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The interplay between real and exchange rate market: an agent-based model approach

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Abstract

We present a multi-country, multi-sector agent-based model that extends Dosi et al. (2019) and incorporates the exchange market and its interaction with the real economy. The exchange rate is influenced not only by trade flows but also by the heterogeneous demand for foreign currencies from financial traders. In this respect, the dual nature of the exchange rate is highlighted, acting both as a transmission channel of endogenous shocks and as a source of shocks. Indeed, differing beliefs bring about real-financial non-linear patterns with feedback mechanisms. Simulations show that the introduction of speculative sentiment behaviour reflects important stylised facts of bilateral exchange rate series. Furthermore, the findings indicate that trend-following behaviour substantially increases financial turbulence and contributes to real economic fluctuations. Finally, we highlight the power and limitations of the central bank as an actor in the exchange rate market, showing that while the central bank's interventions can effectively curb boom-bust cycles, their outcomes differ substantially.

Keywords: agent-based model, exchange rate dynamics, endogenous 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 macroeconomic variables have long perplexed economists across paradigms. Exchange rate dynamics is also foundational in international macroeconomics due to its effect on the determination of economic outcomes at the global level. At the same time, undertaking an open economic analysis is 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).

Despite the proliferation of theoretical frameworks, both within mainstream economics and agent-based modeling (ABM), a comprehensive understanding of the mechanisms driving exchange rate movements and their consequential impact on macroeconomic dynamics remains elusive. Empirical observations underscore the complexity of these phenomena, presenting a series of regularities that challenge existing theories' explanatory power (Dornbusch, 1976; Obstfeld and Rogoff, 1995). This has led to different macroeconomic approaches, 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 behavioral explanations (Frankel and Froot, 1986, 1990; Kirman, 1993; De Grauwe and Grimaldi, 2006; Gori and Ricchiuti, 2018).[1]

Despite recent attempts, the existing frameworks fail to capture and explain the key empirical regularities consistently, including the volatility of exchange rates, their persistence 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 ABM that offers a promising avenue for understanding exchange rate dynamics, financial markets and their macroeconomic implications. Given such premises, ABMs represent 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 encapsulate stylized micro and macro facts, resolving existing puzzles while providing a versatile platform for examining the intricate relationship between exchange rates and economic dynamics. Importantly, it serves as both a laboratory for policy analyses and a tool for exploring the emergent properties of complex economic systems. While recognizing the relevance of the above mentioned features, literature is still lacking in incorporating them in mid-to-large scale macroeconomic models.[2]

The core of our model lies in its ability to capture the heterogeneous behaviors of agents, ranging from individual market participants to institutions, whose interactions give rise to financial and macroeconomic phenomena. By incorporating realistic decision-making processes, bounded rationality, and adaptive learning mechanisms, our model departs from the simplifying assumptions of traditional equilibrium-based approaches, offering a more nuanced depiction of real-world dynamics. In this, we present a multi-country multi-sector ABM that incorporates the financial-behavioral nature of the exchange rate dynamics and its interaction with the real side of the economy.

Our model operates within the Keynes+Schumpeter (K+S) tradition (Dosi et al., 2010, 2013, 2015, 2017, 2019), incorporating endogenous growth mechanisms via research and development (R&D) dynamics, and macroeconomic cyclical fluctuations, driven by aggregate demand. Moreover, the analysis is undertaken within the open economy framework defined by Dosi et al. (2019). The economy comprises a consumption-good sector

[1]Apart from the recognized linkages between exchange rate dynamics and economic performances, the inherent financial nature of the former, together with the role played by heterogeneity in expectation formation within exchange rates, are well established (see De Jong et al., 2010; 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); 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). In (Rolim et al., 2022), the financial nature of the exchange rate is absent.

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 and have an impact on the current account and exchange rate dynamics across nations.[3]

Moreover, whereas Dosi et al. (2019) exchange rate dynamics is solely determined by the real side of the economy, our framework extends the model by considering the influence of both trade flows and the demand for foreign currencies within the financial exchange rate market. Indeed, our model integrates the actions of traders — be they fundamentalist or chartist — in shaping exchange rate dynamics, offering a more comprehensive analysis of this complex phenomenon. 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 economic growth and international trade interactions. The model also integrates the central bank into financial markets, enabling interventions to stabilize currency markets. This framework allows for detailed analysis of the central bank's impact on economic performance while using strategies of currency purchases or sales. We consider and examine two main intervention types — "leaning against the wind" and "leaning against the wind with a short-run target".

Our study yields several notable results. Firstly, by introducing speculative sentiments, we demonstrate that our macro ABM effectively replicates essential 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). Moreover, this heightened instability is characterized by increased persistence and volatility in financial cycles (Jones and Brown, 2018). Furthermore, the study underscores the strong relationship between financial and real components, highlighting how heuristic expectations influence exchange rate dynamics and subsequently propagate to business cycle dynamics (Johnson and White, 2016). Particularly noteworthy is the impact of chartists' behavior, which increases exchange rate fluctuations, consequently affecting a country's international economic growth (Miller and Green, 2019). Additionally, the study reveals the central bank's intervention as a vital tool for reducing the amplitude of fluctuations and the magnitude of speculative activities(Taylor and Lee, 2017). However, the analysis of intervention scenarios reveals the complexity of central bank interventions and their diverse impacts on real-financial markets, with varying outcomes depending on the type of intervention employed (Brown and Smith, 2021).

The study suggests several avenues for future research, including the formalization of alternative expectation formations, the incorporation of additional complexity in international trade structures, and the differentiation between developed and developing countries to understand the exchange rate's role in global convergence or divergence processes. Moreover, understanding the linkage between exchange rate dynamics and macroeconomic variables is deemed essential for policymakers to design effective interventions for sustainable and inclusive growth, with potential extensions to incorporate fiscal policy considerations. These avenues offer promising directions for future research endeavors in this field.

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 simulated results by showing that they can reproduce the main stylized facts regarding foreign exchange markets and exploring the efficacy of central bank interventions. Finally, Section 5 concludes and discusses possible venues for future research.

2 Empirical evidence on exchange rates

Using agent-based modelling (ABM) methodology, this paper builds on extensive literature that can be categorised into two main areas: 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

[3]Differently from Dosi et al. (2019) and in order to be more focused on the interplay between real and financial sectors, we employ a simplified version of this model. Indeed, we have only consumption and not capital goods. We leave the complication of the model to future works in which we will analyze the most complex relationships within the global production network.

framework, we provide an overview of the principal stylised facts (SF) that our model aims to replicate.Such stylized facts are reported in Table 1.

2.1 *Bilateral exchange rate dynamics*

Extensive literature has investigated the behavior of exchange rates, revealing various regularities. First, empirical evidence suggests that these markets exhibit bubbles and crashes, in which prices can experience sudden and sharp movements that are difficult to explain using traditional economic models (Westerhoff et al., 2009; Kohler and Stockhammer, 2023). Examples of a bubble and crash in exchange rates are the Japanese yen in the late 1980s and early 1990, the late 1990s devaluation of the Russian ruble, and the Thai baht's sharp decline, which precipitated the Asian financial crisis. In this context, "animal spirits" could be considered the first source of large fluctuations. Additionally, "puzzles" such as the volatility clustering phenomenon, in which periods of high volatility tend to be followed by other periods of high volatility, and the leverage effect, which indicates that large (small) movements in the exchange rate tend to be followed by periods of high (low) volatility, have been empirically identified (Lux and Marchesi, 2000; De Grauwe and Grimaldi, 2006; De Grauwe and Rovira Kaltwasser, 2012). Together with these, the distribution of exchange rate returns shows fat tails (De Grauwe and Grimaldi, 2005; Spronk et al., 2013), excess kurtosis (Winker and Gilli, 2001; Gilli and Winker, 2003), and skewness (De Grauwe and Grimaldi, 2006), indicating a higher probability of extreme movements than a normal distribution would predict.

Along this line, the analysis of exchange rates contains two empirical "puzzles". The unit root hypothesis implies that exchange rate movements exhibit a random walk pattern, with no predictable trend or pattern in the data (see seminal work of Fama (1984) and Engel (2014) for surveys). The second suggests a disconnection of exchange rates from macroeconomic fundamentals (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) with the general lack of robust co-movement between the two. This misalignment process results in substantial deviations in the exchange rate from its underlying fundamentals, such as purchasing power parity (Rogoff, 1996).

