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

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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 in Dosi et al. (2019, 2021) by incorporating an exchange rate market where heterogeneous chartist and fundamentalist financial traders exchange foreign currencies. This introduces complex interactions between the real and financial side of the economies that reverberate on the dynamics of the exchange rate, which acts both as a transmission channel of endogenous fluctuation and as a source of shocks. Simulation results show that model is able to account for a rich ensemble of stylized facts (e.g., fat tails, volatility clustering, fluctuations and contagion among others) concerning the exchange market and its interactions with the real economy dynamics at different level of aggregation. Moreover, our findings reveal that speculative behavior in the exchange rate market substantially increases financial turbulence and contributes to real economic fluctuations. On the policy side, we highlight the power and limitations of central bank interventions in the exchange rate market.

Keywords: agent-based model, exchange rate dynamics, financial crises, endogenous business cycles, heterogeneous traders, central bank interventions.

Jel codes: E3, F41, O4, O41

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1 Introduction

The dynamics of exchange rates and their intricate interplay with international macroeconomic dynamics has been studied by economists for decades. A deep investigation is indeed crucial for understanding the intricate interdependencies between domestic and foreign markets and their effects on national economic growth (De Grauwe, 2005). This is particularly pertinent given the high degree 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 has shown the complexity of these phenomena, presenting a series of regularities that challenge existing theories' explanatory power (Dornbusch, 1976; Obstfeld and Rogoff, 1995). However, 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 microstructure 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 short to capture and explain the set of key empirical regularities consistently, 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. These patterns highlight the need for innovative approaches capable of integrating micro and macro dynamics in a coherent framework.

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 macroeconomic implications. ABMs represent indeed a natural framework to incorporate the financial-behavioral nature of exchange rate dynamics and their interactions with the real economy (see, in particular, Alfarano et al., 2005, 2008). Our model is designed to provide a versatile platform for examining the intricate relationship between exchange rates and economic dynamics, jointly account for micro and macro facts, while providing an explanation of existing puzzles (e.g., fat tails, volatility clustering, leverage effect and contagion among others). Moreover, 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.[2]

The model expanded the multi-country, multi-sector model in Dosi et al. (2019, 2021)[3] 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 the 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 abroad, potentially altering their market shares. Meanwhile, at the macroeconomic level, speculative exchange dynamics can exert influence on domestic

[1]Other works focus on the financial nature of exchange rate markets together with the role played by heterogeneity in expectation formation, (see De Jong et al., 2010a; Verschoor and Zwinkels, 2013; Goldbaum and Zwinkels, 2014; Gori and Ricchiuti, 2018; Tsai and Tsai, 2021; Hommes, 2021; Ter Ellen et al., 2021; Bassi et al., 2023, among others).

[2]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).

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

economic growth and international trade interactions. The model also integrates the central bank into financial markets, enabling policy interventions to stabilize currency markets. 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, offering a more accurate depiction of the real-world complex dynamics.

Simulation results show that our model is able to reproduce key stylized facts concerning exchange rate dynamics in a multi-country structure, showing the exchange rate market's potential as 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 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 number 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 modelling (ABM) methodology (see Fagiolo and Roventini, 2017; Dawid and Delli Gatti, 2018; Dosi and Roventini, 2019; Haldane and Turrell, 2019), this paper builds on extensive literature investigating the bilateral exchange rate dynamics within a behavioural 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 upon the evidence regarding exchange-rate market dynamics. The second one concerns the interactions between exchange-rate movements and macroeconomic dynamics. Finally, the paper aims also 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 seminal work 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 et al., 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., 2010a; De Grauwe and Grimaldi, 2006).

Exchange rate and macroeconomic dynamics. There is a complex and intricate relationship between exchange rates 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 synchronisation in prices and quantities across countries, which can have destabilising 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).

International trade and macro and micro regularities. While international trade plays a pivotal role in economic growth, it is also subject to various risks and uncertainties which 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 13, SF 14; 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 differing in terms of productivity (SF 15), market shares (SF 16), size (SF 17), and growth rate distributions (SF 18) (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 19, SF 20; Bernard and Jensen, 1999; Bernard et al., 2012).

Table 1: Summary of stylized facts.

	Stylized Fact	Related Literature
	Exchange rate market	
SF1	Fat Tails	De Grauwe and Grimaldi (2005); Spronk et al. (2013)
SF2	Excess kurtosis	Winker and Gilli (2001); Gilli and Winker (2003)
SF3	Skewness	De Grauwe and Grimaldi (2006)
SF4	Volatility clustering	Lux and Marchesi (2000); 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 et al. (2009); Kohler and Stockhammer (2023)
SF8	Fluctuation phenomena 2	De Grauwe and Grimaldi (2006); De Jong et al. (2010a)
	Exchange rate and macroeconomic dynamics	
SF9	Misalignment problem	Rogoff (1996); Obstfeld and Rogoff (2000); Ter Ellen et al. (2021)
SF10	Contagion	Rodrik (2008)
SF11	Synchronization	Bentivogli and Monti (2001); Rodrik (2008)
SF12	Trade level	Bentivogli and Monti (2001); Pericoli and Sbracia (2003)
	International trade and macro and micro regularities	
SF13	Open economy volatility	Uribe and Schmitt-Grohé (2017)
SF14	Open economy persistence	Uribe and Schmitt-Grohé (2017)
SF15	Heterogeneity in productivity	Bartelsman and Doms (2000); Dosi (2007)
SF16	Endogenous market shares structural change	Kuznets and Murphy (1966)
SF17	Departure from normal size distribution	Bottazzi and Secchi (2003); Dosi (2007)
SF18	Fat-tailed firm growth rate distribution	Bottazzi and Secchi (2006); Dosi (2007)
SF19	Fraction of exporters	Bernard and Jensen (1999); Bernard et al. (2012)
SF20	Export productivity premium	Bernard and Jensen (1999); Bernard et al. (2012))

