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Research paper

The complex interplay between exchange rate and real markets: An agent-based model exploration ☆

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ABSTRACT

We extend the multi-country, multi-sector agent-based model of Dosi et al. (2019); Dosi et al. (2021) by integrating a currency market populated by heterogeneous financial agents—chartists and fundamentalists—who form expectations and trade foreign exchange based on boundedly rational heuristics. This addition generates complex real-financial interactions, wherein the exchange rate acts both as a channel of transmission for endogenous macroeconomic fluctuations and as an independent source of financial shocks. Through extensive simulations, the model reproduces salient empirical regularities of exchange rate behavior—such as excess volatility, fat-tailed return distributions, volatility clustering, and cross-country contagion—and sheds light on the amplification mechanisms linking financial speculation to real economic instability. Finally, we evaluate the effectiveness of central bank interventions under different policy rules and market configurations, highlighting their conditional capacity to stabilize macroeconomic dynamics in the presence of adaptive agent behavior.

1. Introduction

The dynamics of exchange rates and their intricate interplay with international macroeconomic dynamics have been studied by economists for decades. A deep investigation is indeed crucial for understanding the interdependencies between domestic and foreign markets and their effects on national economic growth (De Grauwe, 2005). This is particularly pertinent today, given the high degree

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of interconnectedness across countries and the rapid transmission of shocks among them, with exchange rates potentially amplifying the impact of adverse shocks, thereby undermining economic growth and posing increasing risks to financial stability (Casiraghi et al., 2022).

Empirical observations have shown the complexity of these phenomena, presenting a series of regularities that challenge the explanatory power of existing theories (Dornbusch, 1976; Obstfeld and Rogoff, 1995). On the theoretical side, there is not a comprehensive understanding of the mechanisms driving exchange rate movements and their consequential impact on macroeconomic dynamics. Different macroeconomics approaches coexist, either rooted on dynamics optimization (e.g., Rogoff and Obstfeld, 1996; Engel, 2014), or on the micro-structure of the foreign exchange market (Evans and Lyons, 2002; Lyons et al., 2001), or on complexity and behavioral explanations (Frankel and Froot, 1986, 1990; Kirman, 1993; De Grauwe and Grimaldi, 2006; Flaschel et al., 2015; Gori and Ricchiuti, 2018).[1] Moreover, the existing frameworks fail to capture and explain simultaneously and consistently the set of key empirical regularities, including the volatility of exchange rates, their long memory over time, and their often-diffuse relationship with fundamental economic indicators such as interest rates, inflation, and trade balances.

In response to this pressing challenge, our study presents a novel macro agent-based model (ABM; Fagiolo and Roventini, 2017; Dawid and Delli Gatti, 2018; Dosi and Roventini, 2019) that offers a promising avenue for jointly understanding exchange rate dynamics, financial markets and their micro-macroeconomic implications. By incorporating realistic decision-making processes, bounded rationality, adaptive learning mechanisms, and explicit real and financial market interactions, our model departs from the simplifying assumptions of traditional equilibrium-based approaches. Indeed, ABMs represent a natural framework for incorporating the financial-behavioral nature of exchange rate dynamics and their interactions with the real economy.

The model expands the multi-country, multi-sector model in Dosi et al. (2019, 2021)[2] introducing an exchange rate market populated by heterogeneous fundamentalist and chartist traders as in De Grauwe (2012) and Gori and Ricchiuti (2018). The economy also comprises a consumption-good sector where firms invest in R&D process to increase labor productivity. Firms, belonging to different countries and industries, compete within international markets. Their import/export activities influence global trade patterns. Differently from the original model, exchange rate dynamics is now determined by the interplay of international trade transactions occurring in the real side of the economy and the financial flows in the exchange rate market. This intricate interplay between trade flows, behavioral trading strategies, and exchange rate dynamics bears significant implications for both micro and macro-level outcomes. On a microeconomic scale, speculative activities in the exchange rate market may impact firms' competitiveness, potentially altering their market shares in the domestic country and abroad. Meanwhile, at the macroeconomic level, speculative exchange dynamics can exert an influence on domestic economic growth and international trade interactions. The model also integrates the central bank into financial markets, enabling policy interventions to stabilize the currency market.

The present paper contributes to the literature in different ways. For the first time, a financial exchange rate market is incorporated in a macro open-economy large-scale ABM model.[3] In doing this, our model provides a fully endogenous mechanism that explains why financial volatility affects long-run macroeconomic outcomes via firm-level innovation cycles. This theoretical setting not only reproduces exchange rate and macroeconomic stylized facts, but also captures the evolutionary selection process that shapes firm competitiveness, thereby enriching the interaction between the real and financial sectors. Moreover, building on the Keynes meeting Schumpeter tradition (Dosi et al., 2010), our model endogenizes innovation as the engine of growth, capturing a unique feedback loop where exchange rate dynamics influence—and are influenced by—firm-level productivity and international competitiveness. This allows us to replicate not only standard macro stylized facts, but also additional empirical regularities that simpler models cannot explain (e.g., the effects of exchange rate depreciation or its increasing volatility on the total R&D activities at the macro level and for exporter firms at the micro level). In that, our model is designed to provide a versatile platform for examining the intricate relationship between exchange rates and economic dynamics, jointly accounting for micro and macro facts, while providing an explanation of existing puzzles (e.g., fat tails, volatility clustering, leverage effect and contagion among others). Finally, the model can be employed as a laboratory for studying the impact of different combinations of policies on market dynamics, as well as on the macroeconomic performances of countries.

Simulation results show that our model is able to reproduce key stylized facts concerning exchange rate dynamics in a multi-country structure, showing that the exchange rate market can be a source of endogenous instability (Smith et al., 2020). More specifically, eight stylized facts about the foreign exchange market are presented, ranging from fat tails to fluctuations phenomena. Moreover, this heightened financial instability is characterized by increased volatility in financial cycles (Jones and Brown, 2018). Furthermore, the results reveal the strong relationship between financial and real components, showing how heuristic expectations influence exchange rate dynamics and subsequently propagate to business cycle dynamics (Johnson and White, 2016). In particular, the impact of chartists' speculative trading can amplify exchange rate fluctuations, thus affecting countries' business cycle (Miller and Green, 2019). Finally, from a policy perspective, we examine the function of the central bank, whose involvement can mitigate

[1] Other works focus on the financial nature of exchange rate markets together with the role played by heterogeneity in expectation formation, (see Alfarano et al., 2005, 2008; De Jong et al., 2010; Verschoor and Zwinkels, 2013; Goldbaum and Zwinkels, 2014; Tsai and Tsai, 2021; Hommes, 2021; Ter Ellen et al., 2021; Bassi et al., 2023, among others).

[2] Our model is nested in the Keynes+Schumpeter (K+S) tradition (Dosi et al., 2010, 2013, 2015, 2017a) which allows to jointly study the emergence of long-run growth, business cycles and rare crises.

[3] Some large-scale agent-based models feature multi-country structure and market interactions. Nevertheless, part of them refer to the case of "monetary union" where the exchange rate dynamics is not a necessary element (see Caiani et al., 2018, 2019; Catullo and Gallegati, 2015; Dawid et al., 2014, 2018; Petrovic et al., 2017; Wolf et al., 2013; Fanti et al., 2023); others treat the foreign sector as an aggregate sector, with fixed exchange rate and without modeling the feedback effect between two (or more) economies (Dweck et al., 2020); others do not consider the financial nature of the exchange rate (Rolim et al., 2022).

the duration of fluctuations and the extent of speculative activities (Taylor and Lee, 2017). However, our results show the complex impact of policy interventions and the trade-offs faced by the central bank. Indeed, the impact of the monetary policy can vary depending on the type of intervention. Even if "leaning against the wind" strategy can reduce the quota of chartists and the duration of the cycles, the same intervention can increase uncertainty, which manifests as either a non-reduction or an actual increase in volatility, affecting not only financial markets but also the real market (Brown and Smith, 2021).

The remainder of the paper is structured as follows. Section 2 presents a list of stylized facts the model aims to replicate. Section 3 introduces the main features of the model. Section 4 discusses the simulation results, focusing on both stylized fact replication and the impact of central bank interventions in the exchange rate market. Finally, Section 5 concludes and discusses possible venues for future research.

2. Empirical evidence on exchange rates and open economy dynamics

Using agent-based modeling methodology (see Fagiolo and Roventini, 2017; Dawid and Delli Gatti, 2018; Dosi and Roventini, 2019; Haldane and Turrell, 2019), this article builds on extensive literature investigating the dynamics of bilateral exchange rates in a behavioral financial context and the role of the exchange rate as a transmission mechanism between financial markets and the real economy. In this framework, we first provide an overview of the principal stylized facts (SF) divided into three groups (cf. Table 1). The first group concentrates on exchange rate market dynamics. The second group concerns the interactions between exchange rate movements and macroeconomic dynamics. In the third group, the paper aims to replicate the macro and micro stylized facts stemming from international trade (see Dosi et al., 2019).

Exchange rate market. Extensive literature has investigated the behavior of exchange rates, revealing various empirical regularities. First, the distribution of exchange rate returns shows fat tails (SF 1; De Grauwe and Grimaldi, 2005; Spronk et al., 2013), excess kurtosis (SF 2; Winker and Gilli, 2001; Gilli and Winker, 2003), and skewness (SF 3; De Grauwe and Grimaldi, 2006), indicating a higher probability of extreme movements than a normal distribution would predict. Moreover, two "puzzles" have been empirically identified (Lux and Marchesi, 2000; De Grauwe and Grimaldi, 2006; De Grauwe and Rovira Kaltwasser, 2012): volatility clustering phenomenon (SF 4), in which periods of high volatility tend to be followed by other periods of low volatility, and the leverage effect (SF 5), which indicates that large (small) movements in the exchange rate tend to be followed by periods of high (low) volatility. The unit root hypothesis implies that exchange rate movements exhibit a random walk pattern (SF 6), with no predictable trend or pattern in the data (see the seminal works of Fama (1984) and Engel (2014) for surveys). Empirical evidence also suggests that these markets exhibit fluctuation phenomena (bubbles and crashes), in which prices can experience sudden and sharp movements that are difficult to explain using traditional economic models (SF 7; Westerhoff, 2009; Kohler and Stockhammer, 2023). Examples of bubbles and crashes in exchange rates include the Japanese yen during the late 1980s and early 1990s, the devaluation of the Russian ruble in the late 1990s, and the sharp decline of the Thai baht, which triggered the Asian financial crisis. Finally, trend-following behavior, associated with the chartist strategy, exacerbates volatility and contributes to the turbulent dynamics of exchange rates (SF 8; De Jong et al., 2010; De Grauwe and Grimaldi, 2006).

Exchange rate and macroeconomic dynamics. There is a complex and intricate relationship between exchange rate markets and macroeconomic dynamics. First, exchange rate fluctuations appear to be disconnected from macroeconomic fundamentals (SF 9; see Baxter and Stockman, 1989; Flood and Rose, 1995; Obstfeld and Rogoff, 2000; Meese and Rogoff, 1983; Rogoff, 1996; Engel and West, 2005, among others). This misalignment reflects a substantial deviations of the exchange rate from the purchasing power parity (Rogoff, 1996). At the same time, fluctuations in nominal exchange rates can have significant effects on real variables such as employment, output, and investment (SF 10; Rodrik, 2008), which bears important implications for international trade. This has the effect of creating significant synchronization in prices and quantities across countries, which can have destabilizing effects on the global economy as a result of contagion effects (SF 11; Bentivogli and Monti, 2001; Rodrik, 2008). Lastly, increasing or decreasing trade levels between countries due to non-fundamental exchange rate movements underscores the key role of exchange rates in determining international trade patterns (SF 12; Pericoli and Sbracia, 2003).

The exchange rate dynamics can also affect the R&D investment of firms and more generally their innovative performance. Even if the effect of exchange rate movements on R&D expenditures has received limited attention, the few empirical studies have shown that currency depreciation can intensify innovation, likely driven by the enhanced competitive advantages that a weaker currency offers, especially for exporters (SF 13; Alfaro et al., 2018; Becker and Pain, 2008). Simultaneously, heightened volatility of the exchange rate exacerbates uncertainty in the strategic planning of future innovation and research activities, thereby discouraging firms' engagement in innovation processes (SF 14; Wen and Usman, 2024; Caglayan and Demir, 2014).

International trade and macro and micro regularities. Although international trade plays a pivotal role in economic growth, it is also subject to various risks and uncertainties that can have significant implications for economic stability. To this respect, the first macro stylized facts concern the greater volatility of exports and imports compared to output, as well as the persistence in the dynamics of the three series (SF 15, SF 16; Uribe and Schmitt-Grohé, 2017). This highlights the sensitivity of trade to changes in the global economic environment and underscores the importance of international economic relationships. At the micro level, international trade relations lead to greater efficiency and productivity reflected in heterogeneity among firms that differ in terms of productivity (SF 17), market shares (SF 18), size (SF 19), and growth rate distributions (SF 20) (see, e.g. Bartelsman and Doms, 2000; Dosi, 2007; Bottazzi and Secchi, 2003, 2006). The empirical evidence indicates that there are notable distinctions between exporting firms and those that operate solely within the domestic economy. For example, exporters are a subset of the firm population with a premium in terms of productivity and sales (SF 21, SF 22; Bernard and Jensen, 1999; Bernard et al., 2012). Finally, for those firms exposed to the international market as exporters, fluctuations in exchange rates can significantly impact innovation activities with an increase in the latter as a consequence of depreciation phenomena (SF 23; Funk, 2003; Dao et al., 2021).

Table 1
Summary of stylized facts.

	Stylized fact	Related literature
	Exchange rate market	
SF1	Fat tails	De Grauwe and Grimaldi (2005) and Spronk et al. (2013)
SF2	Excess kurtosis	Winker and Gilli (2001) and Gilli and Winker (2003)
SF3	Skewness	De Grauwe and Grimaldi (2006)
SF4	Volatility clustering	Lux and Marchesi (2000) and De Grauwe and Rovira Kaltwasser (2012)
SF5	Leverage effect	De Grauwe and Grimaldi (2006)
SF6	Unit root hypothesis	De Grauwe and Grimaldi (2006)
SF7	Fluctuation phenomena 1	Westerhoff (2009) and Kohler and Stockhammer (2023)
SF8	Fluctuation phenomena 2	De Grauwe and Grimaldi (2006) and De Jong et al. (2010)
	Exchange rate and macroeconomic dynamics	
SF9	Misalignment problem	Rogoff (1996), Obstfeld and Rogoff (2000) and Ter Ellen et al. (2021)
SF10	Contagion	Rodrik (2008)
SF11	Synchronization	Bentivogli and Monti (2001) and Rodrik (2008)
SF12	Trade level	Bentivogli and Monti (2001) and Pericoli and Sbracia (2003)
SF13	Exchange rate-innovation driver	Alfaro et al. (2018) and Becker and Pain (2008)
SF14	Exchange rate-innovation driver 2	Wen and Usman (2024) and Caglayan and Demir (2014)
	International trade and macro and micro regularities	
SF15	Open economy volatility	Uribe and Schmitt-Grohé (2017)
SF16	Open economy persistence	Uribe and Schmitt-Grohé (2017)
SF17	Heterogeneity in productivity	Bartelsman and Doms (2000) and Dosi (2007)
SF18	Endogenous market shares structural change	Kuznets and Murphy (1966)
SF19	Departure from normal size distribution	Bottazzi and Secchi (2003) and Dosi (2007)
SF20	Fat-tailed firm growth rate distribution	Bottazzi and Secchi (2006) and Dosi (2007)
SF21	Fraction of exporters	Bernard and Jensen (1999) and Bernard et al. (2012)
SF22	Export productivity premium	Bernard and Jensen (1999) and Bernard et al. (2012)
SF23	Exporter exchange rate-innovation driver	Funk (2003) and Dao et al. (2021)

3. The model

The direct ancestor of the model is the multi-country model by Dosi et al. (2019, 2021), which features N different economies (indexed by i). Each country contains M consumption-good industries (indexed by h) populated by S firms (indexed by j). Our analysis includes $N = 2$ countries, $M = 2$ sectors for each economy, and $S = 250$ firms for each sector. Firms in the consumption-good sector search for innovations to increase their labor productivity and competitiveness. At the same time, they try to imitate the technology of their competitors. Consequently, production technologies are heterogeneous across firms and endogenously evolve over time. In turn, building on the Keynes meeting Schumpeter family of models (Dosi et al., 2010), long-run economic growth is endogenously driven the innovation activities of firms which perform R&D investment to boost their productivity and their competitiveness. This investment creates a feedback loop whereby firm-level technological progress directly influences, and is influenced by, macroeconomic outcomes such as export performance and aggregate demand.

