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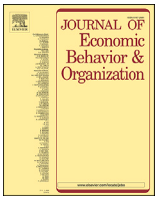

Business cycles, sectoral price stabilization, and climate change mitigation: A model of multi-sector growth in the tradition of the Bielefeld disequilibrium approach

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ABSTRACT

Sectoral price stabilization is critical in the pressing context of de-globalization and the climate crisis. Strategic price controls may be effective in reducing economic volatility, but fail to curb emissions, unlike quantity controls such as rationing consumption. In contrast, carbon pricing may accelerate decarbonization, but generate inflationary pressures. In order to evaluate the effectiveness of sector-oriented policies in stabilizing sectoral prices and accelerating the low-carbon transition at the same time, this paper employs a novel environmentally-extended, data-driven dynamic model of multi-sector growth based on the Bielefeld disequilibrium approach to the microeconomic stability of competitive economies. The general composite model allows to empirically characterize the network structure and intensity of dynamic price-quantity interactions at the sector level, which capture heterogeneous firm behavior by integrating long-run Walrasian price and classical quantity dynamics coupled with short-run Keynesian features in the form of target rate of return pricing and demand-led investment. A Bayesian hierarchical model on US BEA data empirically estimates the linear adjustment coefficients and stable combinations are computed. The US economy is shown to feature a highly hierarchical network structure of intermediate production that is particularly vulnerable to micro-economic shocks driven by wars and climate change. Tax-subsidy schemes are shown to be the most effective in stabilizing sectoral prices and economy-environment interactions.

1. Introduction

Amidst international trade wars, actual wars, oil and grain embargos, and sanctions against the general backdrop of the climate crisis, supply bottle-necks, inflation, and price volatility may become ubiquitous at the sector level in a globalized, inter-dependent economy undergoing value chain decoupling and increasingly frequent climate disasters. This new context of 'overlapping global emergencies' raises the question on how microeconomic sector-specific fluctuations affect the overall resilience of an increasingly fragile economy –coupled with the natural environment– by propagating and amplifying through the highly hierarchical structure of the complex input-output networks of intermediate production (Acemoglu et al., 2012; Weber et al., 2022). When such an economic structure interacts with heterogeneous microeconomic behavior, supply chain disruption due to the COVID-19 pandemic lockdowns, gas embargos due to the Ukraine war, food shortages due to extreme droughts or war, or economic sanctions on chip production may initially originate as sector-specific imbalances between supply and demand, but rapidly become general price shocks of inputs

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that are critical for the economy. Such input cost shocks may be further amplified by imperfect competition, such as productivity heterogeneity, barriers to entry and exit, or market concentration (Carvalho, 2014; Baqaee et al., 2018; Baqaee and Farhi, 2019b).

In the face of the dual inflationary threats of de-globalization and climate change, policy-makers are currently embracing more activist policies of price stabilization such as strategic controls on prices or profits[1] (for instance, on European energy) (Galbraith, 1980; Colander, 1984) or tax-subsidy schemes such as the US Inflation Reduction Act. While conventional economic wisdom considers that price controls lead to scarcity and rationing, such policies are especially relevant in wartime economies featuring excess supply (such as excess *carbon* supply) (Galbraith, 1980). In this direction, the traditional consensus among ecological economists views carbon pricing, a form of price controls, as the optimal policy to push for decarbonization (Blum et al., 2019). However, price controls targeting sectoral stabilization and carbon pricing targeting the low-carbon transition face the risk of canceling each other. Carbon pricing may be inflationary when targeting industries providing critical inputs for the economy if businesses with market power decide to pass these additional costs to the consumer (Moessner, 2022; Santabárbara and Suárez-Varela, 2022). As the scale and urgency of the climate crisis intensifies, experts increasingly believe carbon pricing alone may not be able to successfully curb emissions in time and needs to be accompanied with substantial green investment to achieve the necessary system-wide transformation of the economy (Narassimhan et al., 2017; Tvinnereim and Mehling, 2018; Jenkins et al., 2020; Rosenbloom et al., 2020). A NYU Wagner workshop of academic and policy experts concluded in December 2020 that carbon pricing should be implemented as an integral part of a more diversified, activist policy portfolio, including regulations, R&D subsidies, central-bank financial support, finance instruments, and public investment (Jenkins et al., 2020; Semmler et al., 2021; Braga et al., 2021).

In order to understand how to stabilize at the same time sector-level fluctuations and economy-environment interactions, this paper employs the Bielefeld disequilibrium approach on micro-dynamical processes of adjustment (as developed by Peter Flaschel, Willi Semmler, and co-authors) as a systematic method to empirically characterize both the complex structure and intensity of dynamic sector-level interactions in prices and quantities. With many important contributions by Jorgenson (1960), Scarf (1960), Morishima (1981), Hahn (1970, 1982) or Mas-Colell (1986) among others, the literature on the stability of competitive economies considered particular functional forms of micro-level processes of dynamical adjustment out of equilibrium, characterized by reaction coefficients underlying stylized facts as laws of motion driving sector-level fluctuations in prices and quantities.

Integrating short-run and long-run Walrasian, Keynesian, and classical features as well as macro- and microeconomic levels of analysis, the Bielefeld approach captures heterogeneous firm behavior with industry-level linear adjustment coefficients out of supply-demand imbalances and profitability deviations in a Leontief input-output model of linear production. These coefficients can be dual (price-price and quantity-quantity) in the short run (in the form of oligopolistic pricing and demand-led output reactions), cross-dual (price-quantity and quantity-price) in the long run (in the form of Walrasian pricing and free firm entry), or a general composite form that integrates both forms of adjustment. Using a Bayesian hierarchical linear regression model with mixed effects on US Bureau of Economic Analysis data, the paper empirically estimates the intensity and stability of sector-level adjustments, an important contribution of this paper, as the microeconomic literature mostly addressed the problem analytically and, to a minor degree, computationally (Flaschel and Semmler, 1990; Flaschel, 1991). The findings corroborate the Keynesian emphasis on demand-led quantity reactions, especially in Services, Transportation, and Manufacturing. General price-price interactions are very small, but there is still some evidence for a 'price over volume' strategy in critical industries.

Once empirically calibrated, the stylized model is re-purposed as an environmentally-extended, data-driven dynamic model of multi-sector growth for the evaluation of sector-oriented policies with the dual goal of price stabilization and climate change mitigation, such as price and quantity controls as well as tax-subsidy schemes. While neglecting aggregate issues such as effective demand, income distribution dynamics, and monetary growth, such stylized framework is particularly well-suited to address the complex dynamics of industrial structure, while requiring much less parameters and equations than other macroeconomic models in a way that resembles linear machine-learning methods (Brunton and Kutz, 2022). Rather than promoting scarcity, simulations show how price controls help stabilize fluctuations driven by exogenous shocks driven by actual wars, trade wars, and climate change, but also fail to curb emissions: only quantity controls, i.e. rationing, can do so, as these depend on real consumption. However, curbing emissions by 50% in 10 years, as the UN Inter-governmental Panel on Climate Change calls for, implies an equivalent reduction in consumption that may be untenable for the general population. In this context, structural change is required: the paper finally shows how tax-subsidy schemes can promote price stabilization and climate change mitigation at the same time by substantially accelerating the speed of the phase-in of lower-cost, less-carbon-intensive technologies.

The paper is organized as follows. Section 2 briefly reviews the recent literature on the interaction of microeconomic behavior and the input-output structure of intermediate production, which generally relies on New Keynesian general equilibrium models (featuring Cobb-Douglas production functions and equilibrium marginal pricing) to address the macroeconomic relevance of micro-level fluctuations. Section 3 presents the Bielefeld approach to sectoral fluctuations in prices and quantities out of equilibrium in terms of micro-dynamical processes and characterizes its underlying stylized laws of motion. Section 4 analyzes the network structure of price-quantity interactions of the US economy, identifies its most central industries, and shows it to be highly hierarchical, asymmetric, and star-shaped in a way that will considerably amplify, rather than damp, micro-economic shocks at the industry level. Section 5 empirically estimates the intensity of such price-quantity interactions, documents its challenges, and evaluates the dynamic stability of the empirical composite system. Finally, section 6 explores, through simulations, sector-level policies with the

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[1] For instance, Joseph Stiglitz recently suggested nonlinear pricing in his October 17, 2022 op-ed "Wars Aren't Won with Peacetime Economies", https://www.project-syndicate.org/commentary/west-needs-war-economics-energy-food-supply-shortages-by-joseph-e-stiglitz-2022-10. James K. Galbraith made the case for strategic price policies on January 21, 2022, https://www.project-syndicate.org/commentary/strategic-price-controls-warranted-to-fight-inflation-by-james-k-galbraith-2022-01.

dual goal of price stabilization and climate change mitigation, aimed at increasing the resilience of both the economic system and the environment.

2. Microeconomic behavior and the input-output structure of production

In the context of the 1970s stagflation, Robert Lucas put forward a "diversification" argument appealing to the law of large numbers by which, in fact, independent sectoral disturbances should actually tend to average out, leaving aggregates unchanged (Lucas, 1977). Competitive economies are generally assumed to rest on a stable efficient equilibrium, so that aggregate business cycles are to be considered the self-stabilizing rational outcome of random exogenous idiosyncratic shocks in demand, technology, monetary or fiscal policy, preferences, and so on (Lucas, 1977; Semmler, 1986). Sector-specific shocks would tend to cancel out rather than propagating, through bottle-necks and nonlinear cascade effects, throughout the economy leading to aggregate macroeconomic fluctuations (Lucas, 1977). The early fundamental Hulten aggregation theorem showed that the systemic importance of particular industries in efficient economies can be approximated in the first order by their sales, regardless of the existence of intermediate linkages and complementaries in production (Hulten, 1978).

