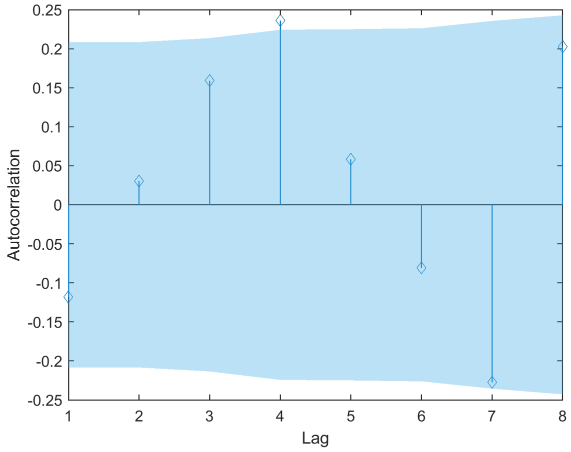


Figure A4: Purified shock series

Notes: Autocorrelation function of the tightening shock series, along with the 95% confidence bands. The left Figure shows the autocorrelation function on the tightening shock series based on equation (4). The right Figure shows the autocorrelation function on the purified shock series retrieved as the residual from an auxiliary regression of the shock series on its own lags in the vein of Miranda-Agrippino and Ricco (2023).

Figure A5: Serial correlation of easing input material shock

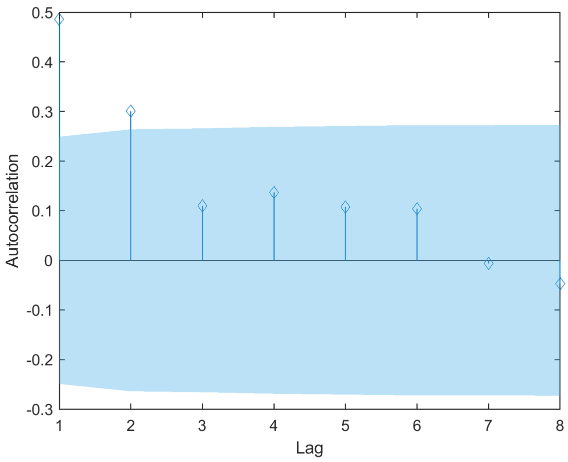


Figure A6: Easing shock series

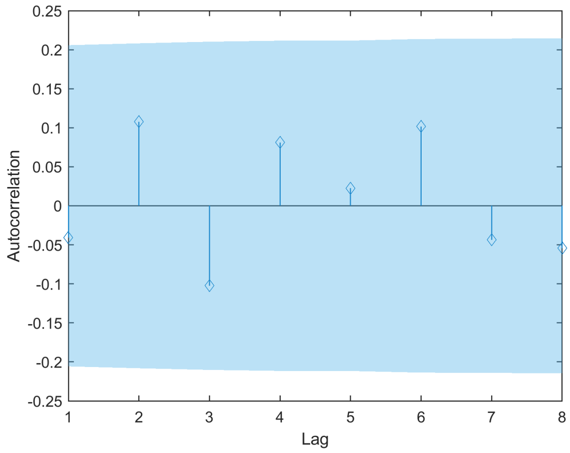


Figure A7: Purified shock series

Notes: Autocorrelation function of the easing shock series, along with the 95% confidence bands. The left Figure shows the autocorrelation function on the easing shock series based on equation (4). The right Figure shows the autocorrelation function on the purified shock series retrieved as the residual from an auxiliary regression of the shock series on its own lags in the vein of Miranda-Agrippino and Ricco (2023).

Additionally, past information should not have any predictive power on the shock series (Ramey, 2016) and would make inference questionable. Table (A1) reports the results of Granger causality tests on the easing and tightening shock series using various macro- and macro financial indicators. While we find some evidence that GDP and commodity prices may have predictive power in forecasting the tightening shock series, we do not find such evidence for the easing shock series. We hence include these two variables in our baseline specification. To keep results comparable, we follow the same strategy for the easing shock series.

