UNIVERSIDADE DE SÃO PAULO
FACULDADE DE ECONOMIA, ADMINISTRAÇÃO, CONTABILIDADE E ATUÁRIA
DEPARTAMENTO DE ECONOMIA

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Essays on the pricing behavior of firms using an agent-based modeling approach

Ensaios sobre o comportamento de formação de preços das firmas usando uma abordagem de modelagem baseada em agentes

São Paulo
2023

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Tese apresentada ao Programa de Pós-Graduação em Economia do Departamento de Economia da Faculdade de Economia, Administração, Contabilidade e Atuária da Universidade de São Paulo, como requisito parcial para a obtenção do título de Doutor em Ciências.

Área de Concentração: Economia do Desenvolvimento
Orientador: Prof. Dr. Gilberto Tadeu Lima

Versão corrigida

(versão original disponível na Biblioteca da Faculdade de Economia, Administração, Contabilidade e Atuária)

São Paulo

2023

Catalogação na Publicação (CIP)
Ficha Catalográfica com dados inseridos pelo autor

Schiozer, Nikolas Alexander van de Bilt.
Essays on the pricing behavior of firms using an agent-based modeling approach / Nikolas Alexander van de Bilt Schiozer. - São Paulo, 2023.
243 p.

Tese (Doutorado) - Universidade de São Paulo, 2023.
Orientador: Gilberto Tadeu Lima.

1. Pricing behavior of firms. 2. Strategic behavior of firms. 3. Agent-based modeling . I. Universidade de São Paulo. Faculdade de Economia, Administração, Contabilidade e Atuária. II. Título.

Com saudades, pro meu vô e meu opa.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to all the institutions that funded my PhD studies. I would like to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), under grant #156838/2018-4, for funding almost all of my PhD period, the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), under grant #88887.576886/2020-00, for funding my stay in Pisa, Italy, and the Research Center on Macroeconomics of Inequalities (Made).

I am also deeply indebted to my supervisor, Gilberto Tadeu Lima. He was the main person who encouraged me to pursue doctoral research in the area of ABM. In addition, he was responsible for introducing me to much of the literature that inspired the main chapters of my dissertation. Furthermore, I owe him the opportunity to conduct my sandwich research, which was a crucial period for the final result of my dissertation. Lastly, I am deeply grateful to him for his enormous patience in attentively reviewing the entire text and for helping me with my English.

I am extremely grateful to Andrea Roventini. Andrea was not only an excellent supervisor at Sant'Anna, but he also received me extremely well and was always helpful when needed. Our conversations about the articles in this dissertation, including the modeling techniques used, flaws and strong points, and potential improvements, were helpful, stimulating, and really pushed me to improve the work. I would also like to thank other professors whose conversations and interactions in Sant'Anna made the research better, Giovanni Dosi and Francesco Lamperti.

I would like to extend my sincere thanks to all the professors at FEA whom I encountered during my PhD program. Laura Carvalho and Fernando Rugitsky made many excellent comments on the first drafts of my dissertation and gave me excellent courses.

Michel Alexandre, not from FEA but introduced to me by Gilberto, acted almost as a co-supervisor by providing valuable comments and feedback throughout various stages of my research and reading multiple drafts of my dissertation. I would also like to thank Fernando and Claudio Lucinda for their good experiences as supervisors of the two courses that I monitored. Other professors for whom I am grateful for the courses offered are Marcio Issao Nakane, Naercio Menezes Filho, Pedro Duarte Garcia, and Renato Perim Colistete. Lastly, Pinho, the head of the graduate office of the Department of Economics, was always helpful, especially during the pandemic times.

I also nead to mention the friends and colleagues I met at FEA who made the whole experience of the doctorate, which was often challenging, better. I had the glad opportunity to have as colleagues and friends during the PhD courses David, Duda, Eduardo, Jéssica and Pedro. I also always enjoyed experiences with all the colleagues and friends from Made. I especially thank João Marcolin and Matias Cardomingo for the help with the research that I carried out at there.

My friends, Lilian Rolim, Mariana Maria, and Mariam Attala, were super important during my period in Italy. With them, I had great conversations that also benefited the final research. Besides, their company in Italy made the whole experience much better.

The pursuit of a PhD would not have been possible without the unwavering support of my family. I extend my heartfelt gratitude to my father, Wandir, and mother, Liedewij, for their unconditional love and support. My brother, Lucas, and sister, Stefanie, have been pillars of friendship. I would like to thank my grandmothers, Jeannette and Wanda, for their kindness and care, sources of strength for me. To my grandfather, Theodorus, I thank for our deep and always enjoyable conversations. Lastly, I thank my other grandfather, Dayr, for his unwavering and enthusiastic support since the very beginning. I am sure that no one would be happier than Dayr in seeing me finally finishing this PhD.

Finally, I would not have been able to complete this journey without the support of my partner, Giuliana. I cannot express in words how essential she was in making this dissertation a reality.

All remaining flaws, mistakes, and typos in this dissertation are solely my responsibility.

This dissertation was written in LaTeX using the IAGTESE class, for theses and dissertations at IAG.

"*How markups move, in response to what, and why, is however nearly terra incognita for macro. . . we are a long way from having either a clear picture or convincing theories, and this is clearly an area where research is urgently needed.* "

Olivier Blanchard

"*... we need to have a price theory that is consistent with our basic presumption that economies are always changing.* "

Richard Nelson

Resumo

A decisão de precificação das empresas desempenha um papel crucial na determinação da competitividade dos bens, dos lucros das empresas e do impacto macroeconômico na economia. Esta tese é composta por um prólogo e três ensaios que visam fornecer insights sobre o comportamento de preços das empresas e seu impacto na economia. O primeiro ensaio apresenta um modelo híbrido DSGE-ABM que considera a informação limitada das empresas sobre as condições de mercado e sua contínua adaptação de estratégias de preços. O segundo ensaio investiga a persistência da heterogeneidade heurística entre as empresas e por que elas não convergem para uma única heurística de preços ideal. O terceiro ensaio explora a questão da rigidez de preços de perspectivas micro e macroeconômicas. O estudo argumenta que um processo evolutivo de seleção de heurísticas de preços pode desempenhar um papel na explicação do porquê as empresas tendem a manter seus preços o mais estáveis possível. Os resultados contribuem para a literatura fornecendo insights sobre o comportamento de preços das empresas, destacando a importância de considerar a heterogeneidade entre empresas nos modelos macroeconômicos e têm implicações para pesquisas futuras sobre os impulsionadores dos ajustes de preços e o impacto da política econômica.

Palavras-chave: Comportamento de formação de preços das firmas, Comportamento estratégico das firmas, Modelagem baseada em agentes.

JEL: E3, L1, C63

Abstract

The pricing decision of firms plays a crucial role in determining the competitiveness of goods, company profits, and the macroeconomic impact on the economy. This thesis consists of a prologue and three essays that aim to provide insights into the pricing behavior of firms and its impact on the economy. The first essay presents an hybrid DSGE-ABM model that considers the limited information of firms about the market conditions and their continuous adaptation of pricing strategies. The second essay investigates the persistence of heuristic heterogeneity among firms and why they do not converge to a single optimal pricing heuristic. The third essay explores the issue of price stickiness from both micro and macroeconomic perspectives. The study argues that an evolutionary process of selection of pricing heuristics may play a role in explaining why firms tend to keep their prices as stable as possible. The findings contribute to the literature by providing insights into the pricing behavior of firms, highlighting the importance of considering heterogeneity among firms in macroeconomic models, and have implications for future research on the drivers of price adjustments and the impact of economic policy.

Keywords: Pricing behavior of firms, Strategic behavior of firms, Agent-based modeling

JEL: E3, L1, C63

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Summary

Chapter 1

Introduction

The pricing decision of firms is a crucial factor that significantly impacts the competitiveness of goods sold by companies and the overall economy. The microeconomic impact of pricing decisions determines the competitiveness of goods sold by companies, affecting their profits, while the macroeconomic impact directly affects the functional income distribution, the inflation rate, and indirectly affects the entire economy. Despite its importance, the pricing behavior of firms is a complex decision that is still not fully understood. This is also due to the fact that these decisions involves a wide array of environmental information. Therefore, the precise process of how firms incorporate different information into their prices, how pricing decisions evolve over time, or how they depend on the environment, remain as open questions. In addition, how the micro behavior of firms affects the overall behavior of the system is still not completely clear.

The complexity of pricing decisions observed through different empirical sources of data has led economists to conclude that economic theory has not yet fully comprehended how pricing decisions are made. For instance, Blanchard (2009) noted that the economic theory's understanding of how markups move and in response to what is still mostly unknown. In turn, markups are a key variable to explain the behavior of prices. Macroeconomic theories, including both mainstream and heterodox approaches, typically consider the markup as a fixed, exogenous component or determined by a given, constant, market concentration. Not many articles dealing with macroeconomic issues have addressed the analysis of economic dynamics considering the possibility that markups are heterogeneous and liable to vary over time. As such, further research is needed to fully understand the mechanisms underlying pricing behavior and their macroeconomic impact.

It could be contended that the limited comprehension of pricing behavior is a deficiency specific to the mainstream economic approaches. Nonetheless, as posited by Nelson (2013), evolutionary economics lacks a coherent price theory that is compatible with the concept that markets are in a perpetual state of transformation. According to Nelson (2013), many evolutionary economist use many of the ideas and framework of the pricing theory of the neoclassical approach. However, this is regarded as peculiar since many of the neoclassical pricing assumptions conflict with numerous evolutionary assumptions. Essentially, still according to Nelson (2013), the unrelenting fluctuation in the environment makes it impossible for economic agents to optimize or to drive markets towards a neoclassical equilibrium.

In a similar vein, Dosi and Virgillito (2021) put forth the notion that contemporary economies must be viewed as complex adaptive systems emerging from the interplay of coordinating mechanisms and drivers of change. Despite the perpetual evolution of the system, there are forces at work that keep the system together, (imperfectly) coordinating the agents. Among the attributes of such imperfect coordination in modern market economies, the behavior of prices is cited as one of them Dosi and Virgillito (2021).

In contrast to the use of the term coordination, Nelson (2013) instead employs the notion of an "orderly market"as the mechanism that coordinates decisions among heterogeneous agents. The orderly market is characterized by a set of routines that are established over time and employed by potential buyers and sellers, resulting in satisfactory transactions for most parties on both sides of the market. According to Nelson (2013), the order of the market may persist despite changes in prices, demand, or supply conditions, although this order is constantly being changed and affected by the agents participating in the markets. For example, new technologies may disrupt the market order by changing the behavior of customers or suppliers. A market that becomes completely disorderly is a market in crisis, as seen in financial market crises. The study of the coordination mechanisms of modern economies, particularly that of orderly markets, as framed by Dosi and Virgillito (2021) and Nelson (2013), is complex and "less easy to model"(Nelson, 2013, p. 31).

The solution presented in Dosi and Virgillito (2021) to formalize and study modern economies and complex dynamic systems is through the use of agent-based models (ABMs). ABMs, as per the concise definition by Tesfatsion (2006, p. 835), refer to "the computational study of economic processes modeled as dynamic systems of interacting agents".

According to Richiardi (2018), ABMs are models comprising multiple agents that interact within an environment (i). These agents are autonomous (ii), using decision-making rules that are specific to each individual. Finally, ABMs are solved numerically (iii). With these three characteristics, Richiardi (2018) differentiates ABMs from other economic model classes and approaches used in evolutionary economics or complexity theory.

This class of models in macroeconomics began to emerge in the early 2000s (Cincotti et al., 2022). These models explain the behavior of macroeconomics aggregates as the outcome of the interactions of heterogeneous agents (such as firms, customers, and banks) making a plethora of decisions to produce and exchange a wide variety of goods. Notably, the agent-based macroeconomic models deal with what actually happens within economic organizations for modeling their individual behavior (Dosi and Roventini, 2019). Consequently, the macroeconomic behavior of the economic system can be regarded as a genuinely emergent property. Since the beginning of the development of the agent-based macroeconomic models, several families of models have been developed (Dawid and Delli Gatti, 2018). However, as we will argue in chapter two, there is still ample scope for the incorporation of the endogenously time-varying heterogeneity in pricing behavior of firms in the agent-based macroeconomic literature.

The present dissertation consists of chapters that aim to contribute to the understanding of the pricing behavior of firms and its macroeconomic implications. To achieve this goal, we followed the evolutionary approach of Nelson (2013) and the suggestion of Dosi and Virgillito (2021) for the study of complex dynamic systems, which are especially appropriate for studying how the micro behavior of agents affects and is affected by the aggregate behavior of economic systems (Dosi and Roventini, 2019). Therefore, we employed agent-based macroeconomic models. In the rest of the introduction, we will present how the dissertation is organized.

The second chapter summarizes the range of stylized facts pertaining to pricing pricing behavior by firms. Specifically, we review the literature that has examined the micro-data of consumer price index from diverse countries around the globe. Additionally, we explore a second category of stylized facts that are derived from surveys conducted with firm managers. The empirical literature in this regard sheds light on several stylized facts that macroeconomic models focused on prices should be expected to replicate. Subsequently, we proceed to provide an overview of how agent-based macroeconomic models have endeavored to formalize the price determination process of firms. This involves a critical evaluation of the strengths and limitations of the existing modeling approaches in light of the aforementioned stylized facts.

The survey on how firms set prices and the statistical moments observed in micro-data of consumer price indexes reveals several stylized facts that are often overlooked in most agent-based macroeconomic models, and even in macroeconomic models in general. The primary objective of this thesis is to examine whether different models can replicate some of these pricing stylized facts. It is important to observe that the same stylized fact can be tested if is replicated using different models. Consequently, we have the opportunity to investigate the same topic from various perspectives and with different analytical tools. The subsequent chapters of this thesis aim to explore the dynamics of pricing behavior through the utilization of different models, in order to assess their ability to replicate various stylized facts.

In chapter three, in the form of an essay, it is presented a hybrid DSGE-ABM model. DSGE stands for "dynamic stochastic general equilibrium". The model considers that firms have limited information about market conditions and can continuously adapt their pricing strategies. The study allows firms to evaluate multiple dimensions of their pricing heuristics and decide which pricing rule to adopt, such as following competitors' prices or adopting cost-based rules with fixed or flexible markup. It assumes that the behavioral parameters of firms are endogenous, and the macroeconomic results are endogenously derived from a co-evolutionary interaction of macro and micro variables. The model does not impose any restrictions on firms adopting fully flexible strategies or a unique pricing strategy. The sensitivity analysis reveals that the heterogeneity in pricing heuristics among firms is a persistent emergent phenomenon, and prices tend to be sticky. These outcomes are emergent properties and are not assumed or imposed a priori by the model.

Chapter four, the second essay of the dissertation, investigates the persistence of heuristic heterogeneity among firms. The chapter presents an agent-based macroeconomic model with a standard structure found in most macroeconomic ABM families (Dawid et al., 2019). The model includes firms that are consumer goods' producers, a firm producer of capital goods, households (divided into workers and capitalists), a government, a banking sector, and a central bank. The innovation of the model is the consideration that consumer goods firms may utilize one of four different heuristics for setting markups and to switch between them based on their relative performance. The findings indicate that there is no evidence of convergence to a single heuristic among firms, and a persistent heterogeneity in heuristics is observed. It is also observed that the performance of markup strategies is cyclical and co-evolves with the business cycle.

In the final chapter of the dissertation, where the last essay is presented, it is explored the issue of price stickiness from both micro and macroeconomic perspectives using an agent-based macroeconomic model. It is shown that that an evolutionary process of selecting pricing heuristics may explain why firms tend to keep their prices stable. The study demonstrates that the ABM can replicate various macro- and micro-stylized facts, including micro-stylized facts not previously addressed in the macroeconomic literature using ABMs. The results suggest that pricing heuristics that make prices more rigid are favored in the consumer goods market. Additionally, it is conducted a sensitivity analysis to test the robustness of the results by changing the values of key parameters and discussed the policy implications of the main findings.

Chapter 2

Pricing behavior of firms: empirical evidence and incorporation in agent-based macroeconomic models

The purpose of this chapter is to offer a comprehensive overview of the literature, encompassing the empirical and theoretical perspectives, that serves as the foundation for the present dissertation. The central theme that guides this dissertation is the pricing decisions of firms and their macroeconomic implications. In the following section, we present a survey of the empirical data that demonstrates what can be inferred about the pricing of firms from micro-data of the consumer price indexes from various countries around the globe. Additionally, we provide the findings of numerous surveys conducted among firm managers in different economies, with the aim of understanding the factors driving and influencing pricing decisions. In the subsequent section, we conduct a review of the agent-based macroeconomic modeling literature, emphasizing the various ways in which the pricing decisions of firms have been modeled.

Therefore, this chapter bridges the gap between two seemingly disconnected topics, namely the empirical evidence on price behavior derived from consumer price indexes and the modeling of pricing decisions within agent-based macroeconomic frameworks. By examining both empirical and theoretical perspectives, we can develop a more holistic understanding of the pricing decisions made by firms and their broader implications on macroeconomic dynamics.

2.1 Empirical results

In the last decades, many articles have been published using micro-data to explain the price-setting behavior of firms. Besides, many surveys with firms were conducted to better understand how firms set their prices and the major causes and factors they consider at the moment of decision. In this section, we reviewed a representative sample of these articles, presenting the general conclusions of this empirical literature.

2.1.1 Evidence on pricing patterns from micro-data

The literature that empirically investigates the micro-data of price setting by firms normally has the goal to discover the main facts about this phenomenon to explain and quantify the stickiness of prices (Alvarez et al., 2006), given its importance for business cycles, welfare, the behavior of real exchange rate, among other topics (Ball and Romer, 1989; Levy et al., 1997; Nakamura and Steinsson, 2013). This literature justifies the investigation of prices micro-data and surveys realized directly with firms as a way to identify the presence of price stickiness, formalized through many standard macroeconomic models, and to provide micro-evidence to calibrate macroeconomic models (Nakamura and Steinsson, 2013).