However, starting with the debate between Horvath (1998, 2000) and Dupor (1999), such a view is increasingly contested, arguing that the microeconomic structure of production is in fact much relevant for macroeconomic analysis (Acemoglu et al., 2012; Carvalho, 2014; Baqaee and Farhi, 2019b). Building on the multi-sector framework of Long and Plosser of real business cycles (1983), Acemoglu et al. show how the amplification of sector-level shocks can occur through the network structure of input-output linkages in intermediate production when certain sectors are disproportionally large suppliers of inputs to the rest of the economy (Acemoglu et al., 2012). In particular, the equilibrium firm size distribution of such an economy depends on the shape and structure of the economic network. Empirical work by Foerster et al. (2011, 2017) applies factor methods to decompose industrial production into components arising from aggregate and sector-specific shocks to show that the relative importance of the latter has substantially increased since the 1980s. Further research by Acemoglu et al. captures the downstream and upstream network effects of demand-side and supply-side industry-level shocks through the 392-sector structure of US production (Acemoglu et al., 2015).

The interaction of input-output networks with sector-level market structure may also impact on the amplification of shocks, generating cascades of firm entry and exit across the economy (Bilbiie et al., 2012; Baqaee et al., 2018; Baqaee and Farhi, 2019b, 2020). In that regard, Gabaix showed how firm-level idiosyncratic shocks can translate into aggregate fluctuations when there is market concentration in the form of a heavy-tailed firm-size distribution where the largest firms contribute disproportionally to aggregate output (Gabaix, 2011). Extending Hopenhayn's (1992) industry dynamics framework, Carvalho and Grassi develop a quantitative theory aggregate fluctuations arising from firm-level shocks and characterize the law of motion of the firm size distribution, which is shown to be Pareto heavy-tailed, with resulting aggregate output and productivity dynamics that are endogenously persistent and volatile (Carvalho and Grassi, 2019). In agreement with the empirical evidence brought by Carvalho et al. (Carvalho, 2014), Baqaee (2018) shows that firm entry and exit, as well as extensive margin adjustment within industries, bears important spillovers on other firms through their inter-sectoral supply and demand chains, with important macroeconomic consequences.

Most of these studies employ the conventional competitive model of marginal cost pricing, Cobb-Douglas production functions, and equilibrium modeling, either efficient (Gabaix, 2011; Acemoglu et al., 2012) or inefficient by introducing frictions due to imperfect competition (Bilbiie et al., 2012; Baqaee et al., 2018; Baqaee and Farhi, 2019a, 2020). All these setups assume some form of equilibrium pricing by considering in principle marginal costs can be computed. However, as noted by the Bielefeld school, in disequilibrium actual market prices prevail, where the "cost" computed will be distorted by the prices out of equilibrium. In his general theory of price controls, Galbraith emphasized the need for a disequilibrium approach, as accelerating inflation could well set in before the supply-demand equilibrium is reached.

An alternative approach is the analysis of 'systemically significant' prices: using a Leontief price model, Weber and co-authors (2022) simulate shocks to each of the 71 industries of the US BEA input-output table and identify the most critical industries for price stability: energy, basic production inputs, basic necessities, and commercial and financial infrastructure. Most importantly, they show how the latent systemic significance of the pre-pandemic economy was realized in the post-shutdown and Ukraine war inflation. Following such an insight, Weber and Wasner argue that the transitory inflation initially driven by COVID-19 sector-level demand and supply shocks became permanent when those shocks propagate and amplify through the complex structure of intermediate production (Weber and Wasner, 2023). In the face of input cost shocks, the price-setting power of firms may be no longer constant and rather vary depending on the firms' upstream or downstream position within the value chain; firms may further adopt a 'price over volume' strategy and concertedly raise their prices to protect profit margins.

3. A data-driven dynamical system in the tradition of the Bielefeld disequilibrium approach

3.1. General mathematical formulation

Seminally developed by the late Peter Flaschel, Willi Semmler, and co-authors, the Bielefeld disequilibrium approach to the microeconomic stability of competitive economies, based on linear production models and micro-dynamical adjustment processes out of equilibrium, is particularly well suited to characterize the complex structure and heterogeneous intensity of price-quantity interactions at the industry level (Semmler, 1986; Flaschel and Semmler, 1987; Flaschel, 1990; Flaschel and Semmler, 1990; Flaschel, 2010). As noted by Flaschel (1997), such study highlights the complex dynamical relation between micro- and macroeconomic adjustment processes, although still neglecting aggregate issues of important concern such as effective demand, income distribution,

Table 1
General Classification of Micro-Economic Adjustment Processes (Goodwin, 1983; Goodwin and Punzo, 1987).

Cross-Dual	*Walrasian Law of Excess Demand* *Classical Law of Excess Profitability*	if demand d_i is above (below) supply x_i, price p_i rises (falls) if price p_i above (below) $cost_i$, quantity x_i rises (falls)
Dual	*Oligopolistic Markup Pricing* *Inventory Adjustment*	if price p_i above (below) $cost_i$, price p_i falls (rises) if demand d_i is above (below) supply x_i, quantity x_i rises (falls)

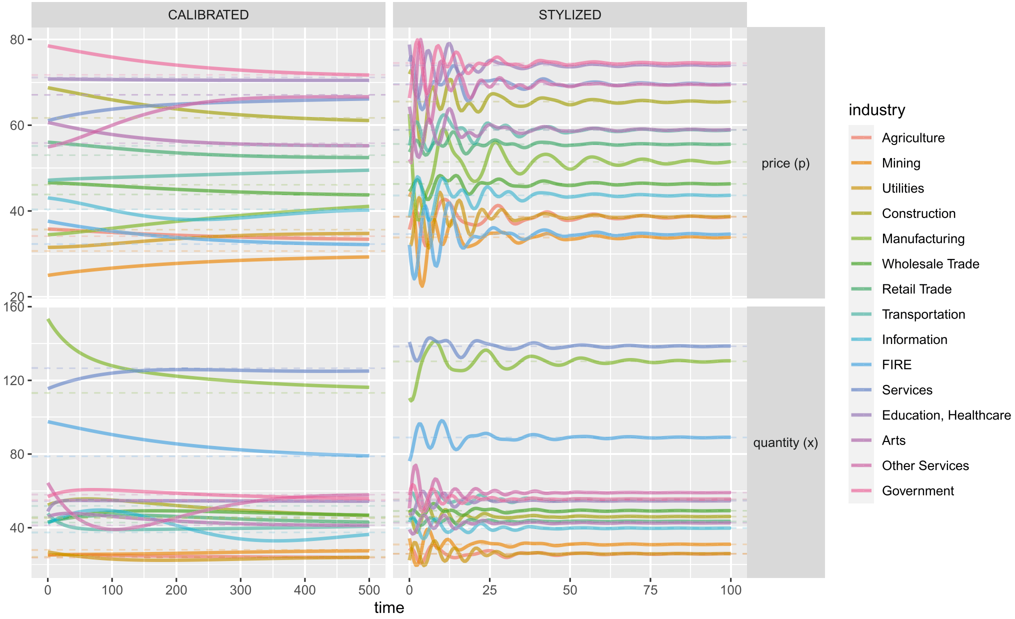

Fig. 1. Simulations of the Composite System With the empirically estimated coefficients (calibrated) and synthetic coefficients to show its stylized dynamics of damped oscillations.

and monetary growth, as well as instabilities in the labor and financial markets. The Flaschel-Semmler composite system characterizes heterogeneous firm behavior by integrating short-run and long-run Walrasian, classical, and Keynesian features in the form of dual/cross-dual dynamics between prices and quantities, which attempts to capture the sectoral imbalances (between supply and demand and as deviations in profitability) driving highly complex systems out of equilibrium (Flaschel and Semmler, 1990; Flaschel, 2010). Under such disequilibrium view, there is no reason by which a competitive economy must always lie on a stable equilibrium that may be efficient or not due to market frictions. At any specific point of time, there is no reason either to assume profitability is uniform across industries, the market price reflects the equilibrium marginal cost of production, or supply equals demand, because all these variables are considered to be constantly changing over time around their equilibrium values (which are subject to changes in final demand, technology, and the distribution of income).

Such general systems of micro-economic adjustment processes can be re-purposed as highly stylized dynamic macroeconomic models of multi-sector growth of constant linear technology that separate prices from quantities and can be empirically calibrated using real training data in a way that resembles machine-learning models. Under composite dynamics in prices and quantities, each of the four laws of motion translates to a single reaction coefficient associated to each particular industry. The general dynamics of the Flaschel-Semmler multi-sector growth for a linear production model without fixed investment can be mathematically represented for N industries by the $2N$ set of dynamical equations for prices (row-vector p) and quantities (column-vector x), with four adjustment coefficients for each sector corresponding to each stylized dynamical law of motion (Table 1):

$$\dot{x} = \underbrace{\delta_{xx}\left[C(g)x + c\right]}_{\text{Keynesian}} - \underbrace{\delta_{xp}\left[C^T(r)p^T + w^T\right]}_{\text{classical}} = \delta_{xx}\Delta_x - \delta_{xp}\Delta_p \tag{1}$$

$$\dot{p}^T = \underbrace{\delta_{px}\left[C(g)x + c\right]}_{\text{Walrasian}} + \underbrace{\delta_{pp}\left[C^T(r)p^T + w^T\right]}_{\text{Keynesian}} = \delta_{px}\Delta_x + \delta_{pp}\Delta_p \tag{2}$$

where

- $C(\alpha) \equiv (1+\alpha)A - I, \quad \alpha = r, g$ is the matrix capturing the *network structure* of price and quantity interactions, respectively (Figs. 3 and 6),
- $\Delta_x \equiv C(g)x + c = (1+g)Ax + c - x$ is the column-vector of supply-demand imbalances,

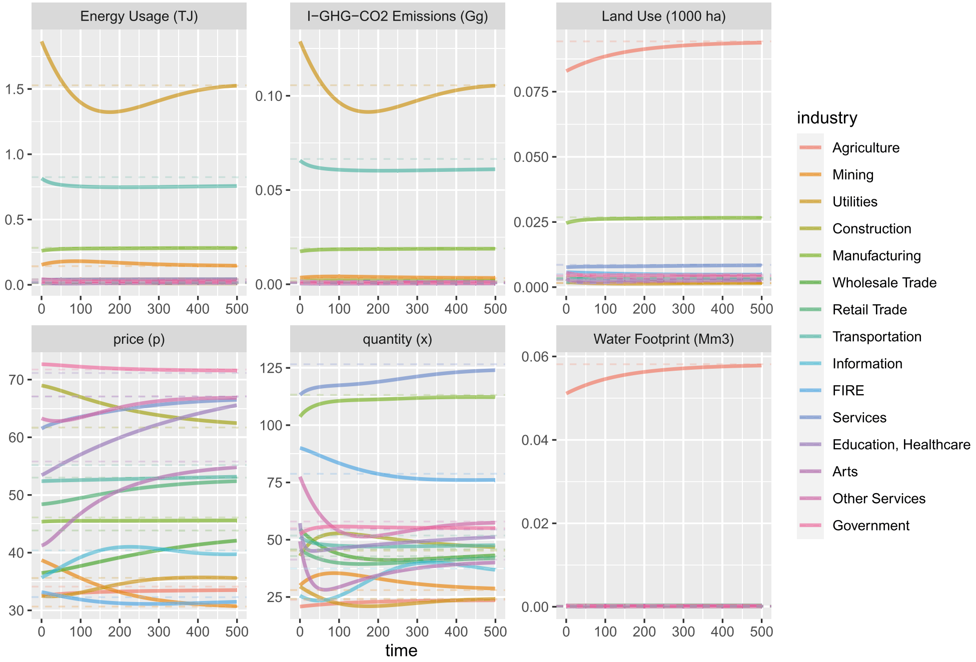

Fig. 2. Calibrated Environmentally Extended Simulation Utilities, Transportation, and Manufacturing use the most energy and emit the most emissions, while Agriculture uses the most land, followed by Manufacturing, and water.