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. The firms in the consumption-good sector search for innovations to increase their labour 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.

We focus only on two countries to better studying 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] Figure 1 illustrates the schematic structure of the model. We extend the model in Dosi et al. (2019) in two ways. *First*, the exchange rate dynamics are not only influenced by trade flows (the real channel, the blue arrow in Fig. 1), but also by the demand for foreign currencies performed by traders on 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 on previously observed prices. Speculative beliefs can influence the exchange rate

[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.

dynamics, bringing instability and non-linear 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 Figure 2 illustrates the steps taken in the paper, highlighting the differences from the previous framework.

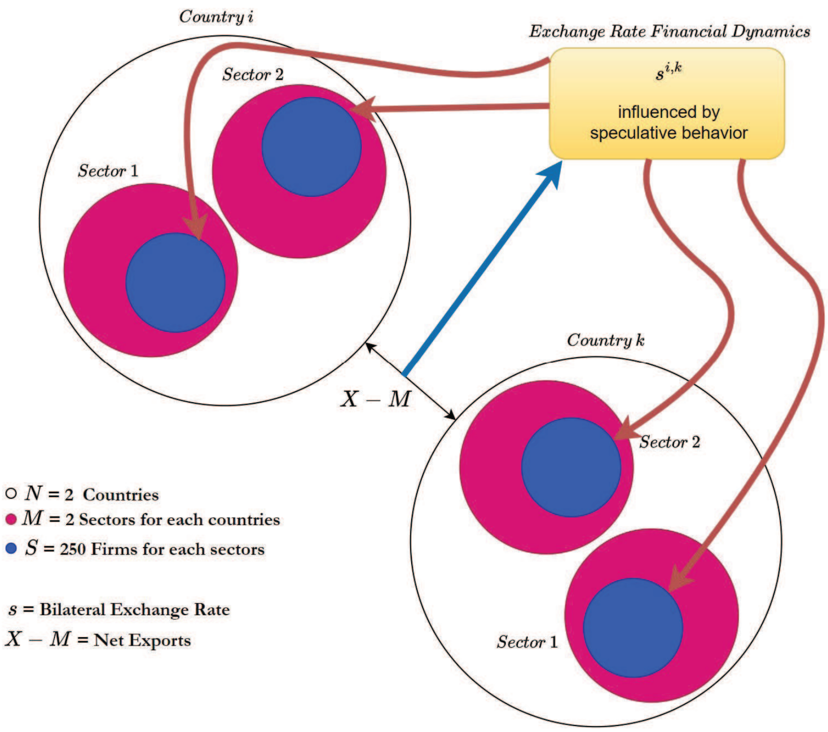

Figure 1: The interaction process between the real market and the financial behavioral exchange rate dynamics in the multi-country, multi-sector ABM model.

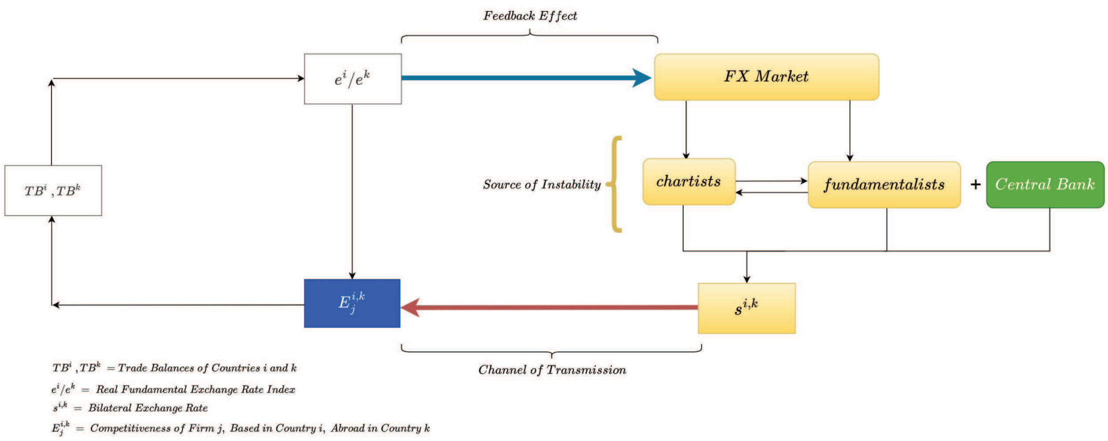

Figure 2: Flowchart illustrating the main difference steps between the baseline model (white + blue) and model with speculative behavior (yellow + blue) and Central Bank (green).