Passing to the real/financial interaction, there is an intricate relationship between exchange rates and real outcomes. A prime example is the Asian Crisis of 1997-98. Within those crises, exchange rates played a crucial role in acting as a transmission channel from a crisis that originated in the financial sector to a crisis that subsequently spread to the real sector. Fluctuations in nominal exchange rates can have significant effects on real variables such as employment, output, and investment, which bears important implications for international trade. This brings significant synchronization in prices and quantities across countries, resulting from contagion effects, which can destabilize the global economy (Dai et al., 2020; Bentivogli et al., 2001). 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 (Pericoli and Sbracia, 2003).

The following list summarizes the stylized facts regarding the behaviour of bilateral exchange rates on a country level and in relation to macro aggregates.

- **Fat tails (SF 1):** The distribution of exchange rate returns exhibits fat tails.
- **Excess kurtosis (SF 2):** The distribution of exchange rate returns is characterized by excess kurtosis. It shows more mass concentration around the mean.
- **Skewness (SF 3):** The distribution of exchange rate returns presents positive or negative skewness.
- **Volatility clustering (SF 4):** Time dependency in the volatility of the exchange rate.
- **Leverage effect (SF 5):** Small exchange rate changes trigger little future volatility while large changes in the exchange rate lead to high future volatility.
- **Unit root hypothesis (SF 6):** The evolution of exchange rates resembles a random walk, as a result, is non-stationary.
- **Bubble and bust cycles (SF 7):** Foreign exchange markets regularly produce significant and frequent bubbles and crashes.

- **Fluctuation phenomena 2 (SF 8):** Trend following behavior increases the turbulent behavior of the foreign exchange market.
- **Misalignment problem or disconnected puzzle (SF 9):** Deviations of the exchange rate from its underlying fundamental.
- **Sixth puzzle (SF 10):** Fluctuations in nominal exchange rates affect real outcomes.
- **Contagion (SF 11):** A significant synchronization in price and quantities across countries resulted from real and financial contagion through the speculative financial channel.
- **Trade level (SF 12):** Increasing or decreasing trade level between countries due to non-fundamental exchange rate movements.

2.2 *Macro- and micro-economic level stylized facts for open economies*

International trade plays a pivotal role in economic growth, as it allows countries to specialize in the production of goods and services where they have a comparative advantage. This leads to greater efficiency and productivity reflected in heterogeneity among firms (Bartelsman and Doms, 2000; Dosi et al., 2007; Bottazzi and Secchi, 2003, 2006). To confirm it, at the micro level, stylized facts indicate significant differences between firms operating in the international market compared to those operating solely in the domestic economy. On this point, exporters are in the minority but with a premium in terms of productivity and sales (Bernard and Jensen, 1999; Bernard et al., 2012). However, international trade is also subject to various risks and uncertainties, which can have significant implications for economic stability and growth. To this respect, one important macro-stylized fact is the greater volatility of exports and imports compared to output (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.

The empirical regularities observed at the open economic level can be summarized as follows:

- **Open economy volatility (SF 13):** Exports and imports are more volatile than output.
- **Open economy persistence (SF 14):** Output, exports, and imports are all positively serially correlated.
- **Heterogeneity in productivity (SF 15):** Large and persistent productivity differentials across firms within the same sector and country.
- **Endogenous structural change (SF 16):** The evolution of industry output shares presents endogenous structural change.
- **Departure from normal distribution (SF 17):** The firm's size distribution deviates from a normal distribution and tends to be right-skewed.
- **Fat-tailed firm growth rate distribution (SF 18):** The firm's growth rate distribution displays fat tails.
- **Fraction of exporters (SF 19):** Only a small fraction of firms export.
- **Export productivity premium (SF 20):** Export productivity premium: exporters appear to be more productive and big than non-exporters.

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. (2010)
	Exchange Rate and Macroeconomic Dynamics	
SF9	Misalignment problem	Obstfeld and Rogoff (2000); Ter Ellen et al. (2021)
SF10	Sixth puzzle	Rogoff (1996)
SF11	Contagion	Bentivogli et al. (2001); Dai et al. (2020)
SF12	Trade level	Pericoli and Sbracia (2003)
	Micro- and Macro- Open Economy Dynamics	
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 et al. (2007)
SF16	Endogenous structural change	Kuznets and Murphy (1966)
SF17	Departure from normal distribution	Bottazzi and Secchi (2003); Dosi et al. (2007)
SF18	Fat-tailed firm growth rate distribution	Bottazzi and Secchi (2006); Dosi et al. (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), which features N different economies (indexed by i). Each country contains M consumption-good industries (indexed by h). In turn, each consumption-good sector is 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 endogenously evolve in search and innovation that increases labour productivity. Consequently, production technologies are heterogeneous across firms and evolve via a stochastic process of innovation and imitation.

The choice to consider two countries allows us to highlight the dual nature of the exchange rate, acting both as a transmission channel of endogenous shocks as well as a source of shocks. This feature shown in Fig. 1 that illustrates the schematic structure of the model and helps to understand the basic framework. One can notice that, differently from Dosi et al. (2019), 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 the fundamentalist or the chartist strategy.[4] 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 FX dynamics, bringing instability and non-linear patterns

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

to the real sector (the brown arrows in Fig. 1).

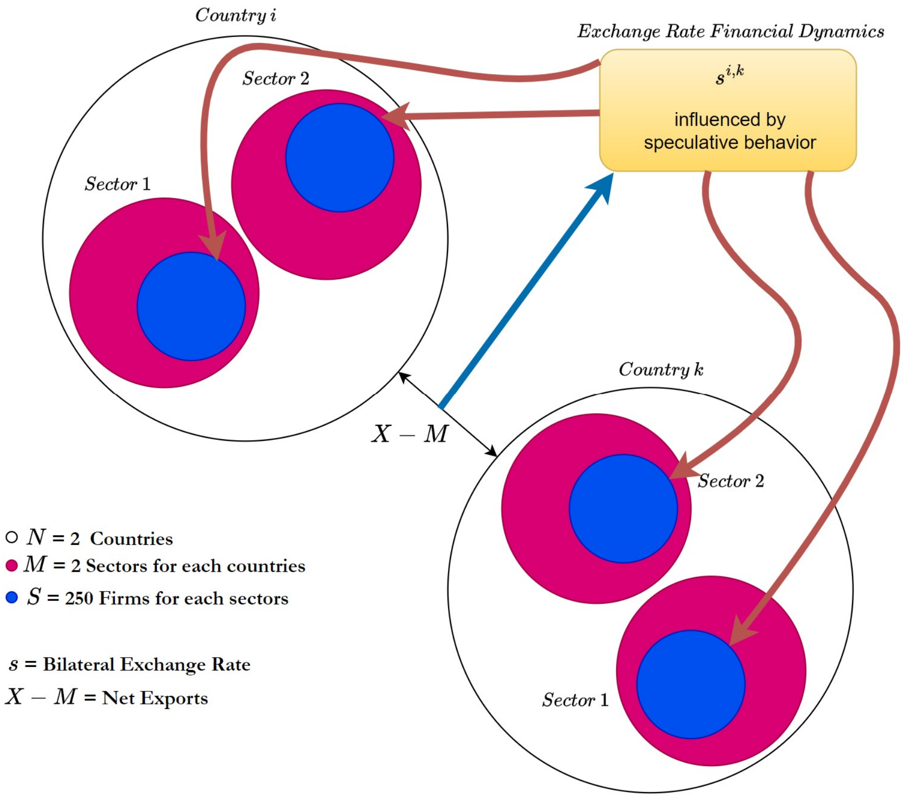

Figure 1: The interaction process between the real market and the financial behavioral exchange rate dynamics in the multi-country, multi-sector ABM model.

Differently from Dosi et al. (2019), the model takes a step forward and features the central bank as an actor in financial markets potentially implementing different forms of interventions, in doing so preventing 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. By formalizing the central bank's behavioral intervention rule and introducing it as an actor in the model, 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. To help the reader, the diagram in Figure 2 illustrates the steps taken in the paper, highlighting the differences from the previous framework.