- $\Delta_p \equiv pC(r) + w = (1+r)pA + w - p$ is the row-vector of profitability deviations,
- g is the aggregate growth rate in terms of physical quantities,
- r is aggregate profitability,
- A is the input-output matrix of direct requirements,
- c is the column-vector of final consumption in quantity terms,
- w is the row-vector of wage compensation per unit of physical output (i.e. unit labor costs), and
- δ_{ij} for $i,j = x,p$ are defined as diagonal matrices with the corresponding coefficients of cross-dual (δ_{xp} and δ_{px}) and dual (δ_{xx} and δ_{pp}) adjustment coefficients, reflecting the *intensity* of price and quantity interactions – which can be estimated empirically. Adjustment coefficients δ are defined as a $4N \times 4N$ matrix composed of four block $N \times N$ matrices δ_{ij} for $i,j = x,p$. In the original composite setup of Flaschel and Semmler, these four block matrices are diagonal and thus capture dual and cross-dual interactions of prices and quantities of the own industry with itself. In practice, these block matrices may not be exclusively diagonal and feature nonzero off-diagonal elements in order to capture cross-industry substitution effects.

3.2. Equilibrium

3.2.1. Quantities

Equilibrium in prices p^* and quantities x^* is achieved when sector imbalances in supply and demand and unit profitability are zero, respectively. In quantities, demand (composed of intermediate production Ax, investment gAx, and consumption c) equals supply x:

$$\Delta_x^* = 0 \tag{3}$$

$$Ax^* + gAx^* + c = x^* \tag{4}$$

$$x^* = -[(1+g)A - I]^{-1}c = -C^{-1}(g)c \tag{5}$$

3.2.2. Prices

In prices, profitability is uniform across sectors, as unit costs (in unit material costs pA, unit profits rpA and unit labor costs w) equal unit revenues p:

$$\Delta_p^* = 0 \tag{6}$$

$$p^*A + rp^*A + w = p^* \tag{7}$$

$$p^* = -w[(1+r)A - I]^{-1} = -wC^{-1}(r) \tag{8}$$

3.3. Walrasian law of excess demand

While competitive equilibrium in prices and quantities is easy to find in a linear production system, its stability through the dynamic adjustment of market prices and quantities over time is less clear, although extensively studied (Hahn, 1970, 1982; Fisher, 1989a,b, 2013). Initial, early contributions from John Hicks (1939) and Paul Samuelson (1947) focused on the dynamic study of the Walrasian tâtonnement as the single law of motion in the form of a single cross-dual price-quantity adjustment, by which prices rise (decrease) to positive (negative) excess demand and output adjusts instantaneously at its profit-maximizing value. In 'fix-price' economies in the Keynesian tradition, prices are instead considered to be fixed, while only quantities react to imbalances in demand, a fundamental quantity-quantity adjustment process in clearing markets out of equilibrium (Hicks, 1939). For any given demand function, stability is always guaranteed when decreasing returns to scale at equilibrium exist sufficiently close to the case of constant returns: stabilizing output reactions approach infinity when technology approaches the constant returns scenario (Flaschel et al., 1997). In general, it can be shown that stability is obtained when goods are gross-substitutes or when the weak axiom of revealed preferences holds (Flaschel et al., 1997; Flaschel, 2010). Yet, the Sonnenschein-Mantel-Debreu 'anything-goes' theorem highlighted the problems of aggregating individual preferences into a single excess demand vector for the whole economy (Kirman, 1992; Rizvi et al., 2006). As Scarf (1960) noted, this process can fail to be even locally stable at a unique equilibrium. In a similar vein, Hahn noted that the study of Walrasian groping has not been very fruitful (Hahn, 1970, 1982).

3.4. Classical law of excess profitability and cross-dual oscillations

In his attempt to formalize Walrasian market dynamics in a production economy, Mas-Colell (1986) suggests a strictly cross-dual framework proposing a complementary adjustment process to the law of excess demand, where output no longer adjusts instantaneously to its profit-maximizing value as quantities adjust in reaction to imbalances between the current price and the marginal labor cost. In a similar vein, the classical economists (Adam Smith, David Ricardo, Karl Marx, and John Stuart Mill) envisioned a law of excess profitability that would give dynamic stability to market economies, by which profitability deviations from equilibrium are self-correcting by changes in quantities driven by the entry and exit of profit-seeking firms (Flaschel and Semmler, 1987; Flaschel, 1990). As Flaschel and Semmler note, cross-duality in its simplest form does give rise to dynamic stability, but not necessarily the conventional 'asymptotic' convergence to competitive economic equilibrium as a single-point rest state with uniform profitability across sectors of production. Instead, cross-duality generally reflects the classical theme of dynamic gravitation, that is, of ceaseless over- and undershooting of sectoral prices, quantities, and profitability around their equilibrium 'natural values' as centers of gravity (Sraffa, 1960; Goodwin, 1983; Duménil and Lévy, 1987; Foley, 2003; Shaikh, 2016). Starting with a sector of production above (below) profitability, profit-seeking firms enter (exit) raising (lowering) output with respect to demand until demand moves above (below) supply. Then, the cross-dual Walrasian mechanism triggers an increase (decrease) in prices, adjusting the supply-demand imbalance and lowering (raising) industry profitability, closing the business cycle and starting anew. These coupled price and quantity oscillations are of the Lotka-Volterra predator-prey variety, where profits as prices play the role of the prey and profit-seeking investment as quantities plays the role of the predator.[2]

3.5. Keynesian stabilizing dual effects

While investment operates within a longer time scale, the Keynesian tradition focuses instead on the short run, characterized by imperfect competition, demand-led quantity reactions, oligopolistic markup price-setting, and barriers to firm entry and exit, (Morishima, 1981; Semmler, 1984). In the general composite version, Keynesian dual interactions are introduced, yielding a stabilizing, damping effect to the endogenous cross-dual fluctuations that may ensure the asymptotic convergence to equilibrium as a single-point rest state (1990). Considering the recent rise in windfall profits, price-price interactions due to oligopolistic market power have recently been suggested as a driver of "profit-led inflation", where firms increase their markups to protect their profit margins in the presence of input cost shocks (Weber et al., 2022; Weber and Wasner, 2023). In this context, cross-dual dynamics have thus been considered unsatisfactory, suggesting dynamic adjustments without cross-effects between prices and quantities where price and quantity movements may even be independent of each other for a while: what Morishima termed "dual dynamics" (Morishima, 1981; Flaschel et al., 1997).

In the short run, Keynesian features prevail, so that oligopolistic firms have market power to set prices at a markup that may establish barriers to firm entry or target a rate of return (price-price interaction), while adjusting their output to variations in demand (quantity-quantity interaction) (Flaschel, 2010, ch. 16). In the cross-dual long run, the free mobility of investment prevails, the markup gravitates around equilibrium profitability, and quantities change through the entry and exit of investment (Franke, 1987; Jacobo, 2022). Other imbalances can be further investigated, such as non-market clearing (i.e. inventory adjustment), supply constraints, or the effects of quantity levels on employment, money wages, and consumption (Flaschel and Semmler, 1990; Flaschel, 2010).

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[2] Lotka-Volterra dynamics are also implemented by the seminal Goodwin model of endogenous fluctuations driven by distributional conflicts, this time with the labor share of income as predator and the employment share as prey (Goodwin, 1982).