Our model uniquely integrates a foreign exchange market into the agent-based structure, whereby exchange rate movements are not simply exogenous shocks but are endogenously influenced by firm-level performance. The dynamic evolution of productivity—stemming from R&D decisions—directly impacts on international trade flows and, hence, the valuation of the currency. This endogenous mechanism is crucial: if productivity were exogenously given, the real sector would remain static and the feedback between firm competitiveness, trade flows, and exchange rate dynamics would be severely limited. Therefore, R&D dynamics are essential to capturing the co-evolution of the real and financial sectors. Hence, this market not only determines the exchange rate, but also interacts with the real economy by affecting firms' R&D decisions and innovation strategies. Specifically, speculative fluctuations in the exchange rate can destabilize R&D investments, which in turn impact firms' international competitiveness and the overall macroeconomic performance. This integrated approach allows us to analyze the bottom-up transmission of financial shocks into real economic variables.

We focus only on two countries to better study the dual nature of the exchange rate, which acts both as a transmission channel of endogenous shocks as well as a source of shocks.[4] Fig. 1 illustrates the schematic structure of the model. We extend the model in Dosi et al. (2019) in two ways. *First*, the exchange rate is influenced not only by trade flows (the real channel, the blue arrow in Fig. 1), but also by the demand for foreign currencies carried out by traders in the financial exchange rate market (the financial channel, the yellow box in Fig. 1). Specifically, trade operators predict future prices by choosing either a fundamentalist or a chartist strategy.[5] Fundamentalists base their decisions on the long-term underlying real fundamental value, while chartists speculate based

[4] In order to focus more on the interplay between real and financial sectors, we employ a simplified version of the model which does not consider the capital good sector. We leave the complication of the model to future works in which we will analyze the most complex relationships within the global production network.

[5] Throughout the entire paper, we will use the terms chartists, trend followers, and technical traders interchangeably.

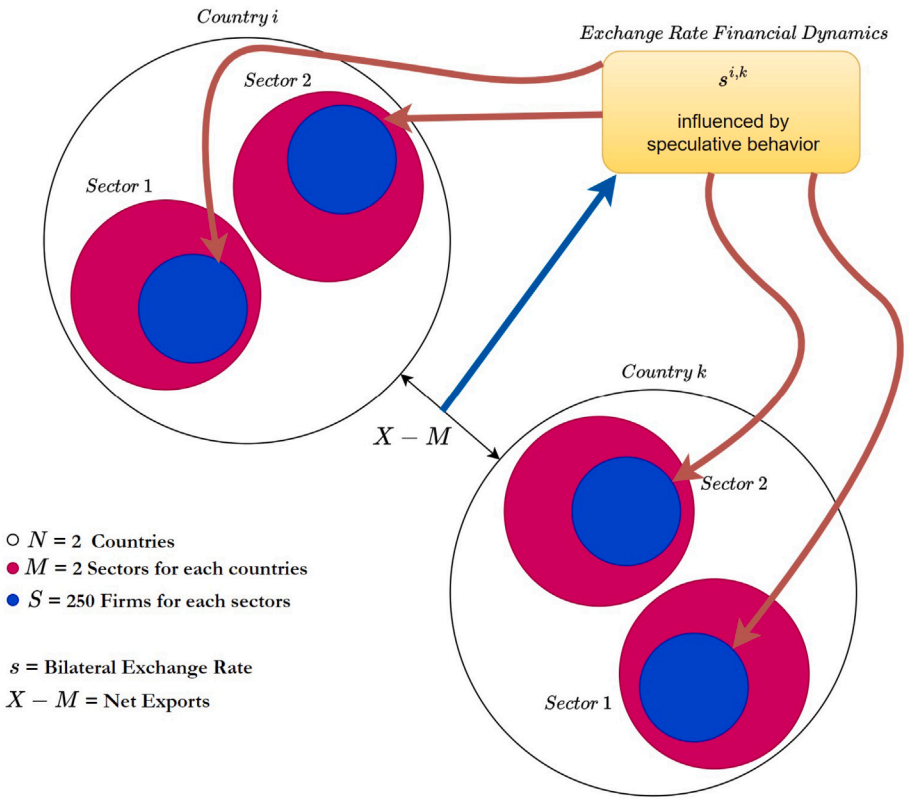

Fig. 1. The interaction process between the real market and the financial behavioral exchange rate dynamics in the multi-country, multi-sector ABM model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

on previously observed prices. Speculative beliefs can influence the exchange rate dynamics, bringing instability and nonlinear patterns to the real sector (the brown arrows in Fig. 1). *Second*, the central bank is now an actor in financial markets potentially implementing different forms of interventions, trying to prevent fluctuation phenomena and reducing volatility in currency markets. These interventions can take various forms, such as buying or selling currencies in the foreign exchange market. In particular, we analyze two types of intervention: "leaning against the wind" and "leaning against the wind with a short-run target". In this way, we can further explore the central bank's impact on overall economic performance. The diagram in Fig. 2 illustrates the steps taken in the paper, highlighting the differences from the previous framework.

3.1. Timeline of events

In every time period t, the sequence of events in the model runs as follows:

1. Firms in the consumption-good industries perform R&D to discover new techniques and imitate competitors closer to the technology frontier. Firms can improve their labor productivity if either innovation or imitation is successful.
2. Production and employment decisions take place. Consumption-good firms set their desired production given their expected demand. Accordingly, they hire workers and expand their productive capacity if necessary.
3. Monetary wages and prices are set.
4. The bilateral exchange rate is determined by the behavioral decisions of trade operators in the foreign exchange market.
5. Imperfectly competitive international consumption-good markets open. Workers spend their income on domestic and imported goods. Firms' market shares evolve according to their price competitiveness.
6. Entry and exit of firms take place. New firms replace the firms with quasi-zero market shares who exit the market.

At the end of each time step, aggregate variables (e.g., output, consumption, exports, imports, etc.) are computed, summing over the corresponding microeconomic variables.

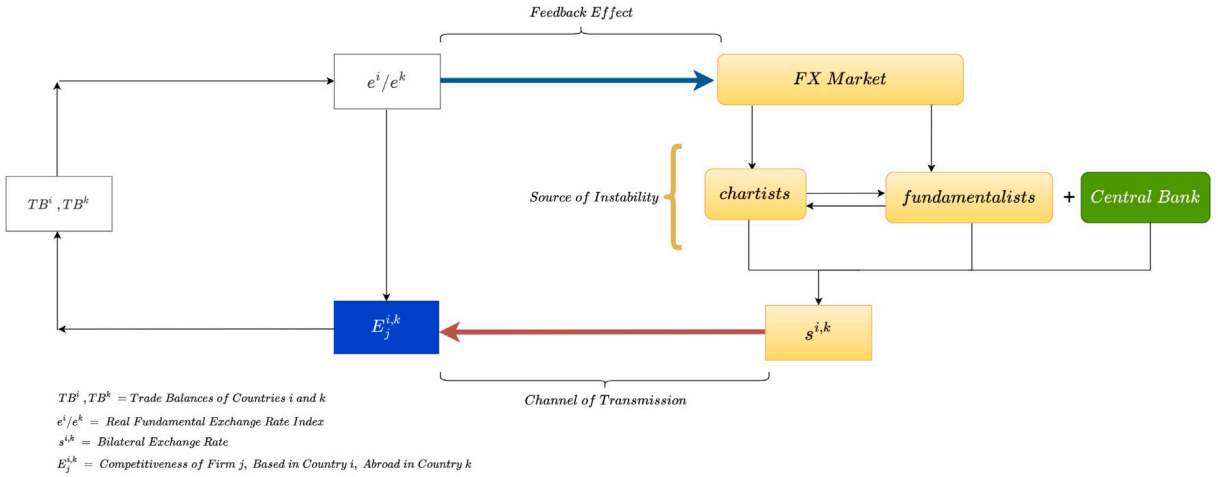

Fig. 2. Flowchart illustrating the main difference steps between the baseline model (white + blue) and model with speculative behavior (white + blue + yellow) and Central Bank (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. The consumption-good sector

The consumption-good sector is populated by S firms in M industries for each country. The consumption-goods firms are the drivers of technical change in the model and invest a fixed proportion $\rho \in (0, 1]$ of their past sales (SS) in R&D:

$$RD^i_{j,h}(t) = \rho SS^i_{j,h}(t-1). \tag{1}$$

Firms split their total R&D efforts between innovation (IN) and imitation (IM) according to the parameter λ ($0 \leq \lambda \leq 1$):

$$IN^i_{j,h}(t) = \lambda RD^i_{j,h}(t), \tag{2}$$

$$IM^i_{j,h}(t) = (1-\lambda) RD^i_{j,h}(t). \tag{3}$$

In line with Dosi et al. (2010, 2019), innovation and imitation are modeled as a two-step stochastic process. The first step consists of draws from a Bernoulli distribution that indicates whether a firm is successful in its innovation search ($\theta(IN)$) and/or in its imitation one ($\theta(IM)$). Note that the success of such a search depends on the R&D expenditures allocated to innovation and imitation, as well as on firms' search capabilities ($\xi_{1,2} > 0$)[6]:

$$\theta(IN)^i_{j,h}(t) = min\{\theta_{max}; 1 - e^{-\xi_1 IN^i_{j,h}(t)}\}, \tag{4}$$

$$\theta(IM)^i_{j,h}(t) = min\{\theta_{max}; 1 - e^{-\xi_2 IM^i_{j,h}(t)}\}. \tag{5}$$

The firm that succeeds in innovation will discover a new production technique associated with a labor productivity coefficient $A(IN)$:

$$A(IN)^i_{j,h}(t) = A^i_{j,h}(t-1)(1 + x^i_{j,h}(t)), \tag{6}$$

where x is drawn from a $Beta(\alpha_1, \beta_1)$ distribution over the support $[\underline{x}_1, \overline{x}_1]$ with $\underline{x}_1$ belonging to the interval $[-1, 0]$ and $\overline{x}_1$ to $[0, 1]$. The support and the shape of the Beta distribution captures the technological opportunities. Note that the high degree of uncertainty describing the innovation process can lead to the discovery of new techniques whose productivity is lower than the ones currently mastered by firms.

Also imitation follows a double-step process. Successfully imitating firms can copy the technology of one of the competitors. The probability of imitating is inversely and proportionally correlated to the technological distance between different pairs of firms. It is measured in terms of the Euclidean metric to weigh the probabilities of imitation. As assumed by Dosi et al. (2019) and in the literature on the technological gap, foreign techniques are fairly difficult to imitate compared to domestic ones (see more in Abramovitz, 1986; Dosi et al., 1990; Fagerberg et al., 2005).[7]

[6] We assume the upper bound $\theta_{max} < 1$ to account for the uncertainty involved in the search activity of firms.

[7] If two firms are based in two different countries, the distance between their technical coefficients is increased by a multiplicative parameter $\epsilon > 1$.

When innovation and imitation processes are completed, each firm selects the production technique that yields the higher labor productivity.

$$A^i_{j,h}(t) = max\{A^i_{j,h}(t-1); A(IN)^i_{j,h}(t); A(IM)^i_{j,h}(t)\}, \tag{7}$$

where $A^i_{j,h}(t-1)$ is a production technique already available to the firm, $A(IN)^i_{j,h}(t)$ and $A(IM)^i_{j,h}(t)$ are production technique discovered in innovation and imitation process, respectively.

The pricing rule (p) relies on the variable mark-up (μ) over the unit cost of production, given the fixed nominal wage (W) at the country level:

$$p^i_{j,h}(t) = (1 + \mu^i_{j,h}(t))\frac{W^i_{j,h}(t)}{A^i_{j,h}(t)}. \tag{8}$$

Although consumption goods are formally homogeneous, market dynamics are characterized by imperfect consumer information and behavioral frictions, akin to the frameworks proposed by Phelps and Winter (1970), Klemperer (1987) and Farrell and Shapiro (1988). As a result, consumers do not instantaneously reallocate their demand to the most competitive (i.e., lowest-price) firm. Instead, demand is allocated via a replicator dynamic that reflects adaptive learning and bounded rationality, allowing for persistent price dispersion and non-zero market shares for less competitive firms. This structure supports endogenous, time-varying markups, which evolve based on firm performance and competitiveness. Such features are consistent with empirical observations on consumer price search and firm-level markup heterogeneity (Rotemberg, 2008; Loecker and Warzynski, 2012). Therefore, the model embeds an imperfect competitive environment with homogeneous goods, reflecting realistic frictions in consumption-good markets.

The mark-up endogenously evolves according to the dynamics of firm market shares (f):

$$\mu^i_{j,h}(t) = \mu^i_{j,h}(t-1)(1 + \upsilon\frac{f^i_{j,h}(t-1) - f^i_{j,h}(t-2)}{f^i_{j,h}(t-2)}), \tag{9}$$

with $0 \leq \upsilon \leq 1$. Accordingly, the size of the markup depends on the firm's innovation efforts, market demand conditions, and the degree of competition they face. This reflects empirical evidence that real-world firms often exhibit significant pricing power (Hall, 1988; De Loecker et al., 2020; Loecker and Warzynski, 2012).

Consumption-good firms produce goods using labor, whose productivity grows over time due to technical change. Firms plan their desired production (Qd) according to adaptive (myopic) demand expectations (D):

$$Qd^i_{j,h}(t) = f(D^i_{j,h}(t-1), D^i_{j,h}(t-2), \dots, D^i_{j,h}(t-k)), \tag{10}$$

where $D^i_{j,h}(t-1)$ is the demand actually faced by firm j at time $t-1$ (k positive integer). Accordingly, the actual production (Q) reads as follows:

$$Q^i_{j,h}(t) = max\left\{Qd^i_{j,h}(t), 0\right\}. \tag{11}$$

3.3. Market dynamics

Market selection allocates international demand for consumption goods across firms belonging to different countries. National consumption equals the wage bill (W) which is the product of employment and the salary. We assume that agents spend an equal proportion of $d_h = 1/M$ of their income in each consumption-good industry, implying sectoral income elasticities of demand to be constant and equal to 1 over time.

Each firm competes in N national markets, all characterized by imperfect information (Phelps and Winter, 1970; Klemperer, 1987; Farrell and Shapiro, 1988). Firms' competitiveness depends on the price they charge. Moreover, in foreign markets, price (and competitiveness) are also affected by trade costs (τ) and the exchange rate (s). In this, the competitiveness of a given firm j from country i and industry h that operates in country k would read as follows:

$$E^{i,k}_{j,h}(t) = \frac{1}{p^i_{j,h}s^{i,k}(t)(1+\tau)}, \tag{12}$$

where $s^{i,k}$ is the nominal exchange rate between country i and k and τ stands for additional cost for competing in foreign markets.[8] The average competitiveness ($\overline{E}$) of industry h belonging to country k is computed as follows:

$$\overline{E}^k_h(t) = \sum_{i=1}^{N}\sum_{j=1}^{S} E^{i,k}_{j,h}(t) f^{i,k}_{j,h}(t-1). \tag{13}$$

Market shares (f) are affected by the market selection via a quasi-replicator dynamics (Dosi et al., 1995, 2017b):

$$f^{i,k}_{j,h}(t) = f^{i,k}_{j,h}(t-1)(1 + \chi\frac{E^{i,k}_{j,h}(t) - \overline{E}^k_h(t)}{\overline{E}^k_h(t)}), \tag{14}$$

[8] $\tau = 0$ if $i = k$ and $\tau > 0$, otherwise.

where $\chi > 0$ and controls the strength of market competition.