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 labour productivity if 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 foreing 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.

3.2 The consumption-good sector

The consumption-good sector is populated by S firms in M industries for each country under consideration. 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) and Dosi et al. (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 succeeded 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.

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

When innovation and imitation processes are completed, each firm selects the production technique that yields the higher labour 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:

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

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 $0 \leq \upsilon \leq 1$.

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):

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

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:

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

3.3 Market dynamics

Market selection allocate international demand for consumption goods across firms belonging to different countries. National consumption equals the wage bill (W) which is a 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 i-th country and industry h that operate 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

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

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

follows:

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

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

$$f_{j,h}^{i,k}(t) = f_{j,h}^{i,k}(t-1)(1+\chi \frac{E_{j,h}^{i,k}(t) - \overline{E}_h^k(t)}{\overline{E}_h^k(t)}), \tag{14}$$

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 h-th industry then reads:

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

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

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

Symmetrically, the foreign demand reads:

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

Accordingly, the total firm demand ($D_{j,h}^i$) is presented as a sum of domestic demand $Dint_{j,h}^i(t)$ and demand for exports $Dexp_{j,h}^i(t)$.

As in national markets, Schumpeterian exit and entry dynamics are 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.

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:[9]

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

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 Figure 2).[10] The market equilibrium is represented by the following equation:

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

from which, we can get the exchange rate:[11]

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

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):[12]

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

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:

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

[9] 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).

[10] 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.

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

[12] 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 et al. (2019).

where β is the chartists' reaction coefficient. These agents focus on short-term market trends and use past performance to predict future market trends.[13] The fractions of agents are not fixed over time: traders can switch from one rule to the other (Westerhoff et al., 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:

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

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):

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

Such a rule is the classical **"leaning against the wind"**: when the bilateral exchange rate depreciate ($s^{i,k}(t-1) < s^{i,k}(t-2)$), the central bank reduces the supply of domestic currencies to try to appreciate the exchange rate; at the opposite, when the bilateral exchange rate appreciate ($s^{i,k}(t-1) > s^{i,k}(t-2)$), 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 needs to 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:

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

with

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

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 labour demand of consumption firms. In line with Lewis et al. (1954) and Cornwall (1977), we assume that the supply of labour is infinitely elastic to variations in demand. Considering that in each country, the functioning of the labour 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

[13] 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.

- 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), one can compute the trade balance: $TB^i(t) = EXP^i(t) - IMP^i(t)$. 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 macro variables, we rely on simulations. We impose identical structural parameters around countries, industries, and firms. Indeed, evolutionary dynamics is an endogenous outcome.[14] 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. More on the empirical validation of agent-based models see (Fagiolo and Roventini, 2017; Windrum et al., 2007; Fagiolo et al., 2019).

Before examining in details 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, 2017). The series in Figure 3) show that growth and fluctuations are genuine emerging properties of the model.[15]

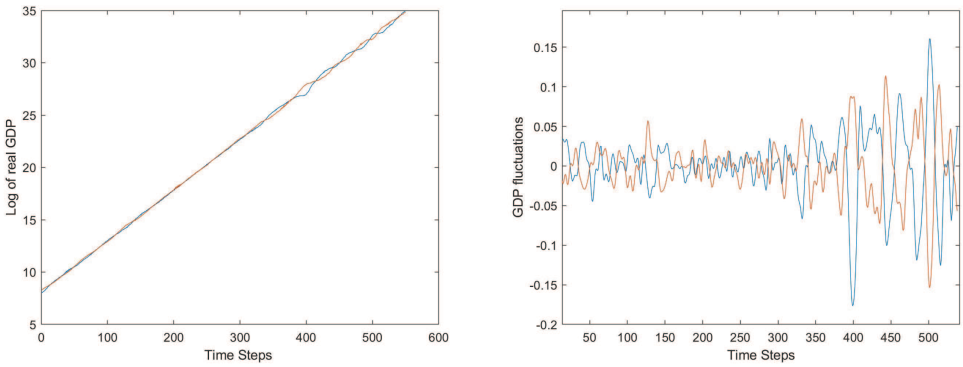

Figure 3: Real GDP growth (left) and business cycles (right) in the two countries.

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.

[14] The benchmark parameterization is reported in 5. 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).

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

Exchange-rate market. We start 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). Figure 4 displays the quantile-quantile plot (QQ) of the quantiles of the simulated exchange return rate ($s^{i,k}$) versus the theoretical values from a normal distribution. The figure suggests 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 (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 (Figure 5). Data appears to be concentrated at the extreme values and in the middle of the distribution, suggesting the non-Gaussian character of asset and asset returns.

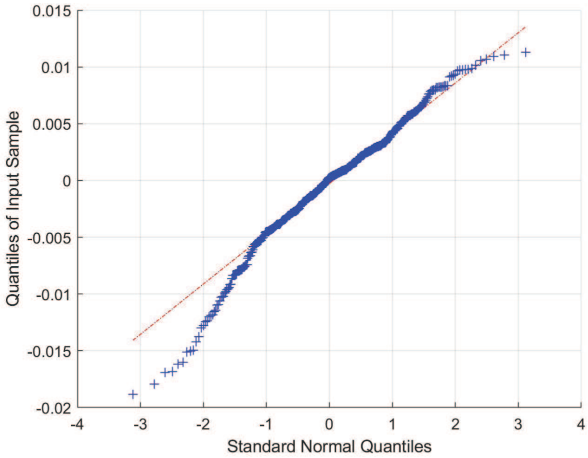

Figure 4: QQ plot of simulated series distribution vs. standard normal.