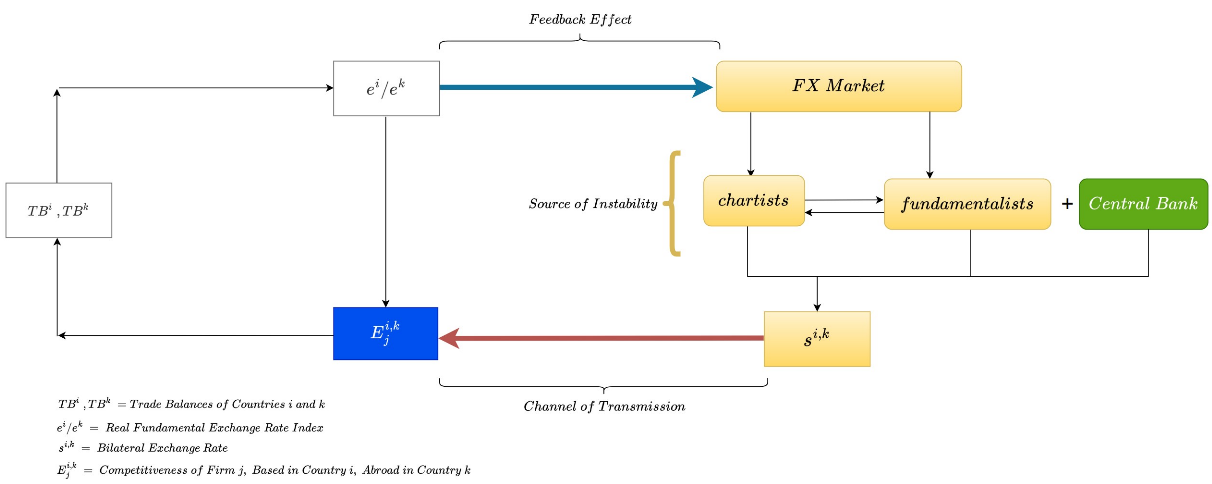

Figure 2: Flowchart illustrating the main difference steps between the baseline model (white + blue) and model with speculative behavior (yellow + blue) and Central Bank (green)

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 decisions at the national level occur, i.e., monetary wages are set. Additionally, bilateral exchange rate dynamics are determined by behavioral decisions of trade operators in the FX market.
4. Imperfectly competitive international consumption-good markets open so workers can spend their income on domestic and imported goods. Firms' market shares evolve according to their price competitiveness.
5. 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. Next, we provide a detailed description of the model rising out of the agent's behavior.

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 $(0 \le \lambda \le 1)$:

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

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

Closely following 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 drawing θ from a Bernoulli distribution that indicates whether a firm is successful in its search: the probabilities for innovation ($\theta(IN)$) and imitation ($\theta(IM)$). Note that the higher the R&D expenditures allocated to innovation and imitation and firms' search capabilities ($\xi_{1,2} > 0$), the higher the probability of success:

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

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

We assume the upper bound $\theta_{max} < 1$ to consider that the search always has a minimum degree of uncertainty. 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 Beta ($Beta(\alpha_1, \beta_1)$) 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 $[0, 1]$. Note that the technological opportunities are captured by the support of the Beta distribution and by its shape. Considering the high degree of uncertainty describing the innovation process, the newly discovered techniques may be less productive than the ones currently used by firms.

As in the case of innovation, also imitation follows a double-step process. Firstly, the possibilities of accessing imitation come from sampling a Bernoulli. Secondly, firms accessing the next stage are able to 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).[5]

When innovation and imitation processes are completed, each firm selects the production technique that yields 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 based on the evolution 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 the productivity of which 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).

Considering that the productive capacity constraints the desired production, 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 is the central mechanism impacting the distribution of international demand for consumption goods across different firms. Each country's consumption equals the wage bill (W). We assume in our artificial economy 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.

The firms compete in N markets at the national level, all characterized by imperfect information and producing the same homogenous good within each industry. Accordingly, the firm competitiveness depends on the price they charge. Moreover, in foreign markets, price and hence competitiveness are also affected by trade

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

costs (τ) and 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.[6] The average competitiveness ($\overline{E}$) of industry h belonging to country k is computed as follows:

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

In its turn, market shares (f) are affected by the market selection mechanism relying on quasi-replicator dynamics in the fashion of (Dosi et al., 1995, 2017), where competitive firms will expand their market shares in each market, while less competitive ones will lose it:

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

where $\chi > 0$ and controls the strength of market competition. Accordingly, the global market share of firm j competing in h-th industry 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 demand for export would read:

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

Accordingly, the total individual 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 are present in international competition, where once again, 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

As in the tradition of asset price dynamics literature, 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, as previous mentioned, $s^{i,k}(t+1)$ is the bilateral exchange rate at time $t+1$ and $d^{\phi}(t)$ is the demand for currency of country i.

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

The demand of the agents, who are assumed to be mean-variance optimizers, can be mathematically derived from the utility maximization function:

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

where $\mathrm{E}^{\phi}\left(t\right)$ is the expectation operator, a is the risk aversion coefficient which is the same for all agents, and V is the variance of wealth. Solving Eq. (19), we obtain the following demand of currency i:

$$d^{\phi}\left(t\right)=\frac{\left(1+r^{i}\right)\mathrm{E}^{\phi}(t)\left[s^{i,k}\left(t+1\right)\right]-\left(1+r^{k}\right)s^{i,k}\left(t\right)}{a\sigma^{2}}. \tag{20}$$

In line with HAMs, there exist Φ groups of agents who hold heterogeneous expectations about future exchange rate. Let $\omega^{\phi}\left(t\right)$ denotes the proportion of agents belonging to type ϕ, with $\sum_{\phi=1}^{\Phi}\omega^{\phi}\left(t\right)=1$ and $\omega^{\phi}\in(0,1)$. In such a scenario, total demand of financial operators, $D(t)$, can be expressed as[7]

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

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).

The market equilibrium is represented by the following equation:

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

from which, we can get the exchange rate[8]:

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

Two types $\{\phi=f,c\}$ of agents populate the financial exchange rate market. One type of traders ($\phi=f$ = fundamentalists) 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. 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)[9]:

$$e^{i}(t)=e^{i}(t-1)(1+\gamma\frac{TB^{i}(t-1)}{\overline{Y}(t-1)}+u_{i}(t)), \tag{24}$$

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:

$$\mathrm{E}^{f}\left(t\right)\left[s^{i,k}\left(t+1\right)\right]=s^{i,k}\left(t-1\right)+\alpha\left[e^{i}(t)/e^{k}(t)-s^{i,k}\left(t-1\right)\right],\qquad\alpha>0, \tag{25}$$

where α is the agents' reaction coefficient.

On the other hand, technical traders or chartists ($\phi=c=$ chartists) take a speculative short-term perspective and are more concerned with past short-term trend lines:

[7] 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).

[8] For analytical tractability we set $r^i=r^k=0$.

[9] 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).

$$\mathrm{E}^{c}(t)\left[s^{i,k}(t+1)\right] = s^{i,k}(t-1) + \beta\left[s^{i,k}(t-1) - s^{i,k}(t-2)\right], \qquad \beta > 0, \tag{26}$$

where β is the chartists' reaction coefficient. These agents focus on short-term market trends and use past performance to predict future market trends, which may destabilize the market and cause the market price to enter a positive or negative price trend.

Fractions of agents are not fixed over time; market participants may switch from one rule to the other (Westerhoff et al., 2009). Chartists follow a selection strategy according to the misalignment process:

$$\omega^{c}(t) = \frac{1}{1 + \psi[e^{i}(t-1)/e^{k}(t-1) - s^{i,k}(t-1)]^{2}}. \tag{27}$$

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 becoming fundamentalists.

