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# Network structure of the economy and the propagation of monetary shocks

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## Abstract

We calibrate a network model and monetary shocks based on empirical data from input-output tables for the Russian economy. We examine various aspects of the propagation of monetary shocks, such as the dispersion of relative prices and the local peak values of the aggregated price index achieved during the convergence to the new equilibrium. We show that these developments depend significantly on the way new money is injected into the economy.

**Keywords:** money supply, inflation, Cantillion effects, networks, input-output tables.

**JEL classification:** C63, C67, D57, E31, E51.

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## 1. Introduction

The wide variety and heterogeneity of economic agents makes it necessary to take into account individual characteristics and the complex structure of relationships when analysing macroeconomic processes. The basis for the analysis of production interactions are Input-output tables, which can be considered as a production network. Mathematically, the network structure of the economy is described by a weighted oriented graph, the nodes of which represent economic agents, and the directed weighted links stand flows of goods (services) and capital. The topological features of the network determine the mechanisms of the impact of various shocks on the economy.

The study of the relationship between the network structure of the economy and the transmission of monetary shocks plays a significant role in modern economic literature. This problem is sometimes called the 'Cantillon effect' in honour of the work of the 18th century French economist Cantillion (1755). A number of researchers have tried to explain the concept of 'price stickiness', which is widely used in macroeconomic theory, using various assumptions about the structure of the economy. Sheshinski and Weiss (1977), Calvo (1983), Mankiw and Reis (2002), and Sims (2003) develop models in which firms adjust prices at different rates in response to monetary shocks due to differences in the frequency and speed at which they receive information about shocks. This situation leads to significant heterogeneity in price changes. Cheng and Angus (2012) extended stickiness to money itself and examine the disproportionate effect of monetary injections. They claim that money itself is sticky in the sense that new money does not arrive in all participants' pockets instantaneously, mainly due to banking procedures. Deryugina and Ponomarenko (2021) develop this idea and show that, due to uncertainty about the nature of the distribution of money in the economy, it is not rational for agents to make decisions on price revision based on the observed aggregate indicator of the money supply. As a result, money becomes a leading indicator for inflation. Dietsch (2021) identifies several forms of bias inherent in different methods of money creation and the associated social effects. (See also the work of Sieroń (2019) for a general discussion of the contemporary relevance of Cantillion effects.)

Consideration of the economic system as a network actually originates from Leontief's well-known input-output model (Leontief, 1936), which has further been used as a relevant structure for the study of the transmission of idiosyncratic technological shocks (Long and Plosser 1983). The idea presented by Long and Plosser (1983) is broadly developed in a series of recent studies (see the comprehensive review of this by Carvalho and Tahbaz-Salehi (2019)). Nevertheless, the key questions asked in these works are still mainly related to the characteristics of the transmission of technological shocks. Only a limited number of studies actually analyse the propagation of monetary shocks using a network model (despite the fact that this approach seems extremely relevant).[1] Ozdagli and Weber (2017) present an empirical assessment of the role of the production network in the transmission of monetary shocks using a pseudo-network model. Mandel et al. (2019) and Mandel and Veetil (2021) study the impact of monetary shocks on price dynamics using an agent-

[1] A notable exception is the strand of literature that studies cross-sectoral heterogeneity in price rigidity and thus incorporates input-output linkages into the models used (Huang and Liu, 2004; Shamloo, 2010; Bouakez et al., 2014; Pasten et al., 2020).

based network model. In our work, we contribute to this strand of research in several ways. We calibrate the network model and monetary shocks using empirical data from input-output tables for the Russian economy. We examine various aspects of the propagation of monetary shocks, such as the dispersion of relative prices and the local peak values of the aggregated price index achieved in the convergence to the new equilibrium. We show that these developments depend significantly on the way new money is injected into the economy.

The rest of the paper is structured as follows: Section 2 describes the details of the network model, Section 3 explains the set-up of the simulations and presents the results of the experiments, and Section 4 concludes.

## 2. Model set-up

We set up an extended version of the model presented by Mandel and Veetil (2021) which allows the analysis of the price dynamics induced by the spread of monetary shocks through the production network.

Time is discrete and is indexed by $t = 1, 2, \ldots$ The economy is populated by several types of agents: numerous agents which may be thought of as industries or firms, the aggregate household, the government, and the rest of world (or an external agent). We denote the set of industries (and the goods they produce) by $N = \{1, \ldots, n\}$. Each firm produces one good and participates in intermediate consumption. In the production process, firms may use self-produced goods, goods produced by other firms, or imported goods, and they also purchase labour from households by paying wages. The representative household supplies $q_H^t$ units of labour, which is normalised to one. The household agent consumes the goods and service produced by the firms. Its preferences are represented by the Cobb-Douglas utility function of the form:

$$\mathrm{u}(c_1, c_2, \ldots, c_n) = \prod_{i=1}^{n} \left(c_i^{dom,t-1}\right)^{H_i^{dom}} \prod_{i=1}^{n} \left(c_i^{imp,t-1}\right)^{H_i^{imp}}$$

where $c_i^{dom,t-1} \geq 0$ and $c_i^{imp,t-1} \geq 0$ are the household consumption of domestically produced (indexed by '*dom*') or imported (indexed by '*imp*') good $i$ and $H_i^{dom}$ and $H_i^{imp}$ are the shares of good $i$ in household consumption, thus $\sum_{i=1}^{n} H_i^{dom} + \sum_{i=1}^{n} H_i^{imp} = 1$.

The government does not participate in the production process but consumes goods, paying using the income received from taxes and thereby redistributing part of the cash flows in accordance with its consumption structure. Both goods produced within the country and imported goods are used for intermediate and final consumption. The external agent supplies the imported goods and creates demand for exports.