Accordingly, the firms whose competitiveness is higher (lower) than the market average will expand (reduce) their market shares. The global market share of firm j competing in hth industry then reads:

$$f^{i}_{j,h}(t) = \sum_{k=1}^{N} f^{i,k}_{j,h}/N. \tag{15}$$

The domestic demand ($Dint$) each firm faces under the given wage (W) and aggregate national employment (L) in case $i = k$ is equal to:

$$Dint^{i}_{j,h}(t) = L^{i}(t)W^{i}(t)d_h f^{i,k}_{j,h}(t). \tag{16}$$

Symmetrically, the foreign demand reads:

$$Dexp^{i}_{j,h}(t) = \sum_{k\neq i}^{N} L^{k}(t)W^{k}(t)s^{k,i}d_h f^{i,k}_{j,h}(t). \tag{17}$$

Consequently, the total firm demand ($D^{i}_{j,h}$) is presented as a sum of domestic demand $Dint^{i}_{j,h}(t)$ and demand for exports $Dexp^{i}_{j,h}(t)$.

As in national markets, Schumpeterian exit and entry dynamics is present in international competition, where the firms with nearly zero market shares leave the market and get replaced by new firms keeping the overall quantity of firms in each industry unchanged. The latter relies on empirical evidence showing that entrants are (roughly) proportional to the number of incumbents (see Geroski et al., 1993). We also assume that entrants are on average smaller than incumbents (see Bartelsman et al., 2005; Caves, 1998, for empirical evidence), and their initial stock of capital is equal to the minimum level in the industry. Entry and exit stem from the process of Schumpeterian competitive dynamics where markets select the most competitive firms and the most productive technologies. In such an evolutionary selection process, the least competitive firms exit when their market shares fall below a threshold, while new entrants, although initially small, introduce novel technologies, contributing to persistent productivity heterogeneity and maintaining the competitive pressure essential for innovation.[9]

3.4. Exchange rate dynamics

In line with the asset-price dynamics literature (Brock and Hommes, 1998; Chiarella et al., 2009), financial operators possess two investment options: a country i asset that yields an interest rate of r^{i}, and a country k asset that provides an interest rate of r^{k}. In this context, wealth (W) of financial operator of type ϕ evolves according to De Grauwe and Grimaldi (2006):

$$W^{\phi}(t+1) = \left(1+r^{i}\right) s^{i,k}(t+1)\, d^{\phi}(t) + \left(1+r^{k}\right)\left[W^{\phi}(t) - s^{i,k}(t)\, d^{\phi}(t)\right], \tag{18}$$

where $s^{i,k}(t+1)$ is the bilateral exchange rate at time $t+1$ and $d^{\phi}(t)$ is the demand for currency of country i.

The agents' utility function is expressed by the following equation:

$$U\left[W^{\phi}(t+1)\right] = E^{\phi}(t)\left[W^{\phi}(t+1)\right] - (a/2)V\left[W^{\phi}(t+1)\right], \tag{19}$$

where $\mathrm{E}^{\phi}(t)$ is the expectation operator, a is the risk aversion coefficient which is the same for all agents, and V is the variance of wealth. Agents determine their asset demand by maximizing their utility function U:

$$\max\left\{U\left[W^{\phi}(t+1)\right]\right\} = \max\left\{\mathrm{E}^{\phi}(t)\left[W^{\phi}(t+1)\right] - (a/2)\,V\left[W^{\phi}(t+1)\right]\right\}. \tag{20}$$

Solving Eq. (20), we obtain the following demand of currency i:

$$d^{\phi}(t) = \frac{\left(1+r^{i}\right)\mathrm{E}^{\phi}(t)\left[s^{i,k}(t+1)\right] - \left(1+r^{k}\right)s^{i,k}(t)}{a\sigma^{2}}. \tag{21}$$

In line with Heterogeneous Agent Models (HAMs), there exist Φ groups of agents who hold heterogeneous expectations about future exchange rate. Next, we will define the two groups of agents, which differ in their expectation formation processes. Let $\omega^{\phi}(t)$ denotes the proportion of agents belonging to type ϕ, with $\sum_{\phi=1}^{\Phi}\omega^{\phi}(t) = 1$ and $\omega^{\phi} \in (0,1)$. In such a scenario, total demand of financial operators, $D(t)$, can be expressed as[10]:

$$D(t) = \sum_{\phi=1}^{\Phi}\omega^{\phi}(t)\left\{\frac{\left(1+r^{i}\right)\mathrm{E}^{\phi}(t)\left[s^{i,k}(t+1)\right] - \left(1+r^{k}\right)s^{i,k}(t)}{a\sigma^{2}}\right\}. \tag{22}$$

[9] While the assumption of a constant number of firms does not capture recent trends in declining business dynamism observed in developed economies (e.g., Decker et al., 2016; Akcigit and Ates, 2021), it allows us to isolate and analyze the core mechanisms of innovation and competitive turnover without introducing additional complexity from fluctuating firm demographics.

[10] Consistent with the tradition of ABM models featuring various groups of agents, we do not address the role of inventory management strategies. However, this area remains underexplored within the ABM literature. Notable preliminary studies in this field include Zhu et al. (2009), Carraro and Ricchiuti (2015), Bargigli (2021) and Mignot and Westerhoff (2024).

Without loss of generality, we may assume that financial dealers have an exogenous market supply equal to zero (Brock and Hommes, 1998). On the other hand, the central bank can increase or decrease the supply of domestic currency, $z(t)$, thereby influencing the dynamics of the exchange rate (see the transmission mechanism in Fig. 2).[11] The market equilibrium is represented by the following equation:

$$D(t) = \sum_{\phi=1}^{\Phi} \omega^{\phi}(t) \left\{ \frac{\left(1 + r^{i}\right) \mathrm{E}^{\phi}(t) \left[s^{i,k}(t+1)\right] - \left(1+r^{k}\right) s^{i,k}(t)}{a\sigma^{2}} \right\} = z(t), \tag{23}$$

from which, we can get the exchange rate[12]:

$$s^{i,k}(t) = \sum_{\phi=1}^{\Phi} \omega^{\phi}(t) \mathrm{E}^{\phi}(t) \left[s^{i,k}(t+1)\right] - a\sigma^{2} z(t). \tag{24}$$

Two types $\{\phi = f, c\}$ of agents populate the financial exchange rate market. One type of traders, the "fundamentalist" ($\phi = f$), base their decisions on the long-term fundamental economic factors that drive trade flows dynamics. Specifically, this dimension is represented by the ratio e_i/e_k which brings in equilibrium the trade balance (see Gori and Ricchiuti, 2018, for a similar mechanism). In fact, exchange rate index (e_i) evolves based on the past current account adding a stochastic noise that is inspired by the models of balance-of-payment constrained growth (see McCombie, 1993)[13]:

$$e^{i}(t) = e^{i}(t-1)(1 + \gamma \frac{TB^{i}(t-1)}{\overline{Y}(t-1)} + u_{i}(t)), \tag{25}$$

where $u_t \sim N(0, \sigma_u)$, TB is the trade balance, $\overline{Y}$ is world GDP, u is white noise, and the parameter γ is responsible for the sensitivity of the adjustment of exchange rate depending on the exchange rate regime. We formalize the heuristic behavior of fundamentalists with the following equation:

$$\mathrm{E}^{f}(t) \left[s^{i,k}(t+1)\right] = s^{i,k}(t-1) + \alpha \left[e^{i}(t)/e^{k}(t) - s^{i,k}(t-1)\right], \qquad \alpha > 0, \tag{26}$$

where α is the agents' reaction coefficient. The other type of agents, the technical traders or "chartists" ($\phi = c$), take a speculative short-term perspective focused on past short-term trend lines:

$$\mathrm{E}^{c}(t) \left[s^{i,k}(t+1)\right] = s^{i,k}(t-1) + \beta \left[s^{i,k}(t-1) - s^{i,k}(t-2)\right], \qquad \beta > 0, \tag{27}$$

where β is the chartists' reaction coefficient. These agents focus on short-term market trends and use past performance to predict future market trends.[14]

The fractions of agents are not fixed over time: traders can switch from one rule to the other (Westerhoff, 2009). Chartists follow a selection strategy according to the misalignment process: the more the exchange rate deviates from its fundamental value, the more traders come to the conclusion that the trend process might collapse. As a result, an increasing number of agents start to switch to the fundamentalist strategy:

$$\omega^{c}(t) = \frac{1}{1 + \psi \left[e^{i}(t-1)/e^{k}(t-1) - s^{i,k}(t-1)\right]^{2}}. \tag{28}$$

Given that the sum of market shares equals one, the weight of the fundamentalists, is expressed as $1 - \omega^{c}$. Let us now formalize the intervention of the central bank. We focused on "sterilized interventions" (see Szpiro, 1994; Ricchiuti, 2004, and De Grauwe and Grimaldi, 2006), which are designed to counteract a possible appreciation or depreciation of domestic currencies. To carry them out, the central bank follows the behavioral rule in the market as in De Grauwe and Grimaldi (2006):

$$z(t) = \varepsilon_{cb} \left[s^{i,k}(t-1) - s^{i,k}(t-2)\right], \qquad \varepsilon_{cb} > 0. \tag{29}$$

This rule is the classical **"leaning against the wind"**: when the bilateral exchange rate depreciates ($s^{i,k}(t-1) < s^{i,k}(t-2)$), the central bank reduces the supply of domestic currencies to try to appreciate the exchange rate; at the opposite, when the bilateral exchange rate appreciates ($s^{i,k}(t-1) > s^{i,k}(t-2)$), the central bank increases the supply of domestic currencies. The intensity with which the central bank conducts these operations is measured by the parameter ε_{cb}. The drawback of the previous rule is that the central bank must continuously interfere in the foreign exchange market, which can be time-consuming and costly. A possible alternative is a **"leaning against the wind with a short-run target"**. This rule can be formalized as follows:

$$z(t) = \varepsilon_{cb} \left[s^{i,k}(t-1) - s^{i,k}(t-2)\right], \qquad \varepsilon_{cb} > 0, \tag{30}$$

[11] It is worth noting that the central bank increases the domestic money supply by buying foreign currency from its foreign reserves in exchange for domestic currency, and decreases the domestic money supply by selling foreign currency in exchange for domestic currency, thereby decreasing its foreign reserves. In both cases, we assume that the reserves are sufficient.

[12] For analytical tractability we set $r^{i} = r^{k} = 0$.

[13] Once we obtain the exchange rate index of countries i and k from Eq. (24), the real fundamental bilateral exchange rate can be calculated as follows: $e^{i}(t)/e^{k}(t)$. On this point, see also Dosi and Roventini (2019).

[14] This way of defining expectations, as well as others that deviate from the rational hypothesis, has also been applied in macroeconomic contexts to formalize the expectation of the output gap and inflation. See, for example, De Grauwe (2012) and De Grauwe and Foresti (2020) for a macro model in a closed economy context.

with

$$\begin{aligned} \varepsilon_{cb} &> 0 \quad if \quad \left|s^{i,k}(t-1) - s^{i,k}(t-2)\right| > M \quad , \quad M = 3 * sd[e^i(t)/e^k(t)] \\ \varepsilon_{cb} &= 0 \quad if \quad \left|s^{i,k}(t-1) - s^{i,k}(t-2)\right| < M \quad , \quad M = 3 * sd[e^i(t)/e^k(t)]. \end{aligned} \tag{31}$$

In this way, the central bank will have less need to constantly monitor and adjust exchange rates. Indeed, the central bank intervenes only when the difference between the exchange rate and the fundamental value derived from the balance of trade exceeds the target M. Following previous research (De Grauwe and Grimaldi, 2006), M is imposed to be equal to 3 times the standard deviation of the underlying economic fundamental value.

3.5. Macroeconomic dynamics

Total employment is determined by the total labor demand of consumption firms. In line with Lewis et al. (1954) and Cornwall (1977), we assume that the supply of labor is infinitely elastic to variations in demand. Considering that in each country, the functioning of the labor market is regulated by institutional rules, monetary wages follow productivity dynamics as in Dosi et al. (2010):

$$W^i(t) = W^i(t-1)[1 + \psi g^i_{prod}(t-1)], \tag{32}$$

where g_{prod} is the lagged productivity growth and $\psi \geq 0$.

At the end of each time period, national aggregate variables (e.g., national consumption - C, total exports - EXP and total imports - IMP) are computed summing up the corresponding micro counterparts:

$$C^i(t) = W^i(t)L^i(t); \tag{33}$$

$$EXP^i(t) = \sum_{h=1}^{M}\sum_{j=1}^{S} Dexp^i_{j,h}(t); \tag{34}$$

$$IMP^i(t) = C^i(t) - \sum_{h=1}^{M}\sum_{j=1}^{S} Dint^i_{j,h}(t). \tag{35}$$

From Eqs. (34) and (35), the trade balance can be computed as $TB^i(t) = EXP^i(t) - IMP^i(t)$. Naturally, the trade balances of all countries cancel out at the global level: $\sum_{i=1}^{N} TB^i(t)e^i(t) = 0$. Accordingly, the national output of country i ($Y^i(t)$) is computed as the sum of the components of aggregate demand.

4. Simulation results

The model presented in Section 3 does not permit closed-form solutions, a common characteristic of agent-based models. This constraint arises from the inherent non-linearities in the decision-making rules of agents and the patterns of their interactions. Consequently, to investigate the dynamics of micro- and macrovariables, we rely on simulations. We impose identical structural parameters around countries, industries, and firms. Indeed, evolutionary dynamics is an endogenous outcome.[15] Simulations have been run for 600 periods (50 transient periods and 550 considered periods). Finally, to assess the empirical significance of the model, statistical tests are based on Monte Carlo simulations with 200 runs of 600 periods. For more on the empirical validation of agent-based models, see Fagiolo and Roventini (2017), Windrum et al. (2007) and Fagiolo et al. (2019).

Before examining in detail the stylized facts reproduced by the model, we consider whether a typical simulation run is able to generate endogenous growth and business cycles (Dosi et al., 2010, 2013, 2015, 2017a). The time series in Fig. 3 represents the simulated GDP of the two countries considered: country i and country k. The left graph displays the series in log levels, capturing the overall growth trends, while the right graph illustrates the fluctuations of these series once the trend has been removed. The dynamics shows that growth and fluctuations are genuine emerging properties of the model.[16]

4.1. Stylized facts replication

Let us now focus on the stylized facts discussed in Section 2. We first discuss the evidence regarding the dynamics of the exchange rate market, then move to the interactions between the exchange rate dynamics and the real economy, and finally evaluate the ability of the model to replicate the other SFs concerning international trade and open economy dynamics.[17]

Exchange rate market. We start by considering the exchange rate return distribution, which is empirically characterized by fat tails and excess kurtosis with respect to the Gaussain benchmark (Huisman et al., 2002). Fig. 4 displays the quantile–quantile plot (QQ) of the quantiles of the simulated exchange rate returns ($s^{i,k}$) versus the theoretical values of a normal distribution. The figure suggests

[15] The benchmark parameterization is reported in Appendix A. For the exchange rate market, simulations assume values of $\alpha = 0.50$ and $\beta = 1$, consistent with the empirical evidence presented in Ter Ellen et al. (2021).

[16] All the results are not displayed here due to space constraints. They are available from the authors upon request.

[17] Table 15 in Appendix D summarizes all the statistical analyses we performed to replicate the stylized facts discussed in the paper.