Although this literature considers more standard macroeconomic models, we argue that it provides empirical evidence of heterogeneous behavior in price setting and that this decision is determined by many interactions that occur between different agents. As we will see, to determine prices, firms consider their cost structure, the frequency of change of input cost, and the possible behavior of their consumers and competitors, among other variables. All of this empirical literature provides evidence of behavior that can be incorporated into models, especially if they aim to better describe the behavior of price indexes. Next, we review some stylized facts concerning pricing behavior that were identified in different regions.

The first fact is about the frequency of price changes. Considering the micro-data from the consumer price index (CPI) in the United States (US), normally, only 10% of prices change each month depending on the period of the year (Nakamura and Steinsson, 2008). This corresponds to a price duration of eight to eleven months (Blinder, 1991; Nakamura and Steinsson, 2008; Klenow and Malin, 2010). If sales are considered, between 19% and 20% of prices change each month. In the European Union, including the sales, around 15% of the prices of the consumer goods change each month (Alvarez et al., 2006; Fabiani et al., 2005; Druant et al., 2009), resulting in a duration of approximately one year. In Brazil, the frequency with which price changes are higher compared to the US or Europe.

The average price duration in Brazil is only 3.3 months (Correa et al., 2018)

About 21% of price changes in the whole sample of the American CPI can be considered as sales (Nakamura and Steinsson, 2008). Temporary price discounts and product turnover often play an important role to determine the price flexibility of the goods (Bils and Klenow, 2004; Klenow and Malin, 2010). When sales are considered, the frequency of price adjustments is much higher for consumer goods. This happens because sales are common in retail markets, while in wholesale the buyers and sellers tend to enter long-term relationships.

There is a considerable degree of heterogeneity in the frequency of regular prices changing among sectors within the economies (Alvarez et al., 2006; Fabiani et al., 2005; Alvarez et al., 2006; Fabiani et al., 2005; Correa et al., 2018), with the distribution of frequency of regular prices exhibiting a pronounced right-skewness (Nakamura and Steinsson, 2008). Fresh food, energy, and airfares, for example, represent goods that experience changes in price at least once a month, while medical care services exhibit much less frequent changes in price (Klenow and Malin, 2010). These observations serve as another evidence of the substantial variability in price-setting behavior, likely due to the high level of heterogeneity in the factors determining the frequency of price change.

Klenow and Malin (2010) reports a positive correlation between the durability of the goods and their price flexibility, with this having important effects over the business cycles, probably explaining why the expense in durable goods (more rigid) tends to be more cyclical. Moreover, the higher the degree of competition, the higher the frequency of price changes. This is seen in Brazil, Europe and US (Fabiani et al., 2005; Klenow and Malin, 2010; Correa et al., 2018). Druant et al. (2009) shows that larger firms in the European Union reported adjusting prices more frequently than smaller ones. Also, in Brazil, Europe, and the US, the larger the type of establishment in which goods are sold, the more flexible the consumer prices are.

Alvarez et al. (2006) affirm that the price flexibility of the goods is related to the sophistication of the products and the volatility of the respective input prices. Differences in cost structure helps to explain the degree of price flexibility. Labor intensity negatively affects the frequency of price adjustments, given that wages normally are readjusted only once a year, while sectors energy-intensive tend to change their prices more frequently. Druant et al. (2009) econometrically demonstrate that firms with higher labor cost-share and with a larger share of white-collar workers have stickier prices. They also demonstrated that the frequency of wage adjustments is much more homogeneous among sectors. Druant et al. (2009) shows that there is evidence of synchronization between wage and price adjustments over time.

Inflation is the most important factor that triggers wage adjustments according to surveys of firms. The general conclusion is that wage and price changes feed into each other at the micro-level and there is a relationship between wage and price rigidity. When the frequency of price adjustment is controlled by the cost structure, much of the sectoral heterogeneity in the price frequency adjustment disappears.

Disaggregating the Brazilian data by sector, Correa et al. (2018) shows that the costs of intermediate goods are considered very important for commerce and industry to drive their price changes. However, while for the first two sectors wages are not as important, for the service sector, this is considered the most important item. This shows, not surprisingly, that the degree of importance of the items listed in the survey depends on the composition of firms' costs and the characteristics of the market in which they operate. For an aggregate inflation index, the importance of each factor will depend on the weight that the products produced by each sector have in the basket used to infer the inflation rate. In conclusion, another stylized fact is that price changes are linked to wage changes (Klenow and Malin, 2010).

Another fact is about the general tendency of the signal of price changes. In the US, only one-third of non-sale price changes are price decreases, showing a considerable degree of nominal downward price rigidity. However, as Nakamura and Steinsson (2008) points out, most models of price rigidity consider that almost all price changes are increases. However, prices decreases should not be disregarded. In Europe, around 40% of the consumer price changes and 45% of the producers' price changes in the data are decreases. However, Alvarez et al. (2006) does not consider the existence of price sales as Nakamura and Steinsson (2008), possibly explaining the higher quantity of price decreases. Possibly for the same reason, Alvarez et al. (2006) mentions that there is a sectoral heterogeneity in the stickiness of prices. Sectors with higher price frequency tend to present more decreases in prices. Sectors that usually do not register sales, like services, tend to have more price increases. In Brazil, Gouvea (2007) documents that approximately 54% of price adjustments are price increases, suggesting some degree of nominal downward price rigidity as well.

Related to the previous fact, not only price changes are lumpy because they remain unchanged for months, but also prices change by large amounts (Alvarez et al., 2006; Fabiani et al., 2005; Nakamura and Steinsson, 2008; Klenow and Malin, 2010; Correa et al., 2018). When considering only regular price changes in the US, the average change is 8.5%. The average increase is of 7.3% and the average decrease is of 10.5%. In the case of sales, the average of the decreases is 29.5%. In the European Union, on average the increases are 8.2% and decrease 10%. This is observed even in sectors with a higher frequency of price change. In Brazil, in terms of size, the average price increase is 16% and the decrease is 13% (Correa et al., 2018). Therefore, another common characteristic in the price dynamics of Brazil, Europe, and the US is the magnitude of price changes. When they change, it is by a large amount.

The high average price changes do not mean that small price changes never occur. Klenow and Kryvtsov (2008) reports that 44% of the regular price change in the US CPI is smaller than 5% in absolute value. The point is that a macroeconomic model that is concerned with price dynamics should be able to reproduce this heterogeneity in the size of price changes.

Despite the low levels of inflation observed in Europe and the US, it is unlikely that price changes higher than 5% are merely adjusting to keep up with inflation. Rather, many of these changes are likely attributable to idiosyncratic shocks and sector-specific considerations, rather than solely reflecting aggregate shocks Klenow and Malin (2010). Meanwhile, the frequency of regular price increases is strongly positively correlated with inflation (Nakamura and Steinsson, 2008; Klenow and Malin, 2010), and this relationship is statistically significant. As inflation rates increase, price adjustments become more synchronized, with the frequency of price increases also rising in response. However, there is no discernible relationship between inflation and the frequency or magnitude of price decreases (Nakamura and Steinsson, 2008).

Sellers do not seem to synchronize their adjustments in response to monetary shocks or over the business cycle (Klenow and Malin, 2010). However, the lack of synchronization does not necessarily indicate that strategic complementarities are not a crucial factor in the price-setting process. Rather, it may reflect the importance of strategic complementarities, which could slow down the frequency of price adjustments as price-setters wait for the reactions of other prices, including those of their competitors and input suppliers. Despite this lack of synchronization, relative prices are found to be transitory in nature, even after accounting for sales. In fact, Klenow and Malin (2010) review articles that indicate that grocery stores tend to abandon extreme relative prices quickly, rather than waiting for other sellers' price adjustments.

In a study by Araujo (2019), using a dataset from the city of São Paulo in Brazil, the relationship between inflation and relative price variability was analyzed for two periods: 1989-1993, characterized by high and unstable inflation, and 1995-2007, a period of low and stable inflation. The study found that inflation had a positive impact on the relative price variability in markets of the same goods. During the period of high inflation, on average, 80% of prices changed every month, with most prices increasing. Surprisingly, even with an inflation rate of more than 25% per month, on average, 6% of prices decreased. The average size of the change was 27.8%, higher than the inflation rate.

In the period of stable inflation, the average frequency of price changes decreased to 37%, resulting in a price duration of 2.2 months. Roughly 35% of the changes during this period were decreases. Increases had an average size of 8%, while decreases had an average size of 10%. Therefore, as in other regions, decreases tended to be almost as frequent as increases and have a larger size. From Araujo (2019), we concluded that another stylized fact is that different macroeconomic environment's lead to different degrees to price stickiness.

Finally, there is little evidence of upward-sloping hazard functions of price changes for individual products (Nakamura and Steinsson, 2008; Klenow and Malin, 2010). In other words, the probability of price to change does not increase with time. There is evidence using micro-data of consumer and producer prices that hazard functions for price changes are decreasing (Alvarez et al., 2005). Using state-dependent models, it would seem intuitive to assume that the hazard of price changes increases over time as a result of accumulating shocks that drive the desired price further away from the current price. By contrast, under a time-dependent model, the expectation would be that the size of price changes increases with the duration of the price. The little connection between the duration of prices and the size of price changes, according to Klenow and Malin (2010), the limited relationship between price duration and the size of price changes, could suggest that firms are not adjusting their desired prices significantly. Alvarez et al. (2005) shows that when it is considered that the frequency of price adjustments is heterogeneous among the goods the hazard function becomes negative.

Summarizing, the empirical literature that studied the micro-data of different price indexes finds that: (1) prices change, on average, at least once a year, but are far from changing every month, (2) there is considerable sectoral heterogeneity in the frequency of price adjustments, (3) this heterogeneity is related to the durability of the goods, their sophistication, different sectoral cost structures and degree of competition, (4) price adjustment are closelly linked with wage adjustments, (5) there is a degree of nominal downward price rigidity, however, decreases should not be disregarded, (6) the size of price changes on average is roughly 10% in different regions, with considerable heterogeneity, (7) although the average size of price adjustments is above 5%, there is a considerable amount of price changes that are classified as small, (8) the frequency of price increases covariates with inflation, (9) sellers do not strongly synchronize their price changes, (10) the degree of price stickiness varies among different price-setting environments, and (11) the hazard functions of price changes are decreasing. The main stylized facts that we aim to replicate in the following chapters are the frequency price changes, the link between wages and prices, degree of nominal downward price rigidity, the average size and statistical distribution of price changes, the covariance of price adjustment frequency with inflation and how different macroeconomic environments affects the price stickiness.

2.1.2 Surveys

In recent decades, numerous surveys have been conducted with firms to gain a deeper understanding of how firms set their prices and the major considerations and factors they take into account at the decision-making moment (Klenow and Malin, 2010). The literature resulting from these surveys, particularly Fabiani et al. (2006), has been widely cited in the agent-based macroeconomic modeling literature to justify the assumptions made in the pricing equations of models such as Dosi et al. (2010); Dawid et al. (2019); Caiani et al. (2016). In this section, we review the literature that reports the results of surveys conducted with firm managers to determine what they consider the most important theories that explain their own behavior.

These surveys enable researchers to inquire about aspects of pricing that are not captured by data sets of price indexes, such as the theories that explain the pricing decision, the primary information used, and the frequency with which price-setters review prices (Klenow and Malin, 2010). The use of surveys to explore firms' price-setting behavior was first introduced by Blinder (1991) using data from the US. In the 2000s, many surveys were published for economies in the developed world (Klenow and Malin, 2010), and from the late 2000s to the 2010s, there have been numerous surveys conducted for emergent economies such as Brazil, Colombia, Mexico, Pakistan, Turkey, among others. Despite the economic diversity among the firms surveyed, it is noteworthy how firms exhibit similar behavior among different countries in terms of pricing-setting strategies.

For the present dissertation, we are particularly interested in the questions related to strategies used by firms to set prices, the causes for price stability, and the drivers of price changes. These are empirical pieces of evidence that are essential for appropriately modeling firms' price-setting behavior.

2.1.2.1 First stylized fact from surveys: state-dependent pricing routines

This first stylized fact is that, overall, firms tend to adopt state-dependent pricing routines, with a higher probability of firms adjusting prices based on their internal conditions as opposed to the time that the price was last changed. Usually, the surveys show that a considerable amount of the firms adopt state-dependent pricing, with a small proportion considering time-dependent pricing explanations relevant (between 20% to 30%). However, even firms that utilize time-dependent strategies admit that they may make non-planned price adjustments if significant events occur. Although the revision of pricing tends to be time-dependent, with the revision of prices occurring periodically, the adjustment tends to be state-dependent on average. All these conclusions are valid, overall, for the Euro area (Fabiani et al., 2006), UK (Greenslade and Parker, 2012), Pakistan (Malik et al., 2008), Turkey (Şahinöz and Saraçoğlu, 2011), Brazil (Correa et al., 2018) and Mexico (Castañón et al., 2008). It is worth noting that Castañón et al. (2008) finds that changes in costs are the primary reason for firms to revise their prices, as opposed to changes in demand.

2.1.2.2 Second stylized fact from surveys: pricing strategies

The second stylized fact pertains to the pricing strategies adopted by firms. Using data from various surveys, Fabiani et al. (2006) identifies the primary price-setting rules used by firms in the Euro area and the factors that influence their pricing strategies. The most prevalent rule adopted by firms in the Euro area is markup pricing (54%). The second most common is following the leading competitor's price (27%), with the remaining firms using other pricing strategies. As expected, the higher the perception of competitiveness, the more critical competitor-based pricing becomes and the more frequently firms will follow the latter rule of thumb. In UK (Greenslade and Parker, 2012), the pricing theories considered most important by the firms are the competitor's price, variable markup, and constant markups. They were considered at least important by 68%, 58%, and 44% of firms, respectively. It should be noted that respondents could consider all the theories equally important. Therefore, many respondents considered "competitor's price"and theories related to markup as equally important. Only 27% considered important the explanation that consumers determine prices and 39% agreed to important that they would set the price as highest as the market could bear. Japan stands out as an exception in the survey sample, with the most important pricing theory for Japanese firms being "market condition", with prices primarily being determined by supply and demand conditions of the market (Nakagawa et al., 2000). The second most important strategy is "market share", which in survey means that prices mainly are driven by competitors' prices weighted by firms' market share.

This predominance of firms following a markup pricing strategy, but with a considerable number following the price of the competitor or the market, is observed in Brazil (Correa et al., 2018), Pakistan (Malik et al., 2008), Turkey (Şahinöz and Saraçoğlu, 2011), and Mexico (Castañón et al., 2008). It is worth noting that Correa et al. (2018) finds that even firms that follow markup pricing take competitors-based prices into account when adjusting prices.

While surveys indicate that most firms adopt a cost-based approach and add a markup factor to their prices, they do not provide clear insights into the underlying drivers of the markup. What can be inferred from these surveys and from the micro-data from firms is that price setting is primarily influenced by the cost structure, level of competitiveness and interaction with competitors, and the relationship with customers. To a lesser degree, demand also plays a role in the pricing decisions of firms.

The literature on pricing strategies in business recognizes a variety of approaches employed by firms (Hinterhuber, 2008; Tellis, 1986; Dolgui and Proth, 2010), which can be classified into one of three categories: cost-based pricing, competition-based pricing, and customer value-based pricing. The first strategy can be defined as pricing approaches that define prices mainly based on the cost structure of firms. The second strategy can be defined as approaches that mainly set prices based on observing or anticipating competitors' prices. Finally, the last approach focuses on the perceived "value"of goods and services by customers for setting prices. One puzzle in this literature is why firms do not adopt the considered optimal strategy, customer value-based pricing, and instead opt for cost-based pricing approaches.

As noted by Hinterhuber (2008), cost-based pricing is considered the weakest approach as it does not, in theory, take into account competitors and customers when setting prices. Articles in the business literature (Johansson et al., 2012; Liozu and Hinterhuber, 2013; Liozu, 2017) suggest that the difficulties in adopting customer value-based pricing are due to a lack of pricing capabilities among firms. These include difficulties in making value assessments, communicating value to consumers, or a lack of adequate understanding by firm managers on how to implement a value-based pricing strategy. However, as seen in surveys, a significant number of firms do tend to consider variables other than cost when determining prices and do consider changes in competitiveness.

In Amaral and Guerreiro (2019), an alternative perspective is proposed, suggesting that even though firms may use cost-based pricing formulas, this does not necessarily imply that they disregard competitors or customers. The argument put forth is that information about competitors and customers is incorporated into firms' prices through the margins. According to the article "via the margin, firms may connect costs to information about competition and value"(Amaral and Guerreiro, 2019, p. 2). The study finds that the majority of firms that use cost-plus formulas do not utilize, as defined in the article, a "cost-plus essence"approach, where the margin is arbitrary and does not connect costs to other types of information. Instead, it is shown the margins are a variable that depends on information about the market competition or product value, cost-based pricing formulas are only auxiliary to the pricing process.

2.1.2.3 Third stylized fact from surveys: causes of pricing stickiness

The third stylized fact pertains to the determinants of pricing rigidity. Beginning in the 1990s, a considerable number of surveys have been conducted with the aim of illuminating pricing behaviors and strategies employed by firms, given the proliferation of theories attempting to account for the origins of sticky prices. Notably, the responses provided by managers provide insights not only into how pricing decisions are made but also into the information that is considered when determining the final prices.