Like Mandel and Veetil (2021), we assume that firms do not retain profit but use all the money received from sales as working capital and spend it on the purchase of goods. The production occurs via the Cobb-Douglas production function of the form

$$q_i^t = \left(L_i^{t-1}\right)^{w_i} \prod_{j=1}^{n} \left(X_{ij}^{dom,t-1}\right)^{a_{ji}^{dom}} \prod_{j=1}^{n} \left(X_{ij}^{imp,t-1}\right)^{a_{ji}^{imp}}, \tag{1}$$

where $L_i^{t-1} \geq 0$ is the labour input, $X_{ij}^{dom,t-1} \geq 0$ is the intermediate consumption of domestically produced good $j$,and $X_{ij}^{imp,t-1} \geq 0$ is the intermediate consumption of imported good $j$. Parameters $w_i$, $a_{ji}^{dom}$, and $a_{ji}^{imp}$ represent the share of labour and the corresponding shares of domestic and imported good $j$ in the production costs of industry $i$. We assume that production technology has constant returns to scale, and therefore, for every $i \in \{1, \dots, n\}$

$$\sum_{\mathrm{j}=1}^{n} a_{\mathrm{ji}}^{dom} + \sum_{\mathrm{j}=1}^{n} a_{\mathrm{ji}}^{imp} + w_{\mathrm{i}} = 1.$$

Matrices $A^{dom} = \left(a_{ij}^{dom}\right)_{i,j \in N} \in \mathbb{R}_{+}^{N \times N}$ and $A^{imp} = \left(a_{ij}^{imp}\right)_{i,j \in N} \in \mathbb{R}_{+}^{N \times N}$ represent the intersectoral links in the economy.

Let $H_j^{dom}$, $H_j^{imp}$, $G_j^{dom}$, $G_j^{imp}$, $Ex_j^{dom}$, and $Ex_j^{imp}$ be the shares of domestic and imported good $j$ in the consumption of the aggregate household, the government, and the external sector ($Ex_j^{imp}$ is therefore re-exports). Further, let $m_j^t$, $m_H^t$, $m_G^t$, and $m_{RW}^t$ be the money stocks in the national currency of industries j $\in \{1, \dots, n\}$, the aggregate household, the government, and the rest of the world. Let $p_j^{dom,t}$ and $p_j^{imp,t}$ be the prices of domestic and imported good j $\in \{1, \dots, n\}$ and let $p^{H,t}$ be the market-clearing mean weighted price of labour:[2]

$$p^{H,t} = \sum_{i=1}^{n} w_i m_i^t \tag{2}$$

Cobb-Douglas production technologies determine the optimal allocation of working capital $m_i^t$ of industry $i$ such that the nominal demand for good $j$ is equal to $a_{ji}^{dom} m_i^t + a_{ji}^{imp} m_i^t$. We assume

[2] As the household's total supply $q_H^t$ is normalised to 1, the household's total income $p^{H,t} q_H^t$ is equal to $p^{H,t}$, which should be equal to the household's total spending $\sum_{i=1}^{n} w_i m_i^t$.

that prices are fully flexible and that the intermediary consumption of good $j$ by industry $i$ implies the following relations:

$$X_{ij}^{dom,t-1} = \frac{a_{ji}^{dom} m_i^{t-1}}{p_j^{dom,t-1}}, X_{ij}^{imp,t-1} = \frac{a_{ji}^{imp} m_i^{t-1}}{p_j^{imp,t-1}}. \quad (3)$$

The definition of $p^{H,t}$ implies a similar relation for labour costs:

$$L_i^{t-1} = \frac{w_i m_i^{t-1}}{p^{H,t-1}}. \quad (4)$$

The dynamics of the money stock of industry $i \in \{1, \ldots, n\}$ is defined by its income from sales:

$$m_i^{t+1} = p_i^{dom,t} q_i^t \quad (5)$$

and the following balance equation holds:[3]

$$p_i^{dom,t} q_i^t = \sum_{j=1}^{n} a_{ij}^{dom} m_j^t + H_i^{dom} m_H^t + G_i^{dom} m_G^t + Ex_i^{dom} \cdot Q \cdot er^t \quad (6)$$

where $Q$ is the money stock in foreign currency (we assume that the rest of the world is in equilibrium and that therefore its money stock does not change), $er^t$ is the exchange rate, and we can set $m_{RW}^t = Q \cdot er^t$ to be the money stock in the national currency used for exports.

The price of good $i$ is obtained from (6):

$$p_i^{dom,t} = \frac{\sum_{j=1}^{n} a_{ij}^{dom} m_j^t + H_i^{dom} m_H^t + G_i^{dom} m_G^t + Ex_i^{dom} m_{RW}^t}{q_i^t} \quad (7)$$

[3] Note that because firms use all the money received from the sales as working capital and spend it on the purchase of goods, the right side of equation (6) determines the nominal demand for good $i$:

$$\mathrm{D}_i^{dom,t} = \sum_{j=1}^{n} a_{ij}^{dom} m_j^t + H_i^{dom} m_H^t + G_i^{dom} m_G^t + Ex_i^{dom} \cdot Q \cdot er^t$$

The money stock of the household is formed by its labour income:

$$m_H^{t+1} = \sum_{i=1}^{n} w_i m_i^t \tag{8}$$

and the money stock of the government is formed by tax incomes:

$$m_G^{t+1} = \sum_{i=1}^{n} taxes_i m_i^t \tag{9}$$

where $taxes_i$ are the share of taxes in the production costs of industry $i$.[4]