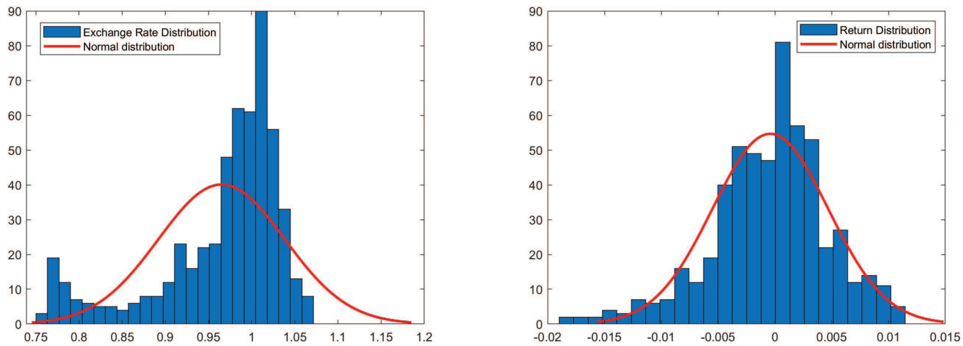

Figure 5: Frequency distribution of the simulated exchange rate (left) and exchange rate returns (right). The red lines indicate the corresponding normal distributions.

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 is shown in Figure 6, the autocorrelation function is positive for all the lags considered. This confirms that volatility in the exchange rate returns has a long memory in time (SF 4).

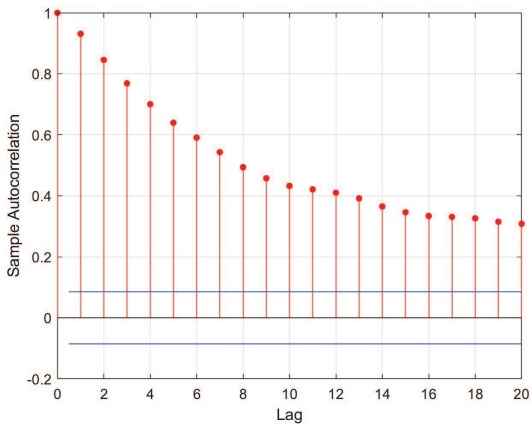

Figure 6: Autocorrelation function.

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

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

where $\Delta s(t)$ is the return of the exchange rate and $\varepsilon(t)$ represent 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.

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.

To detect the leverage effect on the volatility of exchange rates, we plot the volatilities against the returns of the exchange rate based on a five-lag window observation. As shown in Figure 7, we obtain a U-shaped relation, implying that large (small) exchange rate changes trigger high (low) future volatility (SF 5).

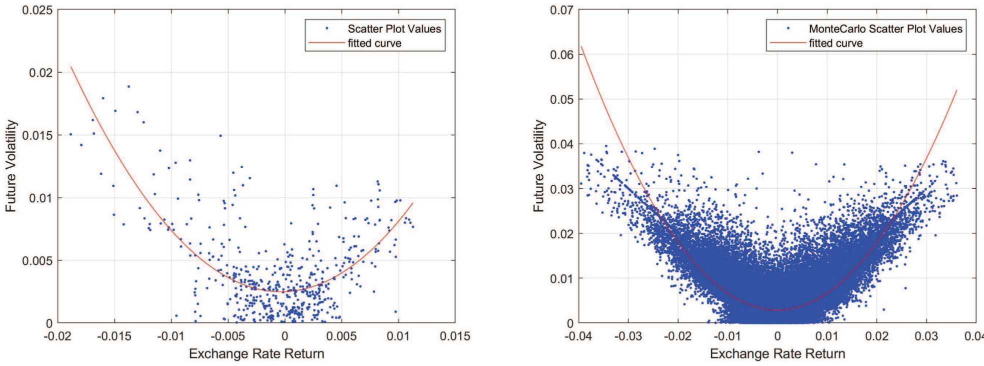

Figure 7: Leverage Effect. One single realization on the left. 200 Monte Carlo realization on the right.

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 Figure 8 .

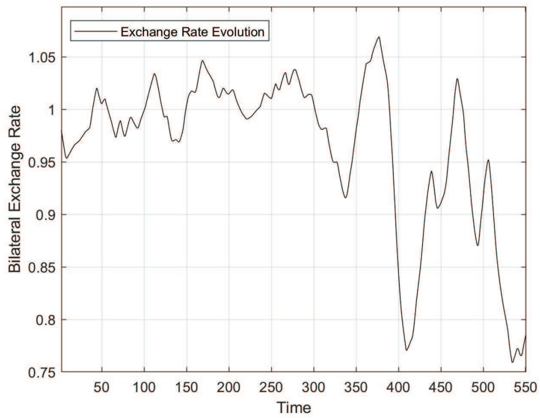

Figure 8: Bilateral exchange rate dynamics $s^{i,k}$.