In a survey conducted in Blinder (1994), US firms were questioned in order to ascertain which of twelve theories best accounted for the stability of their prices over time. The most important explanations, in order of decreasing significance, were coordination failures, cost-based pricing approaches, delays in delivery (whereby firms respond to changes in demand by lagging production, rather than by altering prices), and implicit contracts.

The main causes for price stickiness for firms in the Euro area are implicit contracts, explicit contracts, cost-based pricing, and coordination failure (Fabiani et al., 2006). Fabiani et al. (2006) observe that most of the firms in the Euro area (70%) have long-term relationships with customers and, because of that, firms tend to keep prices as stable as possible to not antagonize customers. In the United Kingdom (UK), the results are similar for the causes of price-stickiness (Greenslade and Parker, 2012). The leading causes considered were coordination failure (60% of the firms agreed with the importance), customer antagonism (56%), explicit contract (47%), and implicit contracts (38%). Surprisingly, only 24% of UK firms agreed that the stability of costs is a reason for price stability.

Research has indicated that in Japan, among nine potential explanations, implicit contracts, and coordination failure are the most prominent theories accounting for pricing rigidity (Nakagawa et al., 2000). Moreover, in some sectors, explicit contracts also emerged as significant determinants. In contrast, the responsiveness to changes in demand through delivery lags was deemed to be the least significant explanation for pricing stability.

Similar patterns have been observed in emerging economies. For instance, in Pakistan, firms also identified consumer antagonism, explicit contracts, and coordination failures as the primary explanations for price stickiness, in decreasing order of importance (Malik et al., 2008). In Turkey, the most significant factors were the existence of a threshold for changes in profit margins, temporary shocks, explicit contracts, and implicit contracts, in decreasing order of importance (Şahinöz and Saraçoğlu, 2011). In Brazil, four theories were found to be relevant in explaining price-setting behaviors, namely menu-cost, cost-based pricing, explicit contract, and implicit contract, while coordination failure and adjustment in non-price factors were considered to be less important but still relevant (Correa et al., 2018). Finally, in Mexico, the responses of firms were similar, with pricing based on costs, implicit contracts, explicit contracts, and coordination failures being the most important theories among nine potential explanations, in decreasing order of importance (Castañón et al., 2008).

The results of surveys have inspired new articles aimed at gaining a deeper understanding of the causes of price stickiness using firms' micro-data. Zbaracki et al. (2004) was the first article to quantify the costs of price adjustments by combining data from firm managers and company data. The adjustment costs were classified into three types: physical costs such as menu costs and price tags, managerial costs, which include information collection, decision-making, and communication costs, and customer costs, which include the costs of communicating price changes to consumers and negotiating with resistant customers. The article finds that managerial costs are more than six times higher than physical costs, and customer costs are more than 20 times higher.

Verhelst and Van den Poel (2012) used supermarket scanner data at the individual customer level to examine the role of implicit contracts in price stickiness. The customer base was divided into three groups based on their behavioral loyalty to the retailer. A demand analysis was conducted on the loyal and non-loyal segments, revealing that loyal customers have a more concave demand curve than non-loyal customers. This result was found to hold true for the majority of product categories, leading to the conclusion that repeat buyers are highly sensitive to prices exceeding previous levels, leading to sticky prices as retailers attempt to maintain their clients' trust by keeping prices stable.

Anderson and Simester (2010) conducted a field experiment to examine customers' reactions to observing a retailer sell a product at a lower price after they have purchased it. The experiment found that customers react by making fewer subsequent purchases from the retailer, with the article characterizing this as a boycott of the customers to punish the firm. This effect was found to be strongest among the most valuable customers, who purchased recently and at the highest prices. Leibbrandt (2020) similarly found that firms avoid price discrimination and overpricing low-value customers in order to maintain the loyalty of high-value customers.

2.1.2.4 Fourth stylized fact from surveys: causes of price changes

Some of the review surveys have attempted to identify the main causes that lead firms to adjust their prices, given the observed rigidity in prices. What the responses show is that the causes may be considerably different depending on the direction of price change (if it is an increase or decrease). In Europe, for example, when asked about the reasons for increasing prices, Fabiani et al. (2006) found that the primary cause cited by firms was an increase in costs, both for raw materials and labor, with a score of 3 in importance. However, other factors were not considered to be unimportant to the point of being disregarded. Increases in financial costs and changes in demand received a score of 2.2, while changes in competitors' prices received a score of 2.4. In terms of price decreases, the competitor's price has the biggest importance (2.8), followed by costs of raw materials (2.6) and changes in demand (2.5). Although most firms use a cost-based pricing approach, this survey shows that changes in demand and competitors should not be disregarded in price-setting models. Also, there is an asymmetry in the causes of price changes. According to Fabiani et al. (2006), firms are more prompted to react to shocks that lead to profit losses than to shocks that lead to profit gains. Fabiani et al. (2006) also observe that costs are more important to explain prices upward, while market conditions (changes in demand and pricing competition) matter more for price decreases.

Blinder (1994) also found this asymmetry with US data. For demand increases 64% of the firms answered that their response would be to increase production, and only 5% would only react to increasing prices. For demand falls, 36% answered that their response would be to decrease output, and 27% prices.

In Turkey, a survey by Şahinöz and Saraçoğlu (2011) found that the leading cause for price increases for firms was by far an increase in costs. Other explanations considered important were exchange rate depreciation and changes in the price of competitors. On the other hand, price decreases due to changes in cost, decrease in demand, and changes in competitors' prices all had practically the same weight.

In Mexico, a survey by Castañón et al. (2008) found that the main causes considered important in explaining price increases were increases in raw materials, labor costs, and exchange rate devaluation. To explain price decreases, the main reasons were decreases in raw costs, in the price of competitors, and labor costs, in decreasing order. In Brazil, although 65% of the firms reported using the same criteria for price increases and decreases, national surveys suggest that demand conditions and competitors' prices are the most important determinants for price decreases, while rises in costs are the main factors driving increases in prices (Correa et al., 2018).

Overall, the main determinants that explain price increases or lack thereof are primarily attributed to cost increases (such as raw materials, labor, energy, etc.), which is considered the most important factor, followed by consumer antagonism and coordination failures. Additionally, changes in demand also play a role, although to a lesser extent. The determinants of price decreases are typically similar, with the exception of the relative importance placed on each factor. Cost increases tend to have less significance while changes in demand and competitor pricing gain prominence. This pattern is consistent among firms in both developed and emerging countries.

In addition to surveys, studies using micro-data provides explanations for the causes that lead firms to change prices. For example, Lein (2010) finds that the current economic conditions of firms, as reflected by state variables such as revenue, input costs, or capacity utilization, are more important in explaining price changes than macroeconomic variables. The article concludes that micro states-variables are significant to justify when firms change prices and that state-dependent pricing is important to explain firms' pricing behavior.

Dhyne et al. (2011), using micro-data from French and Belgium firms, shows that the leading causes for the lumpiness of price adjustment are due to idiosyncratic shocks of the firms in opposition to the possibility of them being caused by common shocks. Loupias and Sevestre (2013), using micro-data from French firms, shows that the main causes for producer price adjustments are changes in input prices, wages, and, lastly, changes in total production. Thus, the results are in line with the surveys for countries in the European Union.

2.1.2.5 Conclusion from surveys

Based on the results of various surveys, it seems that the cost-based approach is the dominant pricing strategy employed by firms. However, it is necessary to consider that there is considerable heterogeneity in the strategies being adopted by firms. A considerable proportion of firms affirm that they follow, or consider it important to follow, the price of their competitors. Additionally, the fact that firms use cost-based pricing formulas does not explain how they internalize information related to customers, competitors, and the overall economy in their markups.

Furthermore, it seems that companies are more influenced by their current state than the time of the last price adjustment. This can be attributed to the accumulation of shocks that do not prompt firms to adjust prices. In terms of theories on price rigidity, the literature highlights three primary explanations: constant costs of production, implicit contracts, and coordination failures, which are particularly relevant in unregulated sectors.

Moreover, firms consider several factors when setting their prices, such as production costs, consumer behavior, competitor prices, and level of demand. Notably, the impact of a factor that prompts a price change is asymmetrical, depending on the sign (positive or negative) of the shock on the final price. These findings are consistent with the factors identified in the literature on business pricing (Piercy et al., 2010).

2.2 *The state-of-art of pricing in macroeconomic agent-based models*

In this section, we provide a review of how a representative sample of agent-based macroeconomic models formalize the pricing strategies and decisions of firms. Although these models share certain general characteristics, there are significant differences as well.

In general, agent-based models assume that the pricing decision of firms is made in an environment where, due to uncertainty and information costs, consumers do not know all the goods offered and their prices. As a result, firms also do not know the demand curve position on the price/quantity space. This uncertainty is generated because transactions do not occur simultaneously in all markets and because of the ever-changing supply/demand conditions (Dawid and Delli Gatti, 2018). Therefore, each firm operates in markets characterized by monopolistic competition or oligopolies. For this reason, firms have market power and can add a markup factor to their unit cost of production. This assumption is in accordance with the substantial empirical evidence suggesting that firms follow this pricing rule, as we have just reviewed in the previous section.

At the beginning of the simulation, consumers' goods prices and production decisions are predetermined. After the first run of the model, firms observe the available information and update their choices for the next period. This is the overall approach adopted in agent-based macroeconomic models, but, from this point on, how pricing decisions are modeled can differ significantly.

Dawid and Delli Gatti (2018) consider that firms receive two signals from the markets: (i) excess or shortage of inventories; (ii) the relative price, i.e., the ratio of the difference between the individual price and average price in the market. According to Dawid and

Delli Gatti (2018), with the first signal, firms infer if they have overestimated or underestimated the strength of the demand. With the second signal, the firms infer their position relative to their competitors. If the firm's price is lower than the average, the firm is undercutting competitors. In the opposite case, the goods produced by the firm are overpriced. The signal and magnitude of the signs are indicators for the changes in quantities and prices in the next period. The decision is not trivial since the elevation of prices may generate a loss in market share and revenues.

A model that is closely related to the aforementioned is presented in Caiani et al. (2016) and Schasfoort et al. (2017). In these articles, firms also use the inventories as a market signal to adapt their behavior. The important difference from Dawid and Delli Gatti (2018) is that firms change the value of the markup. Firms have a target for their inventories. If the total amount is below the target, firms increase the markup. On the other hand, if there is an excess of inventories, firms decrease the markup.

Another model of interest is of Lengnick (2013). This model assumes that the desired markup of the firms is an interval, determining the minimum and maximum price. The firms only readjust their prices if the past markup is inside the interval. In every period, firms draw a random value from a uniform distribution to readjust their prices. However, if the past markup is higher than the upper bound, firms will not increase the prices even if the desired stock of inventories is lower than the threshold. The same happens in the opposite direction; prices will not decrease if the past markup is below the lower bound. With this algorithm Lengnick (2013) control the volatility of price changes. Moreover, Lengnick (2013) introduces a form of time-dependent pricing. Prices will only be readjusted with a certain probability, even if the firm's rules suggest doing so. With that, this model introduces a sort of price inertia that generates price stickiness and controls the variability of prices (Dawid and Delli Gatti, 2018). Also, relative prices do not affect the pricing dynamics.

In Delli Gatti et al. (2011) and Assenza et al. (2015) prices are readjusted depending on two conditions: relative prices and the existence of unsatisfied consumers. This last item is the result of the forecasting error between the expected demand and observed demand. If the error is positive, the observed demand is higher than the production. If the firm's current price is below the market average and the error is positive, the price will increase. By how much is the price increased in determined by a draw from a probabilistic distribution. In the opposite case, with a negative error and a price above the average, the price will decrease.

In all models presented so far, the effective markup is endogenous. Although in Lengnick (2013) the firms determine the desired markups to assess the possible range that prices can vary, the observed markup is endogenous since a stochastic value determines the size of price readjustments. In other words, in these models, signals received by firms indicate whether they should increase or decrease the prices, not the markups. The price trend is not necessarily related to the costs of production. Besides, the adjustments threshold is justified as a simple rule of thumb, with no clear theoretical basis or how it relates to the firms' behavior observed empirically.

In Ashraf et al. (2016, 2017) it is assumed that firms follow a cost-based pricing approach, with them passing through every increase in costs and taxes to the consumers. The regular markup rate is fixed and exogenous. They also assume that firm's, denoted by them as "shops", can make price adjustments based on their inventory-to-sales ratio. In particular, when that ratio exceeds a fixed upper threshold, the price is reduced by a fixed factor, and when the ratio falls below a lower threshold, the price increases by this same factor. If the inventory-to-sales is between the critical thresholds, the price will be normal. Therefore, the frequency of price adjustments is endogenous, depending on the behavior of costs and demand. Some of the empirical literature presented in the previous section is cited to justify the use of cost-based pricing and the adjustment of prices to adequate the inventory-to-sales ratio, like Fabiani et al. (2005).

The models of Eurace (Dawid and Delli Gatti, 2018; Dawid et al., 2018) have a rather complex routine to determine the prices of the firms, closely resembling the pricing process presented in standard microeconomic manuals. It is exogenously determined that prices will only change once a year. To adjust prices, firms initially conduct a market analysis to estimate a demand function that considers the price elasticity, the expected growth of the total market, and the expected market share of the firm. Then, firms do a cost analysis, checking the unitary cost of production given each level of output. With this data, the firms compute the price that will maximize their profits over the year.

Although it is very complex, Eurace seems to have some limitations. First, setting the frequency of price adjustments exogenously is a problem since the empirical data show that the frequency covariates with inflation. Second, surveys of firms show that firms follow more straightforward rules of thumb compared to the ones present in that model. Third, firms tend to follow a state-dependent pricing routine, rather than time-dependent.

In other models, the markup is a fixed variable, determined as a parameter, such as Carvalho and Di Guilmi (2020), Ponta et al. (2018) and Teglio et al. (2019). In these cases, firms adopt a cost-based pricing routine, with fully flexible prices and variable production costs.

In Rolim et al. (2023, 2022), firms also adopt a cost-based pricing routine, applying a markup factor over the normal unitary cost of production. The prices are flexible, and firms face variable production costs. However, unlike all prior articles cited, the authors propose a mechanism where the pass-through of changes in costs to prices is incomplete, with part of the costs being absorbed in the markups. On the other hand, if costs decrease, part of this is absorbed in the form of increased margins.

Seppecher et al. (2018) is a particular case in the ABM literature because it presented a three-sector model that specifically has the objective to explain what drives the level of markup that firms achieve in a market economy. Also, the article analyzed if markups equalize between different sectors and if there is a tendency to grow over time. Firms in that model use an evolutionary algorithm of the learning process, along the lines of (Alchian, 1950), which have two operators: an exploration process that constantly introduces new strategies into the population and an exploitation process that diffuses the profitable strategies among the population of firms.

The exploration process is a central element of the model introduced in Seppecher et al. (2018), which introduces heterogeneity among firms and generates sectorial and macroeconomic dynamics. The article proposes that firms update their markups at every time step of the simulation by drawing from a Gaussian distribution with an average of zero. This process is intended to simulate a “trial-and-error”approach by firms, as they test potentially more profitable strategies. The exploitation process, in contrast, involves the selection of the most profitable firms in the market. Bankrupt firms are replaced by new entrants, who can only choose strategies that are deemed advantageous. The model of Seppecher et al. (2018) is particular among the ABMs models reviewed. Not only it is not imposed some thresholds exogenously for the size of the price variations, but also the model allows that the average markup of the economy fluctuates. In the end, the average markup of the simulated economy is an endogenous result that emerges through a evolutionary selection process.

While in Seppecher et al. (2018) the markup is always changing as a stochastic exogenous process, in the model of Dosi et al. (2010), the markups are determined by the firms' market share. They justify this assumption based on "customer market" models. Basically, in these models, the larger the market share of the firms, the more frequently they can behave like monopolists. It is argued that consumers tend to repeat their purchases with the same firms (Klemperer, 1995). The positive point in Dosi et al. (2010) is that the pricing equation is justified by the behavioral literature, while for the majority of the articles, the pricing equation is not justified behaviorally. Prices are the result of the unitary cost of production computed by the firms multiplied by the markup factor. The market share, in turn, evolves according to a "quasi" replicator dynamics, where the selection criteria driving that variable is the firms' competitiveness. What is interesting in the model of Dosi et al. (2010) is that the markups can change over time and are the result of the strategies of the firms, not of exogenous idiosyncratic shocks.

Considering the models presented as a representative sample of the ABMs that have been developed recently, it becomes evident that there are significant variations among them. Generally, these models assume that prices are fully flexible, and any marginal changes in costs or demand are passed on to final consumers in each period, or they incorporate some form of time-dependent pricing. Only in Rolim et al. (2023) do we find a mechanism where the pass-through is incomplete. In some models, the frequency of the price adjustment is exogenously imposed. Some models consider that the markups are rigidly fixed, while others posit that they evolve through some sort of stochastic process. In other models, markups are endogenous and determined by the evolution of prices and costs. While some models incorporate a form of "sales"by allowing prices to change due to inventory-to-sales ratios, this theme has not been extensively explored. Finally, a few articles have proposed price equations that we considered that more closely align with behavior observed through surveys, where markups are strategic decisions made by firms and determined by their relative competitiveness. However, within the surveyed literature, we did not find any articles that explore the possibility of firms following different pricing heuristics or strategies, with the distribution of these strategies across firms being endogenoulsy time-varying.

To the best of our knowledge, there is currently no article that demonstrates the ability to replicate some of the stylized facts observed in micro-data from consumer price indexes. Moreover, given the high importance of "implicit contracts"and coordination failures for firms pricing behavior and the limited empirical evidence suggesting that consumers impose some form of sanction on firms that change prices, these are aspect's that have not yet been explored in the ABM literature.