The money stock of the rest of the world is formed by the import demand of the country:

$$m_{RW}^{t+1} = \sum_{j=1}^{n} \left[ \sum_{i=1}^{n} a_{ji}^{imp} m_i^t + H_j^{imp} m_H^t + G_j^{imp} m_G^t + Ex_j^{imp} m_{RW}^t \right] \tag{10}$$

The dynamics of the price of imported goods are assumed to be driven by the dynamics of import demand:

$$p_j^{imp,t} = \frac{\sum_{j=1}^{n} \left[ \sum_{i=1}^{n} a_{ji}^{imp} m_i^t + H_j^{imp} m_H^t + G_j^{imp} m_G^t + Ex_j^{imp} m_{RW}^t \right]}{\sum_{j=1}^{n} \left[ \sum_{i=1}^{n} a_{ji}^{imp} m_i^{t-1} + H_j^{imp} m_H^{t-1} + G_j^{imp} m_G^{t-1} + Ex_j^{imp} m_{RW}^{t-1} \right]} \cdot p_j^{imp,t-1} \tag{11}$$

An explicit formula for the price dynamics of domestic goods can be derived. Let us introduce the following notation:

$$U_i^t = H_i^{dom} m_H^t + G_i^{dom} m_G^t + Ex_i^{dom} m_{RW}^t.$$

[4] We take into account the redistributive function of the government in cash flows and recalculate structural indicators.

It follows from (5) and (6) that

$$m_i^{t+1} = p_i^{dom,t} q_i^t = \sum_{j=1}^{n} a_{ij}^{dom} m_j^t + U_i^t. \tag{12}$$

Iterating this expression yields

$$\begin{aligned} m_i^{t+1} &= \sum_{j=1}^{n} a_{ij}^{dom} \left( \sum_{k=1}^{n} a_{jk}^{dom} m_k^{t-1} + U_j^{t-1} \right) + U_i^t \\ &= \sum_{j=1}^{n} \sum_{k=1}^{n} a_{ij}^{dom} a_{jk}^{dom} m_k^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t \\ &= \sum_{k=1}^{n} [A^2]_{ik} m_k^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t \end{aligned} \tag{13}$$

Then, again using (5) yields the following representation of the production volume of industry $i$:

$$q_i^t = \frac{\sum_{k=1}^{n} \left[ \left( A^{dom} \right)^2 \right]_{ik} m_k^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t}{p_i^{dom,t}}. \tag{14}$$

Substituting (3) and (4) into (1) yields

$$\begin{aligned} q_i^t &= \left( \frac{w_i m_i^{t-1}}{p^{H,t-1}} \right)^{w_i} \prod_{j=1}^{n} \left( \frac{a_{ji}^{dom} m_i^{t-1}}{p_j^{dom,t-1}} \right)^{a_{ji}^{dom}} \prod_{j=1}^{n} \left( \frac{a_{ji}^{imp} m_i^{t-1}}{p_j^{imp,t-1}} \right)^{a_{ji}^{imp}} \\ &= m_i^{t-1} \left( \frac{w_i}{p^{H,t-1}} \right)^{w_i} \prod_{j=1}^{n} \left( \frac{a_{ji}^{dom}}{p_j^{dom,t-1}} \right)^{a_{ji}^{dom}} \prod_{j=1}^{n} \left( \frac{a_{ji}^{imp}}{p_j^{imp,t-1}} \right)^{a_{ji}^{imp}}. \end{aligned} \tag{15}$$

Substituting (15) into (14) and expressing $p_i^{dom,t}$ yields

$$p_i^{dom,t} = \frac{\sum_{k=1}^{n}\left[\left(A^{dom}\right)^2\right]_{ik} m_k^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t}{m_i^{t-1}} \times \left(\frac{p^{H,t-1}}{w_i}\right)^{w_i} \prod_{j=1}^{n}\left(\frac{p_j^{dom,t-1}}{a_{ji}^{dom}}\right)^{a_{ji}^{dom}} \prod_{j=1}^{n}\left(\frac{p_j^{imp,t-1}}{a_{ji}^{imp}}\right)^{a_{ji}^{imp}} \tag{16}$$

A key feature of equation (16) is that the direct network-sensitive channel relating $m^{t-1}$ and $p^{dom,t}$ is mediated by the matrix $\left(A^{dom}\right)^2$ .

## 2.1 Model parameters

We use data from Russian input–output tables for 2016 to determine the network structure of the model.[5] We use symmetric[6] tables of domestic and imported products to construct the network structure and take the goods of 98 domestic industries and 98 import industries (goods) into account. Network parameters $A^{dom}$, $A^{imp}$, $H^{dom}$, $H^{imp}$, $G^{dom}$, $G^{imp}$, $Ex^{dom}$, and $Ex^{imp}$ are determined using the input-output tables.[7]

The remaining indicators are determined endogenously via burn-in simulation runs of the model based on formulas (1) – (11) with arbitrarily specified initial values. The resulting (after the burn-in period) indicators values represent the stationary levels in the model. We analyse the post-shock dynamics in relation to these stationary levels. We assume that at $t = 0$, the money stock is distributed equally among all agents, one unit in the national currency, that each firm has one product, and that the exchange rate is 1:

$$m_i^0 = 1, \forall i \in \{1, \dots, n\}$$

$$m_H^0 = m_G^0 = m_{RW}^0 = 1$$

$$q_i^0 = 1, \forall i \in \{1, \dots, n\}$$

$$er^0 = 1$$

[5] Admittedly, it would be preferable to use firm-level data for this purpose. This approach, however, is impeded by the availability of data, and so it is a common choice to use industry-level data to construct network models for Russia. See the work of Leonidov and Serebryannikova (2017, 2019) and Turdyeva (2019) for examples.

[6] Specifically, we convert a product-by-industry table into an industry-by-industry table. The transformation is conducted based on expert judgement.

