

Stabilizing Economic Fluctuations and Economy-Environment Interactions with a Novel Macroeconomic Model of Multi-Sector Growth: Ecological Applications of the Bielefeld Disequilibrium Approach

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Abstract

The complexity of the recent macroeconomic demand and supply shocks, caused by the COVID-19 pandemic and the Ukraine war, has highlighted how little is understood of their propagation through the economic structure of intermediate production and, most importantly, of their management by policy-makers – a growing focus of recent attention in the New Keynesian literature. This paper provides an alternative theoretical framework based on the work of the late Peter Flaschel to study the network-based interplay of micro- and macroeconomic fluctuations. By repurposing the classic literature on microeconomic stability based on adjustment processes in prices and quantities, it contributes a novel macroeconomic model of multi-sector growth that is fundamentally driven by empirical data and works like a machine-learning algorithm with potential for actual predictive power. The general ‘composite’ model operates under long-run Walrasian price and classical quantity dynamics coupled with short-run Keynesian features in the form of markup pricing and demand-led investment. The linear adjustment coefficients can be empirically estimated using a mixed-effects varying-slopes model on the environmentally-extended input-output EORA database and the time series in prices and quantities of the EU KLEMS database. Finally, the paper shows how the model allows testing a diverse set of policies (subsidies and taxes on consumption and production, as well as caps on profits and prices) aimed at stabilizing both the economy and the environment at the same time.

JEL Codes C63, O25, O41, Q55

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1. Introduction

2 The complexity of the recent macroeconomic demand and supply shocks, caused by the COVID-19
3 pandemic and the Ukraine war, has highlighted how little is understood on their propagation through the

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4 structure of economic production and, most importantly, their management by policy-makers remains. The
5 cross-sectoral demand shock due to the pandemic revealed to what extent supply bottle-necks are ubiquitous
6 in a globalized, highly inter-dependent economy that is yet now undergoing a systematic de-coupling of
7 value chains amidst international trade wars, oil and grain embargos, and sanctions. Due to the Ukraine
8 war, specific shocks on key economic sectors supplying intermediate inputs to a wide range of industries,
9 such as energy and food, arguably drive in cost-push way the general inflation that is observed today across
10 countries in the Global North. In this situation, policy-makers currently debate the policies available to
11 stabilize such volatile macroeconomic situation and target sector-level inflationary pressures, whether in the
12 form of the anti-trust policy or caps on prices and profits. Facing a looming climate crisis, inflationary
13 pressures on energy and food are most certainly expected to exacerbate, emphasizing the urgent need of
14 vigorous industrial policy that accelerates the low-carbon transition while at the same time stabilizing key
15 economic sectors.

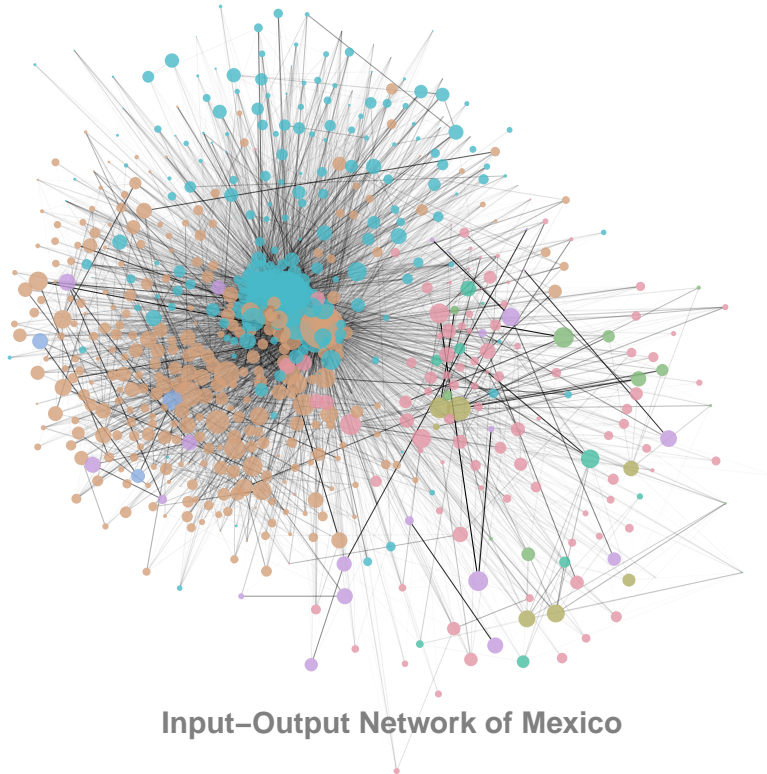
16 In the context of the 1970s stagflation, Robert Lucas initially argued that, in fact, independent sectoral
17 disturbances should actually tend to average out, leaving aggregates unchanged (Lucas, 1977). However, as
18 Acemoglu et al (2012b) suggests, the complex structure of inter-sectoral input-output linkages in intermediate
19 production (seminally studied by Wassily Leontief (1966)) may propagate microeconomic idiosyncratic shocks
20 that lead to aggregate fluctuations and may be further amplified by imperfect competition, productivity
21 heterogeneity, barriers to entry and exit, imperfect information, price-setting firm power and wage rigidities,
22 or market concentration (Carvalho & Gabaix, 2013; Carvalho, 2014; Baqaee et al., 2018; Baqaee & Farhi,
23 2019b). Generally, input-output networks of economic production exhibit a highly hierarchical structure,
24 with key large industries as core hubs (such as retail and wholesale trade, energy, and food) catering to
25 a large number of smaller, peripheral sectors (Cerina et al., 2015; Foerster & Choi, 2017). Starting in
26 the 18th century with the Physiocrats' *Tableau Économique*, classical political economists have paid great
27 attention to the economic structure of intermediate production, although the notion that key consumers or
28 key suppliers can have outsized effects on an economy through their inter-sectoral forward and backward
29 linkages in production can be traced back at least to Hirschman (Hirschman, 1958; Sraffa, 1960; Pasinetti,
30 1977).

31 While much of the recent literature relies on New Keynesian general equilibrium models (featuring Cobb-
32 Douglas production functions and equilibrium marginal pricing), this paper employs instead the theoretical
33 framework of out-of-equilibrium micro-economic processes of dynamical adjustment on linear production,
34 initiated by the early studies by John Hicks (1939) and Paul Samuelson (1947) on the Walrasian law of
35 excess demand. With many important contributions by Jorgenson (1960), Scarf (1960), Burmeister (1973),
36 Fukuda (1975), Morishima (1976; 1981), Hahn (1966; 1970; 1982b) or Mas-Colell (1986) among others, such a
37 framework, integrating short-run and long-run Walrasian, Keynesian, and classical features as well as macro-

38 and microeconomic levels of analysis, was ultimately developed and formalized by the late Peter Flaschel, as
39 well as Willi Semmler and Reiner Franke, within the Bielefeld disequilibrium approach (Flaschel & Semmler,
40 1986, 1987, 1992; Flaschel et al., 1997; Flaschel, 2010). Focusing on the study of the dynamic stability
41 of competitive economies, this literature considered particular functional forms of micro-level processes of
42 dynamical adjustment out of equilibrium, characterized by reaction coefficients underlying stylized facts as
43 laws of motion driving sector-level fluctuations in prices and quantities. These adjustment processes can be
44 dual (price-price and quantity-quantity) in the short run (in the form of markup pricing and demand-led
45 output reactions), cross-dual (price-quantity and quantity-price) in the long run (in the form of Walrasian
46 pricing and free capital entry), or a general composite form that integrates both forms of adjustment. The
47 paper shows how the complex structure of dynamic interactions in prices and quantities evolves over time in
48 the general composite form, not only driven by the input-output matrix of linear technology (which changes
49 in the long run), but also by short-term fluctuations in aggregate growth and profitability.

50 While the literature on disequilibrium micro-economic processes of dynamical adjustment was always
51 theoretical, the paper shows it can be re-purposed as a highly-stylized multi-sector growth model requiring
52 much less parameters and equations than conventional New Keynesian macroeconomic models in a way
53 that is fundamentally driven by empirical data resembling state-of-the-art linear machine-learning methods.
54 In this context, composite linear adjustment coefficients can be estimated empirically using a sector-level
55 hierarchical linear regression model with varying slopes and no intercept on the environmentally-extended
56 input-output database EORA and EU KLEMS time series of prices and quantities. Using one out of the
57 2,631 environmental indicators of the EORA sector-level database (carbon emissions from public electricity
58 and heat production) as an example, computer simulations of the composite model are implemented to
59 explore how sector-level policies, in the form of subsidy-tax mixes as well as caps on prices or profits, can
60 not only stabilize the economy, but also the environment.

61 The paper is structured as follows. Section 2 briefly reviews the recent New Keynesian work on the
62 microeconomic source of aggregate economic fluctuations and interest in the complex networks of input-
63 output intermediate production. Section 3 briefly reviews the microeconomic literature on the stability
64 of competitive economies based on stylized adjustment processes, with special attention to Flaschel and
65 Semmler's composite dynamics and the econometric problem its empirical calibration poses. Section 4
66 studies two ecological applications of the multi-sector growth model, namely the stabilization of economic
67 volatility under caps on prices, recently suggested in the case of European gas markets, and how to reduce
68 the environmental impact of the economy without reducing consumption through technical change.