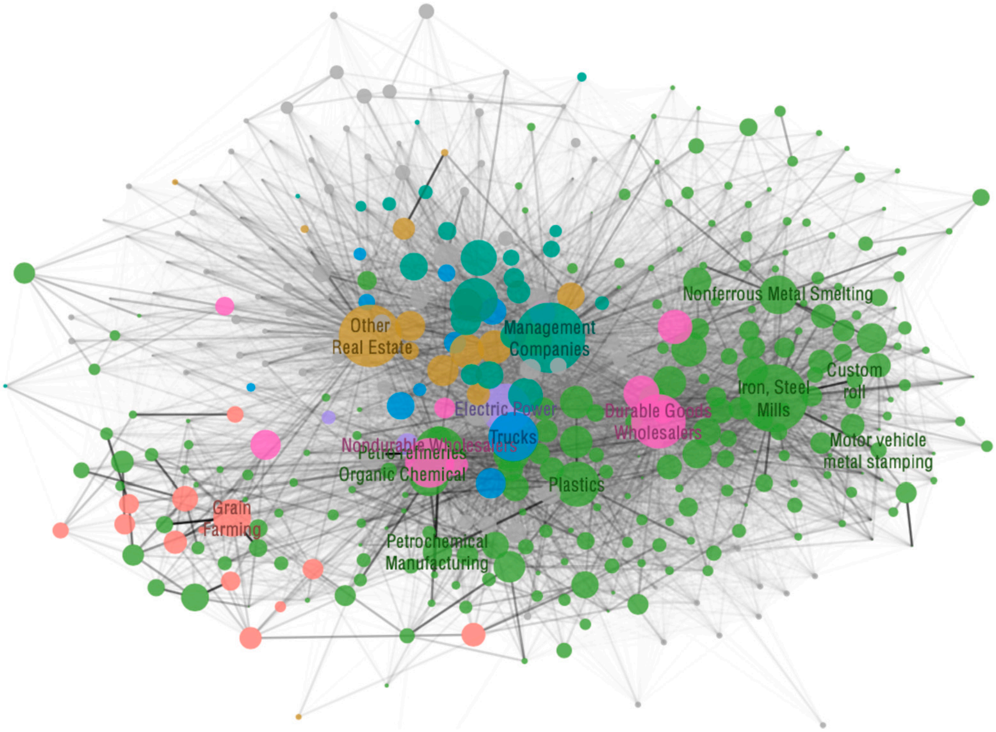

Fig. 3. Network Visualization of the Input-Output Structure A of the US, 401 Industries (BEA 2012) Colors refer to the industry classification (green, Manufacturing; red, Agriculture; turquoise, Services; pink, Utilities; orange, Real Estate). The most central industries are labeled (see Fig. 6). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

3.6. Dynamic stability

Finally, the $2N \times 2N$ Jacobian of the dynamical linear nonhomogeneous system is

$$J(z) = \begin{pmatrix} \delta_{xx} C(g) & -\delta_{xp} C^T(r) \\ \delta_{px} C(g) & \delta_{pp} C^T(r) \end{pmatrix} \qquad z \equiv \begin{pmatrix} x \\ p^T \end{pmatrix} \tag{9}$$

As it operates in continuous time, the composite system will be stable if the real parts of all eigenvalues of the Jacobian are negative. If the dual adjustment coefficients are zero so that the system is purely cross-dual, the eigenvalues of the Jacobian become pure complex conjugates, yielding complex oscillatory dynamics of N nested frequencies. If the system is purely dual (so that the cross-dual coefficients are set to zero), the dynamical system evolves exponentially towards the stable equilibrium with a speed associated to the real eigenvalues of the Jacobian. The general stability of the composite system is a formidable issue to explore analytically (Flaschel, 2010, ch.16). In the general case, the composite dynamics result in cross-dual oscillations that are dampened by the stabilizing effect of Keynesian micro-economic adjustments.

4. The network structure of sectoral interactions in prices and quantities

The matrix A and, by extension, C capture the industry network structure of dynamic interactions in prices and quantities. As developed by von Neumann (1945), the simplest multi-sector model of general equilibrium considers N interdependent processes of production transforming material inputs to single outputs, with linear production technology that can then be characterized by a matrix A of input-output coefficients (Fig. 4). In this closed setup, no final consumption and investment demand are considered as in the composite system, so that equilibrium prices p^* and quantities x^* are the positive row- and column-eigenvectors of the matrix A of input-output coefficients corresponding to the largest, dominant eigenvalue $1/R$ as the expansion factor by the Perron-Frobenius theorem: $x^* = RAx^*$, $p^* = Rp^*A$. Using the spectral displacement property of the eigenvalues Ω of arbitrary matrices, eigenvalues $\Omega_{C(\alpha)} = (1+\alpha)\Omega_A - 1$, but the eigenvectors will be the same. The dominant eigenvector x^* (common to both A and $C(\alpha)$) is denominated as the "standard commodity" in the literature, characterizing a unique gross output composition that enters production as inputs and comes out as outputs unchanged, with the same proportions, that is, the 'invariable standard of value' (Sraffa, 1960) or von Neumann's 'expansion ray' (Von Neumann, 1945).

The ratio of the modulus of the subdominant eigenvalue to the dominant one determines the speed of convergence to equilibrium (Bródy, 1997). In a strikingly parallel way to Lucas, Bródy conjectured, experimenting with random matrices of increasing size, that in 'very large' systems convergence to equilibrium may be attained in just a few iterations. Mariolis and Tsoulfidis empirically

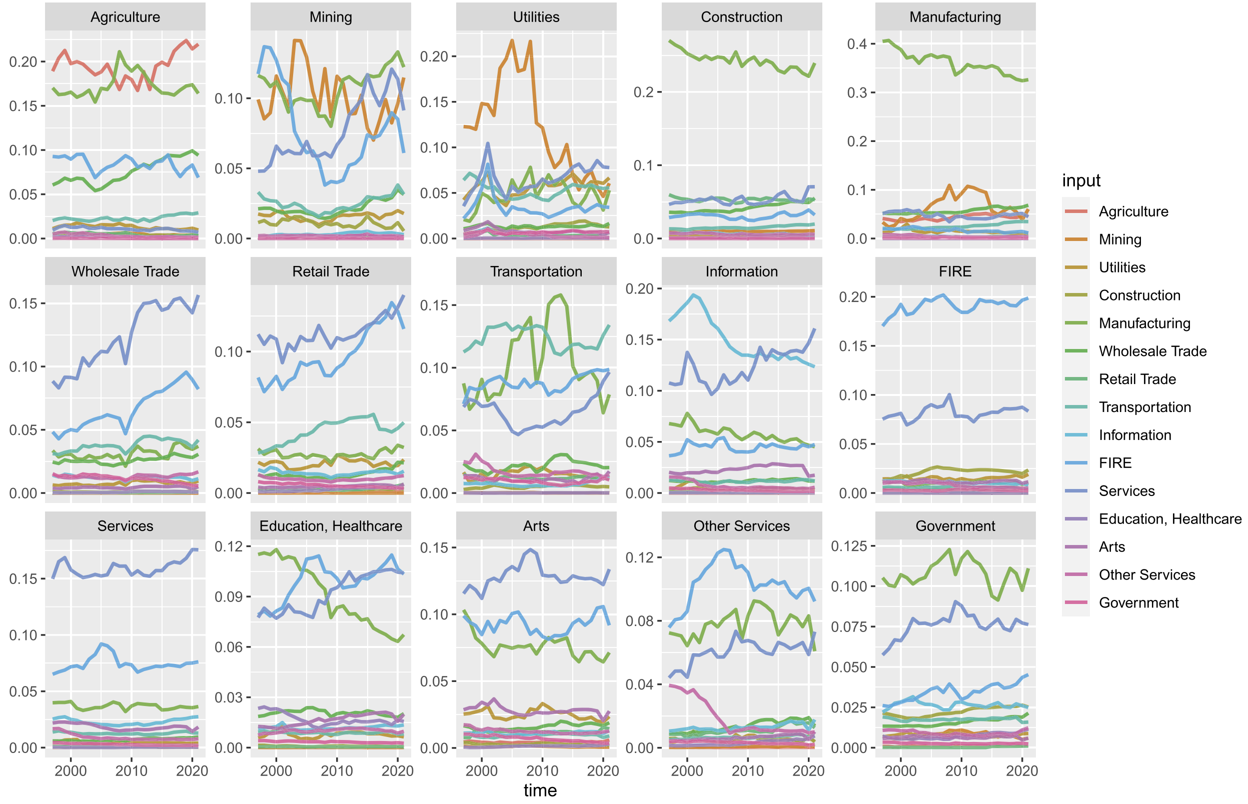

Fig. 4. Time Evolution of the Input-Output Coefficients at the Industry Level Each facet visualizes the particular inputs for each industry.

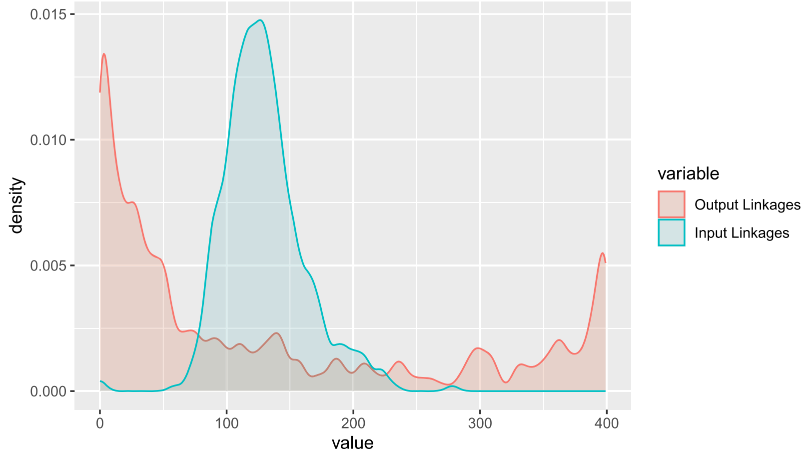

Fig. 5. Distribution of Numbers of Input-Output Linkages (US BEA 2012) Evidence of a highly hierarchical economy: most industries require a common number of inputs around 100 industries but sell outputs either to the whole economy or to less than 10 industries.

examined this assertion for the US economy, suggesting that the ratio between the two largest eigenvalues *increases* (instead of decreasing) both with the size of the input-output matrix and over the years for the same matrix size, lending support to the view of increasing, rather than decreasing, instability (Mariolis and Tsoulfidis, 2016). Empirical statistical analyses of the US input-output matrix show a remarkably persistent exponential distribution for their eigenvalues clustering around zero in the complex plane (Mariolis and Tsoulfidis, 2016; Torres-González and Yang, 2019; Shaikh et al., 2020; Ferrer-Hernández and Torres-González, 2022). From a dynamical-systems perspective, the existence of imaginary values in the eigenvalues suggests a highly complex nested pattern of oscillations operating at different frequencies [Fig. 1].