[7] In our model, production inputs $A^{dom}$ and $A^{imp}$ actually include intermediate consumption and capital depreciation.

The initial price value is determined by formulas (2) and (7). Additionally, during the period of convergence until equilibrium is reached,[8] we assume that the prices in the national currency for the same domestic and imported goods are equal. After the convergence, we use formula (11) for import prices.

### 2.2 Monetary shocks

The purpose of this paper is to analyse the price response to monetary shocks. Instead of employing an abstract 'helicopter drop' approach, we define the money injection procedure in a more realistic manner.

We begin with the theoretical issues. Consider a monetary shock in sector $i$ at moment $t-1$. Let the money stock in this sector be:

$$\widetilde{m_i^{t-1}} = \mu m_i^{t-1}$$

(7) yields the expression for the new prices in the other economic sectors at moment $t-1$:

$$\begin{aligned} \widetilde{p_j^{dom,t-1}} &= \frac{\sum_{k=1}^{n} a_{jk}^{dom} m_k^{t-1} + U_j^{t-1} + (\mu-1) a_{ji}^{dom} m_i^{t-1}}{q_j^{t-1}} \\ &= p_j^{dom,t-1} + \frac{(\mu-1) a_{ji}^{dom} m_i^{t-1}}{q_j^{t-1}} \end{aligned} \tag{17}$$

Substituting (17) into (16) yields

$$\begin{aligned} \widetilde{p_i^{dom,t}} = & \frac{\sum_{k=1}^{n} \left[\left(A^{dom}\right)^2\right]_{ik} m_k^{t-1} + (\mu-1)\left[\left(A^{dom}\right)^2\right]_{ii} m_i^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t}{\mu m_i^{t-1}} \\ & \times \left(\frac{p^{H,t-1}}{w_i}\right)^{w_i} \prod_{j=1}^{n} \left(\frac{1}{a_{ji}^{dom}}\right)^{a_{ji}^{dom}} \left(p_j^{dom,t-1} + (\mu-1)\frac{a_{ji}^{dom} m_i^{t-1}}{q_j^{t-1}}\right)^{a_{ji}^{dom}} \\ & \times \prod_{j=1}^{n} \left(\frac{p_j^{imp,t-1}}{a_{ji}^{imp}}\right)^{a_{ji}^{imp}} \end{aligned} \tag{18}$$

Consider the ratio of prices after and before the shock for sector $i$:

[8] We use 100 iterations to converge to equilibrium.

$$\frac{\widetilde{p_i^{dom,t}}}{p_i^{dom,t}} = \frac{1}{\mu}\frac{\sum_{k=1}^{n}\left[\left(A^{dom}\right)^2\right]_{ik} m_k^{t-1} + (\mu-1)\left[\left(A^{dom}\right)^2\right]_{ii} m_i^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t}{\sum_{k=1}^{n}[(A^{dom})^2]_{ik} m_k^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t} \times \prod_{j=1}^{n}\left(1 + (\mu-1)\frac{a_{ji}^{dom} m_i^{t-1}}{p_j^{dom,t-1} q_j^{t-1}}\right)^{a_{ji}^{dom}} = \frac{1}{\mu}\frac{\sum_{k=1}^{n}\left[\left(A^{dom}\right)^2\right]_{ik} m_k^{t-1} + (\mu-1)\left[\left(A^{dom}\right)^2\right]_{ii} m_i^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t}{\sum_{k=1}^{n}[(A^{dom})^2]_{ik} m_k^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t} \times \prod_{j=1}^{n}\left(1 + (\mu-1) a_{ji}^{dom}\frac{m_i^{t-1}}{m_j^{t-1}}\right)^{a_{ji}^{dom}} \tag{19}$$

Taking the logarithms yields

$$\ln\left(\frac{\widetilde{p_i^{dom,t}}}{p_i^{dom,t}}\right) = \ln\left(\frac{1}{\mu} + \frac{\mu-1}{\mu}\frac{\left[\left(A^{dom}\right)^2\right]_{ii} m_i^{t-1}}{\sum_{k=1}^{n}[(A^{dom})^2]_{ik} m_k^{t-1} + \sum_{j=1}^{n} a_{ij}^{dom} U_j^{t-1} + U_i^t}\right) + \sum_{j=1}^{n} a_{ji}^{dom} \ln\left(1 + (\mu-1) a_{ji}^{dom}\frac{m_i^{t-1}}{m_j^{t-1}}\right) \tag{20}$$

The complete analytical study of this expression is problematic due to the complexity of the real-world input-output network structure. Therefore, we provide the results of numeric exercises in the next subsection. However, a few analytical results regarding the qualitative behaviour of the model after a monetary shock can be provided. First, after the monetary shock, the model asymptotically converges to the new price level with all prices higher compared to before the shock. Second, the price dynamics after the shock are non-monotonous – typically, a significant price increase is observed in the first periods following the shock, followed by a steady, but typically non-monotonous, decline. We therefore proceed with the simulation-based analysis.

## 3. Simulation analysis

Money is predominantly created by bank lending. When a bank grants a loan, it records the loan as an asset and the newly created deposit as a liability. Therefore, when banks lend to borrowers, they create deposits (initially held by the borrowers). The deposits may later be used as payment media and thus may be spread among the agents in the economy (see the work McLeay et al. (2014) for further discussion).

Notably, the loans are taken to finance concrete transactions rather than to conduct an abstract ‘helicopter money drop’. The ports of entry of the newly created money stock are therefore not random but are linked with typical transactions in the economy. We use several approaches to define the types of injection of additional money stock into the network structure of the economy.