2.3 Conclusion

As we saw in the previous section, the ABM literature exhibits significant diversity in modeling firm pricing decisions. It is worth noting that this is not exclusive to the ABM literature. For instance, considerable variation can be observed in how pricing is modeled in DSGE models (Coibion and Gorodnichenko, 2011). The importance of the pricing model in ABM depends on the research questions addressed in the articles. However, even articles with similar research questions use relatively different models. At the same time, each model has positive and negative points related to its capacity to incorporate observed stylized facts. The proposal of this dissertation is to present three different essays that contribute to the macroeconomic ABM literature by exploring models that formalize the pricing mechanism based on behaviors described in surveys and replicate some of the stylized facts.

The first essay of this dissertation, presented in the next chapter, introduces a hybrid model that combines elements of both DSGE and ABM frameworks. By closely resembling the mainstream DSGE model, our hybrid model captures the heterogeneity in prices that persists even when firms follow an evolutionary heuristic switching mechanism. This mechanism allows firms to adapt to different pricing heuristics and have prices with varying levels of flexibility. Through the analysis of this hybrid model, we demonstrate that the traditional assumption of homogenous prices in DSGE models is not supported when considering the heterogeneity and dynamics of pricing behaviors in real-world economies.

The second essay introduces a conventional macroeconomic ABM that adheres to the fundamental framework proposed in (Dawid and Delli Gatti, 2018), while adopting a number of key assumptions put forward in the prominent ABM literature models (Dosi et al., 2010; Dawid et al., 2018; Delli Gatti et al., 2010). A notable contribution of this essay is the incorporation of four distinct pricing heuristics, with the aim of identifying which heuristic dominates in the economy, if any, and how the distribution of heuristics evolves over the course of the economic cycle.

In the third essay, we address the stylized fact that prices tend to be stable over time. Building upon the model presented in the second essay, we introduce a heuristic switching mechanism based on (Seppecher, 2012) to formalize firms' decision-making processes regarding the stability of their prices. Additionally, we incorporate the concept of implicit contracts between consumers and firms into this model. By considering the existence of no, weak, and strong implicit contracts, we investigate the impact of these contracts on the emergence of stable prices and observe their effects on the overall economy.

Chapter 3

Pricing heterogeneity in an hybrid DSGE-ABM model

3.1 Introduction

Recently, there has been a surge in the development of agent-based macroeconomic models to tackle various macroeconomic issues, such as inequality, fiscal policy, financial crises, and productivity growth (Fagiolo and Roventini, 2016). Models that focus on financial crises place a significant emphasis on monetary policy and the potential for crises to develop endogenously in the system. However, these models have paid less attention to the traditional role of monetary policy, which is to control inflation. As a result, the functional forms and discussions of pricing behavior in ABM models are relatively simplistic, despite the abundance of empirical literature and surveys that evaluate how firms make pricing decisions and their primary determinants.

In contrast, mainstream models such as the dynamic stochastic general equilibrium (DSGE) models have placed greater emphasis on pricing decisions to formalize or justify the empirically observed price rigidity in aggregate models. However, empirical studies have shown that pricing decisions are highly heterogeneous and involve extensive interactions between agents. Unfortunately, the macroeconomic literature that utilizes traditional DSGE models to examine the effects of pricing on the economy has paid relatively little attention to this aspect of pricing, with some notable exceptions (Coibion and Gorodnichenko, 2011). This lack of attention may be attributed to the challenge of modeling and analytically solving DSGE models with more than two types of firms.

These issues suggest that ABM is an appropriate type of modeling to incorporate when addressing this problem. Incorporating the heterogeneity and interaction involved in pricing formation through ABMs represents another step in the development of this class of models. Since ABMs are analyzed through simulations rather than being solved analytically, this allows us to examine how pricing heterogeneity dynamics co-evolve with other economic variables.

Therefore, the theme of the present paper is the presence of heterogeneity, interaction in price-setting behavior and price stability. In section 2, we briefly review the empirical literature that studied price behavior. We will present the general conclusions of the literature that has analyzed micro-data from different regions across the world, showing the main stylized facts concerning frequency, size, heterogeneity, and other statistical properties of price adjustments, that are important for the present essay.

In Section 3, we present an hybrid DSGE model with characteristics of the ABMs. The objective of the work was to introduce into a DSGE model heterogeneous pricing strategies among the firms, assuming that this type of agent (i) operate in an environment with fundamental uncertainty, (ii) follow rules of thumb to make decisions and (iii) can continuously learn and change the adopted pricing strategy. In Coibion and Gorodnichenko (2011), a DSGE model is presented with the novelty that it is considered to have the existence of heterogeneity in pricing strategies between firms. However, how firms are heterogeneous in terms of strategies is considered fixed by the authors. That is, they assume that there are four fixed-size segments of firms that adopt four different pricing rules. Also, why this heterogeneity exists and why the distribution of heuristic would be fixed is not discussed in depth. This article aims to go a step further by allowing the size of the segments to vary over time. Our model permits us to observe how firms dynamically change their behavior in a model close to the conventional DSGE model and at the same time reproduce all the data usually tracked in these types of models. We consider this to be the main innovation of the present work compared to the previous literature that sought to model the heterogeneity in pricing strategies across firms.

Another notable innovation of the model is its ability to allow the emergence of price stability through an evolutionary process. Our model allow firms to choose among different degrees of stickness of prices. We demonstrate that firms tend to select strategies that result in relatively sticky prices, even in the absence of any cost associated with price adjustments. Thus, we can confidently state that the observed price stickiness in the model is a genuine emergent property.

The model is open enough not only to have price heterogeneity across firms but allows them to evolve. We show that incorporating basic premises and ideas from the ABM literature related to the micro-behavior of the agents in a conventional model can enrich the model, justifying the existence of pricing heterogeneity, without losing the capacity to reproduce time series close to what is empirically observed.

The paper focuses on the dynamics of price heuristics through business cycles, generating results comparable to the literature that analyses the firm price dynamics during economic cycles. Becauses of that we deliberately formalized a model that does not observe long-term growth. Firm innovation process changes only the relative quality of goods and not the company's production function.

In the same vein, while much of the empirical literature on pricing provides compelling evidence that pricing behavior is conditioned by the sectors in which firms operate, we are interested in comparing our results to macroeconomic models and literature. Developing a multi-sectoral model would exceed the scope of the current essay.

In Section 4 we describe the calibration protocol. We used the method of simulated moments to calibrate the model. Using statistical results from Monte Carlo simulations, the benchmark model was calibrated using a genetic algorithm to find the parameter set that best match empirical statistical moments and target values. This algorithm explores the parameter space to find optimal values given a fitness function. The empirical data included cross-correlations of GDP with various variables, target values for the mean inflation rate, wage share, and microeconomic variables, such as the frequency and size of price changes. The genetic algorithm involved generating a population of parameter sets, evaluating their fitness, selecting sets for reproduction, and applying recombination and mutation. The parameter set that better reproduce that data was then used to simulate the model and analyze its behavior.

In Section 5, we present the key findings of our model simulations. We analyze the macro and micro-series dynamics and discuss their implications. Our results demonstrate that the model successfully replicates the major stylized facts observed in macroeconomic variables. Additionally, we validate the model's ability to reproduce microeconomic stylized facts related to pricing behavior. Furthermore, we investigate the selection of pricing heuristics by firms through their evolutionary switching mechanism protocol.

In Section 6, we conduct a sensitivity analysis to assess the robustness of our model's results. This analysis explores the impact of variations in parameters on the outcomes of the model, allowing us to evaluate the stability and reliability of our findings.

Finally, in Section 7, we draw conclusions based on our findings and discuss their implications for understanding pricing behavior and its influence on macroeconomic dynamics.

3.2 Empirical evidence

In this section, we briefly review some of the main stylized facts that we addressed in the present essay, which are already presented in chapter two.

The empirical literature investigating the micro-data of price setting by firms aims to explain and quantify price stickiness, which is important for business cycles, welfare, and the behavior of the real exchange rate. This literature provides evidence of heterogeneous behavior in price setting, determined by many interactions between different agents. These interactions include cost structure, the frequency of input cost changes, and the behavior of consumers and competitors. This evidence can be incorporated into macroeconomic models to better describe the behavior of price indexes.

Stylized facts on price behavior include the frequency of price changes, with only 10% of prices changing each month in the US, corresponding to a price duration of eight to eleven months. The relation between the size of the establishment and price flexibility is also important. Price changes are linked to wage changes, and a considerable degree of nominal downward price rigidity exists, with only one-third of non-sale price changes being price decreases in the US.

Another stylized fact is that prices change by large amounts, with regular price changes in the United States averaging 8.5%. The high average price changes do not mean that small price changes never occur, as 44% of regular price changes in the US CPI are smaller than 5% in absolute value. Finally, the frequency of price changes covariates with inflation and sellers do not synchronize their price changes.

In summary, the literature that analyzed the CPI's of different countries provides evidence of heterogeneous behavior in price setting, with different factors affecting price rigidity and the size of price changes. This evidence can be incorporated into macroeconomic models to better describe the behavior of price indexes.

Various surveys have been conducted to examine the pricing behavior of firms and the theories that explain their behavior. The results of these surveys suggest that cost-based pricing is the predominant pricing strategy employed by firms, but there is considerable heterogeneity in the strategies being adopted by firms in different countries, with a considerable number following the prices of their competitors. Furthermore, the fact that firms use cost-based pricing formulas does not necessarily clarify how they internalize information related to customers, competitors, and the overall economy in their markups.

The literature on pricing strategies in business identifies various pricing methods used by firms (Hinterhuber, 2008; Tellis, 1986; Dolgui and Proth, 2010), which can be categorized into three types: cost-based pricing, competition-based pricing, and customer value-based pricing. Cost-based pricing sets prices mainly based on the firm's cost structure, while competition-based pricing observes or anticipates competitors' prices. Customer value-based pricing focuses on the perceived value of goods and services by customers to set prices. However, it remains unclear why firms tend to adopt cost-based pricing approaches rather than the considered optimal strategy of customer value-based pricing.

Other evidence from surveys shows that companies are more influenced by their current state than the time of the last price adjustment, which can be attributed to the accumulation of shocks that do not prompt firms to adjust prices. In terms of theories on price rigidity, the literature highlights three primary explanations: constant costs of production, implicit contracts, and coordination failures, which are particularly relevant in unregulated sectors.

3.3 The model

In the present section, we describe the model that was developed to study the object of interest, the pricing behavior of the firms, and their evolution. To this model, we developed an hybrid DSGE-ABM model. The idea to combine characteristics of a standard DSGE model with macroeconomic ABMs is not new. Many articles have developed models with this characteristic, most of the time to evaluate the consequences of changes in certain equations blocks of the standard DSGE model (Brancaccio et al., 2022).

Salle et al. (2013) evaluates how the inflation target can be an anchoring mechanism and the role of transparency and credibility of the central bank in an economy populated by firms that follow behaviors close to the ones described through a New Keynesian model but have bounded rationality and limited information. Similarly, Gobbi and Grazzini

(2019) develops an ABM utilizing the standard DSGE equations but with the characteristic that expectations of the agents are not rational, but bounded, and have limited information. The objective is to analyze how dispersed information affects the expectation formation of the agents and the economic outcome. In Guerini et al. (2018) is analyzed how an ABM that is comparable to a DSGE model leads to a different result if the goods market is modeled as a decentralized search and matching protocol. Ashraf et al. (2017) develops an ABM with many characteristics of a standard DSGE model (price, consumer, and central bank behavior), but introduces many contingencies and imperfections in the financial market, the object of interest. Mayer (2022) develops an evolutionary algorithm to endogenously model the intertemporal decision rules in an agent-based macroeconomic model that adopts most of the assumptions observable in the DSGEs models.

This literature has in common the characteristic that developed models that keep its critics to the DSGE models restricted to some assumptions, normally the existence of a representative agent with rational expectations, and keep other assumptions that are also criticized in the ABM literature (Dilaver et al., 2018; Fagiolo and Roventini, 2016), such as the general equilibrium assumption or dynamics driven by exogenous shocks, exactly to keep the models comparable. In the present essay, we decided to follow this same strategy to develop the model, exactly to create a model that can be compared to more standard DSGE models that assume heterogeneous price-behavior, such Coibion and Gorodnichenko (2011) and Branch and McGough (2018). The model is similar to behavioral models described in De Grauwe and Ji (2019),De Grauwe (2010) and Hommes (2021), where agents are bounded rational and use simple decision heuristics. The innovation of the model is to assume that firm's may follow different pricing heuristics and the main difference to the cited literature is that we solve our model numerically.

Our model has three types of agents: a representative family, firms' producers of final goods, and a central bank. The focus of the present work is the firms. We assume that these agents have bounded rationality and because of this follow heterogeneous heuristics, simple rules of thumb, to make decisions. This was specially detailed for the pricing behavior. Firms also interact locally and persistently with each other with the purpose the learn about the environment they live in and adapting to it. Also, we allow firms to engage in new patterns of behavior, which are themselves a force for learning and adaptation in the economy. Finally, the firms are subject to a mechanism of selection of the fittest, with the market competition acting as a selection mechanism. Therefore, although our model has many of the standard DSGE equations and assumptions, we believe that it also has many characteristics that are usually identified as belonging to ABMs (Fagiolo and Roventini, 2016; Dilaver et al., 2018; Dawid and Delli Gatti, 2018). In special, the model has the two characteristics that Gallegati et al. (2017) considers central to studying the economy as a complex system. The first one is that the model evolves. By this, we mean that the system is adaptive through learning. Agents' behavioral rules are not fixed, but change adapting to variations of the economic environment in which they interact (Gallegati et al., 2017). The second characteristic, the model has a high level of heterogeneity, indirect and above all direct interactions that can generate emergent properties not inferred from the simple analysis of macroeconomic relations (Gallegati et al., 2017). In the next sub-sections, we detail how these processes occur in the model and explain the equations of each agent.

The model is analyzed using simulations and at each time-step is computed a timeline of events where all the decisions are made. The sequence of events occurring in each period runs as follows:

1. It is computed the growth of the total factor productivity, which is common to all the firms $g_{A,t}$.
2. Firms update the quality of their goods through an exogenous and costless process.
3. The new production equilibrium Y_E is computed by the representative household.
4. The inflation expectation of the economy is estimated and internalized by all the agents.
5. The central bank determines the nominal interest rate of the economy.
6. Firms evaluate their performance in terms of the profit from the prior period. If necessary, they review their pricing strategies.
7. Firms update their expectations of nominal wages.
8. Firms set their prices.
9. The representative household updates the expected consumption.

10. Based on expected consumption, expected inflation, and nominal interest rate, total real consumption is computed.

11. Given the relative price and quality of the final goods, the total number of goods that are ordered from each of the firms is determined.

12. Firms hire labor.

13. The desired real wage and nominal wage are updated.

14. The variables are computed: product, inflation, GDP gap, firms' profits, firms' productivity, observed real wages, income distribution. Profit per price strategy and average readjustment parameter used in each strategy.

3.3.1 *The representative household*

The utility function U_t of the representative household of our model can be characterized as a constant relative risk aversion (CRRA) utility function, considering only the current consumption C_t and supplied labor L_t:

$$U_t = \frac{C_t^{1-\sigma}}{1-\sigma} - \gamma \frac{L_t^{1+\nu}}{1+\nu}, \tag{3.1}$$

where σ is the relative risk aversion coefficient, ν the marginal disutility in respect of labor supply, and γ is a parameter to weigh the total effect of the marginal disutility over the utility. In each period, the representative household faces the following budget constraint:

$$C_t + B_t = w_t L_t + \frac{1+i_{t-1}}{1+\pi_t} B_{t-1} + \Delta_t, \tag{3.2}$$

where w_t is the real wage, B_t the real stock of debt owned by the household, Δ is the aggregate profit in real terms, i_t is the nominal interest rate, π_t the inflation rate.

The representative family seeks to maximize the present discounted value of the current and future utility levels, restricted by the present and future expected budget constraints. The problem can be represented through the following lagrangian:

$$\mathscr{L} = E_t\left[\sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma}}{1-\sigma} - \gamma \frac{L_t^{1+\nu}}{1+\nu}\right) + \sum_{i=0}^{\infty} \beta^t \lambda_t \left(w_t L_t + \frac{1+i_{t-1}}{1+\pi_t} B_{t-1} + \Delta_t - C_t - B_t\right)\right], \tag{3.3}$$

$$\beta < 1,$$

where β is the intertemporal discount factor. The first-order conditions of the problem of the household are:

$$d\mathscr{L}_t/dC_t = C_t^{-\sigma} - \lambda_t = 0 \rightarrow C_t^{-\sigma} = \lambda_t, \tag{3.4}$$

$$d\mathscr{L}_t/dB_t = -\lambda_t + \beta E_t[\lambda_{t+1}\frac{1+i_t}{1+\pi_{t+1}}] = 0, \tag{3.5}$$

$$d\mathscr{L}_t/dL_t = -\gamma L_t^{\nu} + \lambda_t w_t = 0. \tag{3.6}$$

From (4) and (5), we get to what can be considered the Euler equation of the model:

$$C_t^{-\sigma} = \beta E_t(C_{t+1}^{-\sigma}\frac{1+i_t}{1+\pi_{t+1}}) \tag{3.7}$$

In words, the present consumption of the representative family is a function of the expected future consumption, the current nominal interest rate, the expected inflation, and the parameters β and σ. We suppose that there is no form of credit rationing in this economy, so households can optimally smooth their consumption.

And, from Equations (4) and (6), we have the leisure-labor relation:

$$w_t = \gamma L_t^{\nu} C_t^{\sigma}. \tag{3.8}$$

Since the model is not solved analytically or restricted to have only one feasible equilibrium, we did not impose the usual transversality restrictions. In the conventional model, this would mean that the representative household could be able to follow an explosive dynamic in terms of consumption (Salle et al., 2013). This is ruled out with the assumption that we made about the expectations formations and, also, the model is tested through simulations only with parameter sets that give rise to stable results.