The Sraffian concept of standard commodity, as well as the equilibrium of the composite system, could not be more relevant in the current discussion on the macroeconomic propagation of micro-economic shocks through the input-output networks of economic

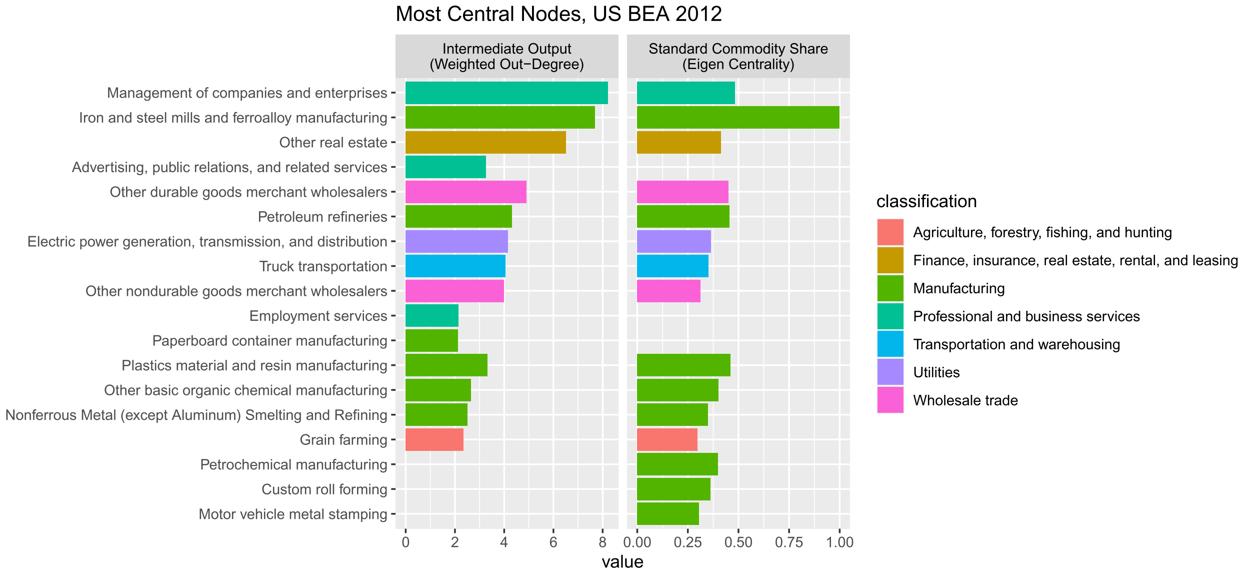

Fig. 6. Most Central Nodes According to Two Measures of Network Centrality, US BEA 2012.

production. This is so because its definition is fundamentally identical to the seminal concept in network theory of eigenvector centrality (Newman, 2018, p.160), used for instance in Google's *PageRank* algorithm, if the matrix A of input-output coefficients is interpreted as the adjacency matrix of a directed weighted network, with non-zero elements indicating linkages and the coefficients indicating its weights (Cerina et al., 2015; Grazzini and Spelta, 2022). In graph theory, eigenvector centrality is a measure of the influence (or prestige) of a node in a network in a way that linkages to high-scoring nodes contribute more than equal linkages to low-scoring nodes: a high eigencentrality corresponds to a node that is connected to nodes that are also very central (and thus will have a great influence on the propagation of economic shocks) (Newman, 2018, p.160). Another (rougher) measure of network centrality is the notion of weighted out-degree (i.e. the weighted number of out-linkages), which would directly correspond to the gross output devoted to intermediate production.

The measure of Katz centrality is also proposed (Newman, 2018, p.163), $\vec{\kappa} = \rho A \vec{\kappa} + \vec{\beta}$: this measure directly corresponds to the equilibrium values in prices and quantities of the composite system, when the vector β corresponds to unit labor costs w and physical final demand c and the attenuation factor ρ is $1 + \alpha$ for $\alpha = r, g$, respectively. Acemoglu et al. (2012, p.1985) define a similar notion of Katz centrality as the "influence vector" (in particular, Bonacich centrality), both of which lie between the extreme measures of degree and eigenvector centrality.

The input-output structure of the US production network is highly hierarchical, with few very well-connected core industrial hubs (such as electricity production and distribution or iron and steel mills, especially industries corresponding to manufacturing) catering to a large number of peripheral, smaller industries as customers downstream. Such is the asymmetric, star-shaped network structure that will considerably amplify, rather than damp, micro-economic shocks at the industry level. Fig. 6 shows the most central nodes according to its shares of intermediate output and the standard commodity (eigencentrality), colored by its industry classification. Fig. 3 shows a visualization of the input-output linkages of 400+ industries for 2012 US BEA data, colored by its industry classification following the same palette and sized by their gross output. The top-left cluster corresponds to services, manufacturing is located on the bottom-right, and agriculture on the bottom-left. The network is sparse, with a low density: only a third of potential linkages are nonzero, 99% of nonzero input-output linkages are less than 0.06. However, the network is still tightly connected, as its diameter is very small (0.13) and all nodes are connected either directly or through a third industry. The distributions of input-output linkages in Fig. 5 show that while most industries require a similar number of inputs of around 100 industries, the number of output linkages are very uneven and cluster around the extreme values of either less than 10 or 400 (that is, the whole economy): industries sell outputs either to the whole economy (such as utilities) or to less than 10 industries.

This cursory network analysis shows why complementing climate mitigation policies with price stabilization is critical for the resilience of the economy. Due to the structure of the US production network, carbon pricing policies could well be counter-effective as they could act as input cost shocks to the whole economy and threaten inflationary pressures that may exacerbate if oligopolistic price-setting exists (Moessner, 2022; Santabárbara and Suárez-Varela, 2022). Many of the most central industries are highly carbon-intensive and thus critical targets for the low-carbon transition, such as electric power, petroleum refineries or truck transportation, and/or highly vulnerable to climate change, such as grain farming, located at the core of the agriculture cluster on the bottom left. The sector with the largest number of output linkages is 'Electric power generation, transmission, and distribution', which may be among the most carbon-intensive of all industries. The most eigencentral industries coincide with those identified by the analysis of 'systemically significant prices' of Weber and co-authors: manufacturing of industrial inputs (iron and steelmills, plastics, petrochemicals), petroleum refineries, as well as electric power (Weber et al., 2022).

Fig. 7. The Empirical Composite System: Assumption of Linear Relation between Industry-level Time Differences in Prices and Quantities with respect to Supply-Demand Imbalances and Deviations in Profitability.

5. Econometric estimation of the adjustment coefficients

5.1. Setup

While the input-output coefficients capture the structure of dynamic price-quantity interactions, reaction coefficients δ capture their intensity in the form of distinct speeds underlying the dynamic laws of motion that translate into heterogeneous firm behavior at the sector level. These reaction coefficients can be estimated empirically to yield a data-driven dynamical system, a first in this literature. Here, the time variation in prices and quantities is defined as a function of the complex imbalances between them (Fig. 7), driven by the input-output technology matrix with aggregate profitability and growth as benchmarks.

The econometric problem thus consists of empirically estimating the various adjustment coefficients of the dynamical equations using a multi-variate Bayesian linear hierarchical model with mixed effects, where:

- the predictors are the industry-level imbalances between supply and demand Δ_x and between cost and revenue Δ_p (x_{1i} and x_{2i} in this notation, respectively),
- the response (dependent) variable is the time difference in prices and quantities, $y_i \equiv (\dot{x}_i, \dot{p}_i) \sim (x_i(t+1) - x_i(t), p_i(t+1) - p_i(t))$ (as the time interval is $\Delta t \equiv 1$ year),
- the random slopes β depend on the jth industry and correspond to the industry-level adjustment coefficients of the composite system (while the fixed effects correspond to the adjustment averages),
- there are no intercepts.

In short, for $i = 1, \ldots, N \times T$ prices and quantities with N industries over a time interval T, the econometric estimation of the composite system involves a multi-level linear regression (Gelman et al., 2013, ch.15):

$$y_i = \beta_{1i} x_{1i} + \beta_{2i} x_{2i} + \epsilon_i \tag{10}$$

with normally distributed errors $\epsilon_i \sim N(0, \sigma_\epsilon^2)$. In Bayesian notation,

$$y \sim N(x_{1ij}\beta_{1j} + x_{2ij}\beta_{2j}, \sigma_y^2) \tag{11}$$

$$\beta_j \sim N(\mu_\beta, \Sigma_\beta) \tag{12}$$

where $\beta_j = (\beta_1, \beta_2)$, Σ_β is the covariance matrix, and μ_β is the hyperparameter driving the fixed effects.

There are many datasets available that can be used in order to calibrate empirically the model with relative success. From national statistics, the World Input-Output Database (Timmer et al., 2015), or EORA, one can obtain input-output tables, which in the EORA case are environmentally extended with 2,631 ecological indicators (Lenzen et al., 2012, 2013). Environmentally-extended input-output data is particularly useful to develop ecological applications of the Bielefeld disequilibrium approach by extracting intensities ϵ for each ecological indicator of interest E in terms of output x, e.g. $E = \epsilon x$ [see Fig. 2]. Such ecological intensities are here assumed constant for simplicity but can be modeled dynamically. Time series data on prices and quantities at the industry level is required and can be obtained from the EU KLEMS database for many Global North economies (Van Ark and Jäger, 2017). However, using different databases is problematic as they may differ in their assumptions and construction.

For instance, a main challenge is that the industry structure differs by database, adding complication to the econometric estimation. Consequently, in order to calibrate the model, it is convenient to extract all relevant information (chain-type price and quantity indices; input-output coefficients; aggregate growth rates and profitability; final demand in quantity terms and unit wage costs) from the same database, in this case the US Bureau of Economic Analysis,[3] which provides data for the same industry structure N (15 and 66 industries)[4] and a time interval T that can be annual (1997 - 2021, 25 years) or quarterly (2005Q1 - 2022Q3, 71 quarters).

5.2. Challenges

The econometric estimation poses many challenges and modeling choices that need to be fully worked out in subsequent iterations of this work.[5] Involving 30 dimensions (prices and quantities for $N = 15$ industries) and a total of 1005 sector-level, time-dependent joint observations of price and quantity changes and their corresponding imbalances ($T = 67$ quarters $\times N = 15$ industries), the Bayesian setup of the composite system is highly complex and may be over-parameterized compared to the relatively little amount of data available and its quality. Simpler setups like the strictly cross-dual form may be more convenient. In order to avoid potential issues in multi-collinearity, it is more convenient to use price and quantities indices directly (rather than combining them with the monetary measures of gross output), while preserving the dimensionality of the system. In order to scale to the proper proportions in prices and quantities, the price and quantity indices can be multiplied by the equilibrium prices and quantities (e.g. the eigenvectors of the time-averaged input-output table). In this context, the correlation among the predictors is very weak (close to zero) and the Variance Inflation Factors are extremely low (very close to 1).