1. *Regular lending*. New money stock is used to purchase goods and services in accordance with the commodity structure of firms’ intermediate consumption[9] and the household’s final consumption. Specifically, we use the Bank of Russia’s data on the volume of loans issued to resident corporations and entrepreneurs, as well as information on lending to individuals, to determine the sector-specific changes in money holdings (*credit*). Formally, the shock is introduced as:

$$m_i^{t_0} = m_i^{t_0} + credit_i \cdot e, \quad \forall i = 1 \ldots n$$

2. *Household consumption*. New money stock is used to purchase goods and services in accordance with the commodity structure of household consumption. Formally, the shock is introduced as:

$$m_H^{t_0} = m_H^{t_0} + e$$

3. *Investment demand*. New money stock is used to purchase goods and services in accordance with the commodity structure of fixed capital investment. Formally, the shock is introduced as:

$$D_j^{dom,t_0} = D_j^{dom,t_0} + invest_j \cdot e, \quad \forall j = 1 \ldots n$$

4. *Government consumption*. New money stock is used to purchase goods and services in accordance with the commodity structure of government consumption. Formally, the shock is introduced as:

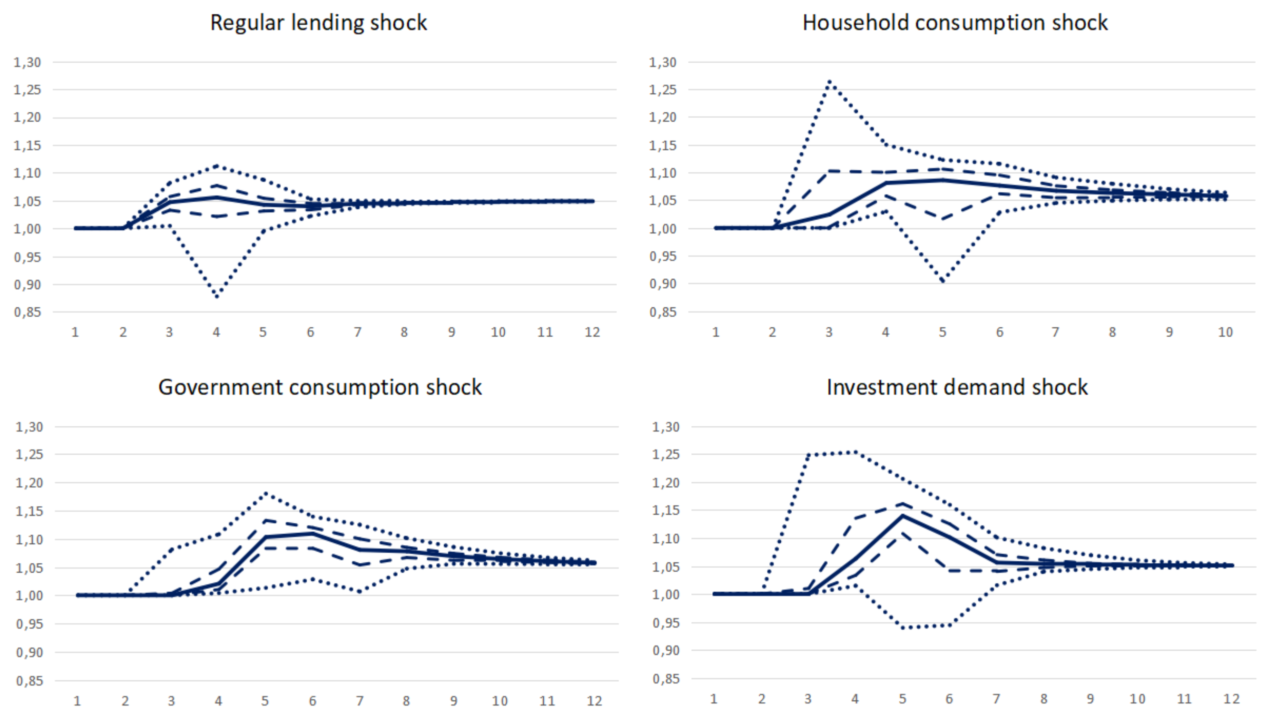
$$m_G^{t_0} = m_G^{t_0} + e$$

[9] Admittedly, associating all lending to firms with intermediate consumption rather than with investment is an arbitrary assumption. Arguably, this type of shock may be interpreted as a representation evenly distributed, newly created money stock.

In each case, we assume that the monetary shock increases the total money supply by $e = 5\%$ once at time $t_0$. Following any type of monetary shock, all prices will eventually increase by 5% as determined by the design of our model. However, the transient dynamics are sensitive to the specification of the shock.