In conventional DSGE it is common to use the Blanchard-Khan method or some other method derived from it to solve the model analytically. This type of solution assumes that all agents have the same set of information and interpret it in the same way. In other words, it assumed rational expectations, and, with this, we are able we calculate $E_t(C_{t+i)})$ for any future i as a function of the information set at each t and the model structure. Because of this, models that incorporate the rational expectation hypothesis do not have equations that describe how the expectations evolve (Farmer, 2002). They are implied by the model.

Given our aim to study how heterogeneity evolves in an environment with agents having diverse information and behavior rules, we find that analytical methods such as Blanchard-Kahn, which assume uniform information and rational expectations, may not be the most appropriate for our purposes. However, because of this, it is necessary to complement the model with equations that describe how the agents form their expectations.

In Salle et al. (2013), where it is also combined the New-Keynesian theory with the ABM methodology and the same question occurs, the problem of indeterminacy of expectations in an economy that does not assume rational expectation is solved assuming that the expected consumption is a function of the expected aggregate production, which, in its turn, is formalized using adaptive expectations. Farmer also proposes as a solution for the indeterminacy of expectations in models with multiple equilibrium's through the adoption of adaptive expectations (Farmer, 2002, 2016), proposing that agents have an initial expectation for their future income and this value is updated given the current income observed. Because of this, the models of the cited articles are functions of the initial value for the expected permanent income of the households. In the present paper, we adopt a slightly different approach.

We suppose that the representative household can compute what would be the optimal level of aggregate production in this economy, Y_e, in an environment without heterogeneity. How this is computed is presented in Appendix 1. With this, our model is closer to the conventional DSGE model, adds consistency to the formation of expectations in the traditional sense, and anchor the most important expectation of the model (equilibrium product) to the long-term equilibrium that would be observed in a model with monopolistic competition and no information imperfections (as in the conventional DSGE model).

Following Farmer (2016); Salle et al. (2013), we suppose that the Y_e is not perfectly known each period. To smooth the expectations formation, we considered that the expectations of future consumption are formed through the following adaptive process:

$$E_t(C_{t+1}) = (1-\zeta)E_{t-1}(C_t) + \zeta C_{e,t}, 0 < \zeta < 1 \tag{3.9}$$

Since in our economy the unique factor of production is labor and there is no government expenses or external sector, the aggregate production of the economy is simple:

$$Y_t = C_t. \tag{3.10}$$

3.3.2 Central Bank

To model the dynamics of the inflation expectations the same question already discussed for the Euler equation was faced. To keep the model close to a conventional DSGE model, we modeled the inflation expectations through an equation close to what would be observed in a traditional model.

$$\pi_t^e = \phi\pi_{goal} + (1-\phi)\pi_{t-1} + \varphi(Y_{t-1}/E_{t-1}(Y_t) - 1); 0 < \phi < 1; \varphi > 0. \tag{3.11}$$

The inflation rate expected , π_t^e, depends on the inflation target set by the central bank, the past inflation, and the observed GDP gap in previous period, given by $(Y_{t-1}/E_t(Y_{t+1}) - 1)$. The value $(1-\phi)$ is the inflation inertia, with $(1-\phi)$ being the weight of the inflation rate of the previous period over the inflation expectation for the next period. On the other hand, ϕ represents the "credibility" of the central bank. Finally, φ is the effect of the GDP gap over the inflation expectation. Observe that the central bank can not do anything to affect the inflation expectation for the current period. This is already determined. If the model converges to an equilibrium where $(Y_{t-1}/Y_{e,t-1} = 1)$ and $\pi_{goal} = \pi_t^e = \pi_{t-1}$, the Equation (3.11) becomes:

$$\pi_t^e = \pi_{goal}. \tag{3.12}$$

We suppose that households and firms adopt the same behavior to form expectations on inflation and, as a result, all of them have the same expectations about future inflation. The objective function of the central bank in each period is simple:

$$\pi_{goal,t+1}^e = \chi\pi_{goal} + (1-\chi)\pi_t^e. \tag{3.13}$$

Given the inflation target, π_{goal}, and the past inflation, the central bank targets an expectation for the next period. We define χ as the reaction function parameter of the central bank. If χ is equal to 1, then every period the central bank will aim to the inflation target. However, if χ is lower than 1, the monetary authority eases its policy, seeking that expectations converge only in the long term to the inflation target.

Substituting the Equations (3.10), (3.11) and (3.13) in the Euler equation, assuming that $Y_{e,t} = E_t(Y_{t+1})$, $\pi_t^e = \pi_t$ and $\pi_{goal,t+1}^e = \pi_{t+1}$, we get:

$$1 + \frac{(\phi - \chi)(\pi_t^e - \pi_{goal})}{\varphi} = (\beta \frac{1 + i_t}{1 + \pi_{t+1}})^{-1/\sigma}. \tag{3.14}$$

The assumptions underlying the equation above are that (1) the inflation rate in the current period will be equal to the inflation expectation, and (2) the inflation rate expectation for period $t + 1$ will converge to the central bank's target as defined by Equation (3.13). Isolating i_t, we get to the reaction function of the central bank:

$$i_t = \left(1 + \frac{(\phi - \chi)(\pi_t^e - \pi_{goal})}{\varphi}\right)^{-\sigma} \frac{1}{\beta}(1 + \pi_{t+1}) - 1. \tag{3.15}$$

Note that for the central bank follow the Taylor rule condition, we need that $\varphi < \phi - \chi$ and $\phi > \chi$. If the inflation expectations converge to the inflation target, from Equation (3.15), we get to the nominal rate of equilibrium:

$$1 + i^* = \frac{1}{\beta}(1 + \pi_{goal}). \tag{3.16}$$

And, from Equation (3.16), we can conclude that the real interest of equilibrium is:

$$1 + r^* = \frac{1 + i^*}{1 + \pi_{goal}} = \frac{1}{\beta}. \tag{3.17}$$

Thus, we get the real interest rate equilibrium equal to what is observed in the DSGE models (Galí, 2015; Costa, 2018). Finally, we consider that the central bank smooths the interest rate. The effective interest rate set by the central bank is a function of its reaction function and the interest rate observed in the past.

$$i_{ef,t} = \Phi i_{ef,t-1} + (1 - \Phi) i_t. \tag{3.18}$$

3.3.3 *Firms, demand, production and wages*

The objective function of the firms in the present model is the profit equation, which is computed as:

$$\Pi_{t,i} = P_{t,i} Y_{t,i} - W_t L_{t,i}, \tag{3.19}$$

where $\Pi_{t,i}$ is the individual profit of each firm , $P_{t,i}$ the price of the consumption good of firm i, $Y_{t,i}$ the production of the firm, W_t the nominal wage, which is common to all firms,and

$L_{t,i}$ the total amount of labor employed by each firm. Firms are not able to maximize their profits since they are not able to coordinate how the aggregate production will be allocated among them through the price mechanism *ex-ante*. So, in the present model, the firms will not seek to optimize its production by the usual neoclassical mechanism adopted in the DSGE models. We suppose that firms use different rules of thumb to decide *ex-ante* what is the final price of their goods, before offering them in the market. Below we detailed how this process happens.

In the present version of the model, we adopted a relatively simple production function commonly used in many DSGE models (such as Coibion and Gorodnichenko (2011),Rupert and Šustek (2019) and Salle et al. (2013)). We consider that the production function of each of the individual firms can be characterized as an increasing concave function:

$$Y_{t,i} = A_t L_{t,i}^{\alpha}, \quad 0 < \alpha \ < 1, \tag{3.20}$$

where $A_{t,i}$ is the level of technology, common to all the firms, and α is the output elasticity with respect to labor. The aggregate production can be defined as:

$$Y_t = \sum_{i=1}^{N} Y_{t,i} = A_t \sum_{i=1}^{N} L_{t,i}^{\alpha}, \tag{3.21}$$

where N is the total number of firms in the economy. For instance, the total labor demand is:

$$L_t = \sum_{i=1}^{N} L_{t,i} = A_t^{-1/\alpha} \sum_{i=1}^{N} Y_{t,i}^{1/\alpha}. \tag{3.22}$$

For the markets clear it is necessary to ensure that:

$$Y_t P_t = \sum_{i=1}^{N} Y_{i,t} P_{i,t}. \tag{3.23}$$

We suppose that the final goods are heterogeneous, with different qualities. To compute what is the market share of each firm, first, we computed the variable score, $S_{i,t}$, for each one of them (3.24):

$$S_{i,t} = (Q_{i,t}/\overline{Q_t})^{\xi_q} (P_{i,t}/\overline{P_t})^{-\xi_p}, \tag{3.24}$$

where $Q_{i,t}$ is the quality of the good sold by the firm i at time t, ξ_q is the elasticity of demand to the relative quality and ξ_p is the elasticity of demand to the relative demand.

The total demand of each firm, is given by:

$$Y_{i,t} = \frac{S_{i,t}}{\sum_{i=1} S_{i,t}} Y_t. \tag{3.25}$$

Thus, the total demand of each firm is determined by the relative quality of the goods, the relative price, and the total aggregate demand. Observe that if the goods are homogeneous and have the same price, the individual demand of each firm will be equal to the aggregate demand divided by the total number of firms. The result expressed in Equation (3.25) is similar to what would be observed in a model with a monopolistic competition market, like the ones that use the Dixit-Stiglitz aggregator. This equation was based on the "sales equation of the ABM developed in Poledna et al. (2023).

We suppose that the household order to each firm the total amount wished to be bought. After that, with the demand known, the firms contract exactly the necessary labor to fulfill the production commitments.

Determined the total labor demand of each firm, the household can compute the total labor demand and, with this, the desired real wage $w_{i,t}$. If we had assumed perfect competition, as in the real business cycle models, this would be equivalent to the marginal productivity of labor.

The New-Keynesian model and ours suppose monopolistic competition and firms are price setters. Because of this, the real wage will be lower than the marginal productivity of labor. In the DSGE models with fully flexible prices, this distributive conflict is solved incorporating the effect of the markup over the real wage (Galí, 2015), decreasing the equilibrium product, employment rate, and real wage. Usually, this is solved analytically supposing that the markup is fixed and constant over time since it is only dependent on a constant heterogeneity of goods.

In our model, the relative quality is constantly changing, being even possible that all goods may have the same quality (becoming homogeneous). Also, all the parameters that regulate the markups and prices are constantly in evolution (as will be detailed below). Thus, in the present model, very differently from the traditional New-Keynesian model, the markups, prices, and, therefore, the functional distribution of income, are endogenous variables.

To set the nominal wage W_t, the representative household uses the following equation:

$$W_t = (1 + \rho_{\pi,h}\pi_t^e + \rho_w(\frac{w_{D,t}}{w_{O,t}} - 1))W_{t-1}. \tag{3.26}$$

The nominal wage is readjusted in every period based on the nominal wage of the previous period,W_{t-1}. We assume that in every period the nominal wage is readjusted reflecting the expectation of inflation in the economy. The $\rho_{\pi,h}$ parameter defines the degree of indexation of the nominal wage and $\rho_{w,h}$ the readjustment of nominal wage given the difference of the desired real wage and the observed real wage in the last period. The second term is an adjustment term for the nominal wage term to match the real wage desired by the representative household. The variable $w_{D,t}$ is the real wage that the representative household aims for a given wage-leisure ratio, as in Equation (3.8). The term $w_{O,t}$ in turn, reflects the real wage observed in the previous period. This is simply:

$$w_{O,t} = \frac{W_{t-1}}{P_{t-1}}. \tag{3.27}$$

We assume that in the modeled economy the representative family does not have perfect information, not knowing the pricing rule adopted by each of the firms in each period. Because of this, the household only discovers the prices *ex-post* the formation of expectation of inflation in the economy. In this way, their real wage may differ from the target if the observed inflation rate is different from the expected one.

More precisely, the following dynamic occurs in the model developed here: (1st) the expectation of inflation in the economy is formed, (2nd) the agents internalize this expectation correcting their prices, whether nominal wages or final consumer goods prices, (3rd) firms go to the labor market to hire labor, (4th) the representative household is allowed to update the nominal wage in t to reflect a change in $w_{D,t}$.

3.3.4 Price-setting behavior

As was discussed previously, not only do we observe heterogeneity in the price strategies of the firms in terms of the pricing heuristic used, but also in terms of price rigidity. Prices are not readjusted at all periods. On the contrary, empirically they tend to be readjusted only once a year and when they are readjusted, the size of the adjustment is close to 10% on average. To incorporate these facts in our model, we suppose that firms follow a two-step process to set their prices. First, they compute the desired price. Second, they evaluate if they switch their current price to the desired one or if they keep their price constant.

In the first step, initially firms compute a estimative of the unitary cost of production. Firms do not know what will be the nominal wage they will have to pay, so they consider the wage negotiated in the previous period, the demand observed in the previous period, and the inflation expectation as references. Thus, their estimate of the unit cost of production in a given period t is:

$$UC_{i,t} = (1 + \rho_{\pi,f}\pi^e_t)\frac{L_{i,t-1}}{Y_{i,t-1}}W_{t-1}, \tag{3.28}$$

where $UC_{i,t}$ is the unitary cost of production and $\rho_{\pi,f}$ is the wage indexation.

After the computation of the unitary cost of production, the firms calculate the desired price. To compute it we suppose that firms can use three different heuristics. The first heuristic we called fixed markup. Firms that follow this heuristic multiply a rigid and fixed markup factor on the estimate of the unit cost of production. All firms at the beginning of the simulation adopt a markup value between 0.1 and 2. Throughout the simulation, they can update this value according to a heuristic switching mechanism that will be described below. Thus, given the markup in a given period t, the price adopted by firms using the first heuristic is:

$$P^D_{i,t} = (1 + m_{i,t})UC_{i,t}. \tag{3.29}$$

The second heuristic is similar to the first, with the difference that firms can adjust their markup to reflect changes in the quality of their final goods. We called it flex markup. We assume that firms can observe the average quality of consumer goods from the previous period. Defining $\Theta_{i,t}$ as the markup adjustment term given the differential of the product quality of company i concerning the market average, we have:

$$P^D_{i,t} = (1 + \Theta_{i,t}\frac{Q_{i,t}}{Q_{t-1}})UC_{i,t}. \tag{3.30}$$

Finally, firms that adopt the third heuristic, called competitors' price, simply follow the average market price, adding to it the current inflation expectation, defined in Equation (3.11). They do not consider any internal variable, such as costs or relative quality, to set their prices.

$$P_{i,t}^{D} = (1 + \rho_{\pi,f}\pi_t^e)\overline{P_{t-1}}. \quad (3.31)$$

These three heuristics were select given the empirical literature reviewed in the chapter two. As we have seen, it is a fact that the majority of the firms adopt a markup pricing rule (such as strategies 1 and 2). After the markup pricing, the second most important pricing rule is to follow the pricing of the market, normally following a market leader. This fact was considered with the 3º heuristic.

The first and second heuristics were adopted to consider two usual pricing equations adopted in the ABM literature. Empirically, these heuristics involve cost-based pricing approaches with the set of a markup, as surveys show that this is a relevant explanation. The difference between the heuristics is that one considers a consumer-based approach, setting the markup given the relative quality of the goods, while the other considers a fixed markup. This was done to separate the heuristics into two categories: the cost-based approach and the customer-based approach, as done in the business literature Hinterhuber (2008).

In the case of the "fix markup" heuristic, this model is adopted in Carvalho and Di Guilmi (2020), Ponta et al. (2018), Teglio et al. (2019), Ashraf et al. (2017), Ashraf et al. (2016). In these articles firms adopt a cost-based pricing routine, with prices being flexible and varying according to the costs of production. The markups are fixed and constant, represented as a parameter.

In the case of the 2º heuristic, the "flex markup" , which considers the effect of quality in the markup, two very different theoretical pieces of literature can be used to justify it. In Dosi et al. (2010), the markups are determined by the market share of the companies. They justify this assumption based on "customer market" models. In these models the larger the market share of the firms, the more frequently they can behave as a monopolist. This happens because consumers tend to repeat their purchases with the same firms (Klemperer, 1995). The prices are the result of the unitary cost of production computed by the firms multiplied by the markup factor. The market share, in turn, evolves according to a "quasi" replicator dynamics, where the selection criteria driving that variable is the firms' competitiveness. In our model, we consider that firms evaluate their competitiveness in terms of the relative quality of the goods. Therefore, firms will only increase their profit margins if they are confident that the higher quality of their goods will compensate for the loss of competitiveness in terms of the relative price. The second piece of literature that can be cited is the New-Keynesian, which explains the origin and persistence of markups, and, therefore, market power, due to the persistent heterogeneity of goods (Galí, 2015; Costa, 2018).

Thus, in the present model, given the heterogeneity of pricing strategies, empirically and theoretically, and their constant evolution and dynamism, we tried to incorporate these differences in one single model to observed how firms behave in such an environment. With this, we can say something about the capacity of all these three heuristics to survive at the same time in the economy or if one, or some of them, tends to dominate in the firms' population.

To account for the characteristic that prices are rigid and not adjusted in all periods, we define that firms will readjust their price to the desired one only if the difference between it and the observed price in the past is above a certain threshold, η , that we called "adjustment threshold" or "band of inaction".