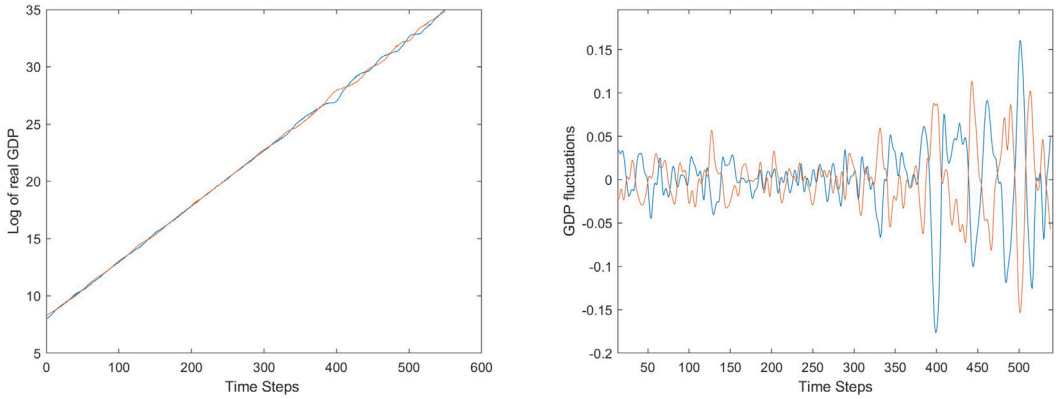

Fig. 3. Real GDP growth (left) and business cycles (right) in Country i (blue line) and in Country k (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

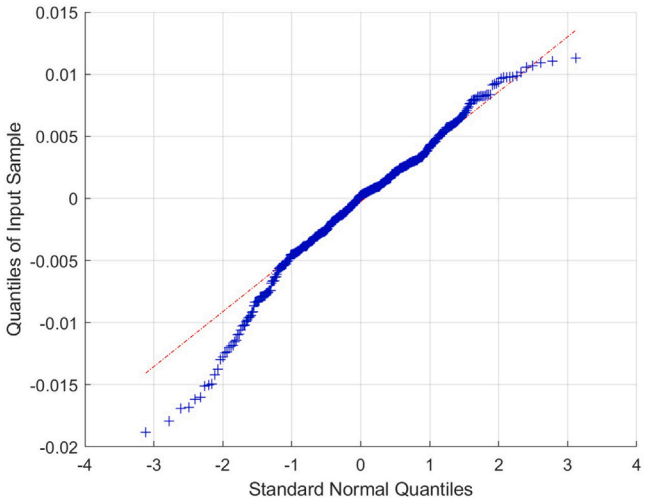

Fig. 4. QQ plot of simulated exchange rate return distribution (blue line) vs. standard normal (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a heavier tail than the normal distribution (SF 1). Also, the Kurtosis index of the simulated exchange rate returns shows a departure from the normal distribution with a value equal to 3.91 (SF 2). At the same time, the simulated exchange rate returns confirm the asymmetry of the simulated data around the sample mean with results equal to −0.5650 (SF 3). The deviation from a normal distribution is also confirmed by the frequency distribution plot (Fig. 5). In Fig. 5, the data appear to be concentrated at the extreme values and in the middle of the distribution, suggesting the non-Gaussian character of asset and asset returns.

We now test the emergence of the volatility clustering phenomenon. We first compute the autocorrelation function of the absolute returns of our simulated exchange rate as a measure of variability. As shown in Fig. 6, the autocorrelation function is positive for all lags considered. This confirms that volatility in the exchange rate returns has a long memory in time (SF 4).

To generalize the previous result, we implement the following GARCH(1,1) model:

$$\Delta s(t) = \varepsilon(t), \quad with \quad \varepsilon(t) = \sigma(t) z(t), \quad z(t) \sim N(0,1),$$

where $\Delta s(t)$ is the return of the exchange rate and $\varepsilon(t)$ represents the innovation process. The conditional variance process of the returns is the following:

$$\sigma_t^2 = b + \alpha \varepsilon_{t-1}^2 + \delta \sigma_{t-1}^2.$$

The estimated GARCH coefficients α and δ in Table 2 are significantly different from zero, implying volatility clustering in the exchange rate returns. Furthermore, the sum of α and δ—an indicator of the degree of volatility's inertia—is nearly one, implying that the impact of volatility shocks fades away gradually.

To detect the leverage effect on the volatility of exchange rates, in Fig. 7, we plot the volatilities against the returns of the exchange rate based on a five-lag window observation. This method tracks how past changes in exchange rates influence future

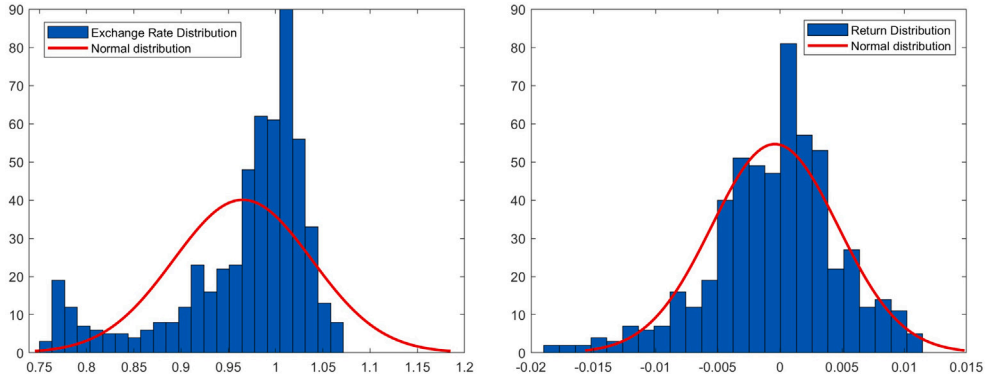

Fig. 5. Frequency distribution of the simulated exchange rate (left) and exchange rate returns (right). The red lines indicate the corresponding normal distributions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

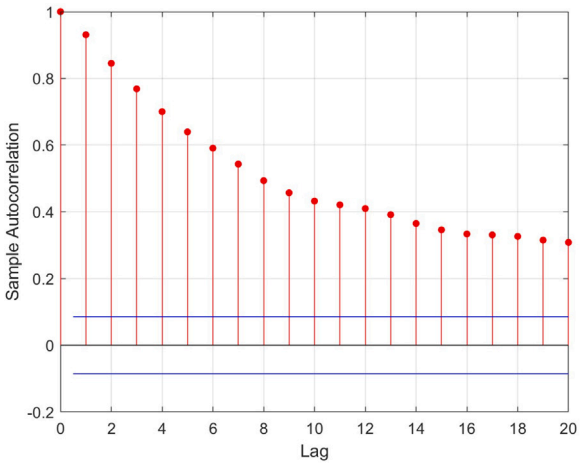

Fig. 6. Autocorrelation function of exchange rate return.

Table 2
GARCH(1,1) conditional variance model.

	α	δ	b
Monte Carlo values	0.8257***	0.1236***	1.31e−06***
s.e.	(0.0057)	(0.0067)	(5.83e−08)

Notes: Monte Carlo simulations standard errors in parentheses.
*, **, *** denotes statistical significance at the 10%, 5%, and 1% levels respectively.
Monte Carlo values are averaged estimated coefficients of 200 replications.

volatility, with each lag representing a successive time period in our analysis. As illustrated in Fig. 7, our findings reveal a U-shaped relationship between exchange rate returns and their subsequent volatilities. This pattern indicates that both large upward and downward fluctuations in exchange rates lead to high future volatility, while small fluctuations result in low future volatility (SF 5).

We now pass to analyzing the dynamics behavior of exchange rates. We first perform a unit root test on the simulated bilateral exchange rate time series. The results indicate that we cannot reject the null hypothesis of a unit root against the stationary alternative at five percent statistical level (SF 6). The spot bilateral exchange series also exhibits significant and frequent bubbles and crashes (SF 7), as shown in Fig. 8 .

The foregoing results may stem from the presence of technical traders, which appear to have a destabilizing effect on financial dynamics, amplifying fluctuations. To test this hypothesis, we compare the duration and volatility of cycles in exchange rate

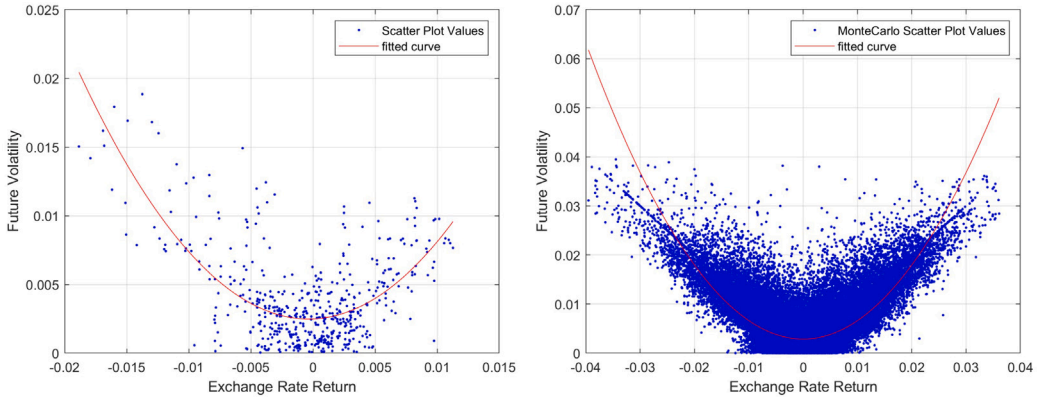

Fig. 7. Leverage Effect. One single realization on the left. 200 Monte Carlo realization on the right.

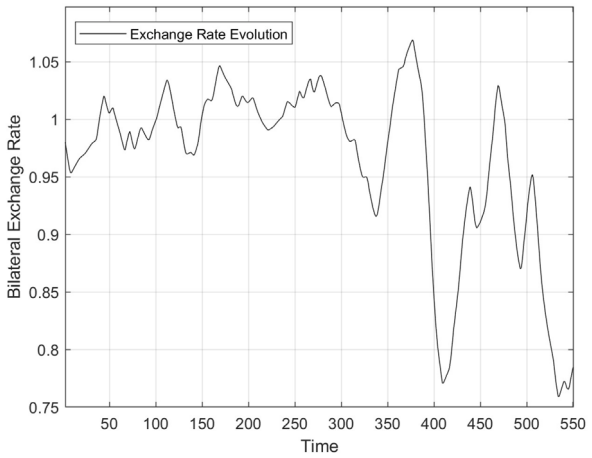

Fig. 8. Bilateral exchange rate dynamics $s^{i,k}$.

generated by our speculative switching model with those in the baseline antecedent by Dosi et al. (2019), which does not account for the financial nature of the exchange rate. We focus on fluctuations by applying a bandpass filter (Baxter and King, 1999)[18] to identify cyclical components in our simulated exchange rate series. We then calculate the duration of these cycles, defined as the period between one peak and the next, where a peak occurs when the bilateral exchange rate $s^{i,k}(t)$ satisfies $s^{i,k}(t) > s^{i,k}(t+h), \quad for\ h = -2, -1, 1, 2$ (Uribe and Schmitt-Grohé, 2017).

The left panel of Fig. 9 displays the cyclical component of the exchange rate series. The upper part presents the results of the speculative model, and the lower part shows the dynamics of the baseline model by Dosi et al. (2019). The right panel highlights the peaks in these cycles. Table 3 compares the duration and volatility of cycles between the speculative model and the baseline model. From the results obtained, we observe that the model with speculative behavior has a longer cycle duration than the baseline model (17 time steps in the speculative model versus 10 time steps in the baseline model). This indicates that the upturn and downturn of the series are more persistent when trend-following traders are present in the exchange rate market. Moreover, introducing trend-following behavior increases the volatility of the exchange rate, resulting in more turbulent behavior in foreign exchange markets (SF 8). Specifically, the results in Table 3 show that the model with speculative behavior presents a standard deviation equal to 0.0101 compared to 0.0087 in the baseline model. Moreover, as can be seen from Table 4, the results of the single simulation are also confirmed by 200 Monte Carlo repetitions at a 1% significance level.

Overall, the obtained results suggest that the speculative model generates longer and more volatile cycles compared to the baseline one, highlighting the relevant role of chartists' traders in understanding exchange rate dynamics. This is confirmed by the results shown in Fig. 10, which shows that agents tend to switch between different strategies over time, but the chartist rule remains prevalent in the market, with a market share that fluctuates around 60% (on this point, see De Grauwe and Grimaldi, 2006).

[18] We apply a bandpass filter (6,32,12) to the series. The results are also robust when a Hodrick–Prescott filter (Hodrick and Prescott, 1997) with a smoothing parameter of 1600 is employed. Such results are available upon request.

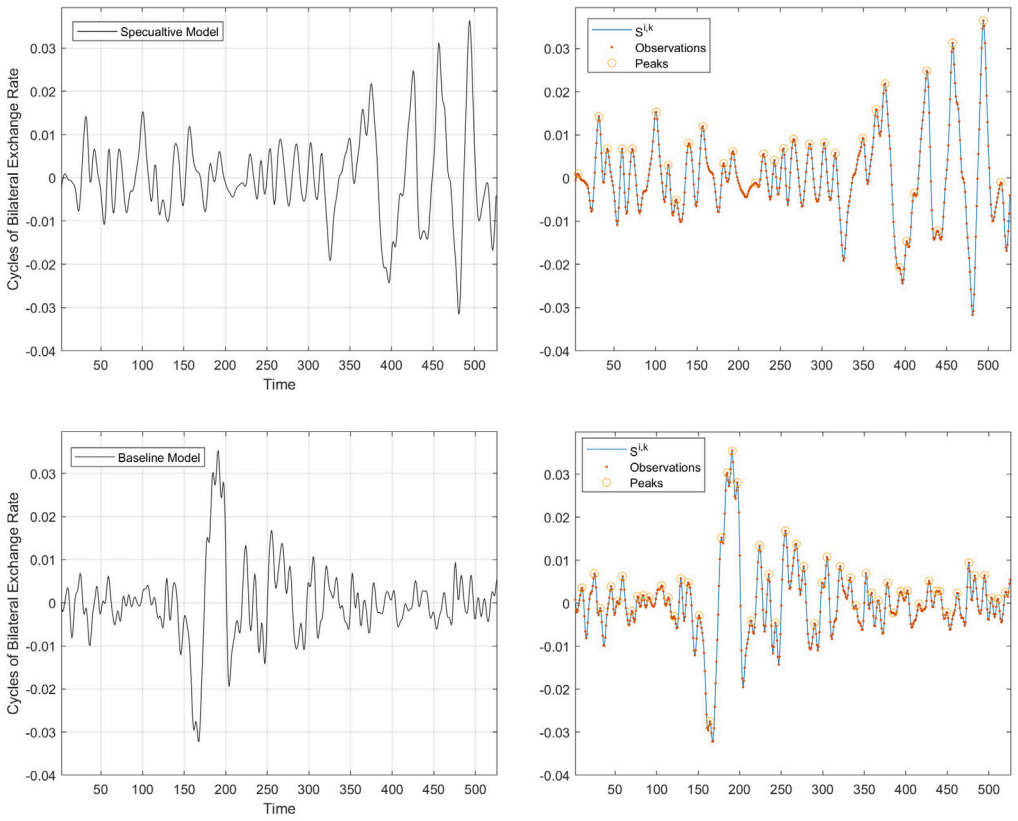

Fig. 9. Cyclical component of the bilateral exchange rate (on the left) and time-series peaks (on the right). The top part illustrates the simulation results from the speculative model while the bottom part of the baseline model by Dosi et al. (2019).

Table 3
Duration and volatility of cycles for $s^{i,k}$ in the two scenarios.

	Speculative model	Baseline model
$s^{i,k}$	$Dcycles = 17$	$Dcycles = 10$
$s^{i,k}$	$std = 0.0101$	$std = 0.0087$

Notes: The baseline model stands for the Dosi and Roventini (2019) model.
$Dcycles$ stands for the duration of cycles, std stands for standard deviation.
$s^{i,k}$ stands for the exchange rate between country i and country k.

Table 4
Duration and volatility of cycles for $s^{i,k}$ in the two scenarios. Monte Carlo results.

	Speculative model	Baseline model	$Dcycles^s > Dcycles^b$
$s^{i,k}_{MCDcycles}$	16.6515	11.6629	4.9886***
			(0.1329)
	Speculative model	Baseline model	$std^s > std^b$
$s^{i,k}_{MCstd}$	0.0116	0.0103	0.0013***
			(0.0003)

Notes: The baseline model stands for the Dosi and Roventini (2019) model.
$s^{i,k}_{MCDcycles}$ stands for the Monte Carlo mean of duration of cycles, $s^{i,k}_{MCstd}$ stands for Monte Carlo mean of standard deviation.
The third column presents the results for the hypothesis that duration of cycles ($Dcycles^s$) and volatility (std^s) in the speculative model are greater than the duration of cycles ($Dcycles^b$) and volatility (std^b) of the baseline case.
Monte Carlo simulations standard errors in parentheses.
*, **, *** denotes statistical significance at the 10%, 5%, and 1% levels respectively.

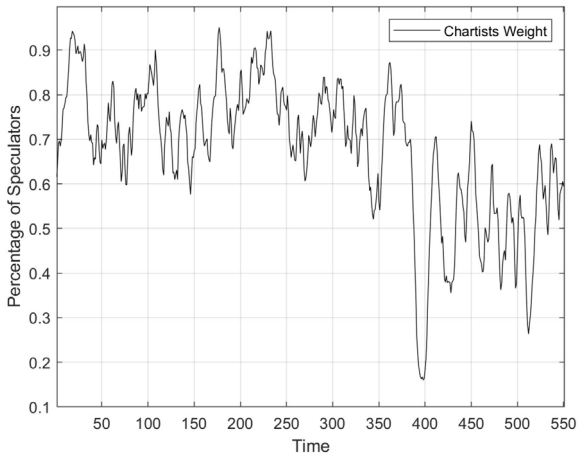

Fig. 10. Percentage of chartists.