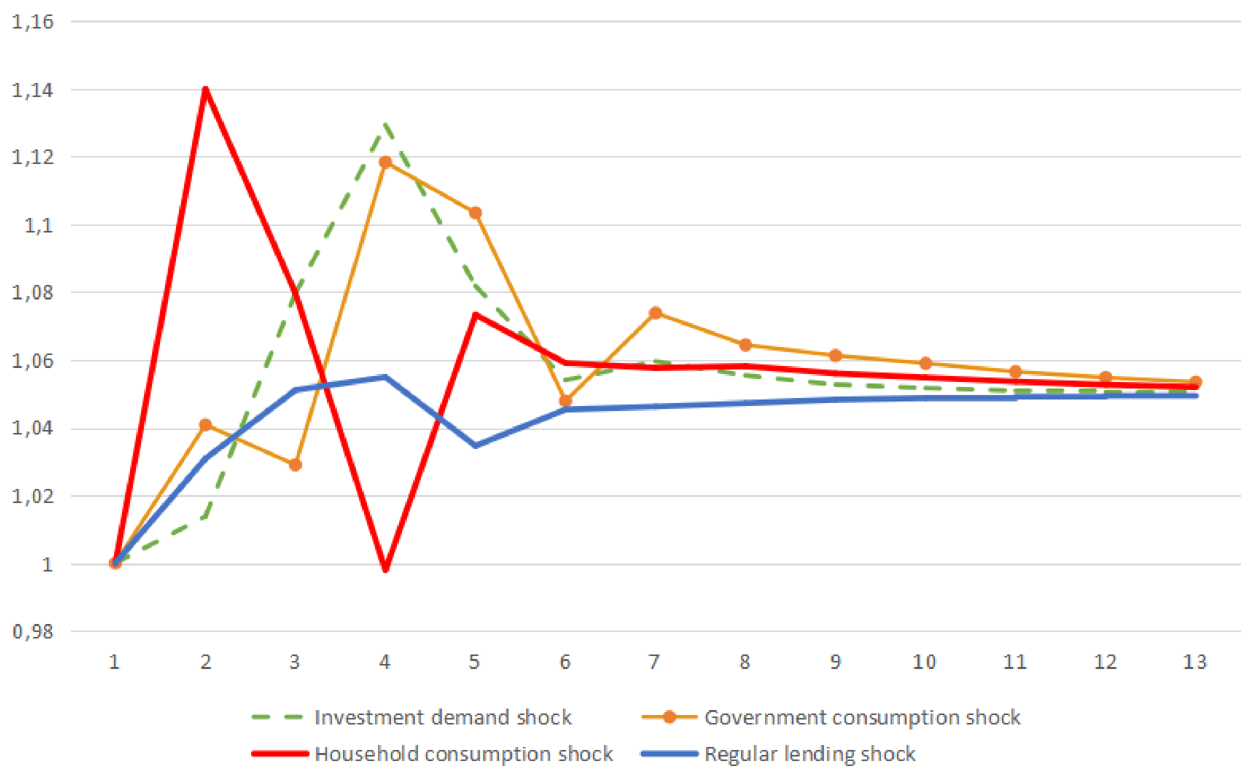
In our analysis, we focus on two aspects of the price adjustment process. Similarly to Mandel et al. (2019) and Mandel and Veetil (2021), we report the cross-sectional dispersion of industry-specific prices. The results are presented in Figure 1 and show the distribution of price responses to various monetary shocks. The solid line shows the median value, the dashed lines indicate the 25th and 75th percentiles, and the dotted lines indicate the 5th and 95th percentiles. All shocks cause temporary fluctuations in prices until eventual stabilisation. Most price indices increase in response to expansionary monetary shocks, although decreasing price indices are also observed. We find that 'regular lending' shock produces the smoothest, fastest-decaying reaction and a uniform response by prices. Shocks to household consumption and investment produce more volatile, longer-lasting, and dispersed reactions.

Figure 1. Distribution of industry-specific price responses to monetary shock (50th, 25th–75th, and 5th–95th percentiles of price levels)




We proceed by examining the response of the aggregate consumer prices index (CPI) calculated using weights linked to the composition of the household's final consumption. We are particularly interested in the local peaks reached during the adjustment to monetary shocks. The results are presented in Figure 2. Notably, only 'regular lending' shock does not result in an overshoot of the aggregate price level. Predictably, household consumption shock, which is by design concentrated in the consumer goods markets, results in an immediate, sharp increase in the CPI. Investment and government consumption shocks have no immediate direct effect on consumer goods. Nevertheless, in subsequent periods, consumer goods prices are substantially affected and also overshoot the long-run steady state.

Figure 2. Aggregate consumer price index response to monetary shocks (price level)




We continue by examining industry-specific monetary shocks (98 in total) where all newly created money stock is entirely used to finance the purchase of a single good or service. Formally, these shocks are introduced as:

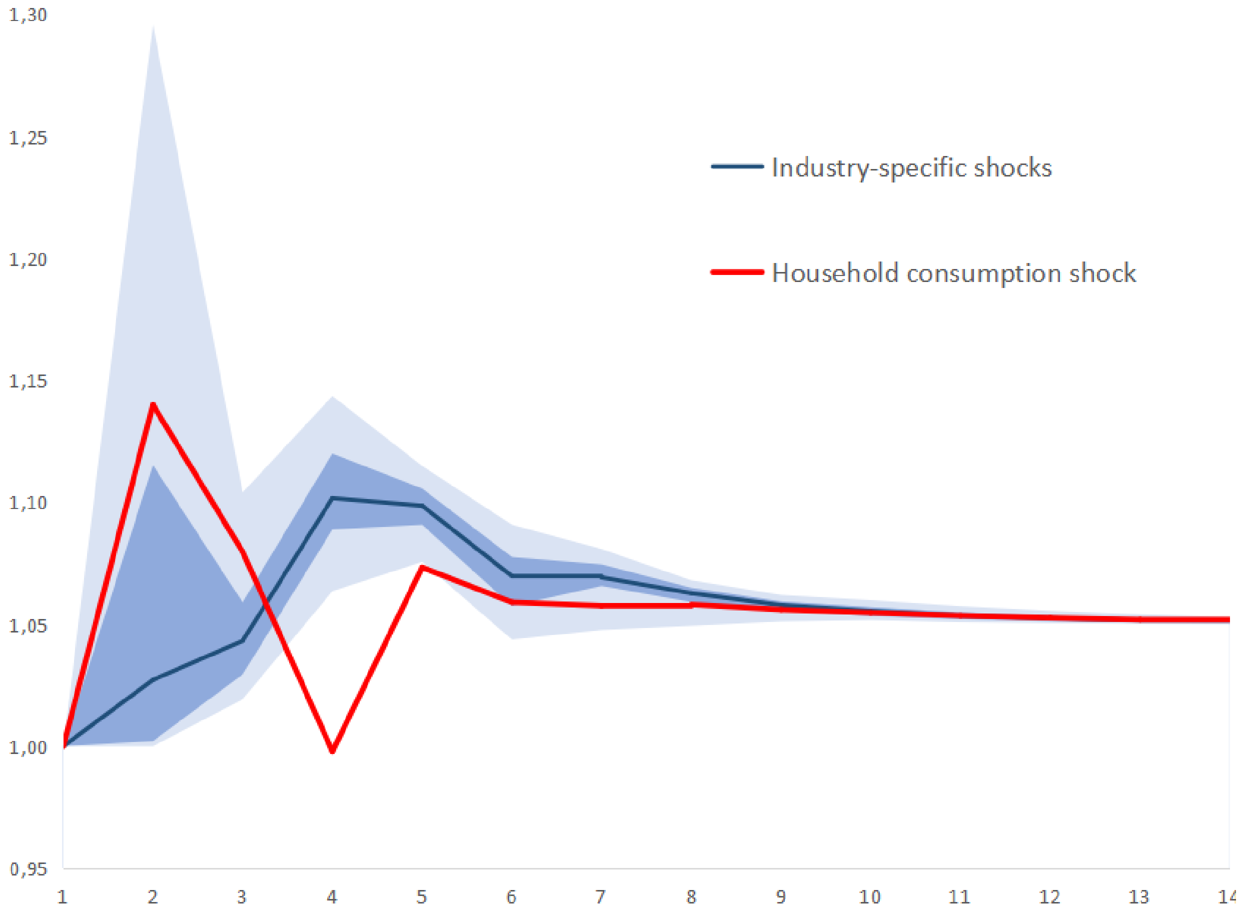
$$D_j^{dom,t_0} = D_j^{dom,t_0} + prod_j \cdot e, \qquad \forall j = 1 \dots n$$