Final consumption and wage compensation, given in dollars, need to be converted to a quantity (c) and a price (w) measure, respectively, at the industry level:

$$c = w_{IO} \times q_{VA}, \qquad w = w_{IO} \times p_{VA} \tag{13}$$

where w_{IO} is the wage compensation per unit of gross output (in dollars) from the input-output tables, while p_{VA} and q_{VA} correspond to the price and quantity indices for value added, respectively. Computing imbalances in prices and quantities Δ_x and Δ_p is also challenging, first of all considering the common equilibrium assumptions involved in the construction of such econometric data are based (such as the equality of supply and demand). In this case, the imbalances are computed following their definitions in the composite system; the great similarity in their construction requires then using a multi-variate Bayesian model that jointly estimates the slopes in order to capture these interdependencies and improve the predictive performance of the model. In addition, the predictors need to be scaled by subtracting their industry-level time averages in order to focus on the variations. The construction of aggregate profitability r is also problematic in this model without fixed investment; the aggregate growth rate in prices is employed as a proxy measure in order to simplify the model while taking advantage of the symmetry of the price and quantity equations. Finally, while in the theoretical model the adjustment coefficients for the excess law of profitability are defined negative in order to ensure stability, no sign is imposed in the model (although this is confirmed by the empirical results).

5.3. Results

Despite the complexity of the linear model relative to the data available, all Markov chains of the Monte Carlo algorithm converge with zero number of divergences per chain, no times the maximum tree depth is hit per chain, and the energy Bayesian fraction of missing information (E-BFMI), which quantifies the efficacy of the momentum resampling in between Hamiltonian trajectories, indicates no pathological behavior as it lies between 60 and 70%. The potential scale reduction factors (*Rhat*), which measure the degree of convergence of the MCMC algorithm, of all parameters are 1. The effective sample sizes (ESS) of each parameter, measuring the number of independent posterior samples, are large, indicating the estimates are reliable.

Fig. 8 shows the posterior distributions of the fixed effects that correspond to the general adjustment coefficients, averaging by sector. In agreement with the Keynesian emphasis on the quantity channel, the demand-led reaction is the most intense and

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[3] Downloaded from https://apps.bea.gov/iTable/?isuri=1&reqid=151&step=1.

[4] In this case, the level of aggregation is chosen at 15 industries: Agriculture, forestry, fishing, and hunting; Mining; Utilities; Construction; Manufacturing; Wholesale trade; Retail trade; Transportation and warehousing; Information; Finance, insurance, real estate, rental, and leasing (FIRE); Professional and business services; Educational services, health care, and social assistance; Arts, entertainment, recreation, accommodation, and food services; Other services, except government; and Government.

[5] A more rigorous alternative may be to directly estimate the system of continuous ordinary differential equations directly (Huang et al., 2006; Poudel et al., 2022), but adding mixed effects to such complex system is very sophisticated and may not substantially improve the results.

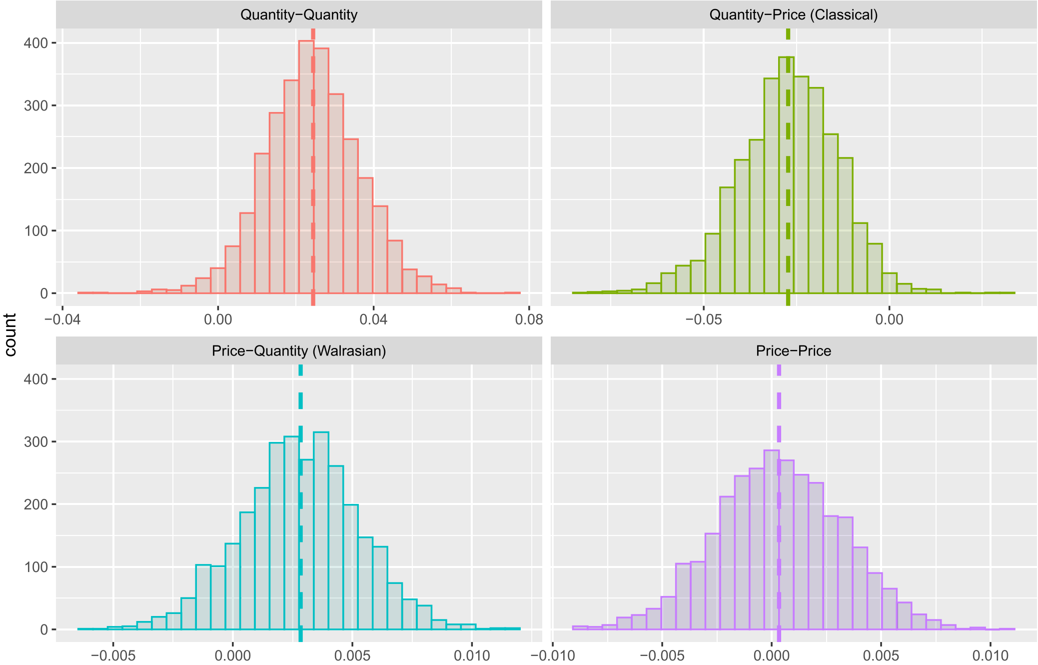

Fig. 8. Posterior Distributions of the General Adjustment Coefficients (Fixed Effects).

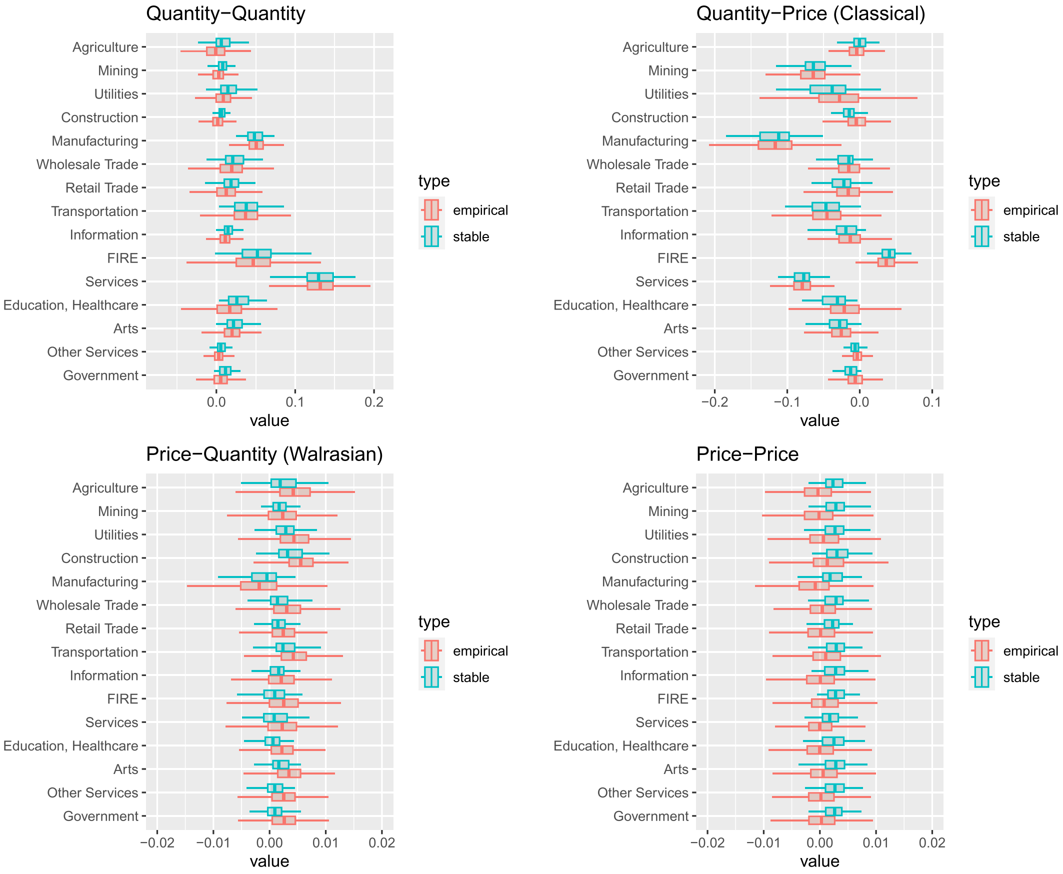

Fig. 9. Boxplot for the Posterior Distributions of the Empirically Estimated and Stable Industry-Level Adjustment Coefficients, by Adjustment.

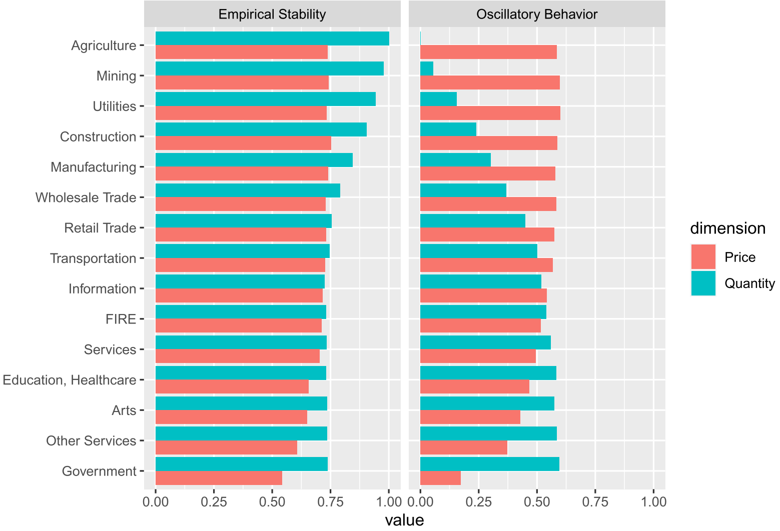

Fig. 10. Stable Dimensions and the Oscillatory Behavior of the Empirical Composite System For each draw of the posterior distribution, the proportion of stable dimensions corresponds to the number of negative real parts of the Jacobian eigenvalues out of $2N$, while the proportion of oscillatory dimensions corresponds to the number of nonzero imaginary parts of the Jacobian eigenvalues out of $2N$.

significant, followed by the classical adjustment driven by firm entry and exit, which is negative as expected by the theoretical framework. In contrast, the Walrasian price-quantity mechanism is less intense and significant and general price-price interactions are the closest to zero, indicating little oligopolistic price-setting in the aggregate.