Input-Output Network of Mexico

Figure 1: **Network Visualization of the Input-Output Structure of Mexico (INEGI)**

69 **2. The Source of Macroeconomic Fluctuations: Endogenous or Exogenous?**

70 In conventional macroeconomic accounts, the endogenous microeconomic source of aggregate or sector-
 71 level fluctuations has received little attention, driven by Lucas’ “diversification” argument. Instead, com-
 72 petitive economies are generally assumed to rest on a stable efficient equilibrium, so that aggregate business
 73 cycles are to be considered the self-stabilizing rational outcome of random exogenous idiosyncratic shocks
 74 in demand, technology, monetary or fiscal policy, preferences, and so on (Lucas, 1977; Semmler, 1986).
 75 Sector-specific shocks tend to cancel out and thus will be unable to propagate, through bottle-necks and
 76 nonlinear cascade effects, throughout the economy, leading to aggregate macroeconomic fluctuations (Lucas,
 77 1977). An early fundamental aggregation theorem in this direction, developed by Hulten (1978), showed
 78 that, for efficient economies under minimal assumptions, the aggregate impact of a microeconomic shock on
 79 sector-level total factor productivity is equal to the sales of the shocked sector as a share of the GDP,

80
$$d \log TFP = \sum_i \lambda_i d \log A_i \tag{1}$$

81 where A_i is the sector-level shock and λ_i is its Domar weight or sales share. Hence, the systemic importance
82 of particular industries in efficient economies can be approximated in the first order by their sales, regardless
83 of the existence of intermediate linkages and complementaries in production.

84 Starting with the debate between Horvath (1998; 2000) and Dupor (1999), New Keynesian circles have
85 increasingly contested such a view, arguing that the microeconomic structure of production is in fact much
86 relevant for macroeconomic analysis (Acemoglu et al., 2012b; Carvalho, 2014; Baqaee & Farhi, 2019b).
87 Building on the multi-sector framework of Long and Plosser of real business cycles (1983), Acemoglu et
88 al. show how the amplification of sector-level shocks can occur through the network structure of input-
89 output linkages in intermediate production when certain sectors are disproportionately large suppliers of
90 inputs to the rest of the economy (Acemoglu et al., 2012b). In particular, Acemoglu et al. show that the
91 equilibrium firm size distribution in an economy characterized by input-output linkages depend on the shape
92 and structure of the economic network. Empirical work by Foerster et al. (2011; 2017) apply factor methods
93 to decompose industrial production into components arising from aggregate and sector-specific shocks to
94 show that the relative importance of the latter has substantially increased since the 1980s. Further empirical
95 work by Acemoglu et al. captures the downstream and upstream network effects of four types of industry-
96 level shocks through the 392-sector structure of US production: two demand-side ones (changes in industry
97 imports from China and in federal spending) and two supply-side ones (total factor productivity shocks and
98 changes in foreign patenting) (Acemoglu et al., 2015). Ghassibe (2021) brings econometric evidence on the
99 contribution of production networks to the effect of monetary shocks on aggregate consumption through the
100 downstream propagation of price rigidities, which are estimated to be at least 30% of the total size. Carvalho
101 et al. document that how the disruption caused exogenously and regionally by the 2011 Japan earthquake
102 propagated upstream and downstream supply chains, affecting direct and indirect suppliers and customers,
103 using a general equilibrium model of production networks (Carvalho et al., 2021).

104 The economic intuition underlying all this recent work can be easily noticed in figures 1 and 2. Figure 1
105 shows a visualization of the input-output linkages of 800+ industries for Mexico, colored by cluster component
106 and sized by their gross output, which is revealed to be highly hierarchical, with few core industrial hubs
107 catering to a large number of peripheral, smaller industries as customers. Cluster analysis of the community
108 structure used the walktrap algorithm for directed networks via short random walks (Pons & Latapy, 2006).
109 In this direction, figure 2 shows the exponential-like decay of gross output by cluster component for Mexico,
110 India, South Africa, and Iran. Such is the asymmetric, star-shaped network structure that Acemoglu et al.
111 (2012b) or Carvalho (2014) note that will considerably amplify, rather than damp, micro-economic shocks
112 at the sector-level, further noting, contra Hulten and Lucas, that network measures of centrality (Newman,
113 2018) may be more relevant to characterize the systemic relevance of key industries instead of their gross
114 output.

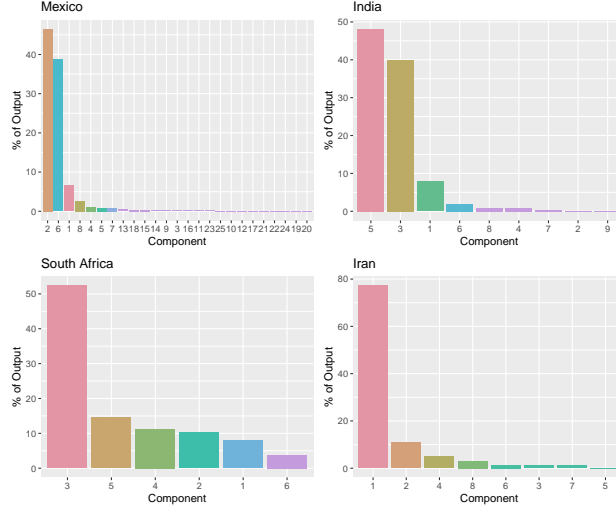


Figure 2: **Percentages of Output for each Community of the Economic Structures of Mexico, India, South Africa, and Iran** Mexico, which features the largest number of sectors, shows the closest to the typical exponential decay that input-output networks display.

115 Further, the interaction of input-output networks with sector-level market structure may also impact on
 116 the amplification of shocks, generating cascades of firm entry and exit across the economy (Bilbiie et al.,
 117 2012; Baqaee et al., 2018; Baqaee & Farhi, 2019b, 2020). In that regard, Gabaix showed how firm-level
 118 idiosyncratic shocks can translate into aggregate fluctuations when there is market concentration in the form
 119 of a heavy-tailed firm-size distribution where the largest firms contribute disproportionately to aggregate
 120 output (Gabaix, 2011). Extending Hopenhayn’s (1992) industry dynamics framework of entry and exit to a
 121 finite large number of firms of heterogeneous Markovian productivity (rather than a continuum such as in
 122 the early monopolistic competition model for product diversification by Stiglitz and Dixit (1977)), Carvalho
 123 and Grassi develop a quantitative theory aggregate fluctuations arising from firm-level shocks alone and
 124 characterize the law of motion of the firm size distribution, which is shown to be Pareto heavy-tailed, with
 125 resulting aggregate output and productivity dynamics that are endogenously persistent and volatile (Carvalho
 126 & Grassi, 2019). In agreement with the empirical evidence brought by Carvalho et al. (Carvalho, 2014),
 127 Baqaee (2018) shows that firm entry and exit, as well as extensive margin adjustment within industries, bears
 128 important spillovers on other firms through their inter-sectoral supply and demand chains, with important
 129 macroeconomic consequences. Most of these studies employ the conventional competitive model of marginal
 130 cost pricing, Cobb-Douglas production functions, and equilibrium modeling, either efficient (Carvalho, 2008;
 131 Gabaix, 2011; Acemoglu et al., 2012b) or inefficient by introducing frictions due to imperfect competition
 132 (Bilbiie et al., 2012; Baqaee et al., 2018; Baqaee & Farhi, 2019a, 2020). All these setups assume some form of
 133 equilibrium pricing by considering in principle marginal costs can be computed; however, in disequilibrium,

134 actual market prices prevail, where the “cost” computed is distorted by disequilibrium prices.

135 Interestingly enough, Baqaee and Farhi (2018) relate their research on the micro-economic source of
136 macroeconomic fluctuations based on their study of aggregate production functions to the early Cambridge-
137 Cambridge controversy of the 1950s and 1960s. For Baqaee and Farhi, British Cambridge ‘won the battle, but
138 lost the war’ against US Cambridge: while the former successfully criticized the theoretical underpinnings
139 of the neoclassical aggregate production function in a way that the distribution of income may not be
140 determined by factor scarcity, as conventionally understood (Harcourt, 1972; Felipe & McCombie, 2014),
141 its analytical tractability prevailed and ensured its popularity. Baqaee and Farhi suggest the old adage,
142 “one needs a model to beat a model”, as an answer to such an outcome. Integrating short-run and long-run
143 Walrasian, Keynesian, and classical features as well as macro- and microeconomic levels of analysis, the work
144 of Peter Flaschel and co-authors on multi-sector growth models, described in the next section, may provide
145 insights on what these alternative models may be.

146 **3. Macro-Economic and Micro-Economic Processes of Adjustment**

147 *3.1. A disequilibrium approach to stability*

148 The economic possibility of endogenous fluctuations, either in the aggregate or at the sector level, is a very
149 familiar theme for the tradition of linear production models and micro-economic adjustment processes as
150 seminally developed by the late Peter Flaschel and co-authors of the Bielefeld disequilibrium school (Semmler,
151 1986; Flaschel & Semmler, 1987; Flaschel, 1990; Flaschel & Semmler, 1990; Flaschel, 2010). Under such a
152 view, there is no reason by which a competitive economy must always lie on a stable equilibrium that
153 may be efficient or not due to market frictions. At any specific point of time, there is no reason either to
154 assume profitability is uniform across industries, the market price reflects the equilibrium marginal cost of
155 production, or supply equals demand, because all these variables are considered to be constantly changing
156 over time around their equilibrium values (which are subject to changes in final demand, technology, and
157 the distribution of income).