where $prod_j = \begin{cases} 1, & j = k, t = t_0 \\ 0, & otherwise \end{cases}$

We present the range of CPI responses to these shocks in Figure 3. The solid blue line represents the median response to shock and the shaded blue areas represent the distribution (the light area represents the 5th- to 95th-percentile range of values, and the darker area represents the

25th- to 75th-percentile range). As can be seen from the chart, certain industry-specific shocks cause an immediate and very significant reactions by the CPI. Obviously, these are shocks directed at markets that are relatively shallow but have substantial weight in the household consumption bundle. More interesting, however, is the fact that the majority of industry-specific shocks lead to substantial overshooting of the CPI in the course of its convergence to the new equilibrium (the detailed results are presented in Table 1 in the Appendix). Apparently, this means that the network structure of the economy enables the delayed (yet concentrated) arrival of the new funds to the consumer goods markets, even though these markets are not affected initially. Presumably, injecting money via industries with high ratios of wages to intermediate consumption (such as services) may lead to such an outcome. Nevertheless, as discussed in Section 2.2, the intuitive interpretation of the mechanics behind the propagation of shocks is complicated, and simulation experiments appear to be the only reliable approach to such analysis.

Figure 3. Aggregate consumer price index response to monetary shocks (50th, 25th–75th, and 5th–95th percentiles of price levels)



## 4. Conclusions

Employing a network structure in modelling the propagation of monetary shocks helps to predict a number of non-trivial effects. Specifically, the existence of multidirectional fluctuations in relative prices as well as the volatility of the aggregate price index during the convergence to a new equilibrium. Importantly, these developments are very sensitive to the initial composition (points of inflow) of the monetary injection.[10]

These findings have certain practical implications. Note that in our simplified model, all the monetary shocks are neutral by design (i.e., in the long-run, they lead to a proportional increase in all prices). Presumably, a more realistic model set-up would allow for the existence of second-round effects such that the overshooting of industry-specific or aggregate prices might translate into self-reinforcing price inflation processes. Policymakers may therefore regard these developments as highly undesirable. The formulation of applied quantitative recommendations lies beyond the objectives of this paper, however, our general finding is that monetary shocks with more ‘concentrated’ money inflows carry relatively higher inflationary risks in the short term.

[10] Note that we calibrate our model using industry-specific data. Presumably, employing firm-level data would help to uncover a substantially more complex network structure and, accordingly, predict more unusual outcomes.

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## 6. Appendix

Table 1. CPI responses to industry-specific monetary shocks

| Industry | Local price level peak | No. of periods after shock when local price level peak is reached |
|---|---|---|
| Agriculture | 1.14 | 2 |
| Agricultural and animal husbandry service activities, except veterinary activities, landscape gardening | 1.14 | 3 |
| Hunting, trapping, and game propagation, including related service activities | 1.22 | 1 |
| Forestry, logging, and related service activities | 1.10 | 3 |
| Fishing, fish farming, and related service activities | 1.11 | 3 |
| Mining of coal and lignite; extraction of peat | 1.11 | 4 |
| Extraction of crude petroleum | 1.12 | 4 |
| Extraction of natural gas | 1.11 | 3 |
| Service activities incidental to oil and gas extraction excluding surveying | 1.11 | 4 |
| Mining of uranium and thorium ores | 1.12 | 4 |
| Mining of iron ores | 1.12 | 4 |
| Mining of other non-ferrous metal ores, excluding mining and preparation of uranium and thorium ores | 1.13 | 3 |
| Other mining and quarrying | 1.11 | 4 |
| Production, processing, and preserving of meat and meat products | 1.26 | 1 |
| Processing and preserving of fish and fish products | 1.18 | 1 |
| Processing and preserving of fruit and vegetables | 1.15 | 1 |
| Manufacture of vegetable and animal oils and fats | 1.12 | 3 |
| Manufacture of dairy products | 1.24 | 1 |
| Manufacture of grain mill products, starches, and starch products | 1.13 | 3 |
| Manufacture of prepared animal feeds | 1.14 | 3 |
| Manufacture of other food products | 1.22 | 1 |
| Manufacture of beverages | 1.28 | 1 |
| Manufacture of tobacco products | 1.30 | 1 |
| Manufacture of textiles | 1.11 | 1 |
| Manufacture of other wearing apparel and accessories | 1.12 | 1 |
| Manufacture of leather and leather products | 1.16 | 1 |