Let us now formalize the intervention of the central bank. We consider what are known in the literature as "sterilized interventions". They are designed to counteract a possible appreciation or depreciation of domestic currencies. To carry them out, we include the role of the central bank, specifying its behavioral rule in the market:

$$z(t) = \varepsilon_{cb}\left[s^{i,k}(t-1) - s^{i,k}(t-2)\right], \qquad \varepsilon_{cb} > 0. \tag{28}$$

The formalized rule is the classical **'leaning against the wind'**; when the bilateral exchange rate decreases (depreciation, $s^{i,k}(t-1) < s^{i,k}(t-2)$), the central bank decreases the supply of domestic currencies, which is reflected in an appreciation of the exchange rate. As the opposite, when the bilateral exchange rate increases (appreciation, $s^{i,k}(t-1) > s^{i,k}(t-2)$) the central bank increases the supply of domestic currencies with a consequent depreciation. 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:

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

with,

$$\begin{array}{llll} \varepsilon_{cb} > 0 & if & \left|s^{i,k}(t-1) - s^{i,k}(t-2)\right| > M & , \quad M = 3 * sd[e^{i}(t)/e^{k}(t)] \\ \varepsilon_{cb} = 0 & if & \left|s^{i,k}(t-1) - s^{i,k}(t-2)\right| < M & , \quad M = 3 * sd[e^{i}(t)/e^{k}(t)]. \end{array} \tag{30}$$

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 in our artificial economy 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 are also following the institutional dimension relying on Dosi et al. (2010):

$$W^{i}(t) = W^{i}(t-1)[1 + \psi g^{i}_{prod}(t-1)], \tag{31}$$

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

The stage finishes by computation of national aggregate variables (e.g., national consumption - C, total exports - EXP and total imports - IMP) as a result of aggregated corresponding micro counterparts:

$$C^i(t) = W^i(t)L^i(t); \tag{32}$$

$$EXP^i(t) = \sum_{h=1}^{M} \sum_{j=1}^{S} Dexp^i_{j,h}(t); \tag{33}$$

$$IMP^i(t) = C^i(t) - \sum_{h=1}^{M} \sum_{j=1}^{S} Dint^i_{j,h}(t). \tag{34}$$

From Eqs. (33) and (34), one can compute the trade balance: $TB^i(t) = EXP^i(t) - IMP^i(t)$. As one can expect, 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.

In what follows, we first analyze the model without interventions. This allows us to compare the model with financial speculation with the baseline model by Dosi, Roventini, and Russo (2019). Then, in section 5, we study how the two possible interventions affect the dynamics of exchange rate.

4 Simulation results

The model, in keeping with K+S tradition (Dosi et al., 2010, 2013, 2015, 2017), is able to explain important empirical stylized facts such as endogenous growth (Fig. 3)[10]

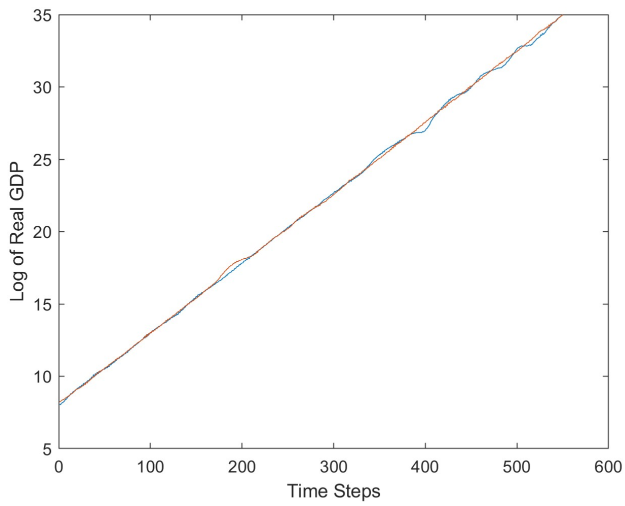

Figure 3: Real GDP dynamics of the two countries.

Additionally, the stylized facts presented in Section 2 are tested to evaluate the explanatory power of our model. We impose identical structural parameters around countries, industries, and firms. Indeed, evolutionary dynamics is an endogenous outcome.[11] 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. We begin by analyzing the bilateral exchange rate series and its relationship with macroeconomic dynamics.

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

[11]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).

4.1 Bilateral exchange rates

As mentioned in section 2, empirical regularities of the exchange rate return distribution have been discovered to be the absence of normality with fat tails and excess kurtosis Huisman et al. (2002). Fig. 4 displays the quantile-quantile plot (QQ) of the quantiles of the simulated exchange return rate ($s^{i,k}$) versus the theoretical quantile values from a normal distribution. The figure suggests a heavier tail (more outliers) than the normal distribution (SF 1). The Kurtosis index of the simulated exchange rate returns has been performed with a result equal to 3.9123, showing the 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 (Fig. 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.

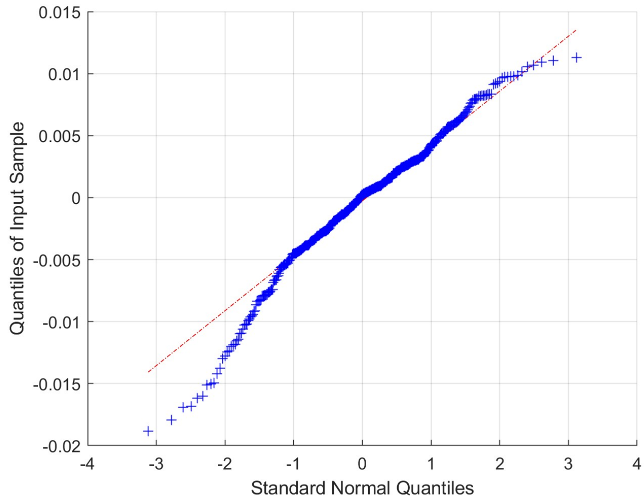

Figure 4: QQ plot of simulated series distribution vs. standard normal.

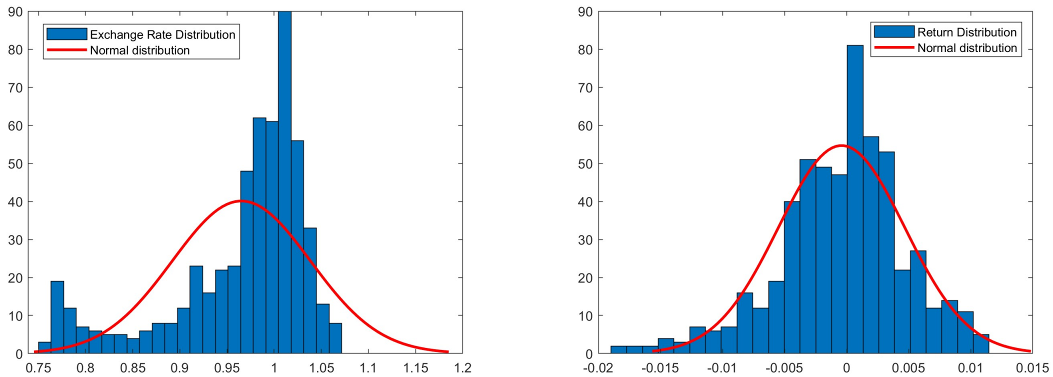

Figure 5: Frequency distribution of the simulated exchange rate (left) and exchange rate returns (right). The red lines indicate the corresponding normal distributions.

We now test the 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 Fig. 6, the autocorrelation function is positive for all the lags considered. This confirms that volatility in the exchange rate returns has a long memory and is persistent in time (SF 4).

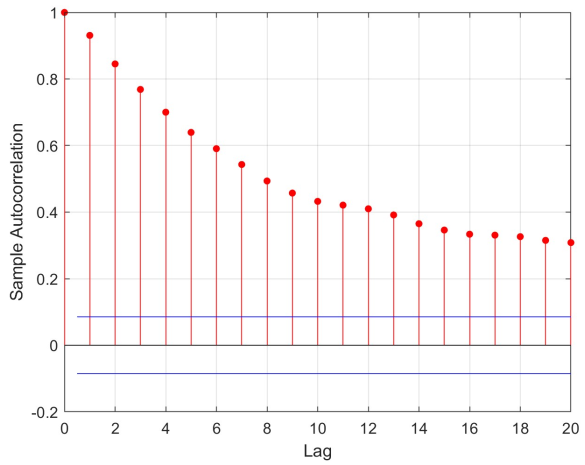

Figure 6: Autocorrelation function.

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

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

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:

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

We present the results in Table 2. We observe that the GARCH coefficients, α and δ, are significantly different from zero, implying volatility clustering in the exchange rate returns. Furthermore, we observe that 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 return based on a five-lag window observation. As shown in Fig. 7, we obtain a U-shaped relation, implying that large exchange rate changes trigger high future volatility while small changes trigger little future volatility (SF 5).