Table A1: Granger causality test results

Lags	Producer Price Index	GDP	Firm-level investment	Commodity index	EUR-USD exchange rate	EUR-CNY exchange rate	ECB short-term rate
Tightening shock series							
1	0.36	0.02	0.94	0.03	0.54	0.29	0.11
2	0.70	0.00	0.97	0.04	0.60	0.11	0.28
3	0.81	0.00	0.98	0.01	0.76	0.23	0.49
4	0.85	0.00	0.99	0.00	0.43	0.39	0.50
Easing shock series							
1	0.96	0.06	0.27	0.14	0.32	0.10	0.06
2	0.96	0.09	0.28	0.19	0.45	0.12	0.11
3	0.94	0.18	0.28	0.37	0.64	0.18	0.09
4	0.96	0.08	0.33	0.44	0.64	0.10	0.11

Notes: The Table reports the p-values on a series of Granger causality tests of the tightening and easing shock series using various macro and macro-financial variables and different lag length specifications.

Finally, identification in the proxy VAR is only valid if the instrument is closely enough related to the shock of interest. Table (A2) holds the F-statistics for the easing and tightening shock series for the baseline specification as well as for the sensitivity checks on model and instrument specification introduced in section (5).

Table A2: F-statistics for shock series

Specification	Easing shock series	Tightening shock series
Baseline	45.55 (25.02)	27.14 (10.4)
Sensitivity analysis: IV specification		
Naive IV	12.89 (21.32)	11.99 (22.69)
Alternative timing expect.	12.62 (5.22)	40.98 (14.67)
Lax price & production	13.27 (23.64)	9.19 (9.94)
No demand condition	20.11 (11.89)	24.49 (26.19)
Sensitivity analysis: Model specification		
No Covid	20.69 (12.26)	46.37 (47.19)
Lag length (3)	52.78 (35.88)	30.22 (46.81)
Alt. Prior	45.55 (25.02)	27.14 (23.43)
GSCPI	14.66 (11.71)	23.33 (27.42)

Notes: The Table shows the robust F-statistics (non-robust F-statistics in parentheses) from the regression of the endogenous supply chain measure onto the instrument (tightening and easing shock series separately). The instrument is constructed as explained in the main text to remove the endogenous share of firms reporting a lack of material. The naive instrument is constructed as the share of firms *solely* reporting material constraints as obstacles to production. The IV based on alternative timing, conditions on price and production expectations in the first month of each quarter, whereas the instrument with lax price and production condition only requires either production or price realizations to differ from their expected developments. The Table also shows F-statistics for specifications detailed in the robustness section. Following Montiel Olea *et al.* (2021), any F-statistic greater 10 is indicative of a relevant instrument. The robust statistic accounts for heteroskedasticity.

Table (A3) shows the average number of firms for each group used in the construction of the proxy variable.

Table A3: Number of observations by firm groups reflecting proxy assumptions

	Tightening shock		**Easing shock**	
	Material impediment	No impediment	Material impediment	No impediment
# Firms only impediment satisfied	299	2,377	523	2,619
# Firms impediment and sign satisfied	168	385	126	243

Notes: The Table shows the average number of firms for each group identified for the construction of our baseline instrument.

A.3. Sector-level results

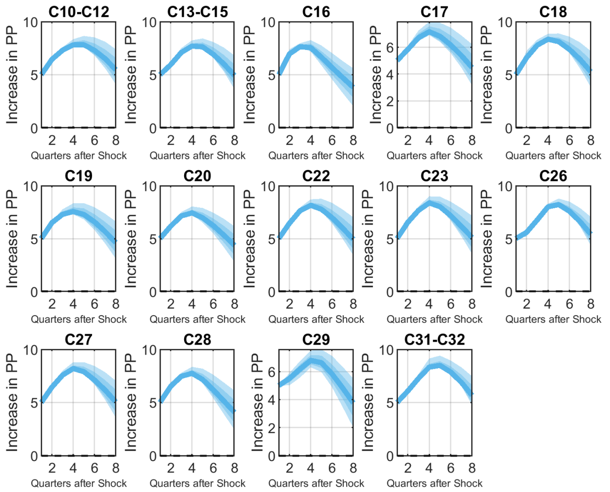
Table (A4) lists the sectors for which an individual sector-level response to a tightening shock is identifiable. Figure (A8) shows the entire set of impulse responses to a sector-level tightening input material shock.