| | | |
|---|---|---|
| Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials | 1.10 | 4 |
| Manufacture of pulp, paper, and paper products | 1.09 | 3 |
| Publishing, printing, and reproduction of recorded media | 1.11 | 3 |
| Publishing, printing, and reproduction of recorded media | 1.11 | 3 |
| Manufacture of coke oven products | 1.10 | 5 |
| Manufacture of refined petroleum products | 1.09 | 4 |
| Manufacture of basic chemicals | 1.10 | 4 |
| Manufacture of pesticides and other agro-chemical products | 1.10 | 3 |
| Manufacture of paints, varnishes and similar coatings, printing ink, and mastics | 1.10 | 4 |
| Manufacture of pharmaceuticals, medicinal chemicals, and botanical products | 1.15 | 1 |
| Manufacture of soap and detergents, cleaning and polishing preparations, perfumes, and toilet preparations | 1.18 | 1 |
| Manufacture of other chemical products | 1.09 | 4 |
| Manufacture of man-made fibres | 1.10 | 4 |
| Manufacture of rubber products | 1.09 | 4 |
| Manufacture of plastic products | 1.09 | 3 |
| Manufacture of glass and glass products | 1.10 | 4 |
| Manufacture of ceramic tiles and flags | 1.11 | 4 |
| Manufacture of cement, lime, and plaster | 1.11 | 4 |
| Manufacture of articles of concrete, plaster, and cement | 1.11 | 4 |
| Manufacture of basic iron and steel and of ferro-alloys; Manufacture of tubes; Other first processing of iron and steel | 1.11 | 4 |
| Manufacture of basic precious and non-ferrous metals | 1.10 | 4 |
| Casting of metals | 1.10 | 4 |
| Manufacture of tanks, reservoirs, and containers of metal; manufacture of central heating radiators and boilers | 1.11 | 4 |
| Forging, pressing, stamping, and roll forming of metal; powder metallurgy | 1.10 | 4 |
| Manufacture of cutlery, hand tools, and general hardware | 1.10 | 4 |
| Manufacture of other fabricated metal products | 1.12 | 3 |
| Manufacture of other general-purpose machinery | 1.23 | 1 |
| Manufacture of office machinery and computers | 1.10 | 4 |
| Manufacture of computers and other information processing equipment | 1.11 | 3 |

| | | |
|---|---|---|
| Manufacture of electrical machinery and apparatus | 1.10 | 4 |
| Manufacture of radio, television, and communication equipment and apparatus | 1.11 | 3 |
| Manufacture of medical and surgical equipment and orthopaedic appliances | 1.11 | 3 |
| Manufacture of instruments and appliances for measuring, checking, testing, navigating, and other purposes, except industrial process control equipment | 1.12 | 3 |
| Manufacture of motor vehicles, trailers, and semi-trailers | 1.09 | 2 |
| Manufacture of other transport equipment | 1.11 | 3 |
| Manufacture of furniture | 1.26 | 1 |
| Manufacture of jewellery and related articles | 1.16 | 1 |
| Miscellaneous manufacturing | 1.10 | 3 |
| Recycling | 1.09 | 5 |
| Production and distribution of electricity | 1.10 | 3 |
| Manufacture of gas; distribution of gaseous fuels through mains | 1.10 | 4 |
| Steam and hot water supply | 1.11 | 1 |
| Collection, purification, and distribution of water | 1.12 | 3 |
| Construction | 1.13 | 3 |
| Miscellaneous sale, maintenance, and repair of motor vehicles and motorcycles; retail sale of automotive fuel | 1.14 | 1 |
| Wholesale trade and commission trade, except of motor vehicles and motorcycles | 1.10 | 4 |
| Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods | 1.30 | 1 |
| Camping sites and other provision of short-stay accommodation | 1.13 | 3 |
| Canteens and catering | 1.30 | 1 |
| Transport via railways | 1.12 | 4 |
| Other land transport | 1.10 | 3 |
| Transport via pipelines | 1.12 | 3 |
| Water transport | 1.11 | 3 |
| Air transport | 1.12 | 1 |
| Supporting and auxiliary transport activities; activities of travel agencies | 1.12 | 3 |
| Post and telecommunications | 1.16 | 1 |
| Financial intermediation, except insurance and pension funding | 1.13 | 3 |
| Insurance and pension funding, except compulsory social security | 1.15 | 1 |
| Activities auxiliary to financial intermediation | 1.15 | 3 |

| | | |
|---|---|---|
| Real estate activities | 1.13 | 1 |
| Renting of machinery and equipment without operator and of personal and household goods | 1.13 | 3 |
| Computer and related activities | 1.15 | 3 |
| Research and development | 1.14 | 3 |
| Other business activities | 1.16 | 3 |
| Public administration and defence; compulsory social security | 1.14 | 3 |
| Education | 1.17 | 3 |
| Health and social work | 1.13 | 3 |
| Sewage and refuse disposal, sanitation, and similar activities | 1.12 | 3 |
| Activities of membership organisations | 1.33 | 1 |
| Recreational, cultural, and sporting activities | 1.13 | 3 |
| Other service activities | 1.30 | 1 |
| Activities of households as employers of domestic staff | 1.33 | 1 |