158 As developed by von Neumann (1945), the simplest multi-sector model of general equilibrium consid-
159 ers N interdependent processes of production transforming material inputs to single outputs, with linear
160 production technology that can then be characterized by a matrix A of input-output coefficients. In this
161 situation, equilibrium prices p^* and quantities x^* are the positive row- and column-eigenvectors of the matrix
162 A of input-output coefficients corresponding to the largest, dominant eigenvalue $1/R$ as expansion factor.
163 Dominant eigenvector x^* is denominated the “standard commodity” and characterizes a unique gross out-
164 put composition that enters production as inputs and comes out as outputs unchanged, with the same
165 proportions, that is, the ‘invariable standard of value’ (Sraffa, 1960) or von Neumann’s ‘expansion ray’
166 (Von Neumann, 1945).

167 The ratio of the modulus of the subdominant eigenvalue to the dominant one determines the speed
168 of convergence to equilibrium (Bródy, 1997). In a strikingly parallel way to Lucas, Bródy conjectured,
169 experimenting with random matrices of increasing size, that in ‘very large’ systems convergence to equilibrium
170 may be attained in just a few iterations. Mariolis and Tsoulfidis empirically examined this assertion for the
171 US economy, suggesting that the ratio between the two largest eigenvalues *increases* (instead of decreasing)
172 both with the size of the input-output matrix and over the years for the same matrix size, lending support to
173 the view of increasing instability (Mariolis & Tsoulfidis, 2016). Empirical statistical analyses of the US input-
174 output matrix show a remarkably persistent exponential distribution for their eigenvalues clustering around
175 zero in the complex plane, suggesting considerable quasi-linear dependencies in distribution (Mariolis &
176 Tsoulfidis, 2016; Torres-González & Yang, 2019; Shaikh et al., 2020). From a dynamical-systems perspective,
177 however, the existence of imaginary values in the eigenvalues suggests a highly complex nested pattern of
178 oscillations operating at different frequencies.

179 3.2. The Walrasian Law of Excess Demand

180 While competitive equilibrium in prices and quantities is easy to find in a linear production system, its
181 stability through the dynamic adjustment of market prices and quantities over time is less clear, although
182 extensively studied (Hahn, 1970, 1982a; Fisher, 1989a,b, 2013). Initial, early contributions from John Hicks
183 (1939) and Paul Samuelson (1947) focused on the dynamic study of the Walrasian *tátonnement* as the single
184 law of motion in the form of a price-quantity adjustment, by which prices rise (decrease) to positive (negative)
185 excess demand. Formally, the law of demand and supply states that the excess demand vector is a smooth
186 continuous function of the vector of market prices p ,

$$187 \quad \dot{p} = z(p) = D(p) - S(p), \tag{2}$$

188 which leads to changes in prices: if demand d_i is above (below) supply x_i , price p_i will rise (fall). In Hicks’
189 formulation of a simple economy with a single commodity solely produced with labor under production
190 function $Y = f(L)$ (1939), the conventional one-sided process of a pure price adjustment can be written as
191 (Flaschel et al., 1997):

$$192 \quad \dot{p} = \beta_p [d(p, L(Y)) - Y] \tag{3}$$

193 while output adjusts instantaneously at its profit-maximizing value, $Y = L'^{-1}(p)$. In ‘fix-price’ economies in
194 the Keynesian tradition, prices are instead considered to be fixed, while only quantities react to imbalances in
195 demand, a fundamental quantity-quantity adjustment process in clearing markets out of equilibrium (Hicks,
196 1939). For any given demand function d , stability is always guaranteed when decreasing returns to scale
197 at equilibrium exist sufficiently close to the case of constant returns: stabilizing output reactions approach
198 infinity when technology approaches the constant returns scenario (Flaschel et al., 1997).

199 In general, it can be shown that stability is obtained when goods are gross-substitutes or when the weak
 200 axiom of revealed preferences holds (Flaschel et al., 1997; Flaschel, 2010). Yet, the Sonnenschein-Mantel-
 201 Debreu ‘anything-goes’ theorem highlighted the problems of aggregating individual preferences into a single
 202 $z(p)$ vector of excess demand for the whole economy (Kirman, 1992; Rizvi et al., 2006). As Scarf (1960)
 203 noted, this process can fail to be even locally stable at a unique equilibrium. In a similar vein, Hahn noted
 204 that the study of Walrasian groping has not been very fruitful (Hahn, 1970, 1982a). Smale (1976) and
 205 subsequent work devised the Global Newton method to evaluate the necessary informational requirements
 206 and universal stability properties for a feasible Walrasian tâtonnement process.¹

207 In his attempt to formalize Walrasian market dynamics in a production economy, Mas-Colell (1986)
 208 suggests a complementary adjustment process to the law of excess demand where output no longer adjusts
 209 instantaneously to its profit-maximizing value. Instead, quantities adjust in reaction to imbalances between
 210 the current price and the marginal labor cost, $\dot{Y} = \gamma[p - L'(Y)]$.

211 The pioneering work of Richard M. Goodwin (1983; 1987) contributed an early classification of micro-
 212 economic adjustment mechanisms and a thorough study of their dynamics, using Lyapunov functions and
 213 gradient processes. In addition to the Walrasian law of excess demand, three other basic types of market
 214 adjustments were identified (table 1)². As noted by Flaschel (1997), such study is particularly relevant as it
 215 highlights the complex dynamical relation between micro- and macroeconomic adjustment processes.

216 3.3. Classical Cross-Dual Dynamics

217 As Flaschel notes (1997), the first two adjustment processes in table 1 are a description of a proportional
 218 autocontrol mechanism through cross-effects between prices and quantities, which Morishima originally iden-
 219 tified as cross-dual dynamics (Morishima, 1981):

- 220 • **law of excess demand:** demand > supply \rightarrow increase in prices
- 221 • **law of excess profitability:** price > cost \rightarrow increase in supply

222 In addition to the Walrasian law of excess demand where supply-demand imbalances drive changes in
 223 prices, the classical economists (Adam Smith, David Ricardo, Karl Marx, and John Stuart Mill) envisioned
 224 a law of excess profitability that would give dynamic stability to market economies, by which profitability
 225 deviations from equilibrium are self-correcting by changes in quantities driven by the entry and exit of
 226 profit-seeking firms (Flaschel & Semmler, 1987; Flaschel, 1990). As mentioned above, Mas-Colell and other

¹Flaschel further notes that standard tâtonnement price dynamics may be augmented by derivative effects that account for the time variation of excess demand may give rise to stability properties if these derivative feedbacks are sufficiently large (Flaschel, 2010).

²In this literature, “costs” include capital costs in the form of normal profits.

227 key formulations have contributed similar laws of profitability, where an excess of prices over costs triggers
 228 supply responses of firms (Mas-Colell, 1986).

229 As noted by Flaschel and Semmler (1987), cross-duality in its simplest form does give rise to dynamic
 230 stability, but not necessarily the conventional ‘asymptotic’ convergence to competitive economic equilibrium
 231 as a single-point rest state with uniform profitability across sectors of production. Instead, cross-duality
 232 generally reflects the classical theme of dynamic gravitation, that is, of ceaseless over- and undershooting
 233 of sectoral prices, quantities, and profitability around their equilibrium ‘natural values’ as centers of gravity
 234 (Sraffa, 1960; Goodwin, 1983; Duménil & Lévy, 1987; Foley, 2003; Shaikh, 2016). The basic dynamics of
 235 cross-dual classical oscillations unfold with a sector of production above (below) profitability, so that profit-
 236 seeking firms will enter (exit). This will raise (lower) output with respect to demand until demand is above
 237 (below) supply. Then, the Walrasian mechanism will trigger an increase (decrease) in prices adjusting the
 238 supply-demand imbalance and lowering (raising) industry profitability, closing the business cycle and starting
 239 anew. Conventional asymptotic convergence to equilibrium as a rest state can be guaranteed by adding an
 240 adjustment of derivative control, where capital investments also take account of the sign of change of extra
 241 profits (or losses) when moving their capitals between sectors.