Table A4: Identification at the sector-level: feasible combinations

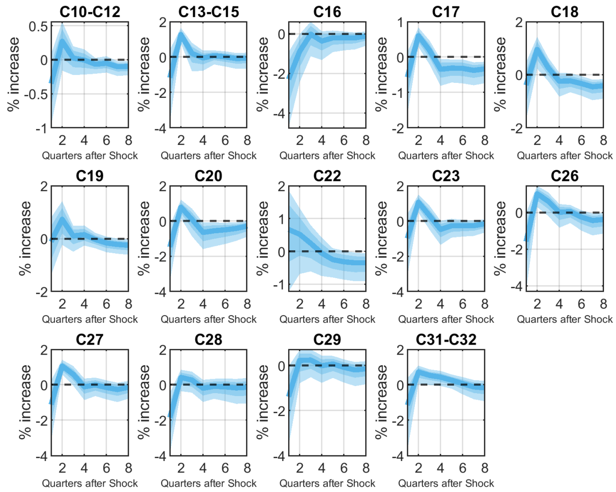
	Tightening shock
C10-C12	x
C13-C15	x
C16	x
C17	x
C18	x
C19	x
C20	x
C21	
C22	x
C23	
C24	x
C25	x
C26	x
C27	x
C28	x
C29	x
C31-C32	x

Notes: The Table lists the sectors where identification at the sector level is feasible either. Identification not feasible if hardly any firms available andor too low F statistics on IV. Classification as in Table (B7).

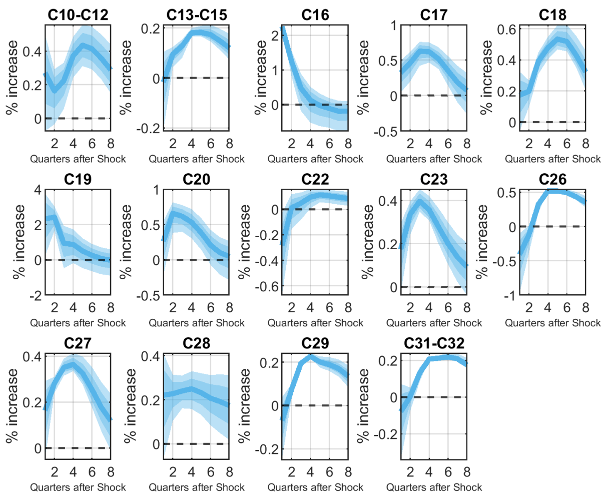
Figure A8: Sector-level impulse responses to tightening shock



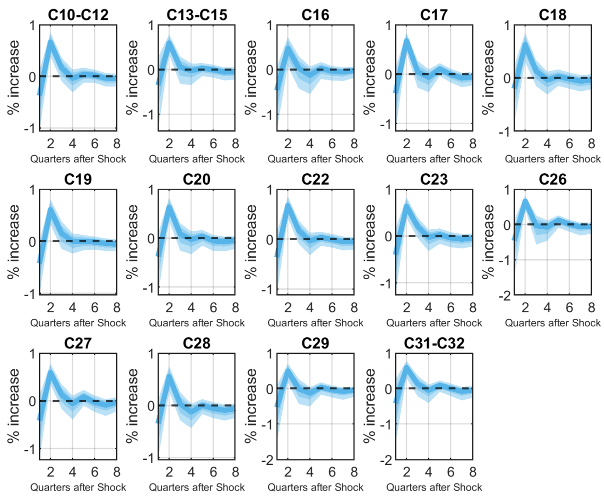
(a) Response of (endogenous) supply chain measure