Fig. 9 shows the posterior distributions for the empirically estimated industry-specific adjustment coefficients, which include the random effects. Demand-led reactions are particularly intense for Services, Manufacturing, FIRE, and Transportation. The firm entry (classical) adjustment is particularly relevant for Manufacturing and Services, while the Walrasian mechanism is the most intense, at a smaller scale, for Construction, Agriculture, and Utilities. While general price-interactions are the closest to zero, the largest coefficients are positive for Construction and Transportation, while negative for Manufacturing. This provides some complex empirical evidence of oligopolistic price-setting occurring in different directions: for the positive values, prices increase in the face of negative excess profits due to input cost shocks, while in contrast for negative values prices increase to protect a rise in profit margins.

5.4. Stability

The analytical stability of the composite system is painstakingly investigated in depth by Flaschel and Semmler (Flaschel, 2010, ch.16). The present empirical estimation contributes a new perspective to this complex problem [Figs. 9]. First of all, the estimated averages of the adjustment coefficients yield a Jacobian that is stable in 26 dimensions out of the total 30. The four unstable dimensions correspond to the price equations for Construction, Retail Trade, Transportation, and Government. 53% of the dimensions display oscillatory behavior as they have complex eigenvalues: seven in quantities and nine in prices. The posterior distributions of the industry-specific adjustments yield 2% of combinations of adjustment coefficients that are unstable in two dimensions or less, 0.63% that are stable in one dimension or less, and 0.01% that are completely stable, which can be employed to calibrate the simulations. Figure 10 shows the proportions of stable and oscillatory dimensions out of $2N = 30$ for each posterior distribution (3 chains, 1000 iterations per chain): quantities are always more stable than prices (an average of 80.6% over 70%), while 51% of the prices show oscillatory behavior (over 40% of quantities). Fig. 9 also shows the stable values of each industry-level adjustment extracted from the empirical posterior distributions.

Regarding the deviations of the stable adjustment coefficients from the empirically estimated averages, the classical quantity-price adjustments mostly coincide, as well as quantity-quantity interactions and price-quantity effects to a minor degree. Interestingly enough, stable price-price effects are all slightly positive instead of the empirical estimates, which cluster around zero. Hence, the stable combinations of adjustments appear to require a conventional oligopolistic markup pricing strategy, by which prices increase in the face of negative excess profits due to input cost shocks.

6. Ecological applications: price stabilization and climate change mitigation

6.1. Price and quantity controls

Once empirically calibrated and environmentally extended, the Biefeleld framework of composite micro-level dynamics in prices and quantities is particularly suitable to investigate sector-level policies aimed at the twin goal of price stabilization and climate change mitigation. In a time of global overlapping emergencies, sectoral price stabilization is critical in the context of the transition

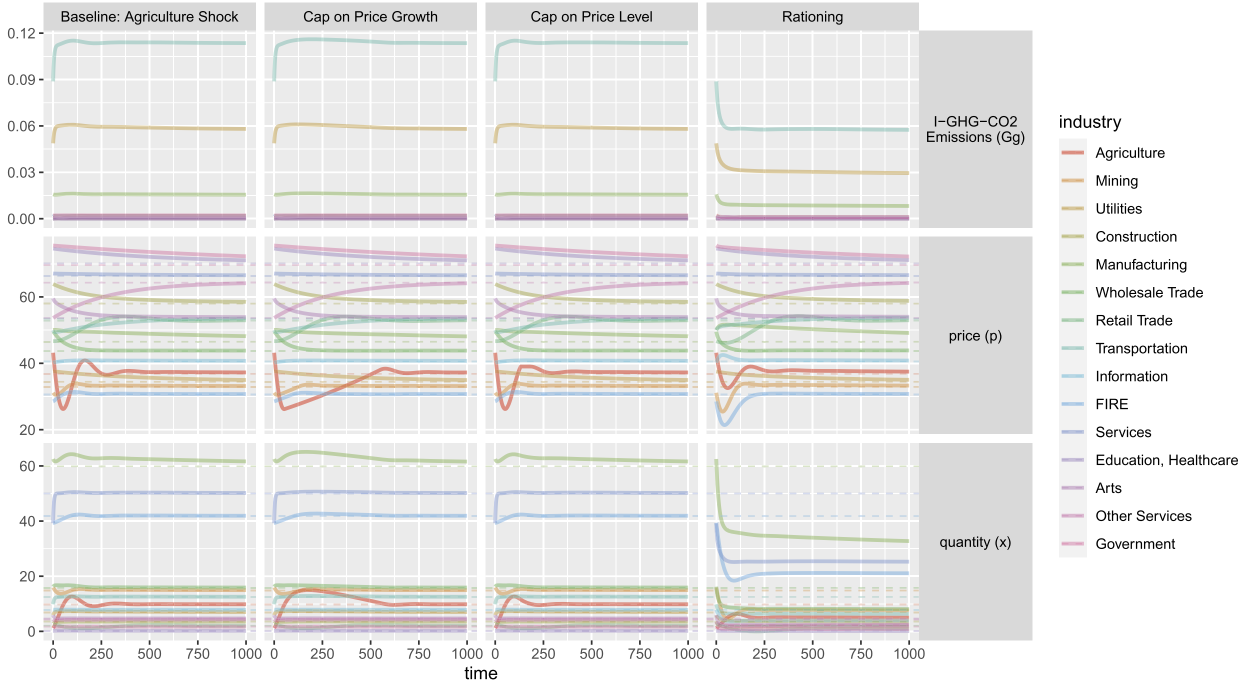

Fig. 11. Ecologically Extended Simulations of an Agriculture Shock of 90% Output Reduction under Price Controls and Quantity Controls (Rationing) Each column refers to a specific scenario.

to a more resilient economy and environment. The following simulations explore controls over the time evolution of prices, either on their level or growth, controls over the equilibrium quantities through rationing consumption, and, finally, tax-subsidy schemes to accelerate structural change towards technologies with less environmental impact.

First of all, a shock on the agriculture sector, by which it loses 90% of its output due to war or drought, is simulated under price and quantity controls, including one of the many ecological indicators available, carbon emissions [Fig. 11]. Although they can target specific sectors, price controls are enforced on all industries either on the level (a cap of 6% above the equilibrium price) or the growth rate (a cap of .075%), while quantity controls are enforced through rationing final demand 50%. In the baseline scenario without policy, the agriculture shock involves a dynamic response by which the quantity first increases and the price (which was above its equilibrium initially) decreases, featuring dampening oscillations towards equilibrium.

Despite the low intensity of price-price interactions found for the empirical adjustment coefficients, Fig. 11 shows an industry-specific cap on the price level to still be very effective in attenuating economic fluctuations. Controls of this form are effective in the composite dynamical system not especially because they curb the firm's market power to set prices, but because they impose a ceiling on profits, as captured by the amplitude the cross-dual oscillations driving economic volatility may reach. Caps on the price level may initially create transitory drops in supply, but also impose well-defined ceilings on the amplitude of the oscillations both in prices and quantities, so that less pronounced booms will precede less pronounced busts until the economy converges to equilibrium. Such controls are successful in reducing economic volatility understood as the amplitude of sector-level fluctuations, with a much more limited effect in perpetuating supply-demand imbalances out of equilibrium. Caps on the price level are the least effective when there is no oscillatory behavior and the dimension is already dominated by Keynesian stabilizing effects.

In contrast, the most important effect of caps on price growth is to decelerate and turn monotonic such convergence to equilibrium, especially in the case of agriculture, but also mining and FIRE, so that supply-demand imbalances will substantially persist over time. Remarkably enough in comparison with conventional economic wisdom, price controls of this form have no clear impact on reducing economic activity, but in fact may even *increase* output if controls do not allow prices to adjust fast enough. Although effective, controls on price growth may theoretically amplify, rather than attenuate, the complex interplay of the imbalances in prices and quantities driving the cross-dual oscillations if the latter were more intense than the Keynesian dual effects, but empirically this is not the case.

6.2. Tax-subsidy schemes

While price controls may be effective in stabilizing economic fluctuations, they are not in mitigating climate change, as the environmental impact of the economy depends on the equilibrium gross output vector

$$E = \epsilon x^* = -\epsilon C^{-1}(g)c, \tag{14}$$

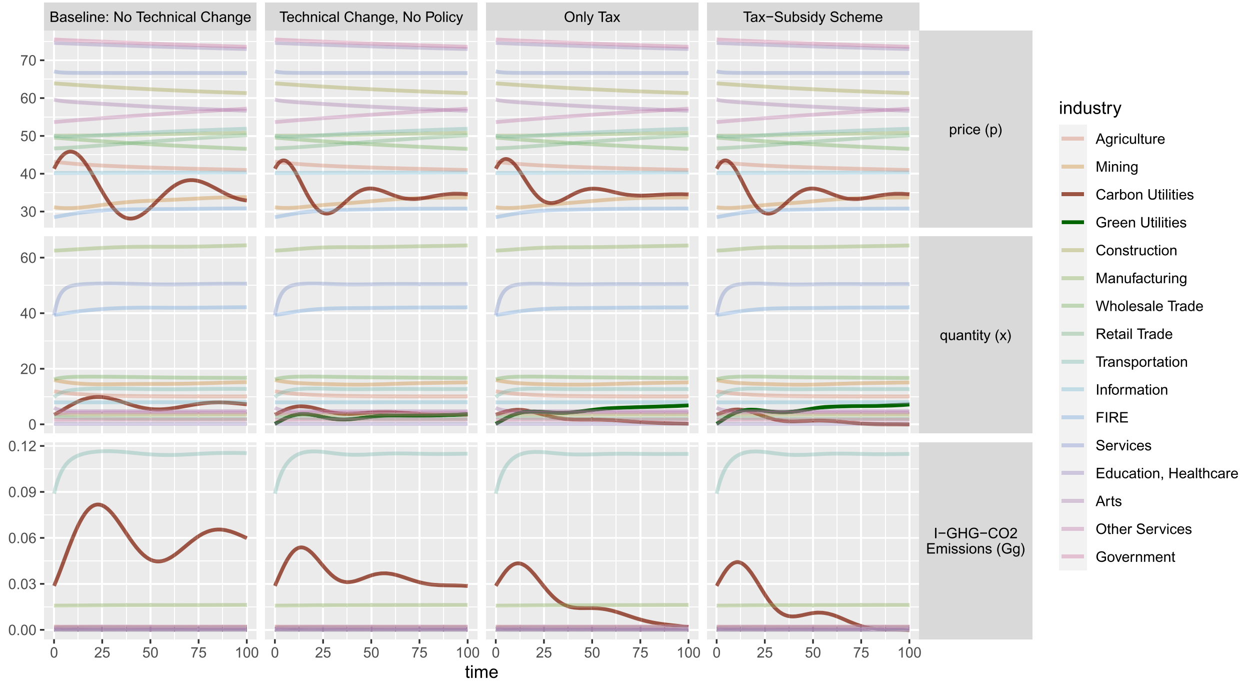

Fig. 12. Ecologically Extended Simulations of a One-Off Process of Technical Substitution and Low-Carbon Transition Each column refers to a specific scenario. The green alternative starts at 5% output of the carbon process, with 95% of its original production costs. The 'Only Tax' scenario features a tax rate of 3%, which is reduced to 2% when green subsidies are added.