This second step was inspired by the (s,S) models of sticky prices (Dhyne et al., 2011). The difference is that this literature considers that firms can calculate which would be the optimal price of their goods. Here we will suppose that firms have a desired price. Another difference is that in the literature of the (s,S) models, normally, the existence of the band of inaction is justified because of the existence of adjustment costs. In the present model, firms do not have any adjustment costs, we suppose that firms want to keep their prices stable as possible because of an implicit contract with the consumer. Anderson and Simester (2010) showed that this is extremely important because price decreases may antagonize consumers and, as we saw in the chapter two, implicit contracts are considered central to firms. We formalize the second step in the decision of price adjustment as:

$$P_t = \begin{cases} P_{t-1} \text{ if } |P^D_{i,t} - P_{i,t-1}| \leq \eta_{i,t}, \\ P^D_{i,t} \text{ if } |P^D_{i,t} - P_{i,t-1}| > \eta_{i,t}. \end{cases} \tag{3.32}$$

The parameter η is specific to each firm, and we assume that initially it is uniformly distributed across firms, with a minimum value of 0 and a maximum of 0.2. The higher the parameter η, the less likely the firm will change its price. This will fundamentally depend on the desired price volatility, which, in turn, will depend on the evolution of the relative quality of goods, average price, labor productivity, and nominal wage. Therefore, the frequency of price adjustment will depend on macroeconomic conditions, as empirically verified. The more volatile is the desired markup, cost of production, and productivity, the more frequently the prices will change.

3.3.5 Firms' evolutionary process

Firms in the present model use an evolutionary algorithm to learn new heuristics, along the lines of Alchian (1950), which have two characteristics: an exploration process that constantly introduces new strategies into the population and an exploitation process that diffuses the profitable strategies among the population of firms.

The strategies of the firms have two dimensions. The first one is the adopted rule to compute the desired price, which is one of the three fixed heuristics just presented. The second dimension relates to the values of the parameters adopted by the firms during their pricing decision. Specifically, the values of the parameters m, Θ and η.

In the case of the first dimension, the number of heuristics is fixed. The difference is that firms are constantly testing these three strategies observing which one of them is better to generate profits and, if one of them is better, it is diffused through the population of firms. The choice of the profit as performance criteria for a firm's learning processes is a usual variable used in the literature, one example being **?**, and can be justified empirically based in Jobber and Hooley (1987) that shows that the majority of the firms aim the choice that generates the higher amount of profits when setting prices.

In the case of the second dimension of the strategies, we permitted that firms constantly create and test new strategies, with the possibility that these new strategies are diffused through the economy.

To model the switching protocol of strategies by the firms we suppose that at the beginning of each round, firms account for the profit they made in the previous period and assess whether they should change the pricing strategy. Being Ω the set of heuristics possible to be adopted by the firms and $P(\omega_i)$ equal and constant for all $\omega_i \in \Omega$, each one of the heuristic is assigned a number as an identifier. When firms decide to select a new heuristic, they make a draw from the discrete uniform distribution U(1,3). Firms decide to revise the pricing strategy when:

$$\omega_t = \begin{cases} \omega_i \sim U(1,3), & if \quad U(0,1) > \Lambda\Pi_{i,t-1}/(\sum_{i=1}^{N}\Pi_{i,t-1}/N) \quad or \quad \Pi_{i,t-1} < 0, \\ \omega_{t-1}, & otherwise. \end{cases} \tag{3.33}$$

In other words, firms draw a new heuristic from Ω, which may even be the one that was being adopted, if and only if, their profit was negative in the previous period or if the value of a drawing from a continuous uniform distribution U(0,1) is higher than $\Pi_{i,t-1}/\sum_{i=1}^{N}\Pi_{i,t-1}$. Given the restriction that the sample space of U(.) stays restricted from 0 to 1, a firm that is showing a higher than average profit will never update its price strategy. On the other hand, the lower the performance of a firm in terms of profit to the average, even if its profit is positive, the possibility of the current strategy to be updated increases. The Λ is a parameter to weight the probability of mutation. If $\Lambda > 1$, it decreases the probability that the firm will revise its price strategy.

If a firm decides to revise its pricing strategy, it will random select a new heuristic to compute the desired price and update the value of the parameters m, Θ and η. All the heuristics are able to be selected, with equal weight, independently of their diffusion in the economy or what was the heuristic being adopted by the firm. The value of any parameter $X \in \{m, \Theta, \eta\}$ is driven by the equation:

$$X_{i,t} = \frac{\sum_{i=1}^{5}\Pi_{t-1,j}X_{t,i}}{\sum_{i=1}^{5}\Pi_{t,j}}U(0.95, 1.05). \tag{3.34}$$

In words, firms select five firms to analyze their strategies. Then, they compute a profit-weighted average to each parameter given the selected sample of firms. This is the process that diffuses the profitable strategies among the population of firms. After, firms draw a random element from the distribution (0.95, 1.05) that multiply the profit-weighted average of parameter X computed. This is the exploration process that constantly introduces new strategies. This is based in Seppecher et al. (2018), where the authors allowed firms to constantly explore new values for the markups. Here we modeled a process that is not so open, but dependent on the winning strategies observed by the firms, and considered that this was done to all the parameters that involve pricing.

The prior process of evaluation of strategies considers that evolution occurs based on the internal performance of the firms. Also, the exploration of heuristics is random. Firms can adopt a new strategy that may have already disappeared among the firms or is not performing well overall. Also, firms may end exploring strategies that go even beyond the limits given by the starting values of the simulation. We believe this is interesting to avoid that the initial conditions of the model affect too much the process of selection of strategies. We are not imposing some threshold for the size of price variations or for the size of the markups. In the end, the average markup of the simulated economy is an endogenous result that emerges through the process of selection. It is also worth mentioning that through the simulation will be selected the firms best adapted in terms of rigidity of the prices. Nothing imposes that this rigidity must exist, firms are free to choose a value of $\eta = 0$ if they evaluate that this is the best option.

3.3.6 Exogenous process

The model has two exogenous processes. The first is the evolution of the variable A_t. The productivity variable in each period is:

$$A_t = (1 + g_{A,t})A_{t-1}. \tag{3.35}$$

The technological growth rate $g_{A,t}$ is exogenous and described by an AR(1) process:

$$g_{A,t} = \rho_A g_{A,t-1} + \varepsilon_A; \quad \varepsilon_A \sim N(0, \sigma_A^2), \tag{3.36}$$

where ρ_A is the effect of the past growth rate over the present rate and ε_A is a stochastic error term which follows a Normal distribution with zero mean and constant σ_A^2 variance.

The quality of the consumption good produced by each firm is described by the equation:

$$Q_{i,t} = (1 + \rho_q(1 - \frac{Q_{i,t-1}}{\overline{Q}_{t-1}}) + \varepsilon_Q)Q_{i,t-1}; \quad \varepsilon_Q \sim U(minq, maxq). \tag{3.37}$$

We are assuming that the quality of the good of each firm can vary a minimum in percentage ($minq$), which can even be negative, and a maximum ($maxq$). A uniform function is used to draw the random term. Also, with the term $\rho_q(1 - \frac{Q_{i,t-1}}{\overline{Q}_{t-1}})$ we assume that the quality of each firm tends to be reverted to the average quality. If the quality of the firm's product is higher than the market average, it will decrease in the following period and the parameter ρ_q determines the speed at which the reversion of the quality to the mean occurs. This property was introduced to ensure that the dispersion of the relative quality of firms' goods is not increasing throughout the simulation, which would lead to a continuous increase in the market power of some firms. If this is a property desired to be observed in the model, it's only necessary to consider $\rho_q = 0$. Also, the value of ρ_q will determine how persistence is heterogeneity among the firms and how long a firm will be able to extract abnormal profits due to a relative quality above the average.

3.4 Simulation protocol and calibration

The method of analyzing the model was through Monte Carlo simulations. In the simulations, we considered that 500 firms were present in the economy. All the simulations performed were tested until the period 1500. The parameter configuration of the benchmark model was mostly obtained through a calibration exercise. The model was calibrated using cross-correlations among quarterly time-series for the US economy, target values for the means and standard deviations of some variables. For some of the parameters, we considered values observed as the literature, such as De Castro et al. (2015). Some of the variables we also calibrated using parcimonious values. We considered that all the parameters related to inflation inercia equal to one. Therefore, agent's fully pass-through the inflation expectation to prices, costs and nominal wages. Also, since the value of φ is bounded by the value of the parameters χ and ϕ, we determined these two parameters *ex-ante* the calibration exercise. Thus, the central bank credibility was defined as $\phi = 0.8$ and the parameter of the objective function of the central bank as $\chi = 0.6$.

To calibrate the model we used the method of simulated moments, as described in Delli Gatti et al. (2017, p. 195) The objective function of the calibration problem was:

$$\hat{\theta} = argmin_{\theta}[\mu^*(\theta) - \mu_R]' W^{-1}[\mu^*(\theta) - \mu_R], \tag{3.38}$$

where θ is parameter vector governing the simulations outputs, $\mu^*(\theta)$ is the vector of statistical moments obtained using a certain vector of parameters, μ_R is the vector of statistical moments observed empirically or the target for the statistical moments and W is a weight matrix.

The correlations considered used to calibrate the model, that composes the vector $\mu^*(\theta)$, were the auto-correlation of the aggregate GDP from period -6 to 6, the cross-correlation of the GDP with inflation rate, the interest rate and the variance of real wages. Therefore, we have 39 empirical moments. These cross-correlation are documented in Stock and Watson (1999). Besides, we calibrate the model with target values for the mean inflation rate, inflation expectation, wage share, frequency of price changes, size of price increases and the standard deviation of the inflation rate, the inflation expectation, wage share and product. So, the model was calibrated considering 39 empirical statistical-moments and 9 target values.

The matrix W was build to weight the importance of each type of statistical moment in the final result of $\hat{\theta}$. For elements in the diagonal matrix of W we considered the relative participation of each type of statistical moment in the total set of moments. When the variable was a cross-correlation, the respective value in the W diagonal was 39/48. For target values, 9/38.

We used the last half periods of the generated time-series to computed the statistics. The parameters free to calibrate were: $\alpha, \sigma, \nu, \gamma, \xi_q, \xi_p, \varphi, maxq, \rho_q$. In Table 3.1, we have the parameter space considered to calibrate the model.

Parametric space			
Parameter	Name	Min Value	Max value
α	Elasticity of production with respect to labor	0.5	1.5
σ	Relative risk aversion coefficient	0.8	3
γ	Weight parameter of labor disutility	0.3	3
ν	Marginal disutility in respect of labor supply	0.05	2
ζ	Effect of past consumption expectation on current expectation	0	1
φ	Effect of GDP gap on inflation expectations	0	$0.2 = \phi - \chi$
Φ	Central bank inertia	0	1
ξ_q	Quality elasticity of demand	0.25	10
ξ_p	Price elasticity of demand	0.25	10
ρ_q	Mean reversion of quality	0.1	0.95
$maxq$	Maximum quality growth	0.001	0.2

Table 3.1 - Range of the possible values of the calibrated parameters

The optimizing problem of the calibration was solved through a search-based genetic algorithm (GA) developed in Scrucca (2013). For an general introduction of the GA algorithm, see McCall (2005). The steps of the algorithm are: generation of a random population of parameters sets inside the given parameter space [1], computation of the fitness value of the populations (which is given by the value of the objective function) [2], select the sets of parameters able to reproduction given their fitness values and the ones that will survive to the next simulation (hyper-parameter called elitism) [3], recombination and mutation of the selected sets' of parameters (recombination create new individuals using the values of the most fitness ones, mutation randomly substitute some parameters with values observed in random individual parents), repeat [2] and [3] until the value of the most fitted individual does not change a minimum of times, counting to eight decimal places, or until a limit of periods of simulations. This algorithm has the advantage that explores all the given parameter space, being able to find the global maximums/minimums of the objective function, without being too computing expensive. Finally, the algorithm does not need a prior (as Bayesian methods of calibration), but a suggested solution can be incorporated in the initial population. The values of hyper-parameters adopted to implement the genetic algorithm are in table 3.2.

Hyper-parameters	
Name	Value
Population	20
Runs	5
Crossover	0.8
Mutation	0.1
Elitism	1

Table 3.2 - Hyper-parameters of the Genetic Algorithm

To set the values of the fixed parameters that are not open to be calibrated in the calibration exercise, we used values already considered in the literature. Specifically, we relied on the work of De Castro et al. (2015), where the authors developed the official DSGE model used by the Brazilian Central Bank (the SAMBA model). For the calibration of the benchmark model, we used the following values:

Parameter	Description	Value	Source
α	Elasticity of production with respect to labor	1.0507	GA Calibration
σ	Relative risk aversion coefficient	2.5961	GA Calibration
γ	Weight parameter of labor disutility	2.1181	GA Calibration
ν	Marginal disutility in respect of labor supply	1.0159	GA Calibration
β	Inter temporal discount factor	0.989	SAMBA
ζ	Effect of past consumption expectation on current expectation	0.8	GA Calibration
ϕ	Central bank credibility	0.8	Calibrated
$1 - \phi$	Inflation inertia on expectations	0.2	Calibrated
φ	Effect of GDP gap on inflation expectations	0.1504	GA Calibrated
ξ_p	Price elasticity of demand	1.7059	GA Calibrated
ξ_q	Quality elasticity of demand	9.7716	GA Calibrated
$\rho_{\pi,f}$	Price Indexation	1	Calibrated
$\rho_{\pi,h}$	Wage Indexation	1	Calibrated
ρ_w	Real-adjustment of nominal wage	1	Calibrated
χ	Central bank reaction	0.6	Calibrated
Φ	Interest rate smoothing	0.9399	GA Calibrated
ρ_Q	Mean reversion of quality	0.3913	GA Calibrated
$maxq$	Maximum quality growth	0.0997	GA Calibrated
N	Number of firms	500	Initial conditions
$P_{i,t}$	Prices of the firms	1	Initial conditions
$Q_{i,t}$	Quality of the firms	1	Initial conditions
A_t	Aggregate productivity	2	Initial conditions
$m_{i,t}$	Fixed markup	0.42 - 1.27	Initial conditions
$\Theta_{i,t}$	Adjustment term of markup to quality	0.1 - 1.80	Initial conditions
$\eta_{i,t}$	Band of inaction	0.01 - 0.2	Initial conditions

Table 3.3 - Parameters and initial conditions of the benchmark model

The initial conditions of the variables expected GDP, expected inflation, nominal interest rate, firm demand, labor demand, reservation real wage, average real markup, expected unitary cost of production were all calculated considering the model in it's aggregate form in the steady-state.

3.5 Simulation results

In this section, we will present the results of the model using the benchmark parameters. In this setting, the economy does not grow over the long run (the shocks to the technology growth are zero). The only source of dynamics in the benchmark model comes from shocks that change the relative quality of the final goods. As a result, the expected equilibrium product of households is constant. However, this does not mean that labor productivity is constant. It will fluctuate depending on the degree of market concentration. Since in our model firms have a production function that is characterized by increasing returns to labor (given the selected value of α) , the more concentrated the market, the higher the labor productivity of the economy. So, we will observe a cyclical behavior of the economy. However, we will not observe a tendency of growth. The level variables of the economy will converge to stable steady-states and growth rates, on average, equal to zero.

In the Figure (3.1), we can observe how the inflation rate, the expectation of inflation, and nominal interest rate of the last 200 periods of one run of the simulation. We observe a cyclical pattern in the three variables. The inflation expectations tend to be lower than the inflation rate over the simulation because of the inflation targeting anchoring, as modeled through the Equation (3.11). The inflation rate tends to fluctuate slightly above the inflation target. The nominal interest shows the expected pattern, being consistently above the inflation rate, as modeled in the central bank reaction function.

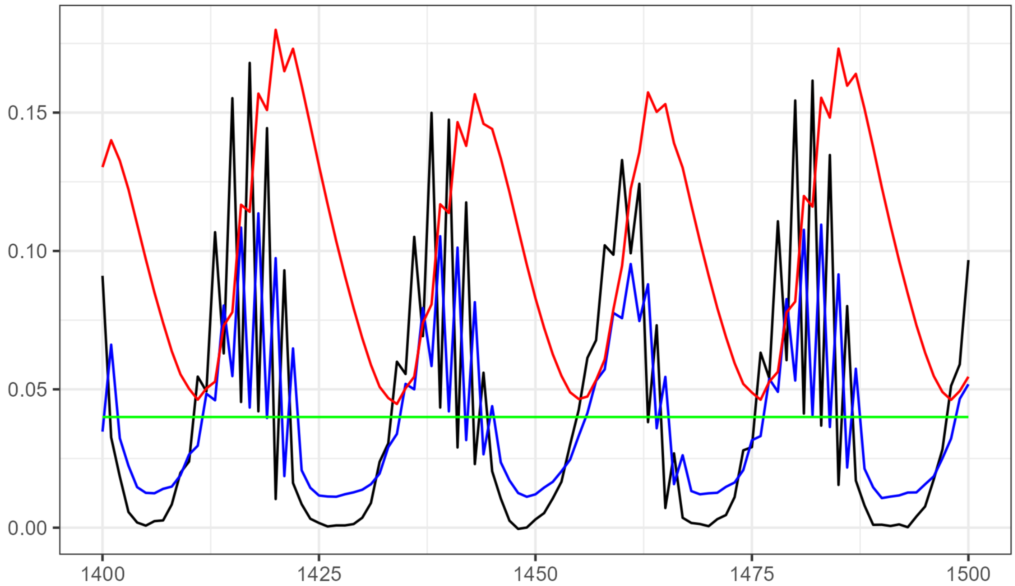


Figure 3.1: Nominal interest rate (red), expectation of inflation (blue), inflation rate (black) and inflation target (green)

In the next Figure (3.2), we have the average inflation rate performing 100 simulations with the benchmark model. On average, the inflation rate stays slightly above the inflation target of 4% annually. The standard deviation of the inflation rate was 0.034. Besides, the average inflation shows a stable behavior, with no trend. In Figure (3.2) we can also observe, with the graph of one simulation run (in blue), that the inflation rate shows a cyclical pattern.