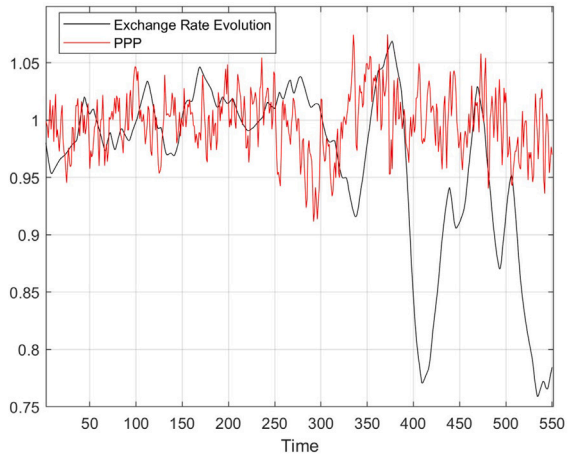

Fig. 11. Bilateral exchange evolution vs. purchasing power parity.

Exchange rate and macroeconomic dynamics. We now compare the exchange rate evolution with the purchasing power parity (PPP). The PPP is endogenously generated by model through the aggregation of the transactions occurring in the goods markets. As shown in Fig. 11, the exchange rate can be close to PPP for many periods, but it can show significant variations. Our model thus seems to generate the "misalignment" puzzle (see SF 9).[19]

To extend beyond the simple graphical analysis, we statistically examine whether PPP and the exchange rate are cointegrated by conducting a test on the following error correction model:

$$\Delta s^{i,k}(t) = \lambda_1 \left(s^{i,k}(t) - PPP \right) + \lambda_2 \left(\Delta s^{i,k}(t-1) \right).$$

The results in Table 5 show that the error correction coefficient λ_1 is statistically significant (and negative, as expected) but remarkably low (−0.0009), implying relatively weak evidence of mean reversion. On the other hand, λ_2 (0.3951) substantially impacts the current change in the exchange rate, suggesting a predominance of the forces pushing the exchange rate away from what the PPP predicts. These results align with empirical evidence indicating that exchange rates are influenced by their past values, which are considered by trend followers in the short to medium term (De Jong et al., 2010; Ter Ellen et al., 2021). This result reflects how the expectations of these agents significantly impact on price dynamics.[20]

[19] On this issue, empirical results are discordant. Indeed, there are studies which identify relationships between exchange rates and the PPP, while others fail to find such connections. See Obstfeld and Rogoff (2000) on this point.

[20] In Appendix B, we have extended our analysis to check whether the stylized fact is observed not only when considering the PPP but also when the fundamental value of our model, the one that brings the trade balance into equilibrium, is considered in the statistical analysis.

Table 5
Error correction model.

	λ_1	λ_2
Values	−0.0009***	0.3951***
	(0.00006)	(0.0070)

Notes: Monte Carlo simulations standard errors in parentheses.
*, **, *** denotes statistical significance at the 10%, 5%, and 1% levels respectively.

Table 6
Duration and volatility of cycles for Y^i and TB^i in the two scenarios.

	Speculative model	Baseline model
Y^i	$Dcycles = 11$	$Dcycles = 10$
	$std = 0.0426$	$std = 0.0214$
TB^i	$Dcycles = 11$	$Dcycles = 9$
	$std = 0.0085$	$std = 0.0044$

Notes: The baseline model stands for the Dosi and Roventini (2019) model.
$Dcycles$ stands for the duration of cycles, std stands for standard deviation.
Y^i and TB^i stand for output and trade balance of country i respectively.

Table 7
Duration and volatility of cycles for Y^i and TB^i in the two scenarios. Monte Carlo results.

	Speculative model	Baseline model	$Dcycles^s > Dcycles^b$
$Y^i_{MCDcycles}$	11.1217	10.9599	0.1618*
			(0.1027)
$TB^i_{MCDcycles}$	10.4897	10.1226	0.3671***
			(0.1169)
	Speculative model	Baseline model	$std^s > std^b$
Y^i_{MCstd}	0.0416	0.0382	0.0034**
			(0.0015)
TB^i_{MCstd}	0.0083	0.0076	0.0007***
			(0.0002)

Notes: The baseline model stands for the Dosi and Roventini (2019) model.
$Y^i_{MCDcycles}$ and $TB^i_{MCDcycles}$ stand for the Monte Carlo mean duration of cycles for output and trade balance respectively. Y^i_{MCstd} and TB^i_{MCstd} stand for Monte Carlo mean standard deviation for output and trade balance respectively.
The third column presents the results for the hypothesis that duration of cycles ($Dcycles^s$) and volatility (std^s) for speculative model are greater than the duration of cycles ($Dcycles^b$) and volatility (std^b) of the baseline line case.
Monte Carlo simulations standard errors in parentheses.
*, **, *** denotes statistical significance at the 10%, 5%, and 1% levels respectively.

We now focus on the real-financial interaction as the foregoing instability phenomena do not remain confined only in the financial sector but can directly affect the dynamics of the real economy. The results in Tables 6 and 7 show that the presence of speculative financial behavior generates a tendency toward more severe real aggregate fluctuations (SF 10).[21] Indeed, the model contemplating trading in the exchange rate market exhibits longer cycles and higher volatility than those observed in the baseline model of Dosi et al. (2019). Once the speculative behavior is eliminated, the bubbles and crashes become more short-lived.

The obtained results are also confirmed by the level of synchronization among real and financial variables which emerges due to non-fundamental exchange rate movements (SF 11). As evidenced from the left panel of Fig. 12, simultaneously with an increasing exchange rate variation resulting from speculative behavior (step 400), we observe more persistent GDP fluctuations compared to the baseline model. At the international level, we observe an increase in the intensity of imports and exports (SF 12), as shown by the normalized trade balance of the country i reported in the right panel of Fig. 12. These last graphical observations are supported by the calculation of the duration of the cycles for the variables of interest ($s^{i,k}$, Y_i, TB_i) when the sample is divided into two sub-samples at the simulation step nr. 400. Table 8 indeed shows that before $t = 400$, both the duration and volatility of the cycles are significantly lower compared to the sample for $t > 400$.

To sum up, financial instability is an emergent property generated by the model which can significantly affect the trade relationship between countries and their ensuing growth processes with possible boom and bust cycles. More specifically, when a country's currency appreciates relative to other currencies, it becomes more expensive for foreign buyers to purchase its goods. This can lead to a loss of firms' competitiveness in foreign markets and a decline in export sales and output. This is reflected in the

[21] As before, to identify the cyclical component in the macro series obtained from the model we apply the bandpass (6,32,12) filter.

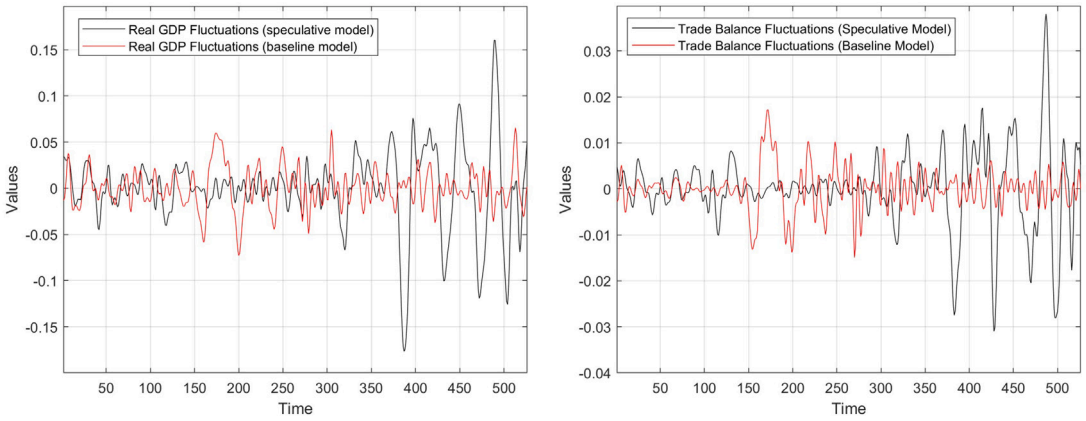

Fig. 12. Cyclical dynamics of real GDP (left) and dynamics of trade balances (right) in the two scenarios for country i.

Table 8
Duration and volatility of cycles for $s^{i,k}$, Y^i and TB^i for $t < 400$ and $t > 400$.

	$T < 400$	$T > 400$
$s^{i,k}$	$Dcycles = 15$ $std = 0.0066$	$Dcycles = 17$ $std = 0.0161$
Y^i	$Dcycles = 10$ $std = 0.0263$	$Dcycles = 15$ $std = 0.0705$
TB^i	$Dcycles = 10$ $std = 0.0050$	$Dcycles = 12$ $std = 0.0142$

$Dcycles$ stands for the duration of cycles while std stands for standard deviation.
$s^{i,k}$ stands for the bilateral exchange rate. Y^i and TB^i stand for output and trade balance of country i respectively.

correlation between the exchange rate and trade balance and between the latter and output growth which are equal to −0.2983 and 0.1478 respectively. On the other hand, currency depreciation can make exports cheaper and boost the competitiveness of businesses in the international market. In this scenario, the speculative component in the bilateral exchange market accentuates this phenomenon: when chartist traders speculate following a positive or negative trend, their behavior reflects into economic activity and the trade level, generating a more persistent upward or downward process.

Before proceeding to the next section, it is essential to clarify that the transmission of dynamics from the financial exchange rate market to both the domestic and international real sectors occurs through a bottom-up process. This process is rooted in the competitiveness of firms and their ability to invest in R&D. We have conducted a cross-correlation analysis to better highlight the temporal relationship between these two variables. To do so, we extracted the *cyclical components* of the simulated aggregated series for both the bilateral exchange rate and R&D using the bandpass filter. We then computed the cross-correlation between the filtered exchange rate series and R&D, shifting the exchange rate variable from −12 to +12 periods while keeping R&D fixed. As one can observe in Fig. 13, the results reveal a clear pattern: for negative lags (i.e., when the exchange rate is shifted backward), the correlation is negative, indicating that past appreciations of the domestic currency are associated with lower R&D investments today. This reflects a loss of competitiveness and reduced profit margins for exporting firms, leading to lower innovation spending (SF13; see, e.g. Becker and Pain, 2008; Alfaro et al., 2018). For positive lags (i.e., when the exchange rate is shifted forward), the correlation turns positive, suggesting that higher R&D investments today are followed by a future appreciation of the domestic currency. This may signal that innovation increases expectations of productivity and competitiveness, possibly strengthening the currency. To sum up, a dynamic feedback loop emerges whereby exchange rate fluctuations influence, and are influenced by, the intensity of R&D investment. This mechanism is critical for capturing the observed empirical regularity that currency movements affect firms' innovation decisions and international competitiveness. Specifically, the model shows that when productivity is endogenised via R&D, the exchange rate is driven by both real economic fundamentals and speculative financial dynamics, thus reproducing key stylized facts that simpler exogenous productivity models cannot capture.

The analysis has also been enriched considering the role of *exchange rate volatility* in shaping R&D investment. Specifically, we extracted the volatility of the exchange rate by estimating a GARCH(0,1) model and filtering the variance (Driver et al., 2005). We then replicated the previous cross-correlation analysis, shifting the volatility series backward and forward in time while keeping R&D fixed. The resulting pattern in Fig. 14 confirms the main empirical findings in the literature: increasing volatility, as a consequence of the speculative position adopted by traders, has a negative lagged correlation with R&D, suggesting that increased uncertainty in the exchange rate tends to reduce future innovation activities (SF 14; see, e.g. Caglayan and Demir, 2014; Wen and Usman, 2024).

In summary, the two implemented analyzes support the idea that both the dynamics and the volatility of the exchange rate are relevant to understanding the dynamics of innovation.

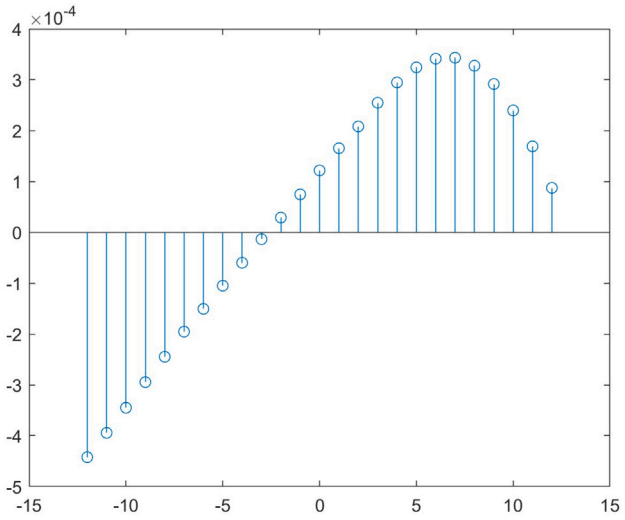

Fig. 13. Cross-correlation between exchange rate and firms' R&D.

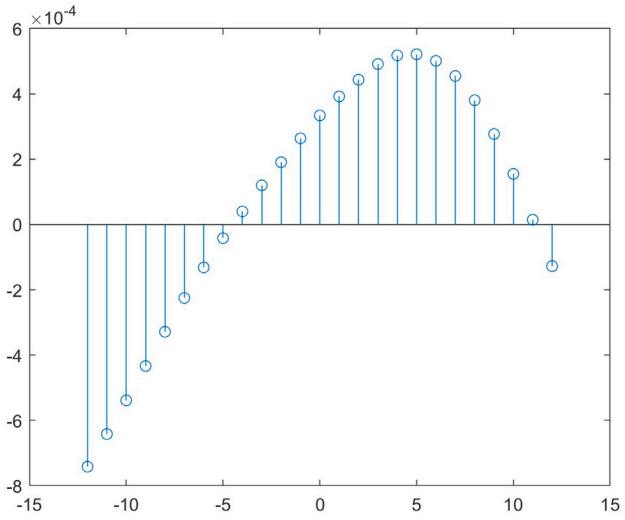

Fig. 14. Cross-correlation between volatility of exchange rate and firms' R&D.

International trade and open economy dynamics. We now consider a last set of stylized facts linked to international trade and, more generally, to the real open economy dynamics. At the macroeconomic level, exports and imports are found to be more volatile than output: the standard deviation of detrended output is 0.0032, while for bandpass-filtered exports and imports, we find values of 0.0049 and 0.0043, respectively (SF 15). Additionally, as shown in Fig. 15, the three time series are all positively serially correlated, indicating persistence in their dynamics (SF 16).[22]

At the microeconomic level, consistent with other evolutionary models, industrial dynamics patterns emerge from the interactions among diverse and innovative firms, which exhibit persistent productivity heterogeneity (Fig. 16, SF 17). These variations in productivity contribute to different dynamics in firm market shares and to endogenous structural change (SF 18; see Fig. 17). Note that such patterns are persistent over time (fluctuations cover 50/60 to 100 quarters), and some sectors are highly concentrated (e.g., sector 2 in country i and sector 1 in country k).

This dynamics is consistent with substantial differences in firm sizes (SF 19). Indeed, the distribution of firm size displays a noticeable right-skew with values equal to 9.87 in country i and 9.46 in country k, indicating the coexistence of few successful large

[22] The same is true for country k. Due to space constraints, results are available upon request.

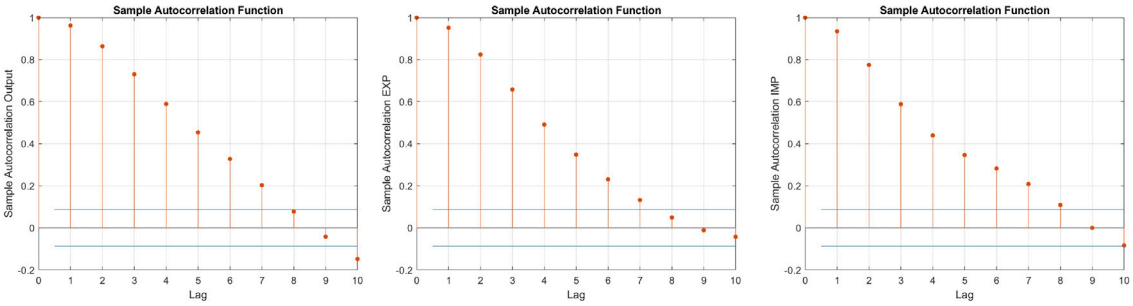

Fig. 15. Autocorrelation functions for output, exports and imports.