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 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)[16] 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 results in Figure 9 and Table 3 show that the model with speculative behavior has a longer duration of cycles. 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.

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

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 portrayed in Figure 10 which shows that agents tend to switch among 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).

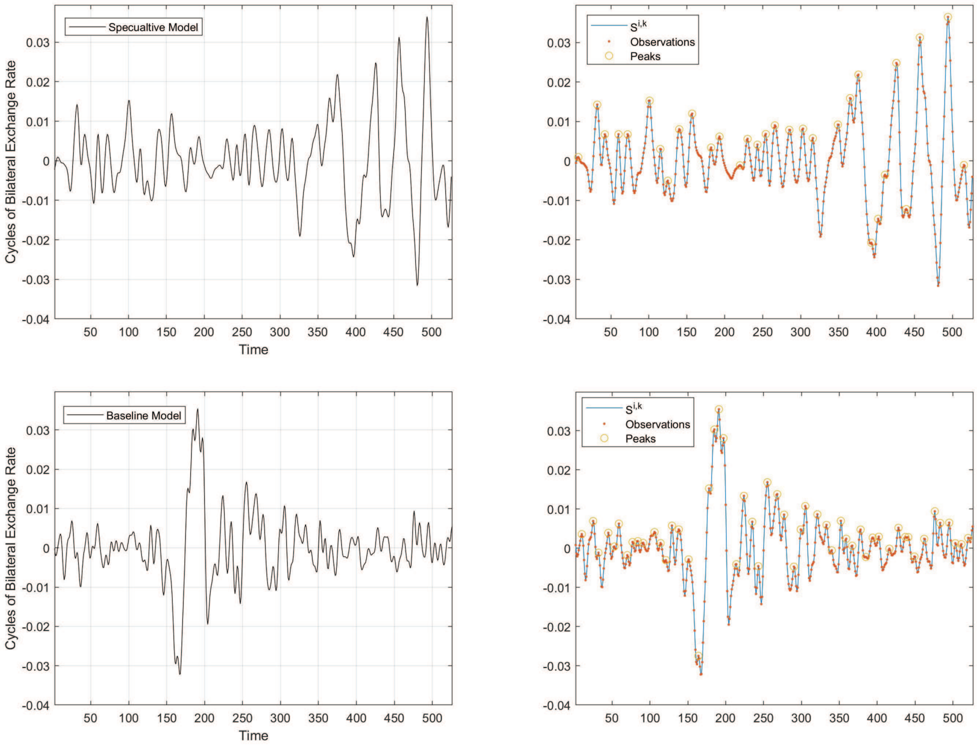

Figure 9: Cyclical component of the bilateral exchange rate (on the left) and peaks (on the right).

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 et al. (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 et al. (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.

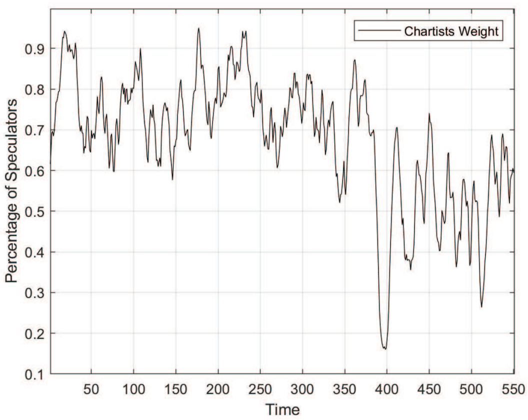

Figure 10: Percentage of chartists.

Exchange rate and macroeconomic dynamics. We now compare the exchange rate evolution with the underlying fundamental value. Most of the works in the literature on bilateral exchange rates apply the concept of purchasing power parity (PPP) as a fundamental value. The PPP is endogenously generated by model through the aggregation of the transactions occurring in the goods markets. As shown in Figure 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).[17]

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

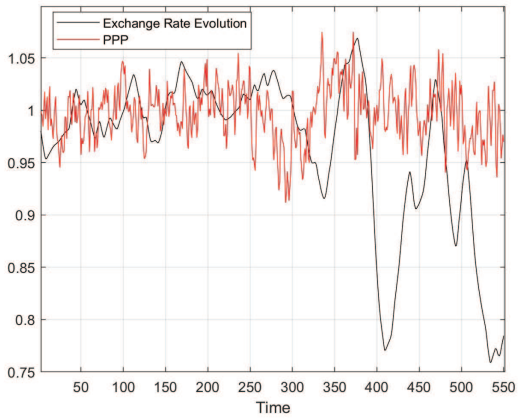

Figure 11: Bilateral exchange evolution vs. purchasing power parity.

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 shows that the error-correction coefficient λ_1 is statistically significant (and negative, as expected) but remarkably low (-0.0009), implying a 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 pulling the exchange rate far from fundamentals. These results align with empirical evidence indicating that exchange rates are influenced by their past values, which are considered by trend followers, or chartists, in the short to medium term ((De Jong et al., 2010b; Ter Ellen et al., 2021)). This result reflects how the expectations of these agents, significantly impact price dynamics.

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.