242 Following the *law of excess demand* (as stylized in table 1), market prices p will decline (rise) if supply x
 243 is greater (smaller) than demand:

$$244 \left(\frac{\dot{p}}{p} \right)^T = -\delta_{px}[I - RA]x = \delta_{px} \left[\underbrace{RAx}_{\text{demand}} - \underbrace{x}_{\text{supply}} \right] \quad (4)$$

245 Following the *law of excess profitability*, quantity x_i will rise (decline) if unit revenues p are greater (smaller)
 246 than unit costs times R , RpA , since investment will flow out of the sectors with below-normal profitability
 247 into the sectors with above-normal profitability:

$$248 \frac{\dot{x}}{x} = +\delta_{xp}[I - RA]^T p^T = \delta_{xp} \left[\underbrace{p^T}_{\text{revenue}} - \underbrace{RA^T p^T}_{\text{cost}} \right] \quad (5)$$

249 where $\frac{\dot{x}}{x}$ is the column vector of the growth rates in relative quantities, $\frac{\dot{p}}{p}$ is the row vector of the growth
 250 rates in relative prices, A is the table of input-output coefficients, and δ_p and δ_x are diagonal matrices with
 251 N positive adjustment coefficients (so they can also be understood as vectors).³

³These coupled price and quantity oscillations are similar to the Lotka-Volterra predator-prey variety without a linear term, where profits as prices play the role of the prey and profit-seeking investment as quantities plays the role of the predator. Lotka-Volterra dynamics are also implemented by the seminal Goodwin model of endogenous fluctuations of capital accumulation driven by distributional conflicts, this time with the labor share of income as predator and the employment share as prey (Goodwin, 1982).

Table 1: **Goodwin Classification of Micro-Economic Adjustment Processes (Goodwin, 1983)**

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

252 3.4. Keynesian Dual Dynamics

253 The Keynesian tradition focuses instead on the short run, characterized by imperfect competition,
 254 oligopolistic markup price-setting, and barriers to capital entry and exit, while investment operates within
 255 a longer time scale (Morishima, 1981; Semmler, 1984). In this context, cross-dual dynamics have thus been
 256 considered unsatisfactory, suggesting dynamic adjustments without cross-effects between prices and quanti-
 257 ties where price and quantity movements may even be independent of each other for a while: what Morishima
 258 termed “dual dynamics” (Morishima, 1981; Flaschel et al., 1997).

259 In the short run, oligopolistic firms set prices as markups over costs, while varying supply through
 260 inventories in response to demand conditions:

261 • **markup pricing:** demand $>$ supply \rightarrow increase in prices

262 • **quantity adjustment to demand:** price $>$ cost \rightarrow increase in supply

263 Mathematically, the dual dynamics of adjustment can be written as, for short-run quantity adjustments
 264 to demand (Flaschel, 2010):

$$265 \quad \dot{x} = \delta_{xx} \left(\underbrace{Ax + gAx + c}_{\text{demand}} - \underbrace{x}_{\text{supply}} \right) = \delta_{xx} (C(g)x + c) \quad (6)$$

266 and for oligopolistic markup pricing:

$$267 \quad \dot{p}^T = \delta_{pp} \left(\underbrace{A^T p^T + rA^T p^T + w^T}_{\text{unit cost}} - \underbrace{p^T}_{\text{unit revenue}} \right) = \delta_{pp} (C(r)^T p^T + w^T) \quad (7)$$

268 where

$$269 \quad C(\alpha) \equiv (1 + \alpha)A - I \quad \alpha = r, g \quad (8)$$

270 The $N \times N$ matrix A is the usual intermediate input matrix, g the rate of growth, c a column N -vector
 271 of final consumption, and r and w denote profitability and the row N -vector of wage payments per unit of
 272 output. In the classical long run, the free mobility of investment prevails, the markup gravitates around
 273 equilibrium profitability, and quantities change through inventories in the short run altogether with capacity
 274 changes in the long run through the entry and exit of investment (Franke, 1987; Jacobo, 2022).

275 As Jorgenson famously noted so in his dual (in)stability theorem, dual dynamics alone have difficulties
 276 to generate stability in a Leontief system, where if the output system is stable, the price system is unstable,
 277 and vice versa (Jorgenson, 1960; Morishima, 1981). Still, prices and quantity adjustments could be made
 278 stable by removing two implicit assumptions in Jorgenson's model, namely the full utilization of capital and
 279 perfect-foresight price expectations (Fukuda, 1975). In addition, other imbalances could be investigated,
 280 such as non-market clearing (i.e. inventory creation), supply constraints, or the effects of quantity levels on
 281 employment, money wages, and consumption (Flaschel & Semmler, 1990; Flaschel, 2010).

282 In the case studied by Flaschel (1990), however, dual dynamics are stable in the form of asymptotic
 283 convergence to equilibrium values that are identical to the composite dynamics scenario, explained below.

284 3.5. General Composite Dynamics

285 In general, it is the composite system that integrates short-run and long-run Walrasian, classical, and
 286 Keynesian features in the form of dual/cross-dual dynamics between prices and quantities that captures all
 287 imbalances in highly complex systems (Flaschel & Semmler, 1990; Flaschel, 2010), following the systematic
 288 Goodwin classification (Goodwin, 1983). Such general systems of micro-economic adjustment processes can
 289 be re-purposed as highly stylized dynamic macroeconomic models of multi-sector growth of constant linear
 290 technology that 1) separate prices from quantities and 2) can be empirically calibrated using real training
 291 data. Under composite dynamics in prices and quantities, each of the four laws of motion translates to a
 292 single reaction coefficient associated to each particular industry. More complex functional forms other than
 293 linear, such as the logistic function, can be also employed to characterize the laws of motion. As well, the
 294 framework can also capture substitution dynamics within industry prices and within quantities up to N^2
 295 laws of motion relating changes in prices and quantities with supply-demand and profitability imbalances.

296 Mathematically, general composite dynamics are obtained by integrating long-run classical cross-dual with
 297 short-run Keynesian dual micro-economic adjustment processes with corresponding reaction coefficients:

$$298 \quad \dot{x} = \underbrace{\delta_{xx} [C(g)x + c]}_{\text{Keynesian}} - \underbrace{\delta_{xp} [C^T(r)p^T + w^T]}_{\text{classical}} \quad (9)$$

$$299 \quad \dot{p}^T = \underbrace{\delta_{px} [C(g)x + c]}_{\text{Walrasian}} - \underbrace{\delta_{pp} [C^T(r)p^T + w^T]}_{\text{Keynesian}} \quad (10)$$

301 where C is defined as in 8, c is the column-vector of final consumption, and w is the row-vector of wage
 302 compensation per unit of output.

303 For expository convenience, a supply-demand imbalance column-vector Δ_x can be defined:

$$304 \quad \Delta_x \equiv C(g)x + c = (1 + g)Ax + c - x \quad (11)$$

305 as well as a unit profitability imbalance row-vector Δ_p :

$$306 \quad \Delta_p \equiv pC(r) + w = (1 + r)pA + w - p \quad (12)$$

307 These two vectors capture the direction of price-quantity interactions, while the adjustment coefficients δ
 308 indicate their intensity.

309 Equilibrium in prices p^* and quantities x^* is achieved when sector imbalances in supply and demand and
 310 unit profitability are zero, that is,

- 311 • demand (composed of intermediate production, investment, and consumption) equals supply:

$$312 \quad \Delta_x^* = 0 \quad (13)$$

$$314 \quad Ax^* + gAx^* + c = x^* \quad (14)$$

$$315 \quad x^* = -[(1+g)A - I]^{-1}c = -C^{-1}(g)c \quad (15)$$

- 317 • profitability is uniform across sectors, as unit costs (in material inputs, wages, and capital) equal unit
 318 revenues:

$$319 \quad \Delta_p^* = 0 \quad (16)$$

$$321 \quad p^*A + rp^*A + w = p^* \quad (17)$$

$$322 \quad p^* = -w[(1+r)A - I]^{-1} = -wC^{-1}(r) \quad (18)$$

324 Hence, the dynamical system can be summarized, in a slightly different way of Flaschel and Semmler (1990),
 325 as:

$$326 \quad \begin{pmatrix} \dot{x} \\ \dot{p}^T \end{pmatrix} = \begin{pmatrix} \delta_{xx}\Delta_x - \delta_{xp}\Delta_p^T \\ \delta_{px}\Delta_x + \delta_{pp}\Delta_p^T \end{pmatrix} = \begin{pmatrix} \delta_{xx} & -\delta_{xp} \\ \delta_{px} & \delta_{pp} \end{pmatrix} \begin{pmatrix} \Delta_x \\ \Delta_p \end{pmatrix} = \begin{pmatrix} \delta_{xx} & -\delta_{xp} \\ \delta_{px} & \delta_{pp} \end{pmatrix} \begin{pmatrix} C(g) \\ C^T(r) \end{pmatrix} \begin{pmatrix} x \\ p^T \end{pmatrix} + \begin{pmatrix} c \\ w^T \end{pmatrix} \quad (19)$$

327 If the dual adjustment coefficients are zero so that the system is purely cross-dual, the eigenvalues of
 328 the Jacobian⁴ are pure complex conjugates, yielding complex oscillatory dynamics of N nested frequencies.
 329 If the system is purely dual (so that the cross-dual coefficients are set to zero), the dynamical system
 330 evolves exponentially towards the stable equilibrium with a speed associated to the real eigenvalues of the
 331 Jacobian. In the general case, the composite dynamics result in classical oscillations that are dampened by
 332 the stabilizing effect of Keynesian micro-economic adjustments.

⁴The Jacobian of the dynamical system is

$$J(z) = \begin{pmatrix} \delta_{xx}C(g) & -\delta_{xp}C^T(r) \\ \delta_{px}C(g) & \delta_{pp}C^T(r) \end{pmatrix} \quad (20)$$

The general evolution of the dynamical system will follow

$$z(t) = \sum_{k=1}^{2N} c_k e^{\lambda_k t} v_k \quad (21)$$

where λ_k are the $2N$ eigenvalues of $J(z)$ and v_k their associated eigenvectors, in addition to c_k constants associated to the initial conditions.