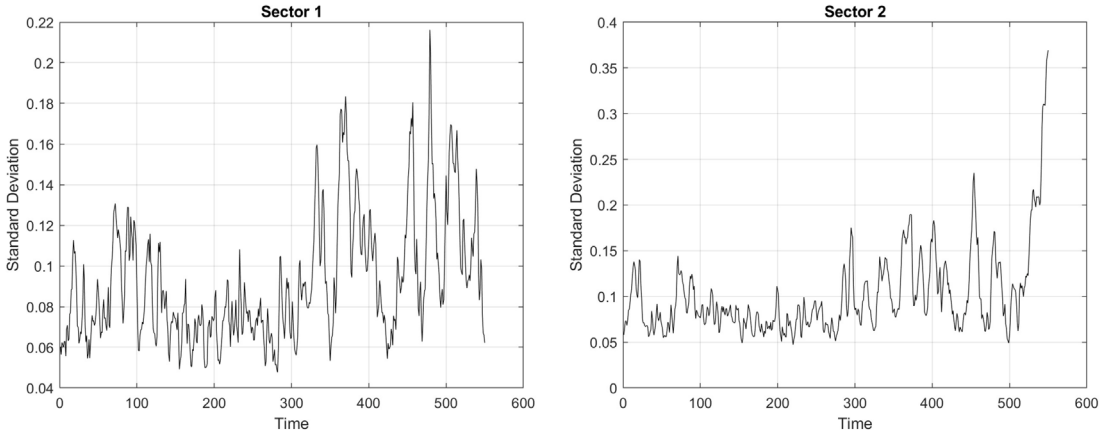

Fig. 16. Firms productivity standard deviation in the two sectors (countries pooling).

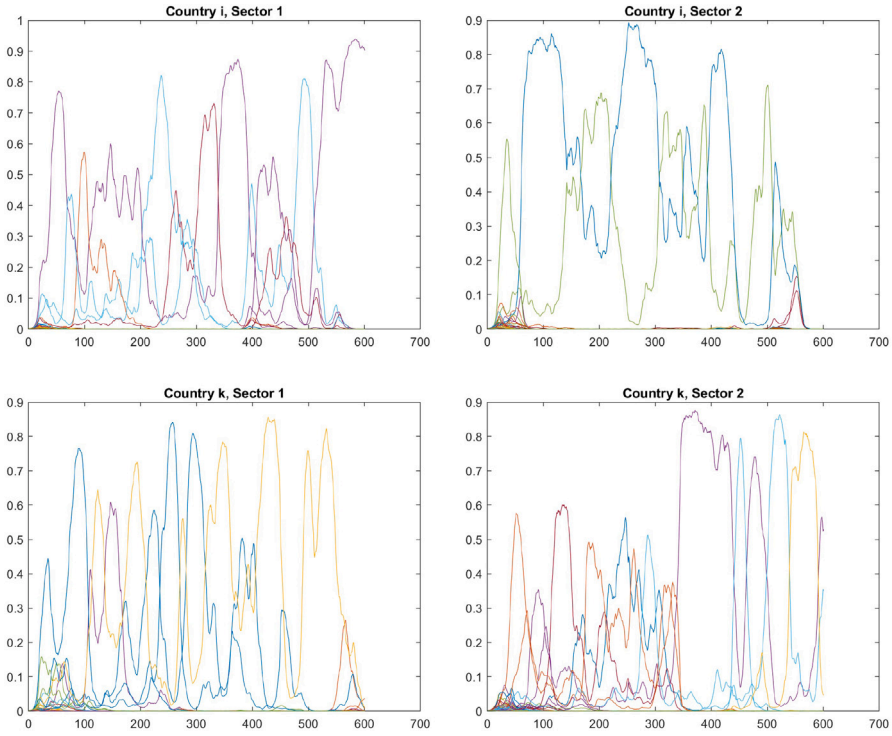

Fig. 17. Firms' output share evolution in each specific country for each industry.

Table 9
Log-size distributions, normality tests for firms' sales (industry pooling).

	Jarque–Bera		
	Pvalue	*C.v.*	*Stat.*
Country i	0	5.8581	22 983.0
Country k	0	5.8581	19 895.0
	Lilliefors		
	Pvalue	*C.v.*	*Stat.*
Country i	0	0.0403	0.4106
Country k	0	0.0403	0.4042
	Kolmogorov–Smirnov		
	Pvalue	*C.v.*	*Stat.*
Country i	0	0.0604	1.0000
Country k	0	0.0604	1.0000

Notes: *C.v.* and *Stat.* are respectively the critical value and the test statistics.

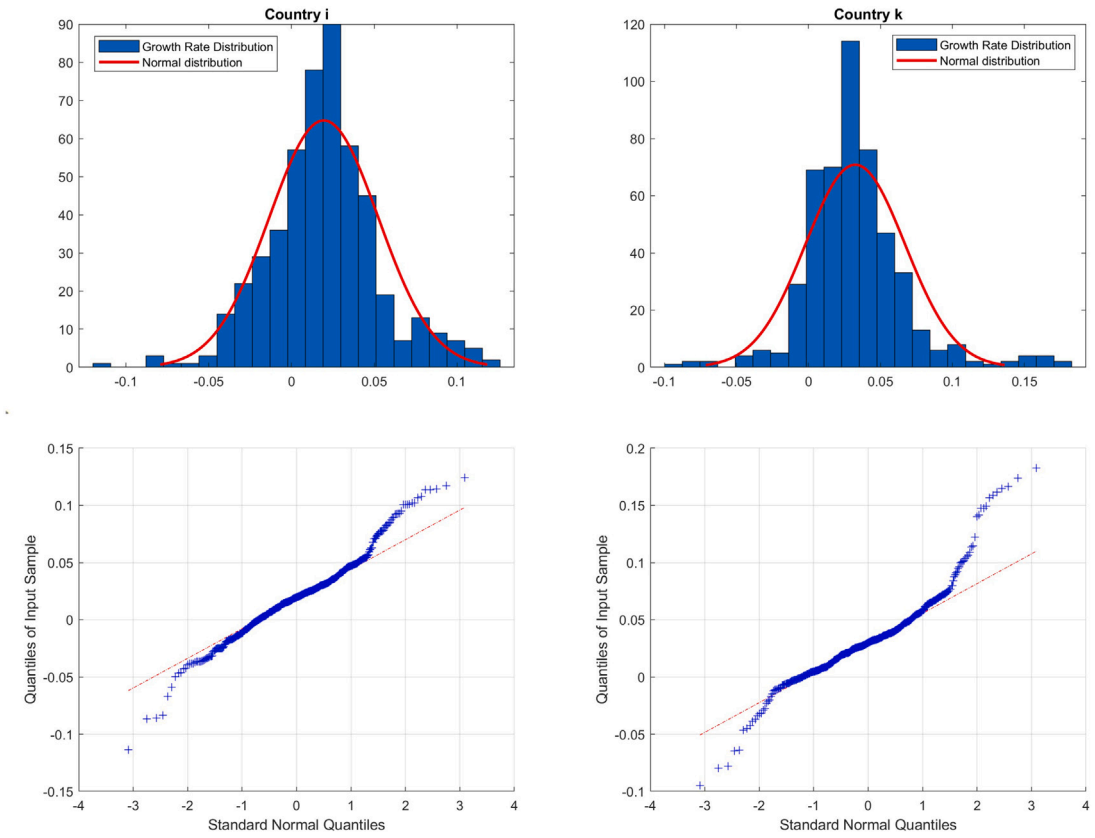

Fig. 18. Firms' growth rates distributions (simulated density in blue vs. normal fit in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

firms with numerous small businesses. Not surprisingly, a battery of tests suggest that firm log-size distributions are not log-normal (see Table 9). At the same time, the distribution of firm growth rates can be well approximated by a fat-tailed shape, as shown in Fig. 18, which is consistent with similar patterns observed at the industry and country levels (SF 20).

Finally, the model successfully reproduces some observed patterns in firm-level dynamics concerning international trade. As depicted in Table 10, only around one third of the firms are able to exports into foreign markets (SF 21). Moreover, empirical observations reveal that there are premiums linked to the export status (SF 22). The results reported in Table 10 clearly show that, on average, exporting firms are larger and more productive compared to non-exporting firms.

Moreover, exporter firms' R&D expenditures appear to be related to the dynamics of the exchange rate through a non-trivial channel, as suggested by microeconomic research (see, e.g., Funk, 2003; Dao et al., 2021). In fact, in Table 11 we report the results

Table 10
Exporters shares and premia at firms level. The two countries and all sectors pooling.

	Share of Exp. (%)	Exporters premia	
		Productivity	Total sales
Firms level	0.35	1.0040	1.1303

Note: A firm is classified as an exporter at time t if the firm's market share in the other country exceeds $1.05 \times [1/(S \times 10)]$.

Table 11
Relation between firms' R&D expenditures and the exchange rate depending on the propensity to export.

	Coefficient	Monte Carlo test	
		$t-test$	$MCs.e.$
R&D	−0.61	−9.04	0.479

Note: Analysis based on regressing $dRD_{i,z,j,t} = \beta_0 + \beta_1 dRD_{i,z,j,t-1} + \beta_2 dS_{j,z,t} + \beta_3 Exp_{i,z,j,t-4} + \beta_4 dS_{j,t} * Exp_{i,z,j,t-4} + \beta_5 time$, where for each firm i, in sector z and country j, dRD is the yearly rate of growth of R&D expenditures, dS is the rate of change of the exchange rate, Exp is the propensity to export at the firm level (that is, the ratio between exports and sales). We also controlled for sector and country fixed effects and clustered errors at the firm level.

of a panel regression model in which we show that R&D expenditures of exporters are negatively affected by the appreciation of the exchange rate (SF 23).

4.2. Central bank interventions in the exchange rate market

Given the good empirical performance of the model, we now study the possible interventions of the central bank in the exchange market and the potential impacts on macro variables and market dynamics. We consider two types of policy interventions: "leaning against the wind" (cf. Eq. (29)) and "leaning against the wind with a short-run target" strategy (cf. Eq. (30)). As central bank policies do not affect the long-run performance of the economies, we focus only on the cyclical components of the variables to dissect the possible changes in their fluctuations.

The results of the "leaning against the wind" policy are reported in Table 12. At the macroeconomic level, we find that this intervention dampens the length of cycles for the exchange rate and trade balance. The reduction in the duration of cycles is mainly due to the central bank's ability to dampen the duration of the exchange rate cycles by disrupting the feedback mechanisms that sustain prolonged trends (Fiess and Shankar, 2009). Through monetary policy, the central bank can counteract speculative momentum, thereby impeding the persistence of trends over extended periods. The central bank's commitment to stabilizing exchange rates is able to anchor market participants' expectations and mitigates the length of exchange rate fluctuations. In turn, such interventions can also dampen trade balance cycles (cf. Table 12; Hsiao et al., 2012). Conversely, no significant differences are observed for GDP cycles (Agénor et al., 2020).

Despite this, the intervention increases volatility, particularly for output and trade balance, highlighting the limitations of monetary policy as a tool for macroeconomic stabilization in the presence of speculative behavior in exchange rate markets. This outcome stems from the fact that central bank interventions may exacerbate uncertainty in the exchange rate market (Dominguez, 1998; Saacke, 2002).[23] In turns, market participants may respond erratically to central bank actions, resulting in increased volatility as traders realign their positions in response to evolving market conditions (Ricchiuti, 2004 and Szpiro, 1994). A similar result was obtained by Proano (2011), who, in a different theoretical context, demonstrated inefficiency in the presence of significant activity by chartists.

From a market structure perspective, the central bank's "leaning against the wind" technique brings a discernible decline in the proportion of chartists which fall from 0.65 to 0.49 (Beine et al., 2009). This outcome is associated with the central bank's objective to stabilize exchange rates, which could diminish the profit opportunities of speculative trading for chartists, thus reducing their market presence. Furthermore, the discretionary central bank intervention could increase market uncertainty and risk, possibly forcing chartists to adopt a more risk-averse approach to their trading strategies, which could diminish their market activity. However, the central bank intervention amplifies the volatility of the quota of chartists active in the market (Gardini et al., 2024). This could be due to the reactions of the traders to the higher level of market uncertainty and risk resulting from central bank intervention. Moreover, the central bank policy could precipitate shifts in trading strategies among chartists, thereby potentially exacerbating market volatility.

Let us now consider the second central bank intervention grounded on the "leaning against the wind with a short-run target" strategy. Table 12 provides a comparison of the results associated to the two central bank's policies and the speculative model

[23] The standard deviation for the model featuring official intervention was measured at 0.00904 and 0.0458, surpassing the volatility observed in the speculative model.

Table 12
Comparison of the models with the two official interventions. Monte Carlo results.

Speculative model					
	ω^c		$s^{i,k}$	TB^i	Y^i
MC_ω^c	0.6593	$MCDcycles$	16.6515	10.4897	11.1226
$MCstd_\omega^c$	0.2444	$MCstd$	0.0116	0.0083	0.0416
Leaning against the wind					
	ω^c		$s^{i,k}$	TB^i	Y^i
MC_ω^c	0.4901	$MCDcycles$	16.2490	10.0761	11.1482
$\omega^c_{cb1} < \omega^c_s$	−0.1692***	$Dc^{cb1} < Dc^s$	−0.4025**	−0.4136***	0.0265
	(0.0088)		(0.1786)	(0.1258)	(0.1285)
$MCstd_\omega^c$	0.2844	$MCstd$	0.0116		
$std^{cb1} > std^s$	0.0334***	$std^{cb1} < std^s$	−0.0005		
	(0.0024)		(0.0004)		
		$MCstd$		0.0090	0.0458
		$std^{cb1} > cstd^s$		0.0006**	0.0042**
				(0.0003)	(0.0018)
Leaning against the wind with a short-run target					
	ω^c		$s^{i,k}$	TB^i	Y^i
MC_ω^c	0.6525	$MCDcycles$	16.5490	10.4067	11.1217
$\omega^c_{cb2} < \omega^c_s$	−0.0068	$Dc^{cb2} < Dc^s$	−0.1025	−0.0830	−0.0126
	(0.0059)		(0.1444)	(0.1208)	(0.1118)
$MCstd_\omega^c$	0.2437	$MCstd$	0.0115		
$std^{cb2} < std^s$	−0.0007	$std^{cb2} < std^s$	−0.00003		
	(0.0024)		(0.0004)		
		$MCstd$		0.0084	0.0418
		$std^{cb2} > std^s$		0.00007	0.0002
				(0.0002)	(0.0016)

Notes: Y^i and TB^i stand for output and trade balance of country i respectively.
$s^{i,k}$ stands for the exchange rate while ω^c stands for the percentage of chartists.
$MCDcycles$ and $MCstd$ refer to the mean value of duration of cycles and volatility resulting from 200 Monte Carlo simulations.
MC_ω^c and $MCstd_\omega^c$ refer to the mean value and volatility of chartists resulting from 200 Monte Carlo simulations.
For each intervention, $\omega^c_{cb} < \omega^c_s$ tests the hypothesis of a reduction of chartists resulting from 200 Monte Carlo.
For each intervention, $Dc^{cb} < Dc^s$ tests the hypothesis of a reduction of duration of cycles resulting from 200 Monte Carlo.
$std^{cb} < std^s$ tests the hypothesis of a reduction of volatility resulting from 200 Monte Carlo.
$std^{cb} > std^s$ tests the hypothesis of an increase of volatility resulting from 200 Monte Carlo.
Monte Carlo simulations standard errors in parentheses.
*, **, *** denote statistical significance at the 10%, 5%, and 1% levels respectively.

without the central bank intervention. The results suggest that there are no statistical difference between the scenario where the central bank abstains to intervene vis-à-vis that when it acts with a short-run target. The obtained result highlights that the sporadic intervention of a central bank may not produce the expected results in terms of reducing both the amplitude of fluctuations and volatility phenomena (see also Proano, 2011, on this point). In other words, the target chosen by the central bank is too wide.