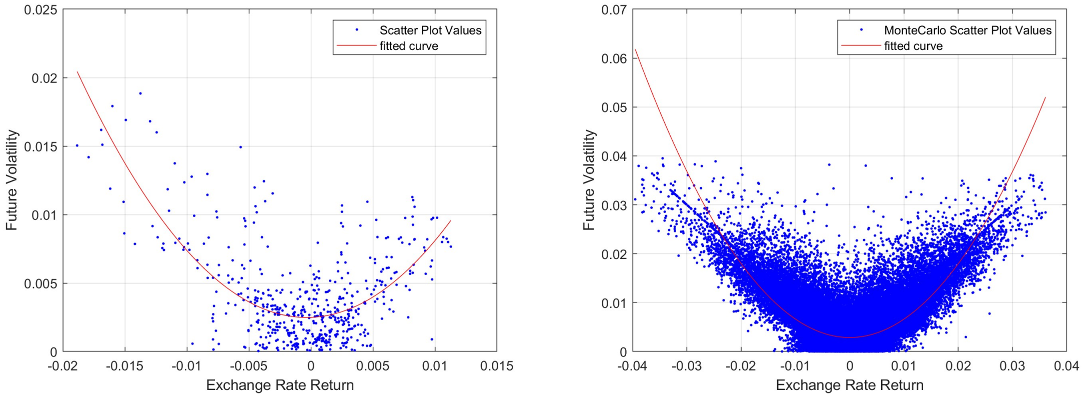

Figure 7: Leverage Effect. One single realization on the left. 200 Monte Carlo realization on the right.

We now pass to analyzing the dynamical behavior. We perform a unit root test on the simulated time series. The Monte Carlo results indicate that this test fails to reject the null hypothesis of a unit root at one percent statistical level (SF 6). With this empirical regularity, the spot bilateral exchange evolution presents significant and frequent bubbles and crashes, as shown in Fig. 8 (SF 7).

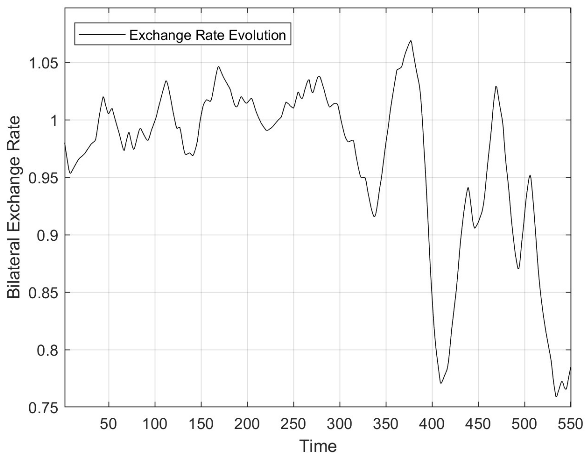

Figure 8: Bilateral exchange rate dynamics $s^{i,k}$.

With respect to this phenomenon, technical traders have a destabilizing effect on financial dynamics, amplifying fluctuations. To demonstrate this, we compare the duration and volatility of cycles in the nonlinear speculative switching model with those in the baseline model by Dosi, Roventi, and Russo (2019), which does not incorporate the financial nature of the exchange rate. We focus on fluctuations, obtaining bandpass-filtered series to identify cyclical components in our simulated exchange rate series (Baxter and King, 1999).[12] 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). In the left panel, Fig. 9 displays the cyclical trend of the exchange rate series, while the right panel highlights the achieved peaks. Table 3 compares the duration and volatility of cycles in the speculative model and in the baseline model.[13] The results 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 behavior is included in the analysis. Moreover, introducing trend-following behavior in the model increases the volatility of the exchange rate, resulting in more turbulent behavior in foreign exchange

[12] Bandpass-filtered (6,32,12) series.

[13] The analysis was also performed with the Hodrick-Prescott filter (Hodrick and Prescott, 1997). The default smoothing parameter of 1600 is suggested for quarterly data. The results obtained confirm the outcomes of the BP filter. Findings are available upon request.

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 model, highlighting the significance of chartists' behavior in understanding the exchange rate dynamics. Additionally, Fig. 10 displays the average weight of chartists over a fixed one-year window. As we can observe, agents tend to switch among different strategies. Moreover, together with switching phenomenon, our findings shed light on the persistence of chartism over time. To confirm it, Fig. 10 shows that 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).

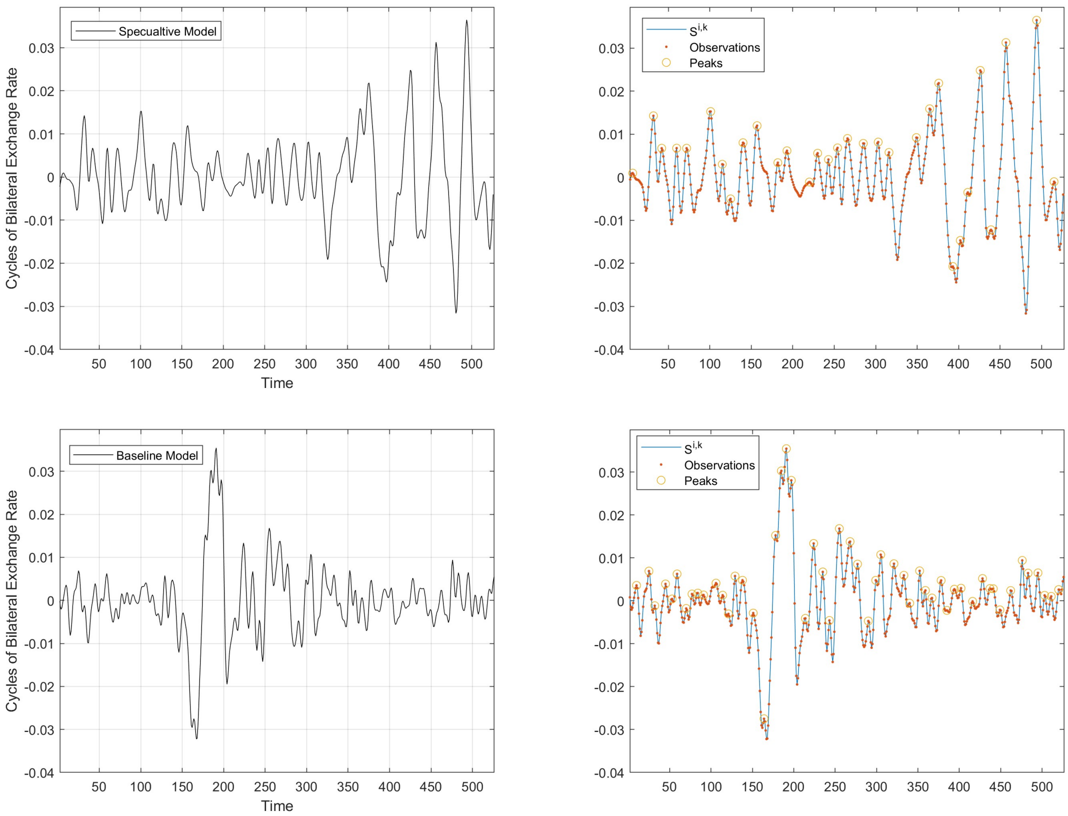

Figure 9: Cyclical component of the bilateral exchange rate (on the left) and peaks (on the right).

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: *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: $s^{i,k}_{MCDcycles}$ 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.

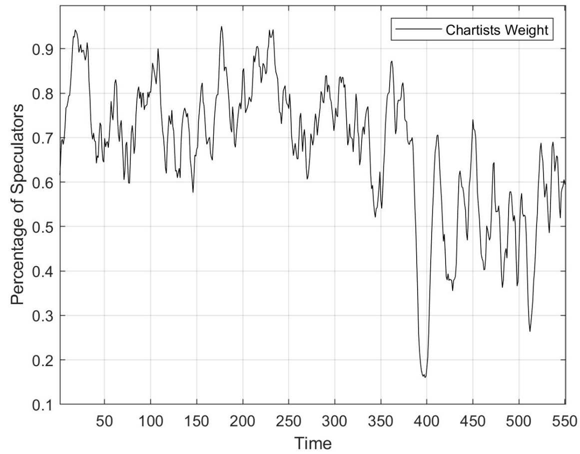

Figure 10: Percentage of chartists.

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. As shown in Fig. 11, the exchange rate can be close to PPP for many periods but can also deviate significantly. In other words, our model seems to generate the "disconnect" puzzle regularity (see SF 9).