In Figure (3.3), we have the behavior of the nominal interest rate set by the monetary authority, as expected, it follows a behavior as expected given the model and that, on average, the inflation rate stay slightly above the inflation target. We observe a trend of growth in the average value of the nominal interest rate. The standard deviation of the nominal interest rate (0.028) is lower than that of inflation, explained by the higher monetary policy inertia in relation to the inflation inertia.

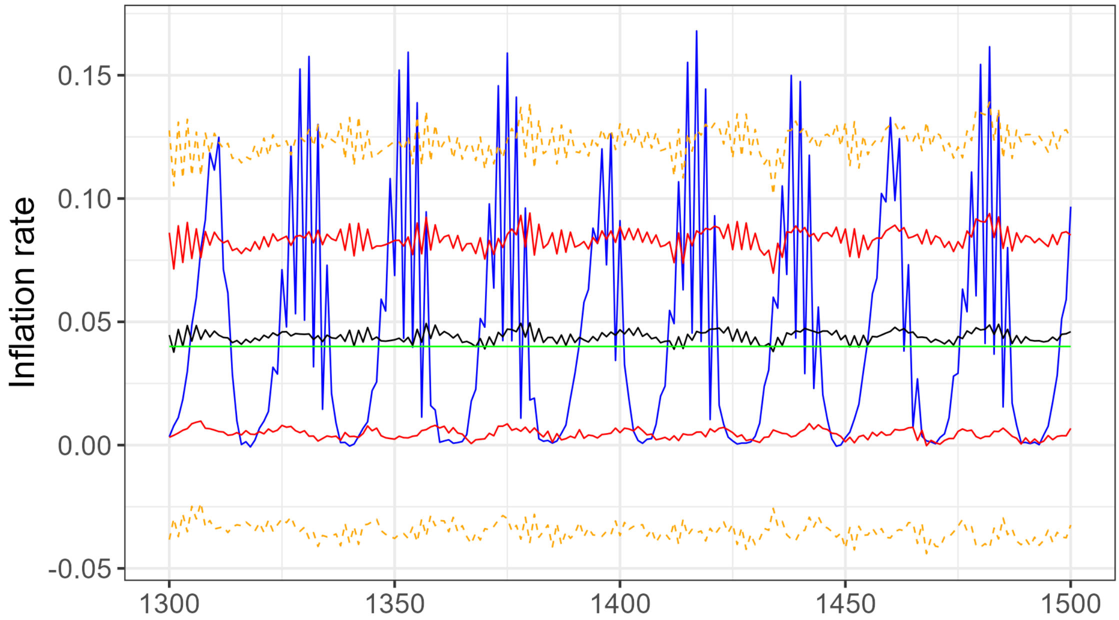


Figure 3.2: Inflation rate

Black = mean. Red = 1 STD. Orange = 2 STD. Blue = one run

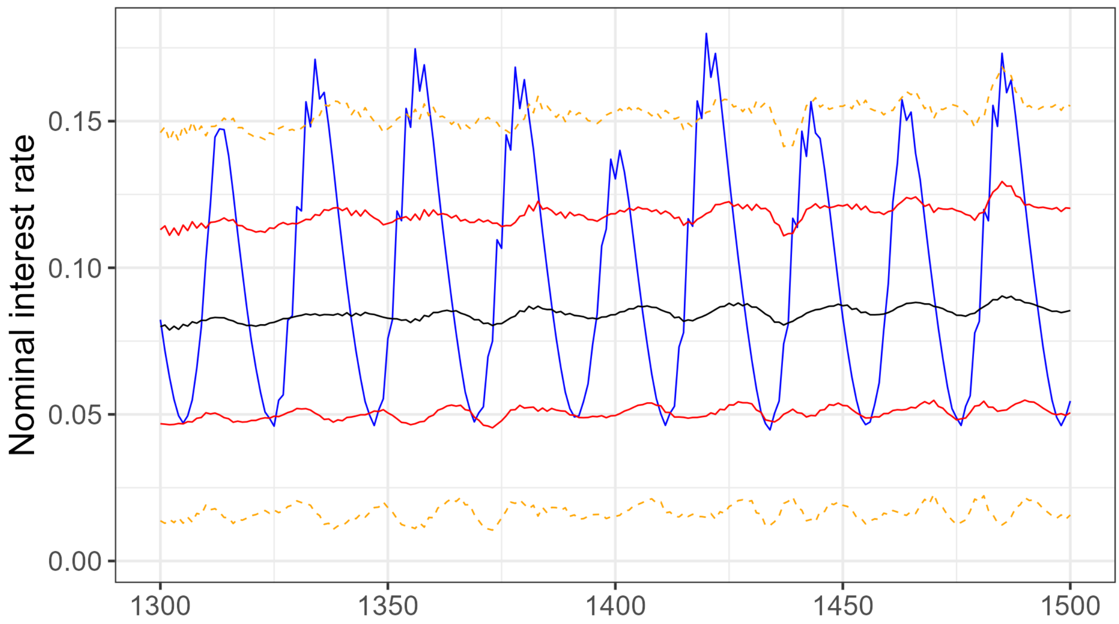


Figure 3.3: Nominal interest rate

Black = mean. Red = 1 STD. Orange = 2 STD. Blue = one run.

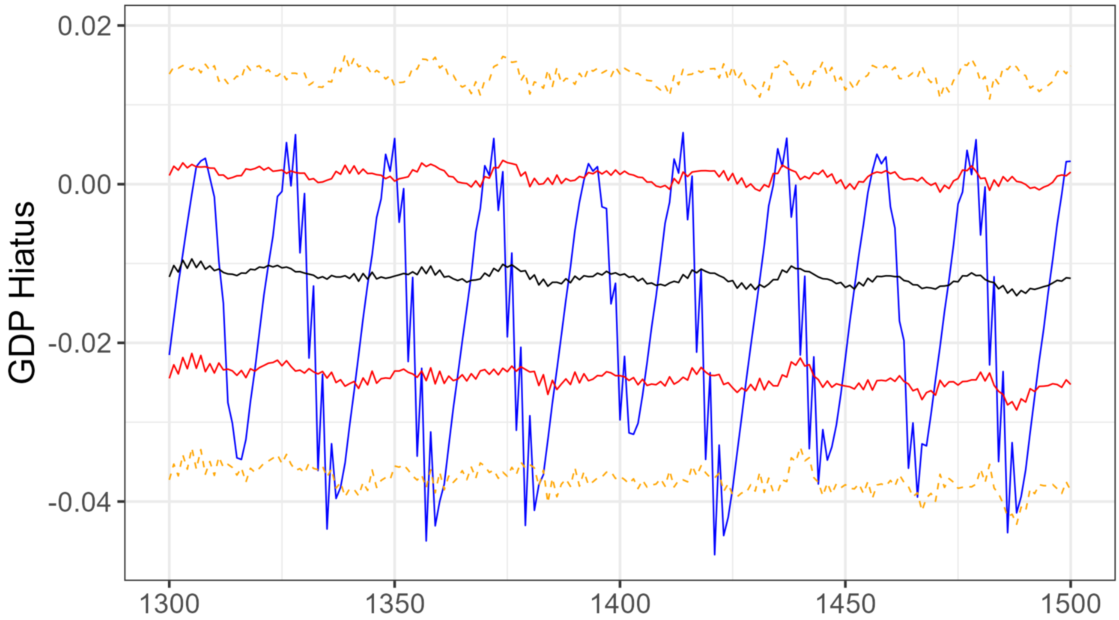


Figure 3.4: GDP gap

Black = mean. Red = 1 STD. Orange = 2 STD. Blue = one run

In Figure (3.4), we have the behavior of the GDP gap, the difference between the current GDP to the expectation of the future GDP. We observe a trend of a continuous decrease in the GDP gap. This means that the current GDP is continuously below the value of the GDP that would be observed in the long term, given the supply conditions of the economy. This happens because, with increasing values of the nominal interest and, therefore, the real interest rate, we have a decrease in the current value of the GDP, as modeled through the Euler equation (Equation (3.7)). However, as we see in the blue line in Figure (3.4), this process is not linear. On the contrary, the GDP gap also shows a cyclical behavior.

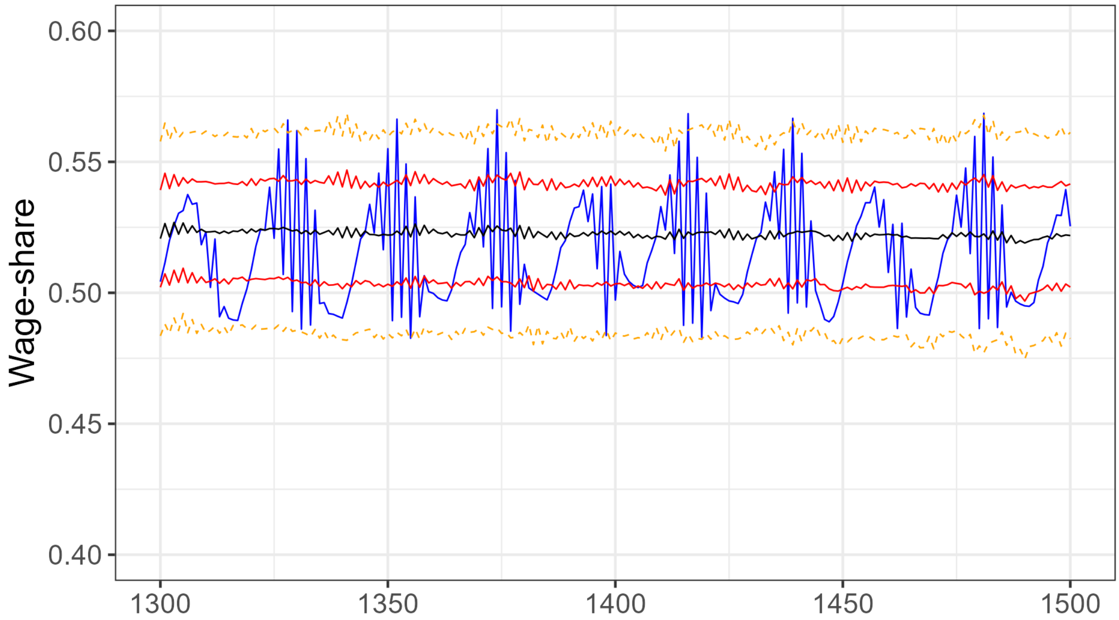


Figure 3.5: Wage share

Black = mean. Red = 1 STD. Orange = 2 STD. Blue = one run

In the case of the wage share, in Figure (3.5), we observe a constant trend when considering the average value of the simulations, with an average value of 0.531 and a standard-deviation of 0.017. However, again, this process is not linear, but subject to cycles and even long periods where the wage share may increase. This can be observed the result of one simulation run (in blue) in Figure (3.5).

We can observe the auto-correlation of the GDP and the cross-correlation of the GDP with the inflation rate, real wage rate, and nominal interest, in Figure (3.6). In black we have the average result of the 100 simulations, the bars give two standard deviations and in red we have the empirical result reported by Stock and Watson (1999) and used to calibrate the model.

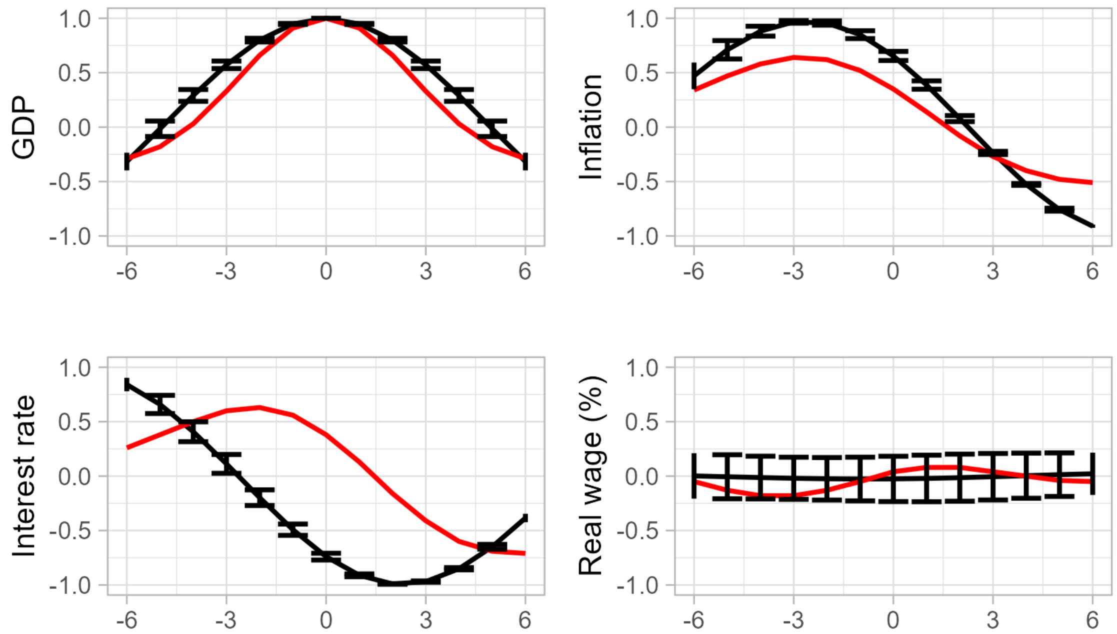


Figure 3.6: Cross-correlation of the GDP

Note: Bpf: bandpass-filtered (6,32,12). GDP is in logarithm. Bars are 2 standard deviations of 100 Monte Carlo average cross-correlations

We can see that with the calibration exercise, on average, the auto-correlation of the simulations presents behavior closer to what is observed empirically for GDP, inflation, and real wages. The auto-correlations show similar magnitude and pattern as those observed empirically. In the case of the inflation rate and nominal interest rate, the cross-correlations obtained through the simulations show an amplitude higher to what is seen empirically. In the case of real wages, the empirical auto-correlation remains within two standard deviations. The only variable that does not exhibit a movement similar to what is observed empirically is the nominal interest rate. Empirically, this variable reacts with a lag to changes in the inflation rate. In the model, however, the interest rate precedes changes in the inflation rate.

Overall, we considered that the results with the macroeconomic variables showed a robustness in reproducing macroeconomic behavior of the macroeconomic variables, with a little difference among the 100 simulations, specially when we consider the small size of the model. This contrasts with the results considering micro variables. But, before to present these results, in Figure (3.7) we have the average results of the behavior of pricing considering the average of the simulations in every period. This figure shows the frequency of firms adjusting their prices each period and the average size of the prices increases. We observe a lot of volatility in the number of firms adjusting prices over time. From the period 1400 to 1500 this proportion fluctuated from 0% to 85%, with an average value of 30%. With a with much lower volatility, the average increase of prices fluctuated from 10.4% to 24%, with an average value of 14.7%. The product of the frequency with the average increase, the red line in Figure (3.7), gives a mean value close to the inflation rate in every period. Therefore, in our model, what is mainly driving the inflation rate volatility is the frequency of price changes. As we have seen in the chapter two, Nakamura and Steinsson (2008) identified with data of the CPI of the US that, indeed, it is the changes in the frequency of price changes, and not the magnitude of the price changes, that mainly explain the behavior of inflation. This is one important stylized fact that the model is able to reproduce.

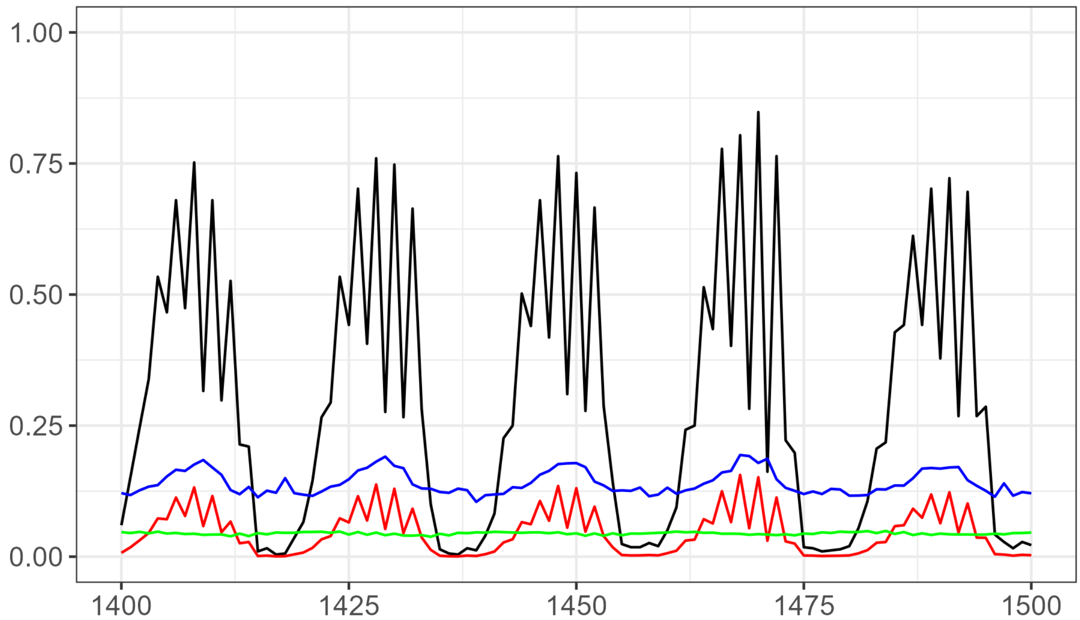


Figure 3.7: Firms that changed prices (black), average size of price increases (blue), inflation rate (green), product of % firms that changed price with the average increase in prices (red) and inflation rate (green)

Now, going to the discussion of pricing strategies, in Table 4.1 we have the values of several statistical moments obtained through the Monte Carlos simulations and the values observed empirically. The statistical moments were calculated only considering values observed after period 500 in the simulations. Overall, the results show that the model is able to reproduce relatively well the stylized facts, although some work is still needed to improve the precision.