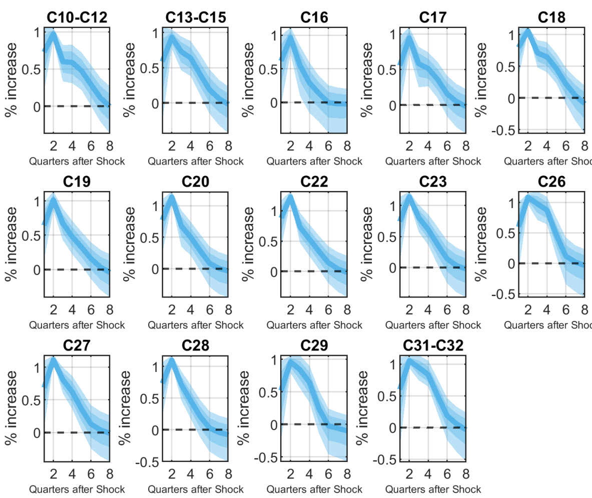
(b) Response of industrial production



(c) Response of producer prices



(d) Response of GDP



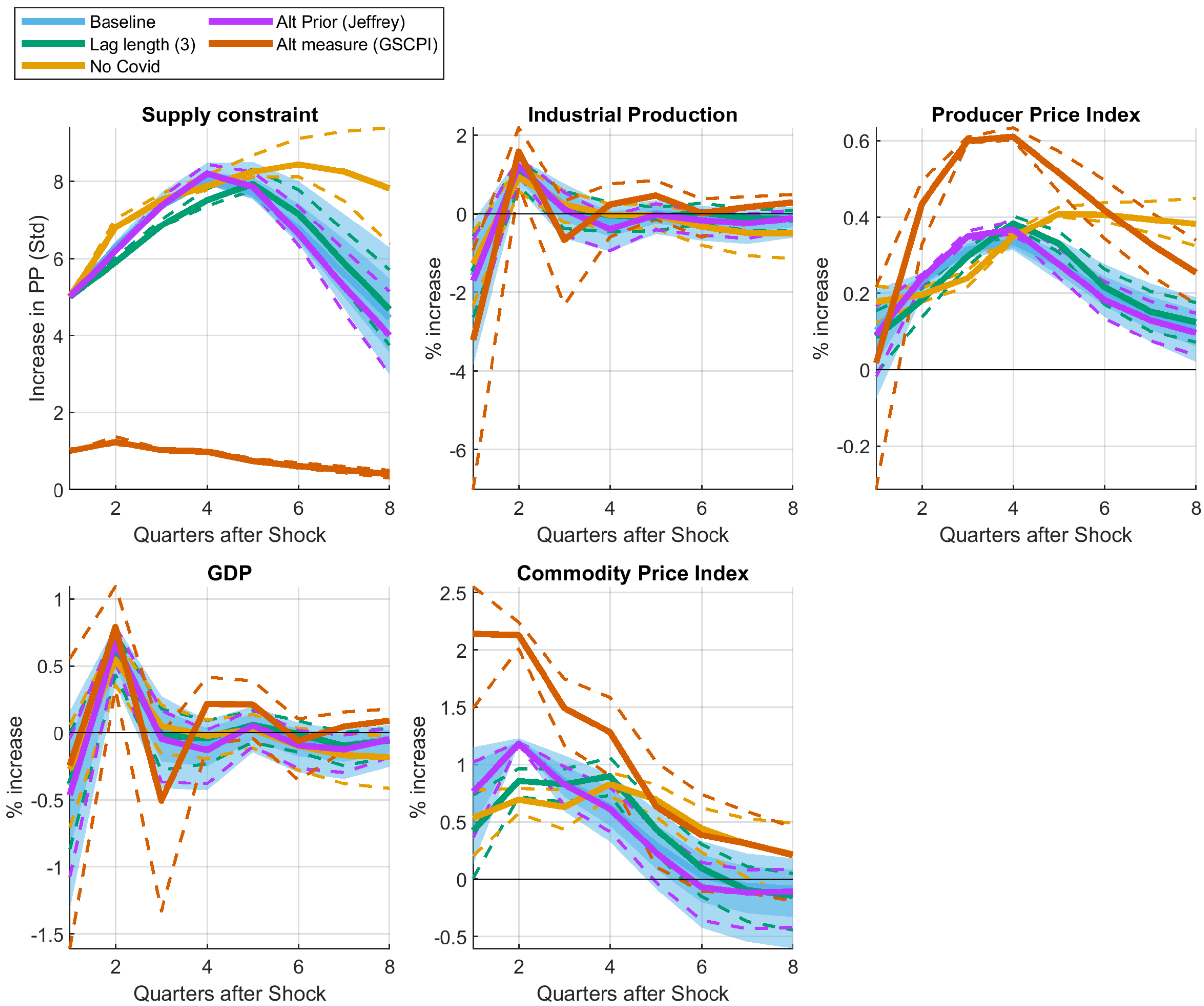
(e) Response of commodity price index

Notes: Impulse responses to an identified tightening supply chain shock at the sector level, normalized to a five percentage point increase in the balance of firms affected by material shortages. Identification based on the IV