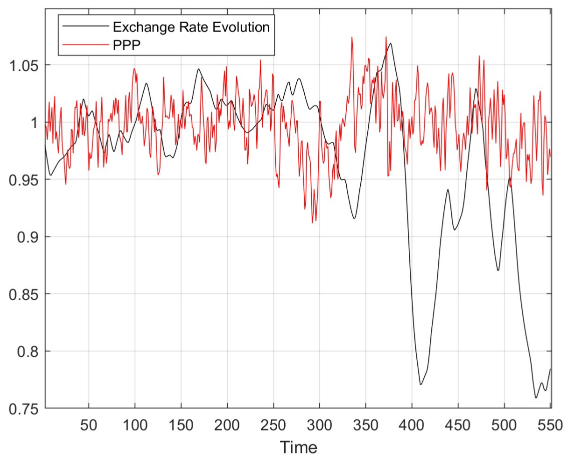

Figure 11: Bilateral exchange evolution vs. purchasing power parity.

However, the Monte Carlo analysis suggests long-run cointegration between the PPP series and the exchange rate. For this reason, as a next step, we specify an error correction model in the following way:

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

As evidenced in Table 5, the coefficient for error correction, λ_1, is found to be negative as expected but remarkably low, implying that the mean reversion process towards the equilibrium exchange rate generated by the presence of fundamentalists takes a very long time. On the other hand, λ_2 substantially impacts the current change in the exchange rate with a value equal to 0.3951. These results are consistent with empirical evidence that suggests the exchange rate is affected by its previous values considered by trend followers in the short-medium run.

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 can now concentrate our attention on real-financial interaction since the instability phenomena, previously found, do not remain only inside the financial sector but directly affect what happens in the real sphere of the economy.

As we can see from Table 6, the presence of speculative financial behavior generates a tendency toward more severe real aggregate fluctuations (SF 10).[14] From the table, the model with non-linear switching results in longer cycles (11 both for output and trade balance) compared to the baseline model (10 and 9 for output and trade balance respectively). As speculative behavior is eliminated, the bubbles and crashes become more short-lived. In addition, the volatility (as measured by the standard deviation) is higher in the model with speculative behavior. Specifically, the model with speculative behavior shows a standard deviation equal to 0.0426 for output and 0.0085 for trade balance, compared to the baseline model (0.0214 and 0.0044, respectively). As before, the obtained results are confirmed based on 200 Monte Carlo simulations. Specifically, for the trade balance, both the amplitude and volatility increase at a 1 percent significance level. For the real output, the increase is significant at 5 percent for volatility and 10 percent for the amplitude of the cycles.

In general, the fluctuations of exchange rates are wider than those of commercial flows. This may be due to the fact that speculative nature originates in financial markets compared to real ones, with subsequent propagation through the exchange rate. During the propagation process, the intensity of the phenomenon can decrease. This also explains the different degree of significance between the financial market (for bilateral exchange rate) and the real market (for output level).

Table 6: Descriptive statistics of cycles 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: *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.

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

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: $Y^i_{MCDcycles}$ 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.

What is interesting to observe is also the synchronization among real and financial variables. In fact, as a consequence of non-fundamental exchange rate movements, fluctuations phenomena can be observed in the real sector simultaneously with the financial fluctuations phenomena (SF 11). As evidenced from left Fig. 12, simultaneously to an increasing exchange rate variation as a consequence of the 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). On this point, see right Fig. 12 for the normalized trade balances of country 1.

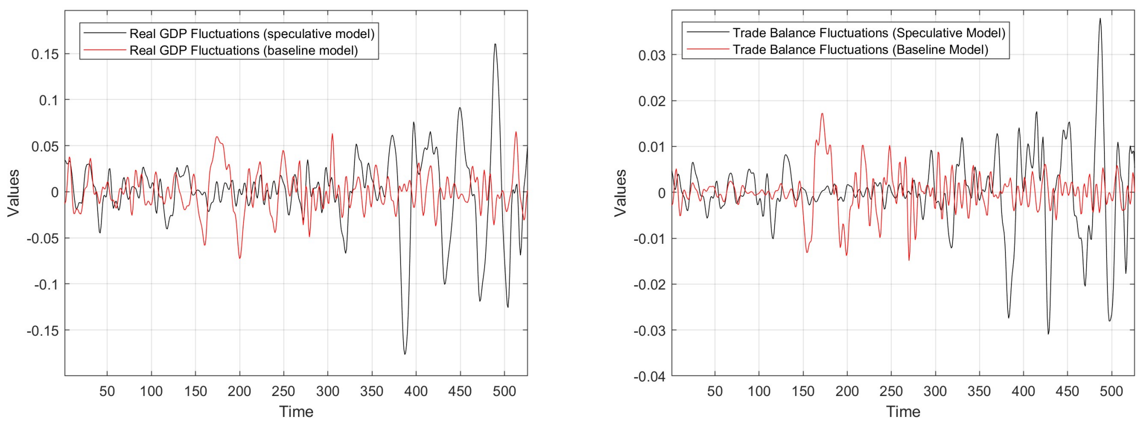

Figure 12: Cyclical dynamics of real GDP (left) and dynamics of trade balances (right) in the two scenarios for country i.

To summarize the results, financial instability, which emerges endogenously, can influence a country's growth process and its market share at the international level. In other words, the exchange rates become endogenous drivers of boom-bust cycles. In an evolutionary agent-based economy, we show that when a country's currency appreciates relative to other currencies, it becomes more expensive for foreign buyers to purchase goods from that country. This can lead to a loss of competitiveness for firms in a foreign country and a decline in export sales and output. The correlation between the exchange rate and trade balance is found to be -0.2983, while 0.1478 between trade balance and rate of growth of output. 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 chartists speculate following a positive trend, their behavior reflects into economic activity and the trade level, generating a more persistent upward process. When chartists speculate following a negative trend, the opposite is true, and behavior precipitates the economy into a more severe downturn.

4.2 Micro- and macro- open economy dynamics

After discussing the previous findings, we will now move on to explore them in an open economy perspective. According to simulation results, this model can account for a wide range of empirical regularities in an open economy. At macro level, exports and imports are found to be more volatile than output. For the three Monte Carlo simulated time series, once they are detrended, the standard deviation of output is 0.0032, while for exports and imports, we find values of 0.0049 and 0.0043, respectively (SF 13). Additionally, the three simulated time series shown in the figures below are all positively serially correlated, indicating persistence in their dynamics (SF 14).[15]

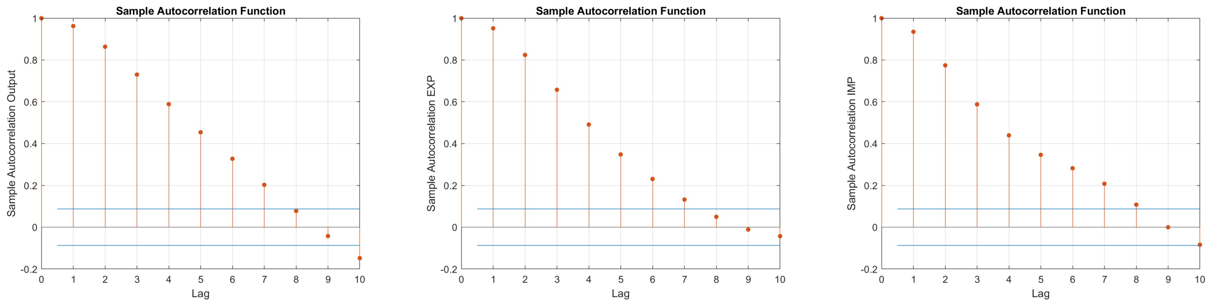

Figure 13: Autocorrelation functions.

At micro 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 differing dynamics in market shares (SF 16) (see Fig. 14), ultimately leading to substantial differences in firm sizes (SF 17).