All in all, the "leaning against the wind" intervention is the only policy having a significant impact on both exchange rate market dynamics and macroeconomic fluctuations. However, simulation results show that in pursuing such a strategy, the central bank may encounter a series of trade-offs. Indeed, central bank intervention can reduce the quota of chartists and the length of cycles but it increases volatility. As mentioned above, the "leaning against the wind with a short-run target" strategy has no statistical significant effect of the macro and financial dynamics compared to the pure speculative model. Bearing this caveat in mind, it becomes crucial to examine the effects generated on wealth accumulation within the financial market under the "leaning against the wind" intervention. Simulation results in Appendix C show that such a policy decreases the accumulated wealth of chartists while increasing that of fundamentalists. This outcome aligns with the observed reduction in the percentage of chartists. The central bank effectively rebalances the system by rendering trend-following behavior less profitable compared to fundamentalist strategies.

5. Conclusions

This paper extended the multi-country, multi-sector agent-based framework of Dosi et al. (2019, 2021) by incorporating a foreign exchange market populated by heterogeneous financial traders—fundamentalists and chartists. This extension introduces novel feedback mechanisms between financial speculation and real economic dynamics, enabling an integrated analysis of the co-evolution of macroeconomic variables and exchange rate behavior.

The simulations replicate key empirical regularities of exchange rate markets—such as volatility clustering, leverage effects, unit root properties, and contagion—while illustrating how speculative behavior contributes to endogenous instability and amplifies

Table 13
Benchmark parameter setting.

Symbol	Description	Value
N	Number of countries	2
M	Number of sectors (each countries)	2
S	Number of firms (each countries)	250
$1-\omega$	Percentage of chartists in a linear setting model	0.80
α	Fundamentalist reaction coefficient in a nonlinear setting model	0.5
β	Chartist reaction coefficient in a nonlinear setting model	1
ψ	Intensity of switching strategy	20 000
d_h	Sectoral demand shares	1/2
υ	Mark-up adjustment parameter	0.04
ρ	R&D investment propensity	0.04
λ	R&D allocation parameter	0.5
$\xi_{1,2}$	Firms search capabilities	0.08
θ_{max}	First stage probabilities upper bound	0.75
$Beta(\alpha_1, \beta_1)$	Beta distribution parameter	[1,1]
$[\underline{x}_1, \overline{x}_1]$	Beta distribution support	$[-0.05, 0.25]$
$Beta(\alpha_2, \beta_2)$	Beta distribution parameter (entrants)	[5,1]
$[\underline{x}_2, \overline{x}_2]$	Beta distribution support (entrants)	$[-0.03, 0.15]$
ϵ	Foreign imitation penalty	5
τ	Foreign competition penalty	0.05
χ	Replicator dynamics parameter	1
ψ	Wage sensitivity parameter	1
γ	Exchange rates flexibility	0.1
σ_e	Exchange rates shocks standard deviation	0.002
ϵ_{cb}	CB reaction parameter	0.5
a	Risk aversion coefficient	0.5
σ^2	Variance of wealth	0.5
	Monte Carlo replications	200

financial cycles. Exchange rate dynamics also transmit financial shocks to the real economy, impacting GDP and trade balances. In particular, the presence of chartist traders increases exchange rate volatility, with real consequences for macroeconomic fluctuations.

Additionally, our model captures the complex interaction between exchange rate dynamics and the innovative activities of firms. More specifically, speculative dynamics in the foreign exchange market affect R&D investment, thereby impacting on firms' productivity and export competitiveness. These findings underscore the importance of endogenizing R&D and integrating a sophisticated financial market structure to fully account for the co-evolution of the real and financial sectors with feedback loops.

On the policy side, we assessed the effectiveness of central bank interventions in the foreign exchange market under alternative "leaning against the wind" regimes. When constrained by short-run targets, such policies exert limited influence on exchange rate dynamics. Conversely, more flexible and aggressive interventions reduce the persistence of currency misalignments by discouraging speculative trading. However, these interventions can backfire by increasing volatility, as discretionary policy moves may generate uncertainty and erratic responses from financial agents. Our results highlight the multifaceted nature of monetary policy in open economies and the inherent trade-offs involved in stabilizing exchange and real variables simultaneously.

Future extensions of the model could include alternative expectation formation rules (e.g., as in Dosi et al. (2020)), a more complex international production structure—such as vertical integration—and the explicit modeling of cross-border capital flows. Moreover, distinguishing between developed and developing economies would allow the study of divergence/convergence dynamics under heterogeneous exchange rate regimes. At the firm level, future extensions could relax the assumption of constant firms to endogenize entrepreneurial decisions and capture demographic trends in firm entry. Lastly, the integration of fiscal policy tools may provide further insights into policy coordination in the presence of financial instability.

Declaration of competing interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript.

Appendix A

The parameter values listed in the following table reflect the findings of previous related studies (see Table 13).

Appendix B

Table 14 presents the results obtained for the Error Correction test on the Monte Carlo simulations. The sign of the parameters and the statistically significant values show the presence and importance of the two financial operators in explaining the dynamics of the exchange rate and its deviation from the fundamental value. Specifically, as with the PPP, the fundamentalists exert a long-term centripetal force ($\lambda_1 < 0$), while the chartists exert a short-term centrifugal force ($\lambda_2 > 0$).

Table 14
Error correction model.

	λ_1	λ_2
Values	−0.2039***	0.1497***
	(0.0031)	(0.0054)

Notes: Monte Carlo simulations standard errors in parentheses.
*, **, *** denotes statistical significance at the 10%, 5%, and 1% levels respectively.

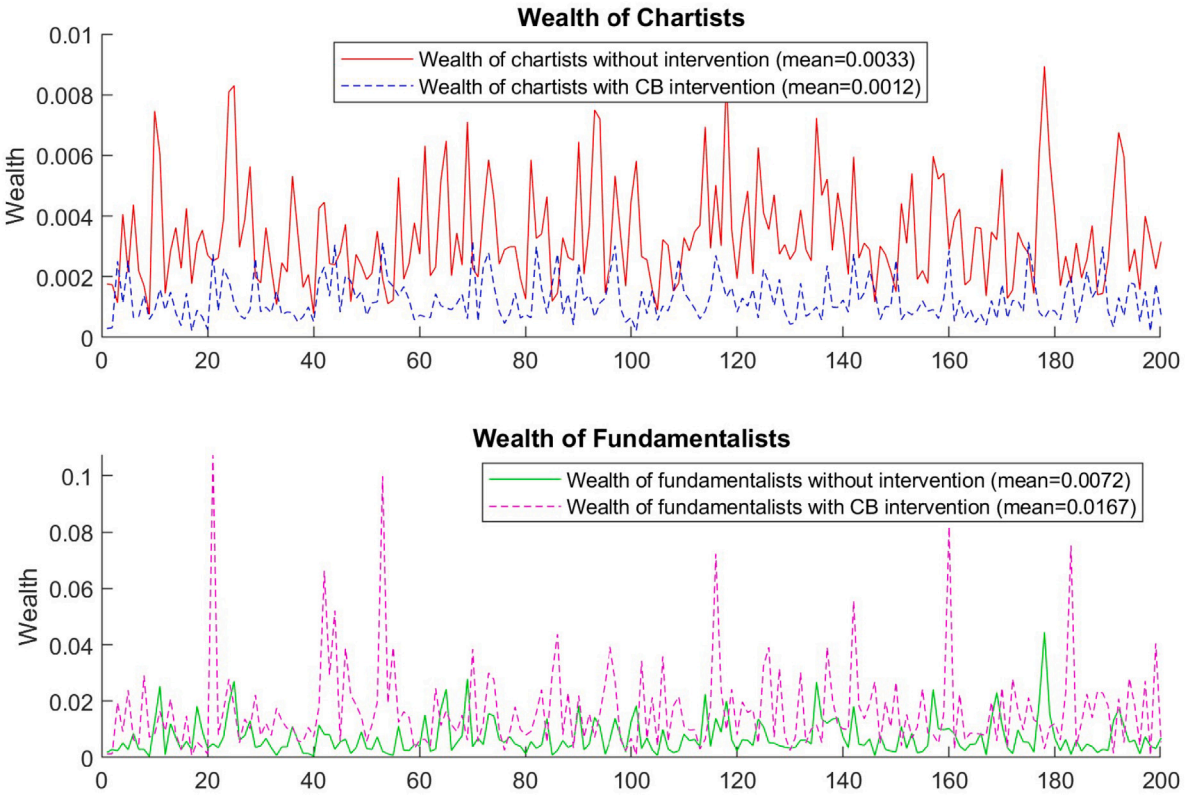

Fig. 19. Dynamics of accumulated wealth with and without intervention of central bank. Results from 200 Monte Carlo replications.

Appendix C

Using Eq. (18), we can calculate the total wealth that financial traders obtained in period $t+1$ using information of the exchange rate up to time t as[24]:

$$W^{\phi}(t+1) = W^{\phi}(t) + \left[s^{i,k}(t) - s^{i,k}(t-1)\right]\left\{\sum_{\phi=1}^{\Phi} \omega^{\phi}(t)\mathrm{E}^{\phi}(t)\left[s^{i,k}(t+1) - s^{i,k}(t-1)\right]\right\} \tag{36}$$

If traders anticipate a rise in the exchange rate and this rise occurs, their wealth matches the actual rise in the exchange rate. Conversely, if the exchange rate falls, they incur in a loss, since they possess foreign assets that have decreased in value.

Fig. 19 shows the impact on investors' wealth. We divide the effect with respect to fundamentalists and chartists. The intervention of the central bank produces an interesting effect regarding the wealth accumulation of the two groups of agents considered. As can be observed from the figure, the intervention reduces the accumulated wealth of the chartists but increases that of the fundamentalists. This result is consistent with the reduction in the percentage of chartists. Indeed, the central bank tends to re-balance the system by making the decisions of a trend follower behavior less profitable compared to those of a fundamentalist.

[24] This is the consequence of market clearing assumption based on auctioneer, by the fact that agents at time $t+1$ do not know the price (refer to De Grauwe and Grimaldi, 2005, on this point)

Table 15
Statistical test performed.

	Stylized fact	Test
	Exchange rate market	
SF1	Fat tails	Quantile–Quantile plot (QQ) + Frequency distribution plot
SF2	Excess kurtosis	Kurtosis Distribution Calculation + Frequency distribution plot
SF3	Skewness	Skewness Distribution Calculation + Frequency distribution plot
SF4	Volatility clustering	Autocorrelation function + GARCH estimation
SF5	Leverage effect	Curve Fitting and Scatter plot
SF6	Unit root hypothesis	Unit Root Test
SF7	Fluctuation phenomena 1	Calculation of Cyclical Duration + Statistical Hypothesis Test
SF8	Fluctuation phenomena 2	Calculation of Cyclical Duration + Statistical Hypothesis Test
	Exchange rate and macroeconomic dynamics	
SF9	Misalignment problem	Error correction model:
SF10	Contagion	Calculation of Cyclical Duration + Statistical Hypothesis Test
SF11	Synchronization	Calculation of Cyclical Duration
SF12	Trade level	Calculation of Cyclical Duration
SF13	Exchange rate-innovation driver 1	Cross correlation function
SF14	Exchange rate-innovation driver 2	GARCH estimation + Cross correlation function
	International trade and macro and micro regularities	
SF15	Open economy volatility	Standard Deviation Calculation
SF16	Open economy persistence	Autocorrelation function
SF17	Heterogeneity in productivity	Standard Deviation Calculation
SF18	Endogenous market shares structural change	Descriptive statistics
SF19	Departure from normal size distribution	Right-Skewness Calculation + Jarque–Bera, Lilliefors, Kolmogorov–Smirnov Test
SF20	Fat-tailed firm growth rate distribution	QQ plot + Frequency distribution
SF21	Fraction of exporters	Percentage Calculation
SF22	Export productivity premium	Productivity and Sales Calculation
SF23	Exporter exchange rate-innovation driver	Panel regression estimation

Appendix D

See Table 15.

Data availability

No data was used for the research described in the article.

References

Abramovitz, M., 1986. Catching up, forging ahead, and falling behind. J. Econ. Hist. 46 (2), 385–406.
Agénor, P.-R., Jackson, T.P., da Silva, L.A.P., 2020. Foreign Exchange Intervention and Financial Stability. Bank for International Settlements, Monetary and Economic Department.
Akcigit, U., Ates, S.T., 2021. Ten facts on declining business dynamism and lessons from endogenous growth theory. Am. Econ. J.: Macroecon. 13 (1), 257–298.
Alfarano, S., Lux, T., Wagner, F., 2005. Estimation of agent-based models: the case of an asymmetric herding model. Comput. Econ. 26, 19–49.
Alfarano, S., Lux, T., Wagner, F., 2008. Time variation of higher moments in a financial market with heterogeneous agents: An analytical approach. J. Econom. Dynam. Control 32 (1), 101–136.
Alfaro, L., Cunat, A., Fadinger, H., Liu, Y., 2018. The Real Exchange Rate, Innovation and Productivity: Heterogeneity, Asymmetries and Hysteresis. Technical Report, National Bureau of Economic Research.
Bargigli, L., 2021. A model of market making with heterogeneous speculators. J. Econ. Interact. Coord. 16 (1), 1–28.
Bartelsman, E.J., Doms, M., 2000. Understanding productivity: Lessons from longitudinal microdata. J. Econ. Lit. 38 (3), 569–594.
Bartelsman, E., Scarpetta, S., Schivardi, F., 2005. Comparative analysis of firm demographics and survival: evidence from micro-level sources in OECD countries. Ind. Corp. Chang. 14 (3), 365–391.
Bassi, F., Ramos, R., Lang, D., 2023. Bet against the trend and cash in profits: An agent-based model of endogenous fluctuations of exchange rates. J. Evol. Econ. 1–44.
Baxter, M., King, R.G., 1999. Measuring business cycles: approximate band-pass filters for economic time series. Rev. Econ. Stat. 81 (4), 575–593.
Baxter, M., Stockman, A.C., 1989. Business cycles and the exchange-rate regime: some international evidence. J. Monet. Econ. 23 (3), 377–400.
Becker, B., Pain, N., 2008. What determines industrial R&D expenditure in the UK? Manch. Sch. 76 (1), 66–87.
Beine, M., De Grauwe, P., Grimaldi, M., 2009. The impact of FX central bank intervention in a noise trading framework. J. Bank. Financ. 33 (7), 1187–1195.
Bentivogli, C., Monti, P., 2001. International Transmission Via Trade Links: Theoretically Consistent Indicators of Interdependence for Latin America and South-East Asia. Technical Report, Bank of Italy, Economic Research and International Relations Area.
Bernard, A.B., Jensen, J.B., 1999. Exceptional exporter performance: cause, effect, or both? J. Int. Econ. 47 (1), 1–25.
Bernard, A.B., Jensen, J.B., Redding, S.J., Schott, P.K., 2012. The empirics of firm heterogeneity and international trade. Annu. Rev. Econ. 4 (1), 283–313.
Bottazzi, G., Secchi, A., 2003. Common properties and sectoral specificities in the dynamics of US manufacturing companies. Rev. Ind. Organ. 23, 217–232.
Bottazzi, G., Secchi, A., 2006. Explaining the distribution of firm growth rates. Rand J. Econ. 37 (2), 235–256.
Brock, W.A., Hommes, C.H., 1998. Heterogeneous beliefs and routes to chaos in a simple asset pricing model. J. Econom. Dynam. Control 22 (8–9), 1235–1274.