presented in the main text. Shaded areas show 68% and 90% confidence bands. The endogenous supply chain constraint is measured by the share of firms reporting material lack as production impediment.

A.4. Sensitivity analysis

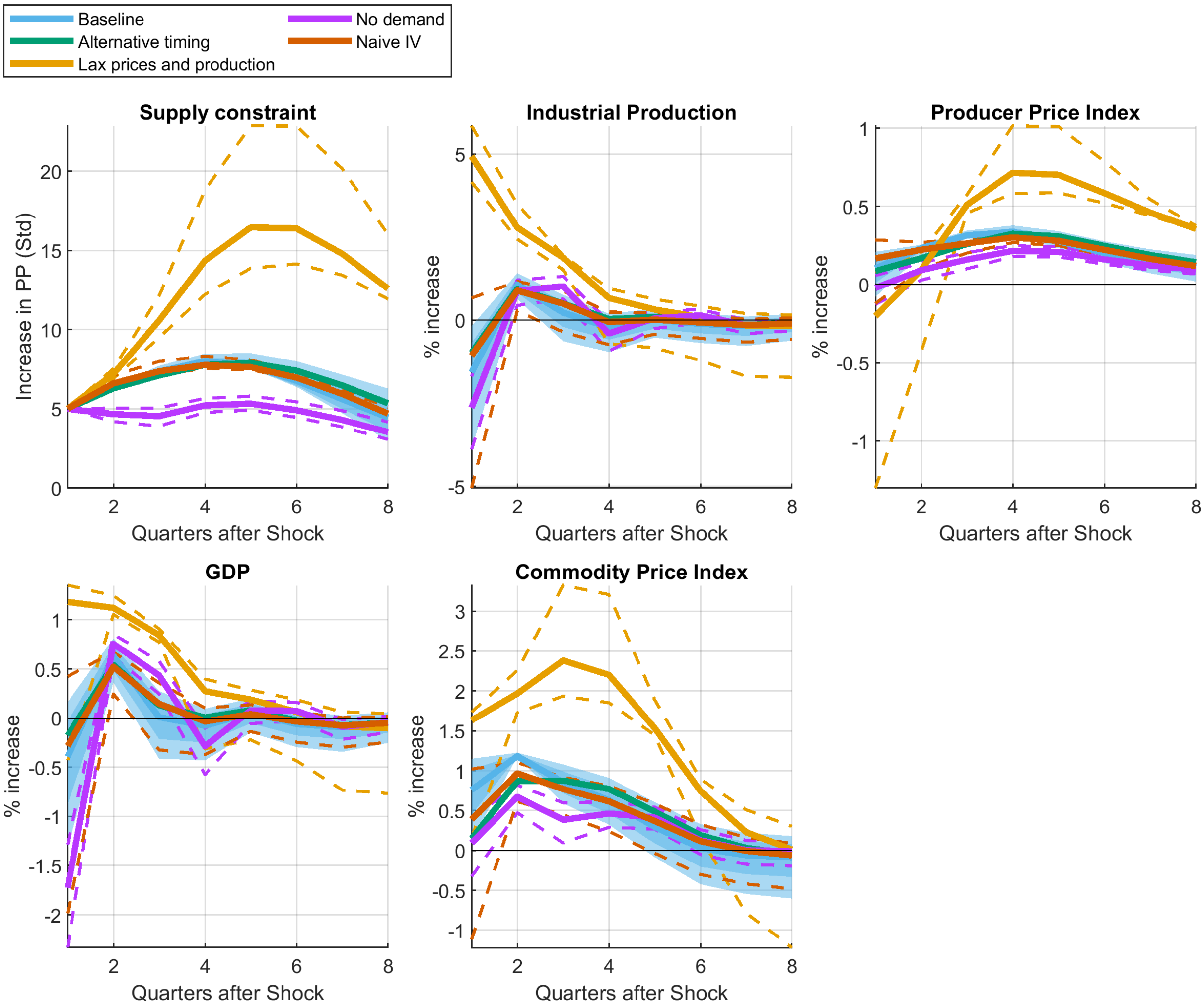
This appendix provides the impulse responses based on the sensitivity analyses for model (Figure (A10)) and instrument (Figure (A11)) specification presented in the main text.