which in turns depends on final consumption c, growth rate g, and input-output technology A. The most recent reports of the UN Inter-governmental Panel on Climate Change call for a reduction of emissions of the order of 50% in 10 years. Reducing the (already low) growth rate to zero, while keeping final demand constant, only reduces gross output and thus emissions by 1.51%. Because emissions are generally coupled to economic output, quantity controls such as rationing final consumption by 50% are effective in reducing the environmental impact of the economy by the same amount. Such a dramatic reduction in life standards may only be tenable for the top income brackets of the Global North, but unfeasible and excessive for the general population. Rather, structural change (on A) needs to occur so that environmentally-intensive technologies can be replaced by greener alternatives and thus uncouple environmental impact from economic activity.

Following an extension of the model to include process innovation and extinction (Flaschel and Semmler, 1992), the Flaschel-Semmler model of composite dynamics is well-suited to study this process of structural change. Composite-dynamics simulations of a one-off process of decarbonizing technical substitution are implemented where an existing process is outcompeted and eventually replaced by a lower-cost, less carbon-intensive alternative. The model with technical change introduces a one-off innovation in the form of a new column in a now rectangular $N \times N + 1$ matrix A', with $N + 1$ quantities and N prices, as the new process produces the same output with zero emission impact (for simplicity) at a lower cost as the old process it will replace.[6] Through structural change, the phase-in of lower-cost, less carbon-intensive technologies may promote price stabilization and decarbonization at the same time. Lower costs of production imply profitability differentials between production technologies that translate into growth differentials determining the speed of the process of technical substitution. However, such substitution due to lower production costs alone may take too long relative to the stringent UN IPCC targets. In this context, fiscal policy can accelerate the low-carbon transition by regulating multi-sector growth towards technologies with less environmental impact through tax-subsidy schemes that act on existing profitability and growth differentials due to differences in production efficiency.

Fig. 12 shows the baseline scenario with no technical innovation, a scenario with technical innovation but no policy, a scenario with only a tax on the output of the carbon-intensive process, and, finally, a scenario with a tax-subsidy scheme that uses the tax revenue to subsidize the lower-cost, less-carbon-intensive alternative. The targeted industry is Utilities, a highly eigencentral, carbon-intensive sector. The simulation results highlight how taxes on output (such as carbon pricing) are substantially effective in accelerating the phase-out of carbon-intensive technology (and thus reducing carbon emissions) by increasing its profitability (and thus growth) differential over the newer, lower-cost alternative. However, inflationary pressures may set in if the process of technical substitution takes too long so that output drops, prices rise, and input cost shocks propagate over the rest of the economy. Adding green subsidies in the policy mix not only accelerates the phase-in of less-carbon-intensive technologies and the reduction of

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[6] The weighted average of the profitability deviation by output is taken when the single price-price interaction needs to be computed from two different values.

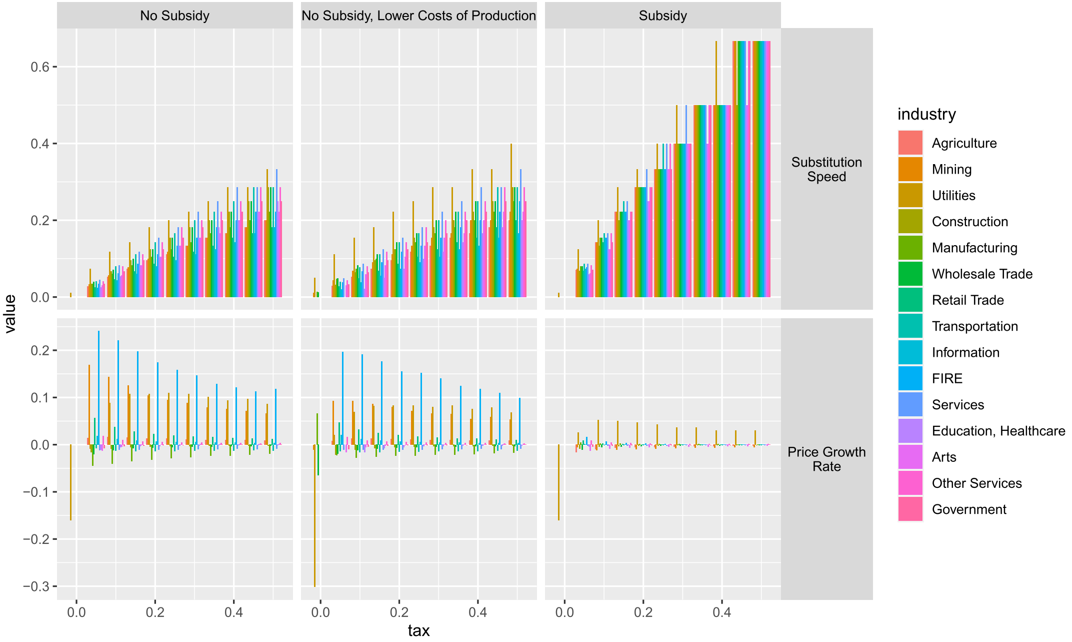

Fig. 13. Comparison of the Speed of Technical Substitution and Price Growth under Tax Only, under Tax Only with Lower Costs of Production, and under Tax-Subsidy Scheme The lower costs of production involve 76% instead of 95% of the original cost. In the tax-subsidy scheme, all tax revenue is re-invested as a subsidy for the new process.

emissions, but also stabilizes the prices of its outputs: sectoral output may not only not drop, but rise, further decreasing prices and stabilizing inflationary pressures while at the same time decarbonizing the economy even faster.

In this direction, Fig. 13 visualizes the impact of the tax rate on the speed of technical substitution for each industry (defined as the inverse of its duration in years) and the growth rate in its prices at the moment when the output of the new process takes over the old one in three situations: without subsidy (e.g. tax only), without subsidy with lower costs of production, and with subsidy. A tax on output shows a large impact on the speed of technical substitution, but it also increases prices substantially. In general, 20% lower costs of production imply a small effect of a slightly larger speed of adjustment and slightly lower price growth. It is the addition of subsidies that truly accelerates the dynamic process of substitution while stabilizing its prices. Policy needs to pay attention to the heterogeneous behavior of firms in their responses to imbalances: the impact on the speed of substitution and price growth is sensitive to the sign and intensity of the adjustment coefficients as it may lead to counter-intuitive effects: if the Walrasian adjustment is negative and the classical adjustment is positive, lower costs of production imply a slower substitution speed, such as in Education and Healthcare. A negative Walrasian adjustment as for Manufacturing implies that its price grows the least at higher costs of production and without subsidies, although this effect is actually very small and can be neglected.

7. Conclusions

This paper presents an environmentally-extended, data-driven dynamic model of multi-sector growth in the tradition of the Bielefeld disequilibrium approach to the stability of competitive economies. By integrating short- and long-run Walrasian, Keynesian, and classical micro-dynamical processes in a stylized form that resembles state-of-the-art machine learning models, the theoretical framework is particularly well-suited to empirically characterize both the structure and the intensity of price-quantity dynamic interactions out of equilibrium, despite neglecting aggregate issues of important concern for Peter Flaschel such as effective demand, income distribution dynamics, and monetary growth, as well as feedbacks due to instabilities in the aggregate product, labor, and financial markets. With core industrial hubs providing critical inputs to the whole economy, the hierarchical network structure of US intermediate production is shown to be particularly vulnerable to exogenous micro-economic shocks driven by de-globalization and climate change; some of the most central industries such as electric power, transportation, heavy industry, or agriculture are also particularly environmentally intensive. Theoretically, the equilibrium quantity vector of the composite system directly relates to the most central industries within the complex structure of economic production following fundamental concepts in network theory (e.g. eigencentrality and Katz-Bonacich).

In a time of overlapping global emergencies when policy-makers are increasingly embracing activist industrial policy, the paper further shows how the framework can be employed to explore sector-oriented policies that regulate industrial growth to ensure the resilience of the economic system and its interactions with the environment. The effectiveness of such policies critically depends on the heterogeneity of industrial behavior responding to disequilibrium supply-demand imbalances and deviations from profitability at the sector level, which can be captured empirically by the intensity of the adjustment coefficients. Despite small general price-price effects were empirically found indicating oligopolistic market power, simulations show strategic sector-oriented controls on the price level and growth to be still effective to stabilize economic fluctuations, either by dampening the oscillatory booms and busts driven by cross-dual interactions or decelerating the convergence to equilibrium driven by the Keynesian dual effects. In contrast, carbon pricing targeting decarbonization may be inflationary if businesses decide to pass these additional costs to the consumer, especially if they hold the power to set prices. While rationing consumption is able to curb emissions, strategic tax-subsidy schemes targeting excess carbon supply while substantially providing much-needed green investment may be the most effective in accelerating structural change towards climate change mitigation while lowering the costs of critical inputs for the economy.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Data availability

Data will be made available on request.

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