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 Table 6 and 7 show that the presence of speculative financial behavior generates a tendency toward more severe real aggregate fluctuations (SF 10).[18] Indeed, the model contemplating trading in 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 Figure 12, simultaneously to an increasing exchange rate variation stemming 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 country i reported in the right panel of Figure 12.

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

Table 6: Duration and volatility of cycles for Y^i and 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 et al. (2019) model.
$Dcycles$ stands for the duration of cycles, std stands for standard deviation.
$s^{i,k}$ stands for exchange rate between country i and country k. 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 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 et al. (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.

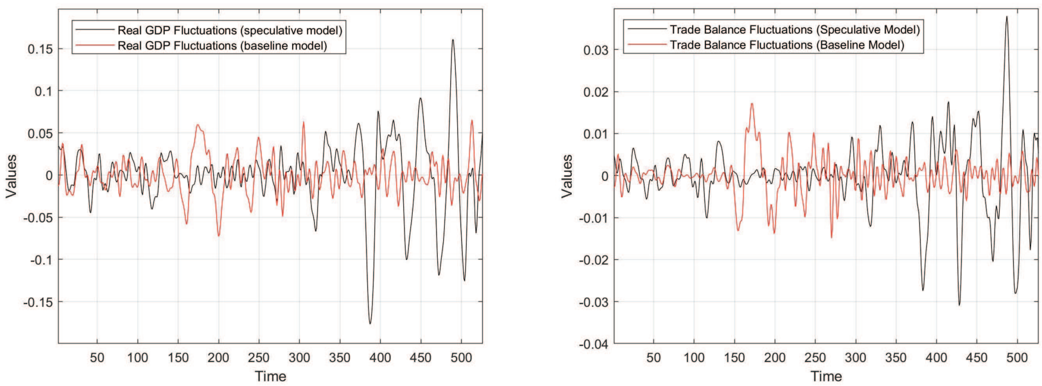

Figure 12: Cyclical dynamics of real GDP (left) and dynamics of trade balances (right) in the two scenarios for country i.

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 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 trend, their behavior reflects into economic activity and the trade level, generating a more persistent upward process. On the contrary, when chartists follows a negative trend, the economy falls into a more severe downturn.

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 badpass-filtered exports and imports, we find values of 0.0049 and 0.0043, respectively (SF 13). Additionally, as shown in Figure 13, the three time series are all positively serially correlated, indicating persistence in their dynamics (SF 14).[19]

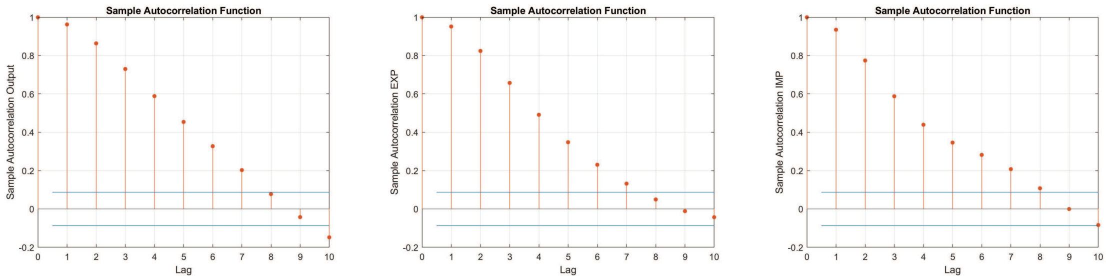

Figure 13: Autocorrelation functions.

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 (SF 15). These variations in productivity contribute to different dynamics in firm market shares and to endogenous structural change (SF 16; see Figure 14).

[19]The same is true for Country k. Due to space constrains, results are available upon requests.

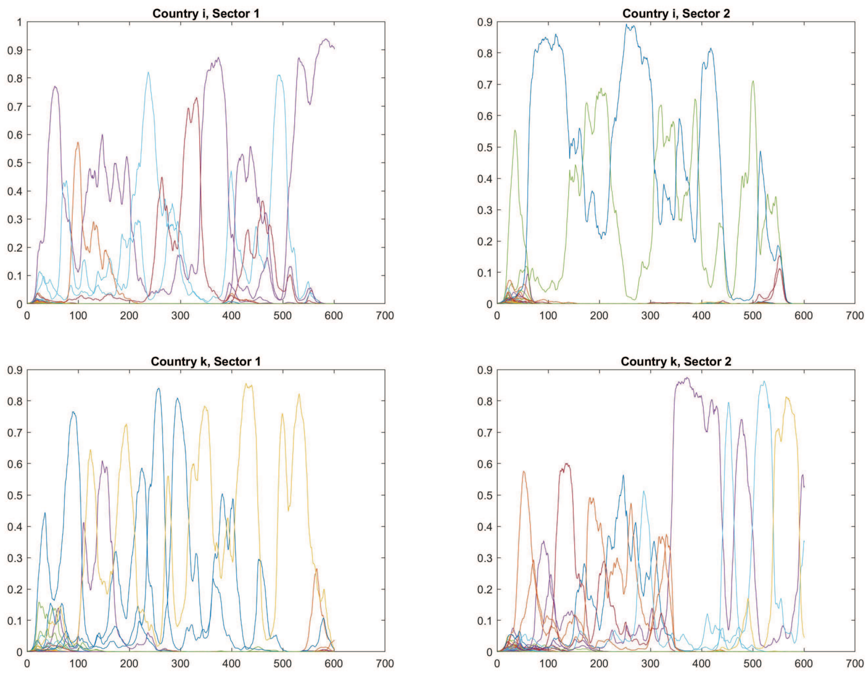

Figure 14: Firms' output share evolution in each specific country for each industry.