Brown, D., Smith, J., 2021. Complexity of central bank interventions: A scenario analysis. J. Financ. Econ..
Caglayan, M., Demir, F., 2014. Firm productivity, exchange rate movements, sources of finance, and export orientation. World Dev. 54, 204–219.
Caiani, A., Catullo, E., Gallegati, M., 2018. The effects of fiscal targets in a monetary union: a multi-country agent-based stock flow consistent model. Ind. Corp. Chang. 27 (6), 1123–1154.
Caiani, A., Catullo, E., Gallegati, M., 2019. The effects of alternative wage regimes in a monetary union: A multi-country agent based-stock flow consistent model. J. Econ. Behav. Organ. 162, 389–416.
Carraro, A., Ricchiuti, G., 2015. Heterogeneous fundamentalists and market maker inventories. Chaos Solitons Fractals 79, 73–82.
Casiraghi, M., Habermeier, K., Harjes, T., 2022. Choice of exchange rate arrangement. In: Monetary and Capital Markets Department Technical Assistance Handbook. International Monetary Fund Washington DC, USA, pp. 1161–1176.
Catullo, E., Gallegati, M., 2015. Emerging economic product complexity: a multi-country agent based model.
Caves, R.E., 1998. Industrial organization and new findings on the turnover and mobility of firms. J. Econ. Lit. 36 (4), 1947–1982.
Chiarella, C., Dieci, R., He, X.-Z., 2009. Heterogeneity, market mechanisms, and asset price dynamics. In: Handbook of Financial Markets: Dynamics and Evolution. Elsevier, pp. 277–344.
Cornwall, J., 1977. Modern capitalism: its growth and transformation.
Dao, M.C., Minoiu, C., Ostry, J.D., 2021. Corporate investment and the real exchange rate. J. Int. Econ. 131, 103437.
Dawid, H., Delli Gatti, D., 2018. Agent-based macroeconomics. Handb. Comput. Econ. 4, 63–156.
Dawid, H., Harting, P., Neugart, M., 2014. Economic convergence: Policy implications from a heterogeneous agent model. J. Econom. Dynam. Control 44, 54–80.
Dawid, H., Harting, P., Neugart, M., 2018. Cohesion policy and inequality dynamics: Insights from a heterogeneous agents macroeconomic model. J. Econ. Behav. Organ. 150, 220–255.
De Grauwe, P., 2005. Exchange Rate Economics: Where do We Stand? Vol. 10, MIT Press.
De Grauwe, P., 2012. Booms and busts in economic activity: A behavioral explanation. J. Econ. Behav. Organ. 83 (3), 484–501, URL https://www.sciencedirect.com/science/article/pii/S0167268112000352. The Great Recession: motivation for re-thinking paradigms in macroeconomic modeling.
De Grauwe, P., Foresti, P., 2020. Animal spirits and fiscal policy. J. Econ. Behav. Organ. 171, 247–263, URL https://www.sciencedirect.com/science/article/pii/S0167268120300159.
De Grauwe, P., Grimaldi, M., 2005. Heterogeneity of agents and the exchange rate: a nonlinear approach. In: Exchange Rate Economics: Where do we Stand. pp. 125–167.
De Grauwe, P., Grimaldi, M., 2006. The exchange rate in behavioral finance framework.
De Grauwe, P., Rovira Kaltwasser, P., 2012. The exchange rate in a behavioral finance framework. Handb. Exch. Rates 111–132.
De Jong, E., Verschoor, W.F., Zwinkels, R.C., 2010. Heterogeneity of agents and exchange rate dynamics: Evidence from the EMS. J. Int. Money Financ. 29 (8), 1652–1669.
De Loecker, J., Eeckhout, J., Unger, G., 2020. The rise of market power and the macroeconomic implications. Q. J. Econ. 135 (2), 561–644.
Decker, R.A., Haltiwanger, J., Jarmin, R.S., Miranda, J., 2016. Declining business dynamism: What we know and the way forward. Am. Econ. Rev. 106 (5), 203–207.
Dominguez, K.M., 1998. Central bank intervention and exchange rate volatility. J. Int. Money Financ. 17 (1), 161–190.
Dornbusch, R., 1976. Expectations and exchange rate dynamics. J. Political Econ. 84 (6), 1161–1176.
Dosi, G., 2007. Statistical regularities in the evolution of industries. a guide through some evidence and challenges for the theory. In: Perspectives on Innovation. Cambridge University Press, pp. 153–186.
Dosi, G., Fagiolo, G., Napoletano, M., Roventini, A., 2013. Income distribution, credit and fiscal policies in an agent-based Keynesian model. J. Econom. Dynam. Control 37 (8), 1598–1625.
Dosi, G., Fagiolo, G., Napoletano, M., Roventini, A., Treibich, T., 2015. Fiscal and monetary policies in complex evolving economies. J. Econom. Dynam. Control 52, 166–189.
Dosi, G., Fagiolo, G., Roventini, A., 2010. Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. J. Econom. Dynam. Control 34 (9), 1748–1767.
Dosi, G., Marsili, O., Orsenigo, L., Salvatore, R., 1995. Learning, market selection and the evolution of industrial structures. Small Bus. Econ. 7, 411–436.
Dosi, G., Napoletano, M., Roventini, A., Stiglitz, J.E., Treibich, T., 2020. Rational heuristics? Expectations and behaviors in evolving economies with heterogeneous interacting agents. Econ. Inq. 58 (3), 1487–1516.
Dosi, G., Napoletano, M., Roventini, A., Treibich, T., 2017a. Micro and macro policies in the keynes+ schumpeter evolutionary models. J. Evol. Econ. 27, 63–90.
Dosi, G., Pavitt, K., Soete, L., 1990. The Economics of Technical Change and International Trade. In: LEM Book Series, Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced ....
Dosi, G., Pereira, M.C., Virgillito, M.E., 2017b. The footprint of evolutionary processes of learning and selection upon the statistical properties of industrial dynamics. Ind. Corp. Chang. 26 (2), 187–210.
Dosi, G., Roventini, A., 2019. More is different... and complex! the case for agent-based macroeconomics. J. Evol. Econ. 29, 1–37.
Dosi, G., Roventini, A., Russo, E., 2019. Endogenous growth and global divergence in a multi-country agent-based model. J. Econom. Dynam. Control 101, 101–129.
Dosi, G., Roventini, A., Russo, E., 2021. Public policies and the art of catching up: matching the historical evidence with a multicountry agent-based model. Ind. Corp. Chang. 30 (4), 1011–1036.
Driver, C., Temple, P., Urga, G., 2005. Profitability, capacity, and uncertainty: a model of UK manufacturing investment. Oxf. Econ. Pap. 57 (1), 120–141.
Dweck, E., Vianna, M.T., da Cruz Barbosa, A., 2020. Discussing the role of fiscal policy in a demand-led agent-based growth model. Economia 21 (2), 185–208.
Engel, C., 2014. Exchange rates and interest parity. Handb. Int. Econ. 4, 453–522.
Engel, C., West, K.D., 2005. Exchange rates and fundamentals. J. Political Econ. 113 (3), 485–517.
Evans, M.D., Lyons, R.K., 2002. Order flow and exchange rate dynamics. J. Political Econ. 110 (1), 170–180.
Fagerberg, J., Mowery, D.C., Nelson, R.R., 2005. The Oxford Handbook of Innovation. Oxford University Press.
Fagiolo, G., Guerini, M., Lamperti, F., Moneta, A., Roventini, A., 2019. Validation of agent-based models in economics and finance. In: Beisbart, C., Saam, N.J. (Eds.), Computer Simulation Validation: Fundamental Concepts, Methodological Frameworks, and Philosophical Perspectives. Springer Verlag, pp. 763–787.
Fagiolo, G., Roventini, A., 2017. Macroeconomic policy in DSGE and agent-based models redux: New developments and challenges ahead. J. Artif. Soc. Soc. Simul. 20 (1), 1.
Fama, E.F., 1984. Forward and spot exchange rates. J. Monet. Econ. 14 (3), 319–338.
Fanti, L., Pereira, M.C., Virgillito, M.E., 2023. The North-South divide: sources of divergence, policies for convergence. J. Policy Model. 45 (2), 405–429.
Farrell, J., Shapiro, C., 1988. Dynamic competition with switching costs. Rand J. Econ. 123–137.
Fiess, N., Shankar, R., 2009. Determinants of exchange rate regime switching. J. Int. Money Financ. 28 (1), 68–98.
Flaschel, P., Hartmann, F., Malikane, C., Proaño, C.R., 2015. A behavioral macroeconomic model of exchange rate fluctuations with complex market expectations formation. Comput. Econ. 45, 669–691.
Flood, R.P., Rose, A.K., 1995. Fixing exchange rates a virtual quest for fundamentals. J. Monet. Econ. 36 (1), 3–37.

Frankel, J.A., Froot, K.A., 1986. Understanding the US dollar in the eighties: the expectations of chartists and fundamentalists [abridged version of a paper given at a conference held by the centre for economic policy research, ANU and the centre for studies in money, banking and finance, Macquarie university at Australian national university, 1986]. Econ. Rec. (1986).
Frankel, J.A., Froot, K.A., 1990. Chartists, fundamentalists, and trading in the foreign exchange market. Am. Econ. Rev. 80 (2), 181–185.
Funk, M., 2003. The effects of trade on research and development. Open Econ. Rev. 14, 29–42.
Gardini, L., Radi, D., Schmitt, N., Sushko, I., Westerhoff, F., 2024. Exchange rate dynamics and central bank interventions: On the (de) stabilizing nature of targeting long-run fundamentals interventions. Nonlinear Dyn. Psychol. Life Sci. 28 (2).
Geroski, P., Machin, S., Van Reenen, J., 1993. The profitability of innovating firms. Rand J. Econ. 198–211.
Gilli, M., Winker, P., 2003. A global optimization heuristic for estimating agent based models. Comput. Statist. Data Anal. 42 (3), 299–312.
Goldbaum, D., Zwinkels, R.C., 2014. An empirical examination of heterogeneity and switching in foreign exchange markets. J. Econ. Behav. Organ. 107, 667–684.
Gori, M., Ricchiuti, G., 2018. A dynamic exchange rate model with heterogeneous agents. J. Evol. Econ. 28, 399–415.
Haldane, A.G., Turrell, A.E., 2019. Drawing on different disciplines: macroeconomic agent-based models. J. Evol. Econ. 29, 39–66.
Hall, R.E., 1988. The relation between price and marginal cost in US industry. J. Political Econ. 96 (5), 921–947.
Hodrick, R.J., Prescott, E.C., 1997. Postwar US business cycles: an empirical investigation. J. Money Credit. Bank. 1–16.
Hommes, C., 2021. Behavioral and experimental macroeconomics and policy analysis: A complex systems approach. J. Econ. Lit. 59 (1), 149–219.
Hsiao, Y.-M., Pan, S.-C., Wu, P.-C., 2012. Does the central bank's intervention benefit trade balance? Empirical evidence from China. Int. Rev. Econ. Financ. 21 (1), 130–139.
Huisman, R., Koedijk, K., Kool, C., Palm, F., 2002. Notes and communications: The tail-fatness of FX returns reconsidered. De Econ. 150 (3), 299–312.
Johnson, D., White, E., 2016. Heuristic expectations and business cycle dynamics. J. Econom. Dynam. Control.
Jones, R., Brown, E., 2018. Instability in financial cycles: Evidence from multi-country analysis. J. Financ. Stab..
Kirman, A., 1993. Ants, rationality, and recruitment. Q. J. Econ. 108 (1), 137–156.
Klemperer, P., 1987. Markets with consumer switching costs. Q. J. Econ. 102 (2), 375–394.
Kohler, K., Stockhammer, E., 2023. Flexible exchange rates in emerging markets: shock absorbers or drivers of endogenous cycles? Ind. Corp. Chang. 32 (2), 551–572.
Kuznets, S., Murphy, J.T., 1966. Modern Economic Growth: Rate, Structure, and Spread. Vol. 2, Yale University Press New Haven.
Lewis, W.A., et al., 1954. Economic development with unlimited supplies of labour. Manch. Sch. 22 (2).
Loecker, J.D., Warzynski, F., 2012. Markups and firm-level export status. Am. Econ. Rev. 102 (6), 2437–2471.
Lux, T., Marchesi, M., 2000. Volatility clustering in financial markets: a microsimulation of interacting agents. Int. J. Theor. Appl. Finance 3 (04), 675–702.
Lyons, R.K., et al., 2001. The Microstructure Approach to Exchange Rates. Vol. 333, Citeseer.
McCombie, J.S., 1993. Economic growth, trade interlinkages, and the balance-of-payments constraint. J. Post Keynes. Econ. 15 (4), 471–505.
Meese, R.A., Rogoff, K., 1983. Empirical exchange rate models of the seventies: Do they fit out of sample? J. Int. Econ. 14 (1–2), 3–24.
Mignot, S., Westerhoff, F., 2024. Explaining the stylized facts of foreign exchange markets with a simple agent-based version of paul de grauwe's chaotic exchange rate model. Comput. Econ. 1–32.
Miller, J., Green, J., 2019. Impact of chartist behavior on exchange rate fluctuations. J. Int. Econ..
Obstfeld, M., Rogoff, K., 1995. Exchange rate dynamics redux. J. Political Econ. 103 (3), 624–660.
Obstfeld, M., Rogoff, K., 2000. The six major puzzles in international macroeconomics: is there a common cause? NBER Macroecon. Annu. 15, 339–390.
Pericoli, M., Sbracia, M., 2003. A primer on financial contagion. J. Econ. Surv. 17 (4), 571–608.
Petrovic, M., Ozel, B., Teglio, A., Raberto, M., Cincotti, S., et al., 2017. Eurace Open: An Agent-Based Multi-Country Model. Technical Report.
Phelps, E.S., Winter, S.G., 1970. Optimal price policy under atomistic competition. Microecon. Found. Employ. Inflat. Theory 309–337.
Proano, C.R., 2011. Exchange rate determination, macroeconomic dynamics and stability under heterogeneous behavioral FX expectations. J. Econ. Behav. Organ. 77 (2), 177–188.
Ricchiuti, G., 2004. Fear of Floating (Ph.D thesis). University of Florence, Italy.
Rodrik, D., 2008. The real exchange rate and economic growth. Brook. Pap. Econ. Act. 2008 (2), 365–412.
Rogoff, K., 1996. The purchasing power parity puzzle. J. Econ. Lit. 34 (2), 647–668.
Rogoff, K., Obstfeld, M., 1996. Foundations of International Macroeconomics.
Rolim, L., Baltar, C., Lima, G., 2022. The impact of international trade shocks on domestic output, income distribution, and inflation in an agent-based model. Texto Para Discuss. Inst. Econ. UNICAMP 441, 1–30.
Rotemberg, J.J., 2008. Behavioral Aspects of Price Setting, and their Policy Implications. Technical Report, National Bureau of Economic Research.
Saacke, P., 2002. Technical analysis and the effectiveness of central bank intervention. J. Int. Money Financ. 21 (4), 459–479.
Smith, J., Johnson, S., Brown, M., 2020. Macro ABM: A study of exchange rate dynamics. J. Macroecon..
Spronk, R., Verschoor, W.F., Zwinkels, R.C., 2013. Carry trade and foreign exchange rate puzzles. Eur. Econ. Rev. 60, 17–31.
Szpiro, G.G., 1994. Exchange rate speculation and chaos inducing intervention. J. Econ. Behav. Organ. 24 (3), 363–368.
Taylor, R., Lee, M., 2017. Central bank intervention in real-financial markets. J. Monet. Econ..
Ter Ellen, S., Hommes, C.H., Zwinkels, R.C., 2021. Comparing behavioural heterogeneity across asset classes. J. Econ. Behav. Organ. 185, 747–769.
Tsai, P.-C., Tsai, C.-M., 2021. Estimating the proportion of informed and speculative traders in financial markets: evidence from exchange rate. J. Econ. Interact. Coord. 16, 443–470.
Uribe, M., Schmitt-Grohé, S., 2017. Open Economy Macroeconomics. Princeton University Press.
Verschoor, W.F., Zwinkels, R.C., 2013. Do foreign exchange fund managers behave like heterogeneous agents? Quant. Finance 13 (7), 1125–1134.
Wen, J., Usman, M.A., 2024. An empirical investigation of the relationship between real exchange rate and innovation: evidence from China. Int. J. Financ. Econ. 29 (3), 2991–3006.
Westerhoff, F., 2009. Exchange rate dynamics: A nonlinear survey. Handb. Res. Complex. 287–325.
Windrum, P., Fagiolo, G., Moneta, A., 2007. Empirical validation of agent-based models: Alternatives and prospects. J. Artif. Soc. Soc. Simul. 10 (2), 8.
Winker, P., Gilli, M., 2001. Validation of agent-based models of financial markets. IFAC Proc. Vol. 34 (20), 401–406.
Wolf, S., Fürst, S., Mandel, A., Lass, W., Lincke, D., Pablo-Marti, F., Jaeger, C., 2013. A multi-agent model of several economic regions. Environ. Model. Softw. 44, 25–43.
Zhu, M., Chiarella, C., He, X.-Z., Wang, D., 2009. Does the market maker stabilize the market? Phys. A 388 (15–16), 3164–3180.