Figure A10: Sensitivity analysis on model specification



Notes: Impulse responses to an identified tightening input material shock, normalized to a five percentage point increase in the balance of firms affected by material shortages. Identification based on the IV presented in the main texts. The endogenous supply chain constraint is measured by the share of firms reporting material lack as production impediment, except for the results based on the NY FED GSCPI. Blue shaded areas show the 90% and 68% confidence bands for the baseline results. Dashed lines represent 68% confidence bands on sensitivity specifications of the VAR.

Figure A11: Sensitivity analysis on IV specification



Notes: Impulse responses to an identified tightening input material shock, normalized to a five percentage point increase in the balance of firms affected by material shortages. Identification based on the IV presented in the main text. The endogenous supply chain constraint is measured by the share of firms reporting material lack as production impediment. Blue shaded areas show the 90% and 68% confidence bands for the baseline results. Dashed lines represent 68% confidence bands on sensitivity specifications of the instrument.

A.5. Easing supply chain shocks

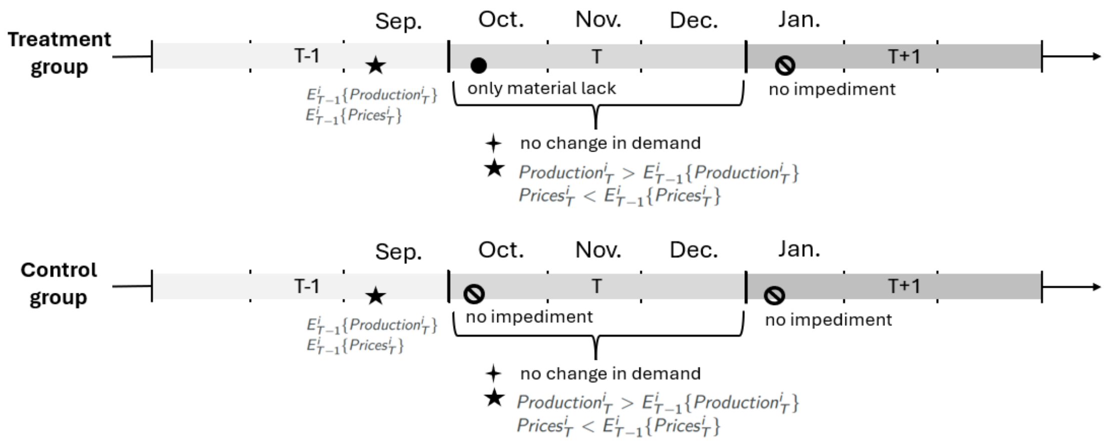
We follow an approach similar to the identification of a tightening shock to identify easing supply chain shocks, e.g. a situation where firms are surprised by the availability of material. We think of an easing shock as the opposite of a tightening shock, wherefore conditions on identifying firms hit by this shock are the reverse of what we impose for a tightening shock.