Such a dynamics is consistent with substantial differences in firm sizes (SF 17). 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 firms with numerous small businesses. Not surprisingly, a battery of tests suggest that firm log-size distributions are not log-normal (see Table 8). At the same time, the distribution of firm growth rates can be well approximated by a fat-tailed shape as shown by Figure 15, which is consistent with similar patterns observed at the industry and country levels (SF 18).

Table 8: Log-size distributions, normality tests for firms' sales (industry pooling).

	Jarque–Bera		
	Pvalue	*C.v.*	*Stat.*
Country i	0	5.8581	22983.0
Country k	0	5.8581	19895.0
	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.

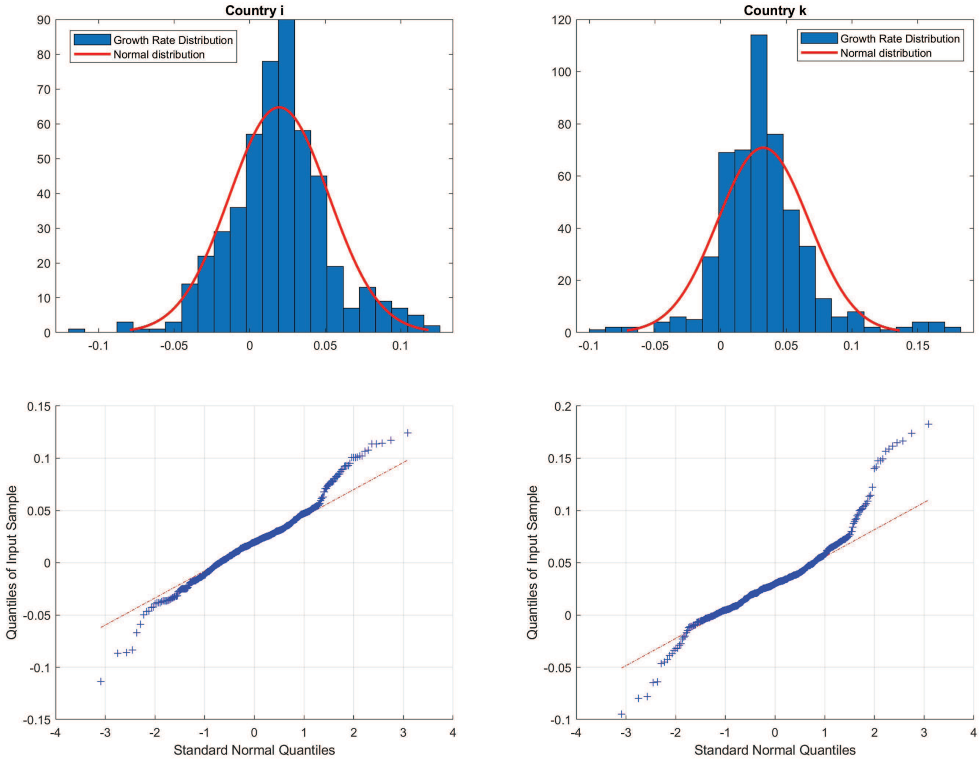

Figure 15: Firms' growth rates distributions (simulated density vs. normal fit in red).

Finally, the model successfully reproduces some observed patterns in firm-level dynamics concerning international trade. As depicted in Table 9, only around one third of the firms are able to exports into foreign markets (SF 19). Moreover, empirical observations reveal that there are premiums linked to the export status (SF 20). The results reported in Table 9 clearly show that, on average, exporting firms are larger and more productive compared to non-exporting firms.

Table 9: Exporters shares and premia at firms level. The two countries and all sectors pooling.

		Exporters Premia	
	Share of Exp. (%)	*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 $1.05 \times [1/(S \times 10)]$.

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, i.e., "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 perfomance 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 10. 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 for primarily stems from the central bank's ability to dampen the duration of 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 turns, such interventions can also dampen trade balance cycles (cf. Table 10; 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 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).[20] 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 number of chartists active 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 10 provides a comparison of the results associated to the two central bank's policies and the speculative model 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 number 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 5 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.

[20] 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 10: 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 interventions, $\omega^c_{cb} < \omega^c_s$ tests the hypothesis of a reduction of chartists resulting from 200 Monte Carlo.
For each interventions, $Dc^{cb} < Dc^s$ 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 increasing of volatility resulting from 200 Monte Carlo.
Monte Carlo simulations standard errors in parentheses.
*, **, *** denotes statistical significance at the 10%, 5%, and 1% levels respectively.

5 Conclusions

This work expanded the multi-country, multi-sector model in Dosi et al. (2019, 2021) by explicitly accounting for the dynamics of an exchange rate market populated by heterogeneous fundamentalist and speculative (chartist) traders. We then employed the extended model to study the impact of micro-founded exchange rate fluctuations on the dynamics of real side of the economies.