333 *3.6. Econometric Problem*

334 Reaction coefficients δ capture the distinct speeds underlying the dynamic laws of motion, such as the
335 Walrasian law of demand, firm entry and exit driven by profitability differentials, or short-run quantity
336 adjustments to demand and markup pricing, in a way that can be estimated empirically resembling a novel
337 machine-learning algorithm. Here, the time variation in prices and quantities is defined as a function of the
338 complex imbalances between them driven by the input-output technology matrix and aggregate profitability
339 and growth. In its basic definition, the matrix of adjustment coefficients $\hat{\delta}$ is composed of four block matrices
340 with the corresponding adjustment coefficients of price-quantity interactions in the diagonal and zeros in the
341 off-diagonal elements. It can be empirically estimated using the time series in both sector-level prices and
342 quantities p_t and x_t (such as the EU KLEMS database (Van Ark & Jäger, 2017)) as dependent variables,
343 following a linear mixed-effects model with varying slopes and no intercept of the form:

$$344 \quad y_{it} = \beta_{1i}x_{1it} + \beta_{2i}x_{2it} + \epsilon_{it} \quad (22)$$

345 where the independent variables 1 and 2 refer to the i th sector-level time series of supply-demand imbalances
346 $\Delta_{x,it}$ and profitability deviations $\Delta_{p,it}$. Such computation presents an econometric challenge as these values
347 need to be extracted from harmonized input-output data that also features sector-level final consumption and
348 wage compensation, such as the World Input-Output Database (Timmer et al., 2015) or EORA (Van Ark &
349 Jäger, 2017). In the model, the linear slopes β_{1i} and β_{2i} directly correspond to the same reaction coefficients
350 δ as they capture how industry prices and quantities react dynamically to sector-level imbalances in supply
351 and demand as well as profitability. That said, the off-diagonal elements of the block matrices do not
352 necessarily need to be empirically zero, as they may capture substitution effects in prices and quantities.
353 However, this substantially increases the difficulties posited by the econometric problem.

354 **4. Stabilizing Economic Fluctuations and Economy-Environment Interactions: Ecological Ap-**
355 **plications**

356 In the current context of rising prices in energy and food (key industries that are particularly vulnerable
357 to climate change), caps on levels and growth rates of prices and profits are suggested in order to stabilize
358 the (war) economy, while other authors apply conventional microeconomic comparative statics to warn
359 of deleterious consequences in the form of scarcity and rationing. In this section, we see how Flaschel's
360 theoretical framework of composite micro-level dynamics in prices and quantities is particularly suitable to
361 investigate and shed light to clarify these issues.

362 A natural environmental extension of the model of multi-sector growth in prices and quantities is to
363 include a N vector of environmental impacts by sector, here stylized as sector-level emissions e in the form

	1	2	3	4	5	6	7
1 Agriculture	.2008	.0000	.0011	.0338	.0001	.0018	.0009
2 Mining	.0010	.0658	.0035	.0219	.0151	.0001	.0026
3 Construction	.0034	.0002	.0012	.0021	.0035	.0071	.0214
4 Manufacturing	.1247	.0684	.1801	.2319	.0339	.0414	.0726
5 TTU	.0855	.0529	.0914	.0952	.0645	.0315	.0528
6 Services	.0897	.1668	.1332	.1255	.1647	.2712	.1873
7 Other	.0093	.0129	.0095	.0197	.0190	.0184	.0228

^a TTU: Trade, Transportation, and Utilities

Table 2: **2003 US Direct Requirements Matrix**

364 of a linear function of its corresponding quantity, with sector-level emission intensities ϵ as their constants
365 of proportionality:

$$366 \quad e = \epsilon x \quad (23)$$

367 Actual values for environmental impact intensities can be empirically estimated from environmentally-
368 extended data such as the EORA database, which features a comprehensive satellite list of 2,631 sector-level
369 environmental indicators, including emissions of many greenhouse gases from different sources, 36 categories
370 of material usage, nitrogen and phosphorus use by fertilizer and manure, crop and pasture use, water use,
371 and others. In the simulations, the sector-level intensities capturing a general environmental impact are
372 randomly taken from a Gaussian distribution of mean 1 and variance 0.1.

373 *4.1. Reducing Economic Volatility*

374 As a first example, the stylized effects of a cap policy on the price level, price growth, and profits are
375 studied, using a 7-sector input-output matrix for the US in 2003 (Miller & Blair, 2009, p.29). In this scenario,
376 the remaining parameters of the dynamical system are not empirically estimated, but manually selected in a
377 way that the policy effects can still be observed in a stylized form. The adjustment coefficients are chosen so
378 that the dynamical system generates dampened oscillations: $\delta_{xx} = \delta_{pp} = 0.1$, $\delta_{xp} = \delta_{px} = 1$ for all sectors.
379 Profitability r and the growth rate g are set to 0.05. Consumption c and wage compensation per unit of
380 output w are set to 0.01 for all sectors. The initial values in the simulations are random deviations from the
381 equilibrium values in prices and quantities which arise from multiplying the latter by a normal distribution
382 of mean 1 and variance 0.25.

383 Figure 3 shows two single simulations of composite multi-sector dynamics in prices, quantities, and
384 emissions, with and without a policy of a cap on the price level for all sectors, where any price increases
385 above a threshold are forbidden. Such a threshold is defined by policy parameter p_{\max} that multiplies
386 the corresponding equilibrium prices. While the policy successfully stabilizes economic and environmental
387 fluctuations, it fails to reduce the aggregate environmental impact. The stabilization of economic fluctuations,

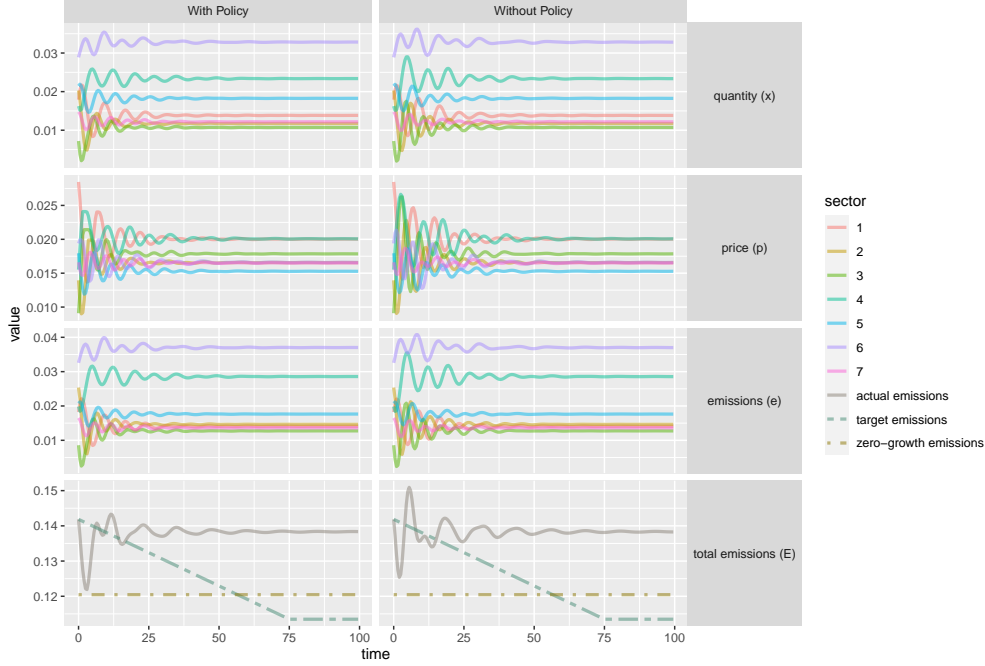


Figure 3: **Single Simulation of Composite Multi-Sector Dynamics** showing dampened oscillations in prices, quantities, and emissions, with and without a policy of a cap on the price level for all sectors. While the policy stabilizes the economic and environmental fluctuations, it fails to reduce the environmental impact. Here, the maximum price level is defined by $p_{\max} = 1.25$.

388 understood as a reduction in the statistical variance of prices and quantities computed as

$$389 \quad \frac{\text{variance}_{\text{with policy}}}{\text{variance}_{\text{without policy}}} - 1, \quad (24)$$

390 can be clearly seen in figure 4, where 100 simulations are computed for each value of the p_{\max} parameter,
 391 ranging from 1.1 to 1.4 at intervals of 0.025 units. Linear regressions show a greater impact of economic
 392 stabilization for lower thresholds on the price level; a higher cap on the price level reduces variance less.