Table A5: Sign restriction on the forecast error to identify a (generic) positive supply shock

Shock type	Production (IP)	Prices (PPI)
Easing	$E^i_{Q-1}\{IP^i_Q\} < IP^i_Q$	$E^i_{Q-1}\{PPI^i_Q\} > PPI^i_Q$

We hence flag a firm as being hit by an easing material constraint shock if i) price and production expectations for quarter Q were worse than actual realizations, ii) in quarter Q, the firm indicates that production is (uniquely) constrained by material shortages but in the following quarter, no production impediment is reported, and iii) the firm does not report a change to demand during quarter Q. Table A5 summarizes the sign restrictions for identifying the generic positive supply shock.

Figure A12: Timing of survey answers and firm level constraints for identification of an easing material supply chain shock



Notes: Panel visualizes the identification of an easing material input supply shock at the firm-level. The upper graph shows constraints for firms hit by such a shock, the lower graph refers to the control group of firms that is not affected by such a shock. The visualization generalizes to any generic quarter.

Figure (A12) again visualizes the constraints imposed at the firm level. To arrive at the economy-wide shock series, we follow the exact same steps as in the main text.

As for the negative supply shock, we then aggregate the sector-level series for the treatment and control group up to the manufacturing level:

$$sh^{Easing}_{t,j,s|\bar{d}} = \frac{weighted\ \#firms\ sign^{Easing}\ \&\ impediment\ (j)\ satisfied}{weighted\ \#firms\ impediment(j)\ satisfied}$$

$$\forall j \in (mat, noimp),\ \ s \in manufacturing\ sector.$$

Aggregate series are the weighted sum of sector-level shares, where the share in gross value added of total manufacturing serves as weights:

$$sh^{Easing}_{t,j|\bar{d}} = \sum_{s=1}^{N} sh^{Easing}_{t,j,s|\bar{d}} \frac{GVA_{Y,s}}{GVA_Y} \quad \forall j \in (mat, noimp),$$

The aggregate exogenous shock series iv^{Easing}_t is hence given as the difference between treatment and control group.

$$iv^{Easing}_t = sh^{Easing}_{t,mat|\bar{d}} - sh^{Easing}_{t,noimp|\bar{d}}.$$

B. Appendix: Data

This appendix provides additional information on the data used for the analysis.

B.1. Data sources and transformations

Table (B6) provides an overview of the series entering our analysis, including potential transformations and their sources.

Table B6: Data, Data sources, Data transformations

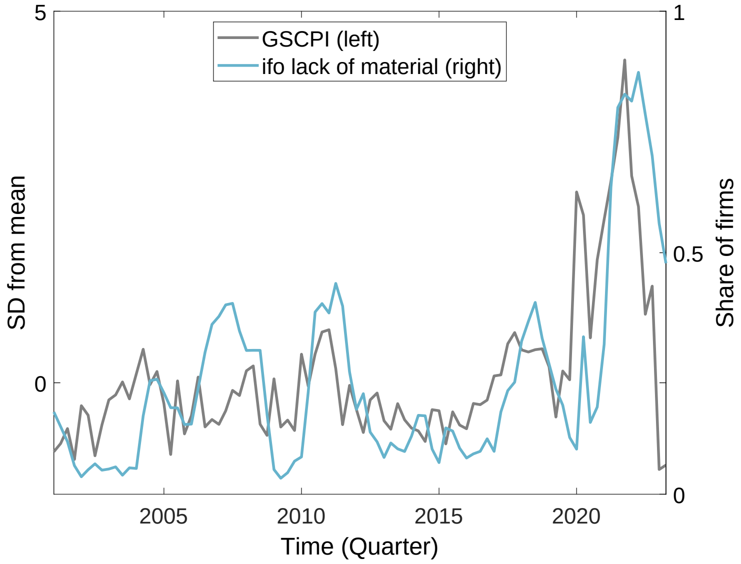
Variable	**Source**	**Transformation**
Share of firms reporting material constraints	ifo Business Survey	First difference
Stock of finished products (inventory)	ifo Business Survey	First difference
Industrial Production (price-, calendar-, seasonally adjusted)	Eurostat	Log difference
Producer Price index (calendar-, seasonally adjusted)	Eurostat	Log difference
GDP (price-, calendar-, seasonally adjusted)	German Federal Statistical Office	Log difference
Firm-level investment (calendar-, seasonally adjusted)	German Federal Statistical Office	Log difference
Commodity price index (calendar-, seasonally adjusted)	IMF	Log difference
ECB policy rate	German Central Bank	Change Basis Points
Global Supply Chain Pressure Index	New York Federal Reserve	Standard Deviations
Exchange rates	German Central Bank	First difference