Simulation results show that the model is able to replicate an ensemble of relevant stylized facts regarding the dynamics of the exchange rate market (e.g., volatility clustering, leverage effect, unit root hypothesis and fluctuation phenomena, among others). Moreover, we find that the exchange rate fluctuations can be the source of endogenous instability which is reflected in a more persistent and higher volatility of financial cycles. At the same time, exchange rates can transmit financial shocks to real variables thus affecting international trade and business cycle dynamics. In particular, the speculative behavior of chartist traders can increase fluctuations in exchange rates which in turn impact on countries' GDP and trade balance.

Finally, we employed the model to study the financial and real impacts of different "leaning against the wind" interventions of the central bank in the exchange rate market. When such a policy contemplate a short-run target, the central bank is not able to significantly affect the dynamics of the exchange rate market. On the contrary, the unconstrained "leaning against the wind" policy can reduce the duration of the fluctuations of the exchange rate by reducing the population of speculative traders. This contributes to mitigate the duration of the cycles of trade balance. However, despite such potential benefits, central bank intervention exacerbate the volatility of exchange rates. The higher volatility is triggered by the higher market uncertainty due to the discretionary interventions of the central bank which leads to erratic responses from market participants. Our analysis suggest the complex and multifaceted impacts of central bank interventions on financial and real markets and the possible emerging policy trade offs.

The model can be extended along different research avenues. First, expectations could be formalized differently by introducing other heuristic formations as in Dosi et al. (2020) and study their effects on the dynamics of the exchange rate in an open economy context. Second, additional complexity could be introduced on the international trade side by allowing for a vertically integrated structure and distinguishing between stages of the production process. In a similar vein, the model could be extended to explicitly account for international capital flows. Third, the model could be calibrated to distinguish between developed and developing countries to understand the role played by the exchange rate in the process of divergence or convergence between nations at the global level. Finally, one could introduce different fiscal policy interventions and study their interactions with the policies followed by the central bank.

Appendix A

The parameter values listed in the following table reflect the findings of previous related studies.

Table 11: 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	20000
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

Appendix B

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[21]:

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

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.

Figure 16 shows the impact on investors' wealth. We divide the effect with respect to fundamentalists and chartits. 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 rebalance the system by making the decisions of a trend follower behavior less profitable compared to those of a fundamentalist.

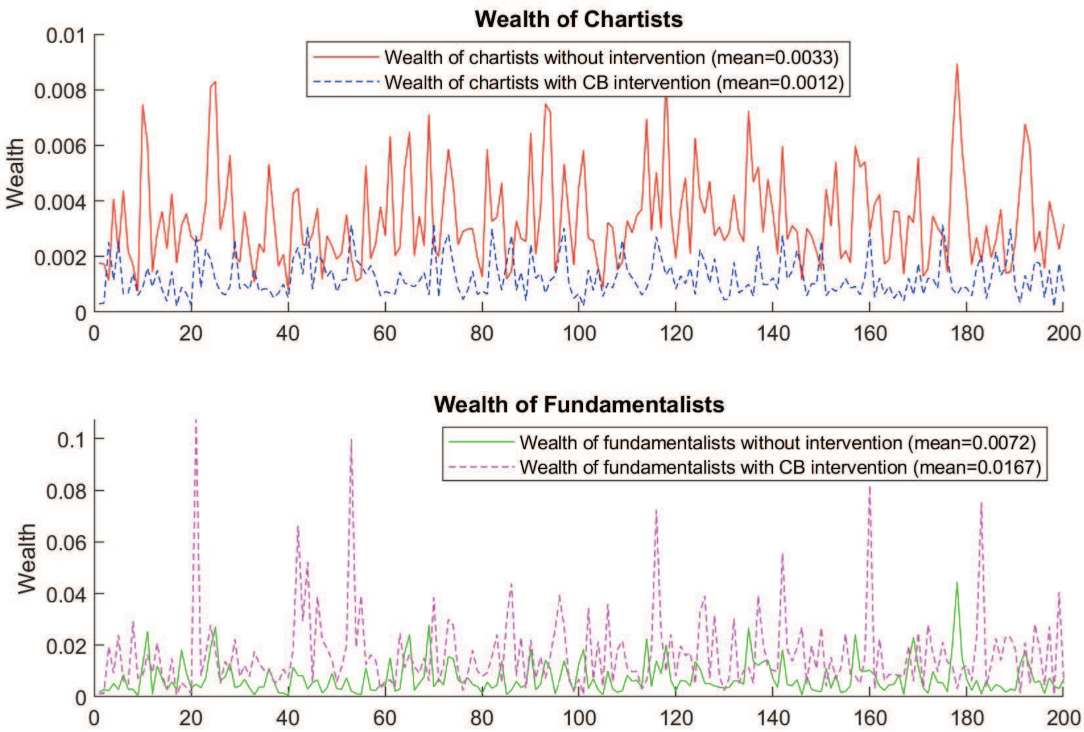

Figure 16: Dynamics of accumulated wealth with and without intervention of central bank. Results from 200 Monte Carlo replications.

[21] 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)

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