393 The same computational procedure can be repeated for a policy of a cap on the rate of price growth,
 394 rather than the price level 5. In this scenario, price increases beyond a threshold rate are forbidden, where
 395 the threshold can range from 0.025 to 1 at intervals of 0.1 units. The simulation results show that caps on
 396 price growth rates, rather than levels, generally amplify, instead of stabilize, economic fluctuations except
 397 for very high thresholds on price changes. The general reason for the effectiveness of a cap on the price
 398 level instead of its change is that volatility in the composite dynamics of the model is given by the cross-
 399 dual oscillations, while the Keynesian dynamics are stabilizing: hence the mechanism on which the price
 400 caps operate is the entry and exit of capital, as it depends on out-of-equilibrium price (i.e. profitability)
 401 deviations. A cap on the price level accelerates the stabilization of economic fluctuations by canceling the
 402 most extreme values: less investment flows in when profitability is high, thus inducing a subsequent smaller

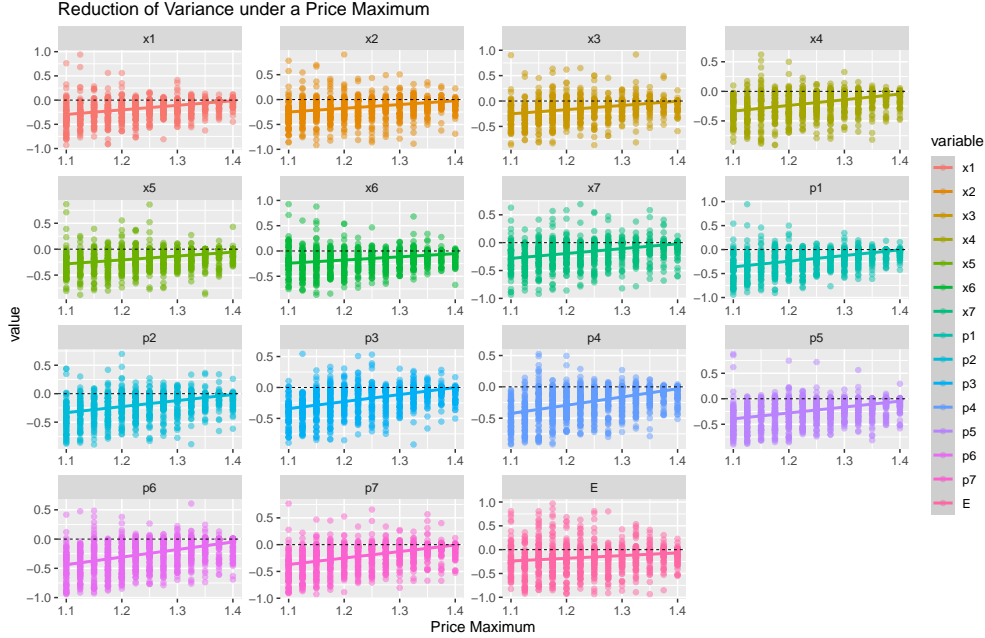


Figure 4: **Stabilization of Economic Volatility (i.e. Statistical Variance) due to a Policy of a Cap on the Price Level for All Sectors** 100 simulations are computed for each value of the policy parameter p_{\max} . A negative (positive) dependent variable implies a reduction (rise) in volatility. Regression lines are included to show the increasing impact of the policy parameter on the variance, so that a lower maximum threshold reduces volatility more for all variables.

403 imbalance in quantities. In contrast, a cap on price increases just de-stabilizes the cross-dual oscillations
 404 by preventing them from running its course, only marginally reducing volatility when canceling the most
 405 extreme values. The effect of a price cap on windfall profits (a combination of prices and quantities) on
 406 stabilizing economic fluctuations turns out to be negligible (not shown).

407 4.2. Reducing the Environmental Impact

408 Price caps successfully stabilize the environmental impact of the economy, but not reduce it, as it depends
 409 on the equilibrium gross output vector and, thus, final consumption:

$$410 \quad E^* = \epsilon x^* = \epsilon [I - (1 + g)A]^{-1} c \quad (25)$$

411 Hence, aggregate emissions can only be reduced either by:

- 412 1. reducing the growth rate g
- 413 2. reducing final consumption c by taxation or rationing (figure 6)
- 414 3. reducing input-output coefficients A (i.e. increasing technical productivity, figure 7)
- 415 4. reducing emissions intensities by process substitution ϵ (figure 10):

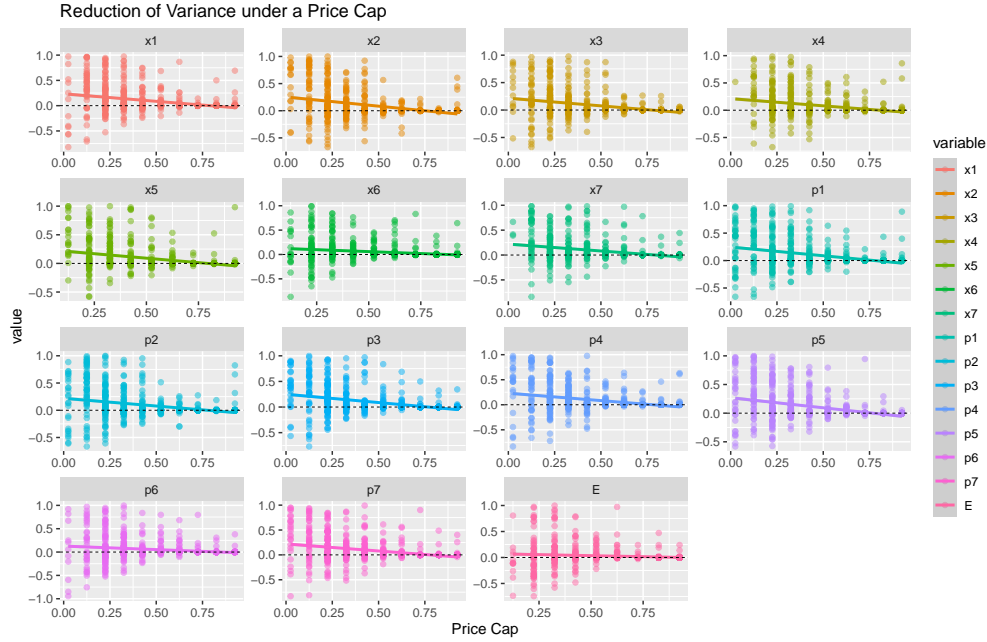


Figure 5: **Stabilization of Economic Volatility (i.e. Statistical Variance) due to a Policy of a Cap on the Price Level for All Sectors** 100 simulations are computed for each value of the policy parameter p_{max} . A negative (positive) dependent variable implies a reduction (rise) in volatility. Regression lines are included to show the decreasing impact of the policy parameter on the variance, so that a higher threshold on price changes increases volatility less for all variables.

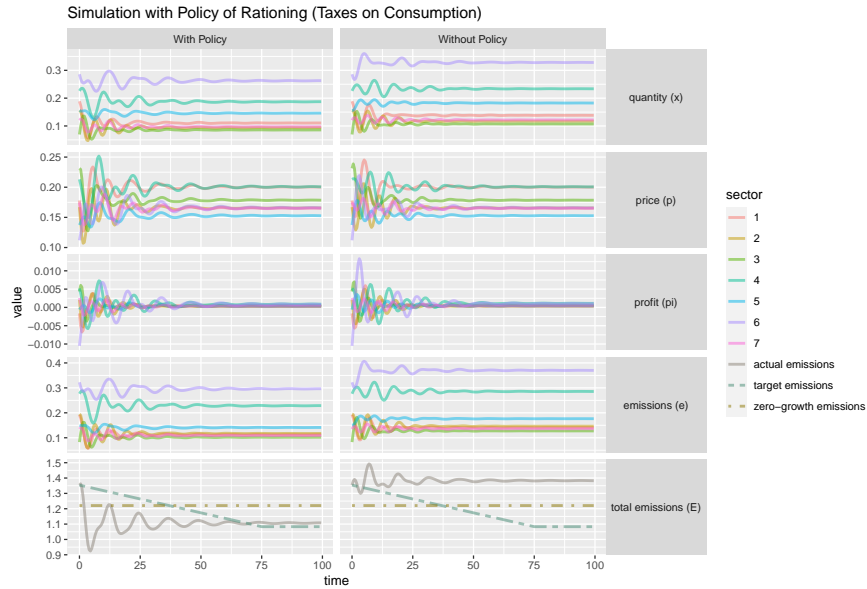


Figure 6: Reduction of environmental impact of the economy of input-output table 2 through a reduction in consumption

416 Reducing the growth rate (1) and final consumption (2) are both important policy recommendations in
 417 the de-growth literature. However, reducing the growth rate even to zero does not guarantee the necessary