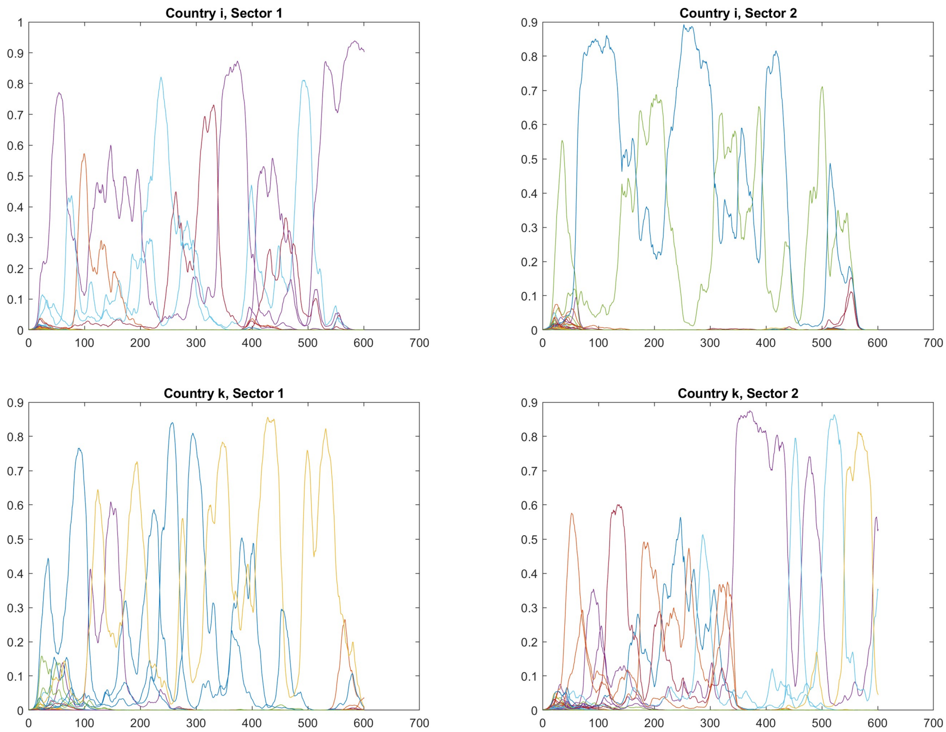

Figure 14: Firms' output share evolution in each specific country for each industry.

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

In fact, in accordance with SF 17, 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 that there are only a few successful large entities co-existing with numerous small businesses and normality tests suggest that firm log-size distributions are not log-normal (see Table 8). Meanwhile, the distribution of micro growth rates can be well approximated by a fat-tailed shape as evidenced by Fig. 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.

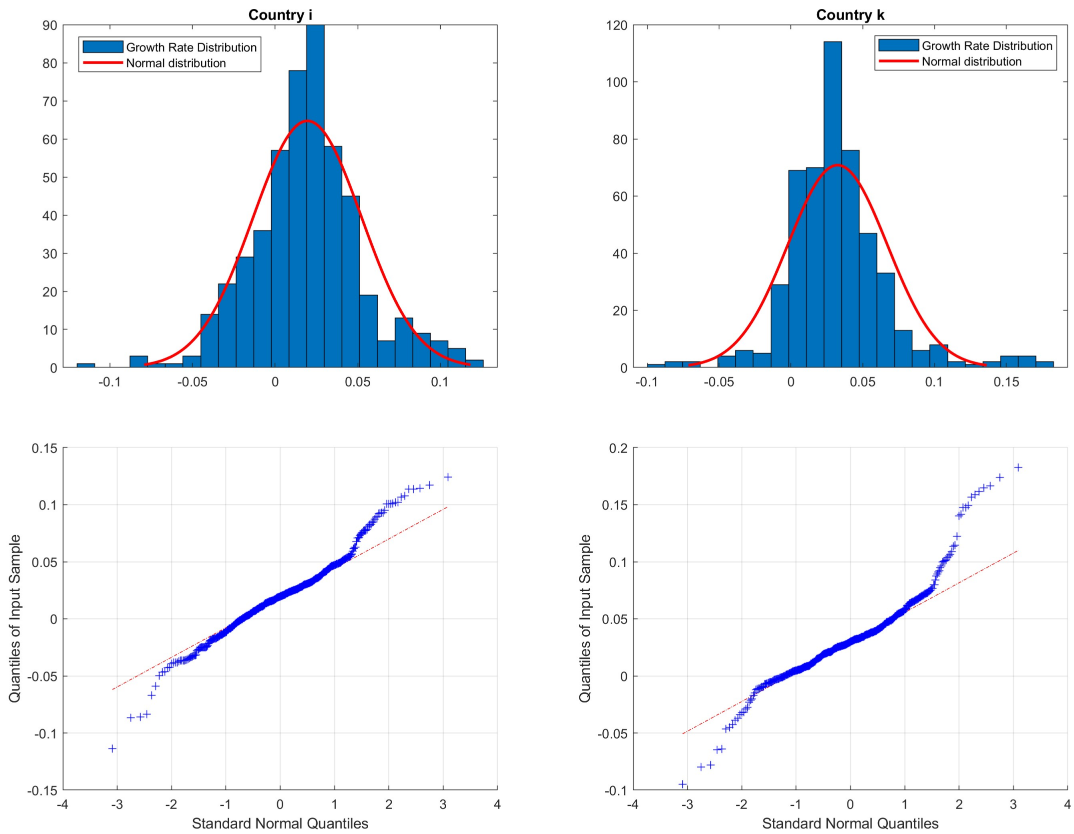

Figure 15: Firms' growth rates distributions (simulated density vs. normal fit in red)

Finally, the model successfully reproduces some observed patterns in firm-level dynamics at the international trade level. As depicted in the second column of Table 9, less than average portion of firms (35%) exports into foreign markets (SF 19).[16] Concurrently, empirical observations reveal that there are premiums linked to the export status (SF 20). Calculating premiums as the logarithmic ratio between the average foreign sales and productivity of exporting firms and non-exporting firms, columns two and three of 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. Country and sectors pooling.

		Exporters Premia	
	Share of Exp. (%)	*Productivity*	*Total sales*
Firms Level	0.35	1.0040	1.1303

4.3 Official intervention in FX market

At this point of the analysis, we examine the possible intervention of the central bank and its role in altering the dynamics of financial and macro variables. To investigate the potential impact of the intervention, we isolate cyclical components and scrutinize the characteristics of the cycles, employing the established array of parameters utilized in prior studies. Commencing with the first form of intervention, denoted as 'leaning against the wind' (referenced as Eq. 28), the Monte Carlo simulations outlined in Table 10 yield noteworthy outcomes. Notably, upon the central bank's intervention, there is a discernible decline in the proportion of chartists, averaging at 0.49 (Beine et al., 2009). This outcome is plausibly associated with the central bank's objective to stabilize exchange rates, thereby diminishing the profitability or perceived risk of speculative trading for chartists. If central bank actions effectively mitigate exchange rate fluctuations, chartists may perceive fewer avenues for speculative gains, prompting a reduction in their market presence or activity. Furthermore, central bank intervention introduces market uncertainty and risk, particularly if market participants view such actions as unpredictable or ineffectual. Consequently, chartists may adopt a more cautious or risk-averse approach to their trading strategies, thereby diminishing their share of market activity. Additionally, central bank intervention amplifies chartist volatility within the market (Gardini et al., 2024). This phenomenon is likely attributable to the introduction of market uncertainty and risk by central bank intervention, potentially culminating in heightened volatility as market participants react to evolving conditions. Moreover, alterations in market dynamics induced by central bank intervention could precipitate shifts in trading strategies among chartists, thereby potentially exacerbating market volatility.

Regarding the duration of cycles, a notable disparity emerges between the models with and without intervention. Specifically, the inclusion of official intervention results in a reduction in the duration of cycles for $s^{i,k}$. This phenomenon primarily stems from the capacity of central bank intervention to truncate the duration of exchange rate cycles by disrupting the feedback mechanisms that sustain prolonged trends (Fiess and Shankar, 2009). Through measures such as liquidity injection or interest rate adjustments, the central bank can counteract speculative momentum, thus impeding the persistence of trends over protracted periods. Central bank intervention signifies a commitment to stabilizing exchange rates and fostering economic equilibrium. This serves to manage the expectations of market participants and mitigate the magnitude of fluctuations in both exchange rates and trade balances.

Moreover, the findings indicate that central bank intervention can attenuate the amplitude of fluctuation phenomena concerning trade balances (Hsiao et al., 2012). Conversely, for output, no significant differences are discerned (Agénor et al., 2020). This observation can be elucidated through two plausible explanations: (1) Monetary Policy Transmission Lags: The influence of central bank intervention on output may operate

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

with a delay, not manifesting immediately. Changes in interest rates or exchange rates may necessitate time to impact investment and consumption decisions, thereby resulting in a deferred response in output fluctuations. (2) Other Economic Factors: Output fluctuations are shaped by a multitude of factors beyond mere exchange rate stability, encompassing domestic demand and productivity among others. Central bank intervention may not directly address these underlying factors, thus exerting a limited impact on the output cycle.