Notes: Table shows the variables entering our analysis, along with their sources and transformations.

B.2. GSCPI and ifo material constraint measure

The overall share of firms indicating to suffer from a lack of material is, with a correlation coefficient of 0.64, closely related to the Global Supply Chain Pressure index provided by the New York Federal Reserve (figure B13).

Figure B13: Measures of supply chain disruptions



Notes: The graph shows the evolution of the GSCPI and the share of firms reporting material constraints as production impediment in the ifo Business Survey.

B.3. Manufacturing industries included in the ifo survey

Table B7 lists all German manufacturing industries included in the ifo survey and hence, in our analysis.

Table B7: Subsectors of the Manufacturing sector (C)

ISIC Code	Subsector
C10-C12	Manufacture of food products, beverages and tobacco
C13-C15	Manufacture of textiles, wearing apparel, leather and related products
C16	Manufacture of wood and of products of wood and cork, except furniture
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of pharmaceuticals, medicinal chemical and botanical products
C22	Manufacture of rubber and plastics products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, trailers and semi-trailers
C31-C32	Manufacture of furniture, other manufacturing

Notes: The Table lists the manufacturing subsectors covered in the ifo Business survey, following the ISIC Rev. 4 sector classification.

B.4. ifo Business Survey: Questions relevant for our analysis

While the questions regarding plans and expectations for the upcoming three months, as well as the questions regarding the review of the month ahead, are asked every month, the special question is elicited every first month of the quarter (January, April, July and October).

German (Original)	*English*
Pläne und Erwartungen für die nächsten 3 Monate:	**Plans and expectations for the upcoming 3 months:**
1. Unsere Produktionstätigkeit wird voraussichtlich *steigen/etwa gleich bleiben/abnehmen/keine nennenswerte inländische Produktion* 2. Unsere Preise werden voraussichtlich *steigen/etwa gleich bleiben/sinken*	1. Our production activity is expected to *increase/remain about the same/decrease/no significant domestic production* 2. Our prices are expected to *increase/remain about the same/decrease*
Rückblick: Tendenzen im Monat t	**Review: Trends in Month t**
1. Die Nachfragesituation hat sich im Vergleich zu t-1 *gebessert/nicht verändert/verschlechtert* 2. Unsere Produktionstätigkeit ist im Vergleich zu t-1 *gestiegen/gleichgeblieben/gesunken/keine nennenswerte inländische Produktion* 3. Unsere Preise wurden im Vergleich zu t-1 *erhöht/nicht verändert/gesenkt*	1. Compared to t-1, the demand situation has *improved/not changed/deteriorated* 2. Compared to t-1, our production activity *increased/remained about the same/decreased/no significant domestic production* 3. Compared to t-1, our prices *increased/not changed/decreased*
Sonderfragen	**Special Questions**
1. Unsere Produktionstätigkeit wird zurzeit behindert *ja/nein* Wenn ja, durch folgende Faktoren: *zu wenig Aufträge/Mangel an qualifizierten Fachkräften/Mangel an geringqualifizierten Arbeitskräften/Finanzierungsengpässe/Mangel an Rohstoffen oder Vormaterialien/zu geringe technische Kapazitäten/sonstige Faktoren*	1. Our production activity is currently hindered *yes/no* If yes, by the following factors: *insufficient orders/lack of skilled employees/lack of low-skilled employees/financial bottlenecks/lack of raw materials or pre-materials/insufficient technical capacities/other factors*