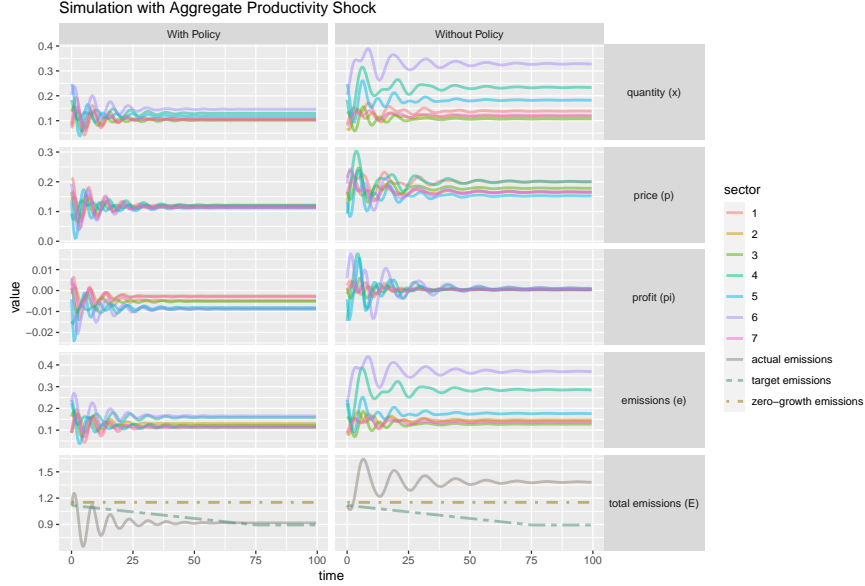


Figure 7: Reduction of environmental impact of the economy of input-output table 2 through an aggregate productivity shock

418 reduction in emissions to stabilize economy-environment interactions as established by the most recent reports
 419 of the UN Inter-governmental Panel on Climate Change, which are of the order of 50%. Likewise, the linear
 420 relationship between emissions and final consumption implies that a reduction of emissions of 50% may also
 421 require a reduction in consumption of a similar order. In order to see this, if the environmental impact needs
 422 to be reduced by a fraction σ , final consumption has to decrease by the same fraction σ *ceteris paribus*:

$$423 \quad \Delta E^* \equiv \sigma E^* = \sigma \epsilon x^* = \sigma \epsilon [I - (1 + g)A]^{-1} c = \epsilon [I - (1 + g)A]^{-1} (\sigma c) \quad (26)$$

424 Such a demand may make sense for the highest income brackets of the Global North, but is simply untenable
 425 for the general population. However, it must be noted that an aggregate reduction in emission intensities ϵ
 426 by a homogeneous fraction σ (4) yields the same effect than a reduction in consumption by the same fraction
 427 (2).

428 Reducing input-output coefficients A (3) by a general factor $\gamma < 1$ in the form of an aggregate capital
 429 productivity shock will reduce gross output x and the subsequent emissions:

$$430 \quad \Delta E^* \equiv \sigma \epsilon x^* = \epsilon [I - (1 + g)(\gamma A)]^{-1} c \quad (27)$$

431 In this scenario, equilibrium prices will also drop:

$$432 \quad p^{J*} = w [I - (1 + r)(\gamma A)]^{-1} \quad (28)$$

433 Since profitability tends to be greater than growth, i.e. $r > g$, prices will generally decrease more than
 434 quantities under such a general productivity shock. The labor share of income will expand and the profit
 435 share of income will contract.

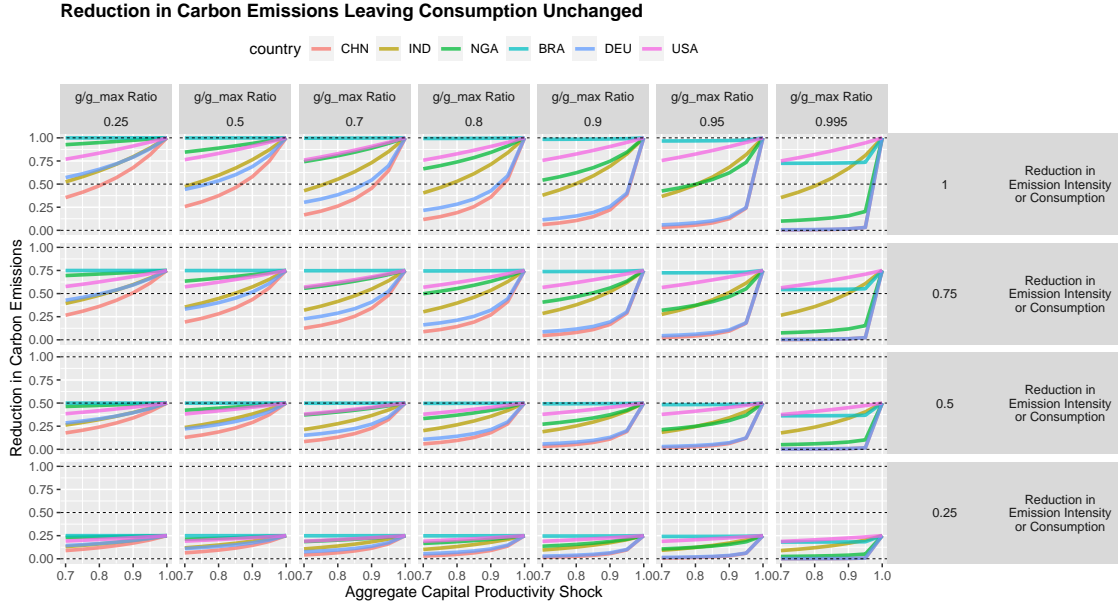


Figure 8: Reduction of carbon emissions for six selected world economies (China, India, Nigeria, Brazil, Germany, and the USA) by an aggregate capital productivity shock γ at different levels of capacity utilization ν and an aggregate reduction in emission intensity ϵ by fraction σ (or consumption c , as they display an equivalent effect)

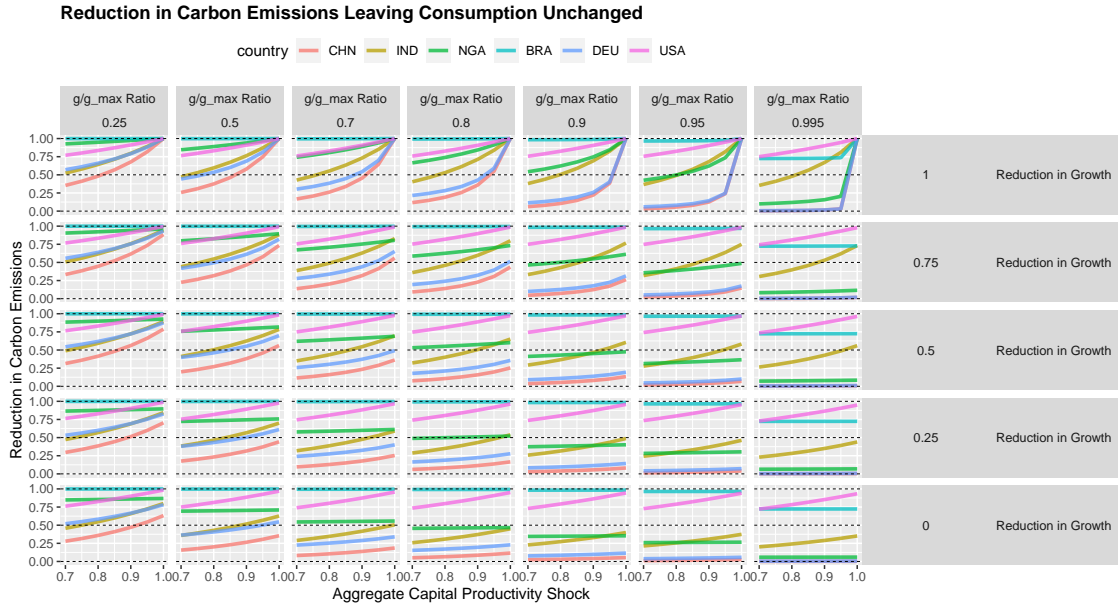


Figure 9: Reduction of carbon emissions for six selected world economies (China, India, Nigeria, Brazil, Germany, and the USA) by an aggregate capital productivity shock γ at different levels of capacity utilization ν and a reduction in the growth rate

436 Figures 8 and 9 visualize many combinations of technical parameters (an aggregate capital productivity
 437 shock, a general reduction in emission intensity, and a reduction in the rate of growth) that are capable of
 438 reducing the environmental impact while leaving consumption unchanged. Covering a single environmental
 439 indicator out of the 2,631 available in the EORA database, figure 8 shows the reduction of carbon emissions
 440 from public electricity and heat production for some of the largest world economies by continent (China,
 441 India, Nigeria, Brazil, Germany, and the USA) due to a productivity shock γ on the input-output coefficients
 442 A and an aggregate reduction in emission intensities ϵ or consumption c by a fraction σ , as computed from
 443 the EORA database:

$$444 \frac{\Delta E^*}{E^*} = \frac{\sigma \epsilon [I - (1 + \nu g_{\max})(\gamma A)]^{-1} c}{\epsilon [I - (1 + \nu g_{\max})A]^{-1} c} \quad (29)$$

where g_{\max} is the maximum rate of expansion associated to the original A matrix and ν is a parameter
 associated to the rate of capacity utilization in the economy,

$$\nu \equiv \frac{g}{g_{\max}}$$

445 Capital productivity growth γ also increases the new maximum growth rate g'_{\max} that the input-output
 446 system can reach:

$$447 \frac{g'_{\max}}{g_{\max}} = \frac{1 - \gamma \lambda}{\gamma - \lambda} \quad (30)$$

where λ is the original dominant eigenvalue of A . In the computations for figure 8, the original and new
 growth rates g are identical as functions of a rate of capacity utilization ν :

$$g' = g = \nu g_{\max},$$

showing the reduction of emissions for different levels of ν . In order to study de-growth scenarios, figure 9
 displays the reduction of carbon emissions from public electricity and heat production where there is also a
 reduction in the growth rate of the form:

$$g' = \nu' g = \nu' \nu g_{\max}$$

448 However, the intensity of the environmental impact is distributed across industries very unevenly: for in-
 449 stance, the intensity of carbon emissions of the sector “Electricity Production, Distribution, and Generation”
 450 from public electricity and heat production is of three orders of magnitude greater than the other sectors of
 451 the economy. In this sense, reducing the intensity of the environmental impact of specific sectors (4) may
 452 be preferable, following the technical substitution of carbon-intensive processes of production by equivalent
 453 green processes of lower carbon content. The basic dynamics of technical substitution were explored by
 454 Flaschel and Semmler in the context of cross-dual adjustment processes, where two processes of production
 455 compete with different activity levels but the same price using a rectangular matrix of input-output coeffi-
 456 cients (Flaschel & Semmler, 1992). While more cost-efficient processes will outcompete less efficient ones as

457 the former features higher profitability and thus growth rates, the substitution can be greatly accelerated
458 by tax-subsidy policy mixes (Acemoglu et al., 2012a; Golosov et al., 2014; Acemoglu et al., 2016). Most
459 recently, windfall profit taxation to raise revenue for investment has also been suggested by Joseph Stiglitz
460 as a tool to stabilize the war economy.