Simultaneously, the findings indicate that intervention fails to mitigate financial turbulence in exchange rates. This outcome is not unexpected, given that central bank intervention can exacerbate volatility in exchange rates by introducing market uncertainty (Dominguez, 1998; Saacke, 2002). Market participants may respond erratically to central bank actions, resulting in increased volatility as traders realign their positions in reaction to evolving market conditions. Indeed, the standard deviation is most pronounced among output and trade balance, indicating heightened volatility and uncertainty (see also Gardini et al., 2022). Specifically, 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.

To summarize, in the first scenario, when the central bank employs a leaning against the wind technique, its action clearly dampens the amplitude of cycles for exchange rate and trade balance. In spite of this, the intervention increases volatility phenomena underscoring the constraints of monetary policy as a tool for macroeconomic stabilization when dealing with agents who exhibit bounded rationality. In other words, the source of instability arises from the central bank's action in the context of speculative phenomena. This outcome highlights the inefficiency of central bank action when market operators move according to heuristic expectations. A similar result was obtained by Proano (2011), who, in a different theoretical context, demonstrated inefficiency in the presence of significant activity by chartists. Unlike Proano (2011), the intervention is not based on the standard Taylor type monetary policy rules but on direct intervention in exchange rate market.

Table 10 also provides a comparison of different models with a focus on the effectiveness of the second type of intervention ('leaning against the wind with a short-run target', Eq. 29). The results suggest that the switching model and the model with an intervention have very similar outcomes, with no statistical difference. 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.

Table 10: Comparison of the models with the two official interventions.

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.

The first intervention reveals that the central bank may encounter a series of trade-offs. Among them, in analyzing the intervention of the central bank among different scenarios, it becomes crucial to examine the effects generated on wealth accumulation within the financial market. 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[17]:

$$W^{\phi}(t+1) = W^{\phi}(t) + \left[s^{i,k}(t) - s^{i,k}(t-1)\right]\left\{\sum_{\phi=1}^{\Phi} \omega^{\phi}(t)\mathrm{E}^{\phi}(t)\left[s^{i,k}(t+1) - s^{i,k}(t-1)\right]\right\} \tag{35}$$

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.

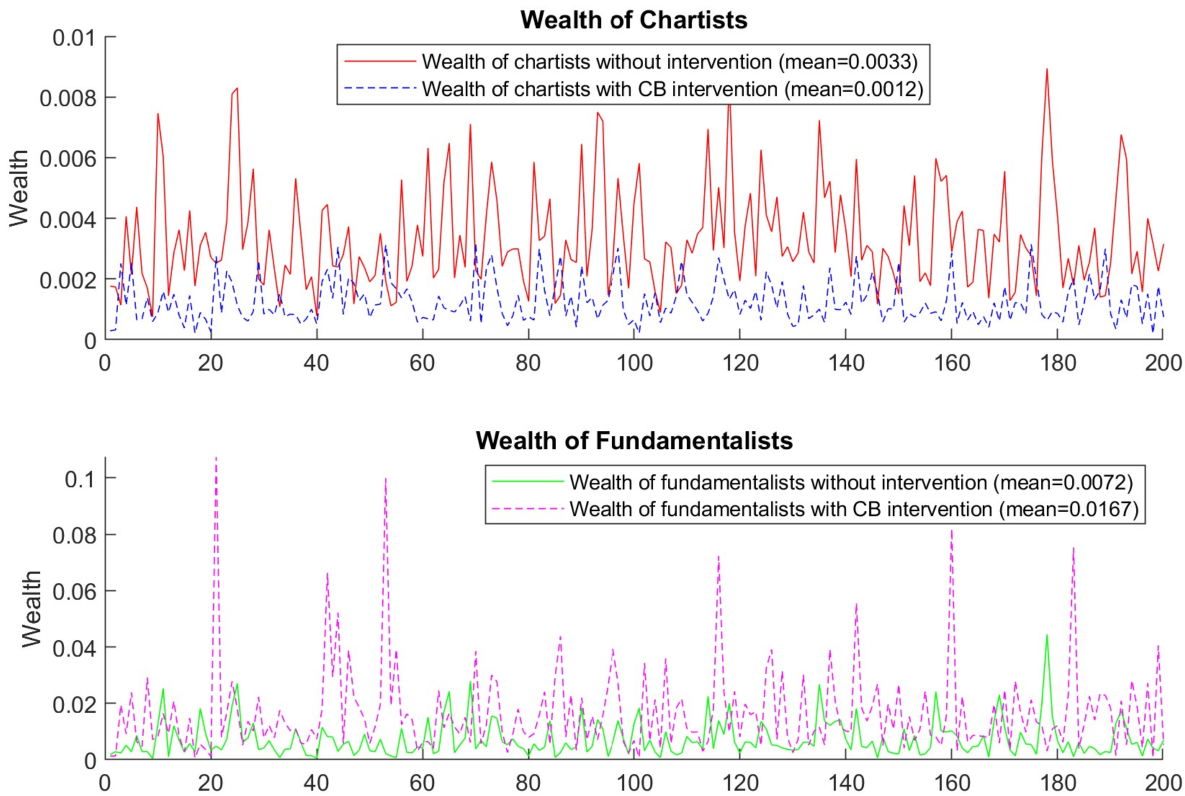

Figure 16: Dynamics of accumulated wealth with and without intervention of central bank. Results from 200 MC replications.

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

5 Conclusions

This work expanded the multi-country, multi-sector K+S model to highlight the importance of considering speculative FX trade expectations in an open economy structure. This is important for understanding the dynamics of exchange rate market and its impact on the real side of the economy.

With the introduction of speculative sentiments, our model was able to replicate important stylized facts regarding the dynamics of the exchange rate in a multi-country structure. In particular, we showed that the exchange rate market can be the source of endogenous instability which is reflected in a more persistent and higher volatility of financial cycles. At the same time, since exchange rates are a transmission variable for shocks, it was highlighted how a strong relationship exists between the financial and real components. We found that the influence of heuristic expectations on exchange rate dynamics can propagate to business cycle dynamics. In particular, chartists' behavior can increase fluctuations in exchange rates which in turn can impact a country's economic growth at the international level. Finally, we showed that the central bank's intervention is an essential tool for reducing instability phenomena in the exchange rate and real market. However, the analysis of these scenarios underscores the complexity of central bank interventions and their varied impacts on real-financial markets. In fact, for different types of intervention, different results are obtained. In the first scenario, the central bank effectively reduced the percentage of chartists by employing a "leaning against the wind" technique. This decline can be attributed to the central bank's efforts to stabilise exchange rates, which reduces the profitability or perceived risk of speculative trading for chartists. Additionally, central bank intervention reduces the duration of exchange rate cycles by disrupting the feedback mechanisms that sustain prolonged trends. The findings also indicate that central bank "leaning against the wind" intervention can attenuate the amplitude of fluctuations in trade balances, although there is no significant impact on output fluctuations. This may be due to monetary policy transmission lags and other economic factors not directly addressed by exchange rate stability. However, despite these potential benefits, central bank intervention fails to mitigate financial turbulence in exchange rates and, in fact, exacerbates volatility. This increase in volatility is due to the introduction of market uncertainty, leading to erratic responses from market participants. This outcome underscores the constraints of monetary policy as a tool for macroeconomic stabilisation when dealing with agents who exhibit bounded rationality. In the alternative scenario, "leaning against the wind with a short-run target", the central bank's sporadic intervention failed to achieve the desired reduction in instability, with a non-significant reduction in the share of chartists and market volatility compared to the baseline outcome. This highlights the importance of accurately chosen targets.

The model can be extended along different research avenues. Firstly, expectations can be formalized differently: we could introduce other heuristic formations and study their effect on the dynamics of the exchange rate in an open economy context. Secondly, additional complexity can be introduced on the international trade side by allowing for a vertically integrated structure and distinguishing between stages of the production process. In this setting, the inclusion of capital flows between countries would further enrich our analysis. Thirdly, our model is initialized as fully homogeneous, with no geographical or technological differences across the two countries. In future research, it would be interesting 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, understanding how the exchange rate and its behavioral components impact the competitiveness of businesses abroad and influence macroeconomic variables is essential for policymakers. In other words, understanding the linkages between the financial sector and the real economy is crucial for designing effective policy interventions and promoting sustainable and inclusive growth. For this reason, fiscal policy could be introduced to have a bigger picture of the problem. We leave these ideas for future research.

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

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