461 Price controls are generally considered undesirable as they create scarcity by lowering an industry’s
462 profitability and thus expelling investment. However, the economic consensus considers carbon pricing as
463 an effective tool to create a scarcity of carbon emissions that is much needed in the face of climate change.
464 In the context of Flaschel’s framework of processes of micro-economic adjustment, tax-subsidy mixes can
465 take advantage of the cross-dual oscillations that arise from the complex interplay of the Walrasian law of
466 excess demand and the classical law of excess profitability by artificially expanding profitability and growth
467 rate differentials using the revenue of a tax on carbon-intensive output to subsidize less carbon-intensive
468 output. The effect of these sector-oriented policies may not only reduce the aggregate environmental impact
469 of the economy, but also reduce the prices of the targeted sectors, thus stabilizing them and reducing general
470 inflationary pressures at the same time in case these sectors provide critical inputs for the rest of the economy.

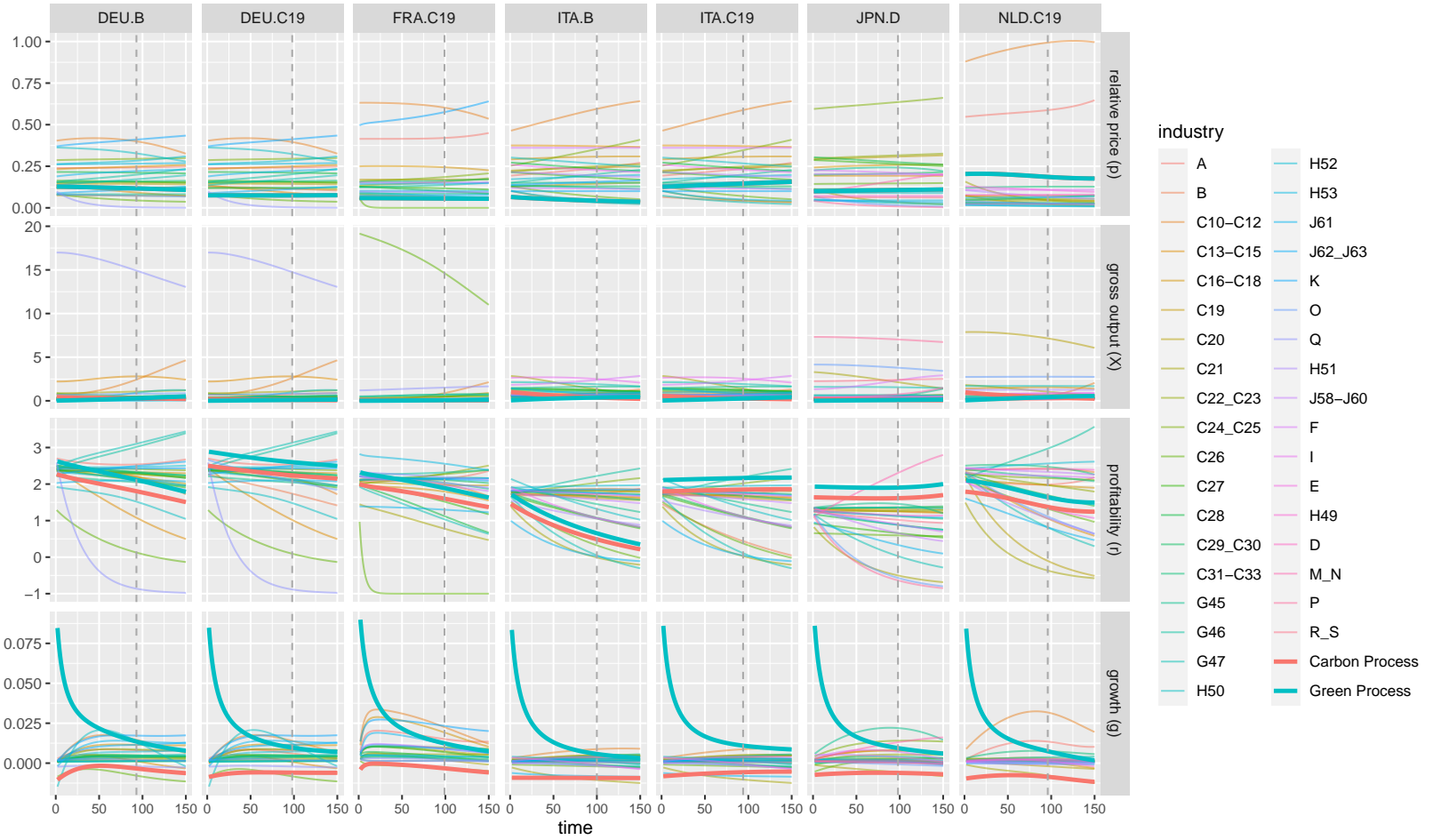
471 Figure 10 shows the results of computer simulations of these substitution dynamics for the basic cross-
472 dual model and seven specific critical carbon-intensive industries, namely “Electricity, gas, steam and air
473 conditioning supply” (D), “Manufacture of coke and refined petroleum products” (C19), and ‘Mining and
474 Quarrying’ (B). In this case, the cross-dual adjustment coefficients have been empirically estimated for six
475 Global-North economies using the price and quantity time series of the EU KLEMS dataset (Germany,
476 France, Italy, Japan, Netherlands, and the US) for 23 years between 1995 and 2017 (Van Ark & Jäger,
477 2017), harmonized at the industry level with input-output data extracted from the WIOD dataset (Timmer
478 et al., 2015).

479 5. Conclusions

480 Integrating short-run and long-run Walrasian, Keynesian, and classical features as well as macro- nad
481 micro-economic levels of analysis, the seminal contributions by the late Peter Flaschel and co-authors to
482 the classic micro-economic literature on the stability of competitive economies can be re-purposed as highly
483 stylized, yet very general macroeconomic disequilibrium models of multi-sector growth. These models are
484 fundamentally driven by empirical data and, properly calibrated, may exhibit actual forecasting power as they
485 function as state-of-the-art machine-learning algorithms. These dynamic models cogently and systematically
486 relate micro-economic processes to macro-economic fluctuations through abstract laws of motion in the form
487 of adjustment processes that separate prices and quantities: cross-dual dynamics in the long run in the
488 form of the Walrasian law of excess demand and the classical law of excess profitability and, dual dynamics
489 in the short run in the form of Keynesian markup pricing and quantity adjustment to demand conditions.

Scenario Simulation of the Low-Carbon Transition: Tax-Subsidy Mix 1

$\theta = 0.9$ $\sigma_0 = 0.055$ $\tau = 0.01$ $\rho = 0.5$



23

Figure 10: Technical substitution of processes of production under emission intensity differentials implemented by a tax-subsidy mix. The vertical dashed line indicates the moment where the green process takes over the carbon-intensive process. Policy parameters correspond to the tax rate τ , subsidy rate τ' , initial ratio between carbon and green investment σ_0 , and cost efficiency ratio between carbon and green processes θ

490 More complex functional forms, as well as higher-quality data, can be employed for the adjustment processes
491 in order to better calibrate them empirically. Substitution effects between prices and quantities can also
492 be introduced by adding non-zero off-diagonal elements to the block matrices of adjustment coefficients,
493 although it considerably raises the stakes of the econometric challenge for their empirical estimation.

494 Last but not least, this paper sheds light on the great potential of this family of macroeconomic models
495 for ecological applications when empirically calibrated with environmentally-extended input-output data, as
496 well as the general evaluation of sector-oriented policies such as price controls or trade wars that require the
497 separation of prices and quantities instead of treating economic aggregates. In particular, the paper shows
498 that caps on the price level may reduce economic volatility successfully, especially in contrast to caps on
499 price changes or profits. However, it is sector-oriented tax-subsidy policy mixes that tax carbon output and
500 use the revenue to subsidize green investment that may stabilize inflationary pressures on critical industries,
501 at the same time that these industries decarbonize while leaving consumption unchanged.

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