The results in Table (4.1) show that prices of the model tend to be more rigid compared to what is observed in empirical data. The average duration of the prices in the model is 10.3 months while empirically it is observed a duration of 8 months for consumer prices in the US (disregarding sales). The percentage of price increases, (99%) is much higher compared to what is observed empirically (60%). As a result of the price stickness of the model, price changes were much greater comparing to what is observed empirically. The average value of price increases in simulations was 13.7%, while in the US it is 7.3%. The average decrease of prices was 12.3% in the model simulations, while empirically it is 10.5%.

Microeconomic statistical moments			
Parameter	Average	SD*	Empirical value
Frequency of price changes	0.1023 (monthly)	0.0079 (monthly)	0.12 (monthly)
Implied price duration	9.77 (months)	-	8 (months)
% Price increases when prices changed	0.9968	0.0024	0.60
Value of price increases	0.1447	0.0057	0.073
Value of price decreases	-0.1093	0.0056	- 0.105

Table 3.4 - Simulated microeconomics moments vs. stylized facts

* The standard deviation (SD) is calculated from the average of the results of the 100 simulations.

Notes: The empirical moments are presented in Nakamura and Steinsson (2008). The simulation process occurs on a quarterly basis, and the resulting values are then transformed into monthly values for comparison with the empirical data.

In the next figure, we observe the average quantity of firms that adopted the different heuristics to set the markup in the 100 simulations. We can see that, although the averages fluctuate, the heuristic mostly adopted by firms is, on average, is the “flex markup”heuristic, expressed in the Equation (3.31). The average value of firms adopting these heuristics fluctuates between 31.9% and 38.9%. On average, 38.2% of the firms adopt this strategy in every period. The second strategy mostly adopted by the firms is the "fix markup". On average, 31.2% of the firms used this strategy in every period between the simulations. Lastly, the least adopted heuristic was "competitors' price", with 30.7% adopting it.

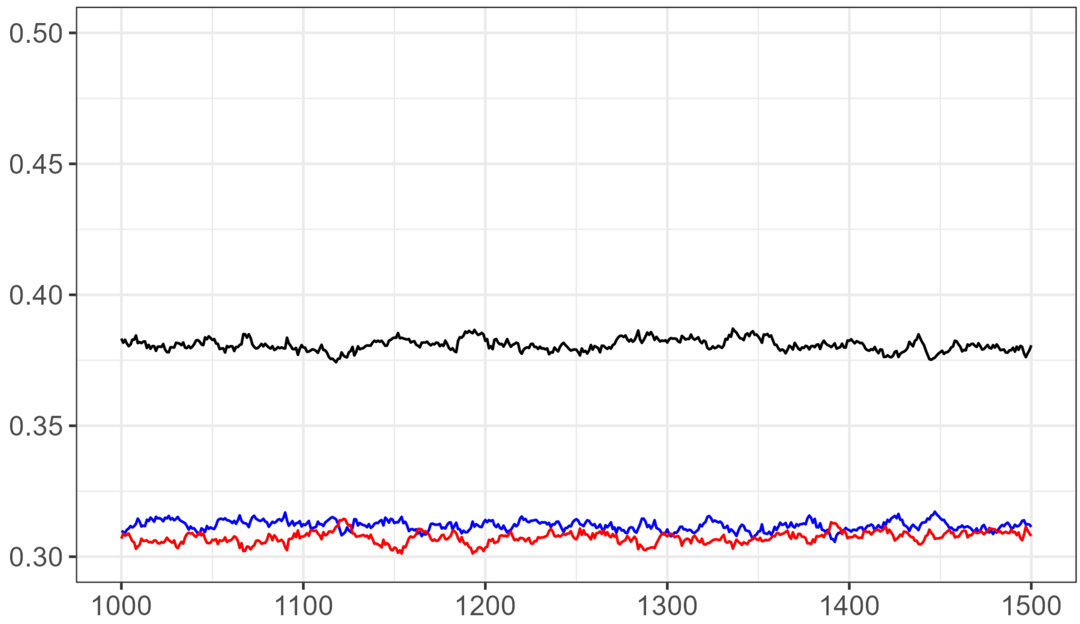


Figure 3.8: Average number of firms using one of the heuristics at each period

Black = Flex markup. Blue = Fix markup. Red = Competitors' price

By refraining from imposing any restrictions on the rules that could be selected by firms or any limits to the percentages, we were able to obtain results that were notably similar to those observed empirically. As detailed in section 2, in various regions, approximately 50% of firms adopt cost-based pricing, while between 20% to 30% choose to follow their competitors' pricing. In our model, 69% of firms opted for a cost-based pricing approach, which closely aligns with the number of firms in the study by Correa et al. (2018) who claimed that cost-based pricing is a relevant factor in explaining their price-setting behavior. In essence, our model was able to replicate the observed heterogeneity of firms with stable results without imposing any heterogeneity. On the contrary, it was observed as an emergent phenomenon. Furthermore, the heterogeneity remained consistently strong over time, with no clear indications of any pricing heuristics gaining an increased share of the firm population.

However, Figure (3.8) obscures an important aspect of the heterogeneity of price behavior. Although the average value of heuristic participation remains relatively constant over time, we observe a cyclical behavior in the distribution of heuristics when considering only one simulation, in Figure (3.9). In this figure, we can observe that the prevailing heuristic among the population of firms changes periodically.

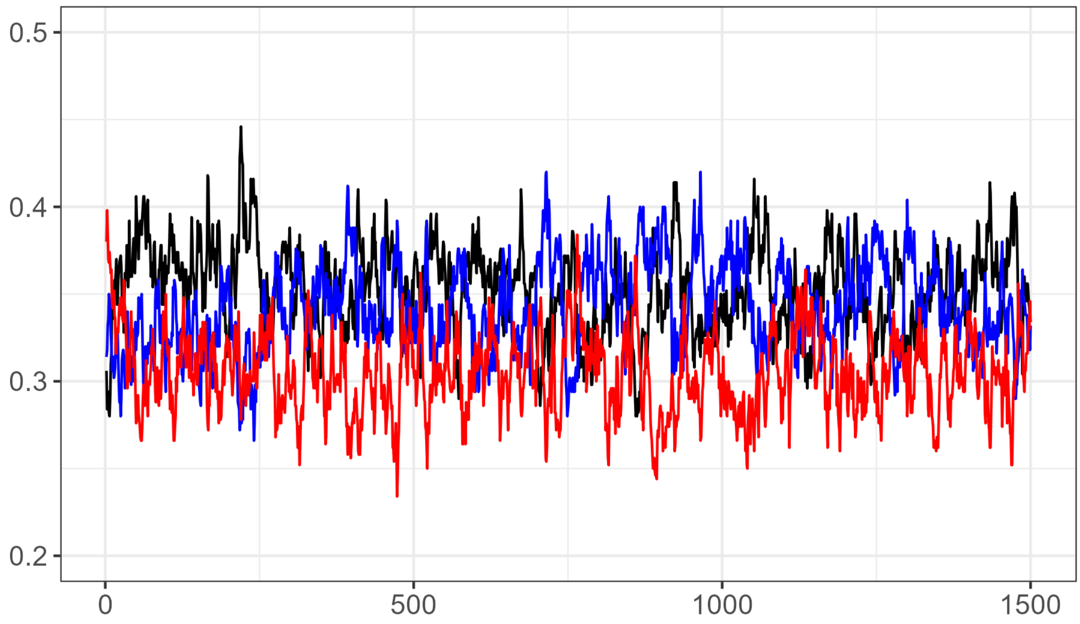


Figure 3.9: Distribution of pricing heuristics among firms in one simulation

Black = Competitors' price. Blue = Fix markup. Red = Flex markup

We will now examine the average values of the microeconomic behavior parameters that firms can modify over time, namely $\Theta_{i,t}, m_{i,t}, \eta_{i,t}$. These parameters are of particular interest because they determine the dynamics of the inflation rate, real wages, and hence the functional distribution of income. Moreover, these variables are typically considered parameters in most macroeconomic models (such as ABMs or DSGEs), rather than results of an evolutionary process shaped by market competition forces. Thus, the findings we will present can be regarded as novel.

In the following figure, we illustrate the behavior of the parameter $\Theta_{i,t}$, which denotes the markup adjustment to relative quality, over time. This strategy the called the "flex markup"heuristic. We observe that this parameter did not stabilize even after 1500 periods, with the average value of $\Theta_{i,t}$ at 1.045. This suggests that, on average, firms utilizing this strategy increased their prices by more than the proportion of their quality advantage. As we are assuming rigid prices, firms with a higher value of $\Theta_{i,t}$, were better suited to operate in this environment, as they could change their prices faster to exploit quality advantages or avoid market share losses due to excessively high prices.

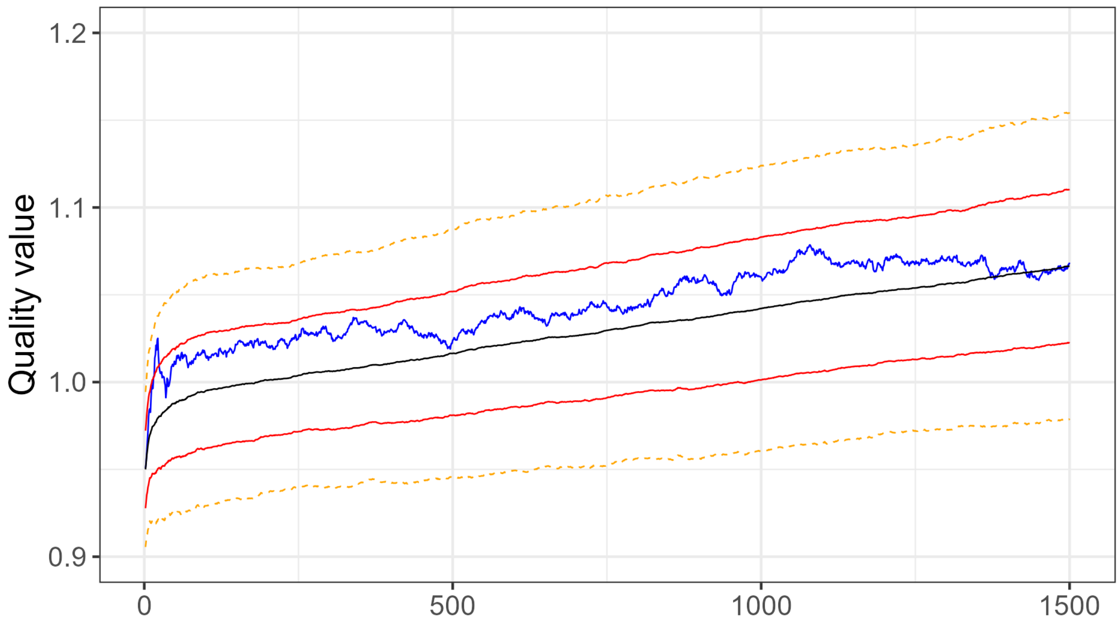


Figure 3.10: Average flex markup

Black = mean. Red = 1 STD. Orange = 2 STD. Blue = one run

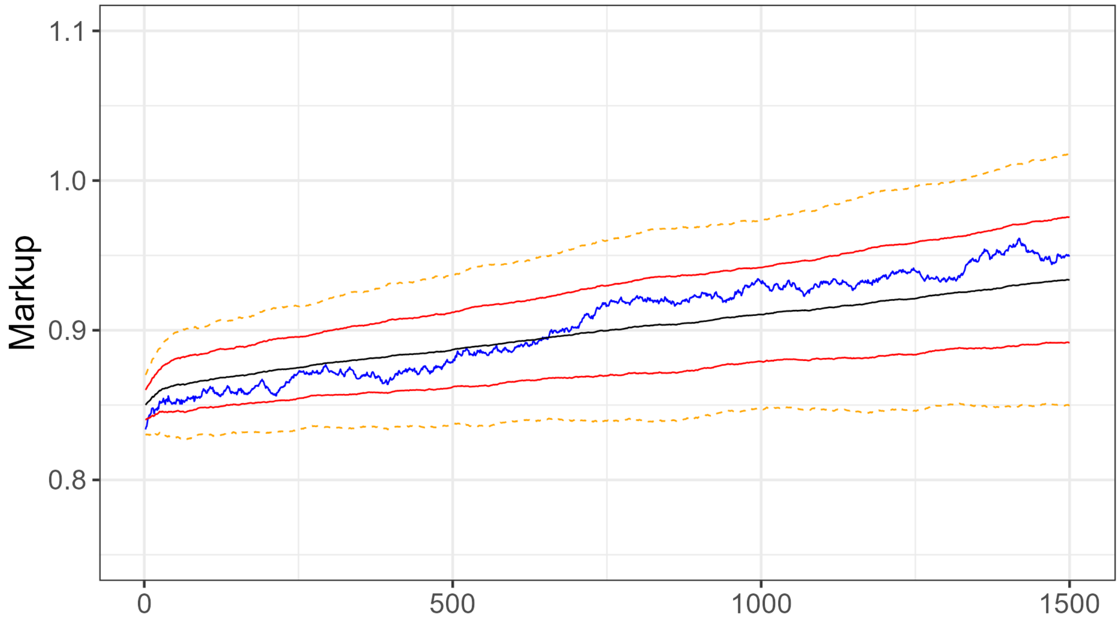


Figure 3.11: Average fix markup

Black = mean. Red = 1 STD. Orange = 2 STD. Blue = one run

When we focus on the average value of $m_{i,t}$, we also see a persistent increase in the average value of this parameter and a relatively higher volatility result when comparing with the macroeconomic results. Differently from the case where firms increase their prices to avail competitive advantages, in this case, firms do not have necessarily a quality competitiveness. However, since the firms that utilize the flex markup are persistently increasing their markups on average, this means that firms that follow different strategies can also increase their prices without necessarily losing market share. Actually, the average value of $m_{i,t}$ ended after 1500 periods substantially lower than the average value of $\Theta_{i,t}$, in 0.91, although in every simulation they started with the same value.

When comparing firms with the same product quality at the end of the simulations, the firm that follows a fix markup heuristic will, on average, have a price advantage over the firm that uses the flex heuristic. This means that, although firms using the fix markup heuristic do not achieve higher profits when their products have higher quality, on average, they adopt pricing strategies that give them a competitive price advantage.

The evolution of the markups, determined by the evolutionary algorithm developed, explains the behavior of the macroeconomic variables of the model. First, it explains the behavior of the wage share. If the surviving firms are the one's that adopt a higher markup, this means that the wage share will decrease in the economy over time. This also explains why workers never obtain a real-wage equal to the desired one, the inflation is usually higher then the inflation expectation due to the growth of the markups. This pushes the nominal wages to growth above the inflation expectation, as modeled through Equation (3.26).

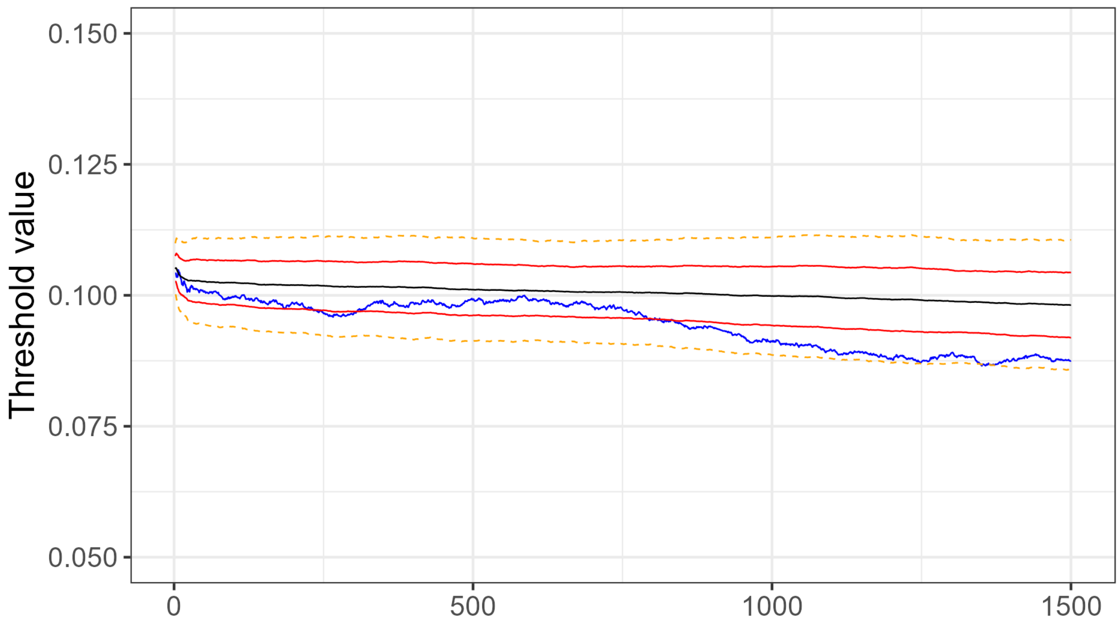


Figure 3.12: Average band of inaction

Black = mean. Red = 1 STD. Orange = 2 STD. Blue = one run

Finally, in terms of the parameter $\eta_{i,t}$, different from the other pricing parameters, we observe a downward tendency. At the final period of the simulation, the average value of parameter η is close to 0.1 among the 100 simulation. Firms started with values of $\eta_{i,t}$ between 0.01 and 0.2, so, we observe that the value of parameter that tended to be adopted by the firm is close the average value. This can be observed in Figure (3.12). Through the Figure (3.13), we can see that, considering only one simulation, the value of the parameter η quickly converge to the mean value of that parameter in the population of firms. This suggests that the optimal strategy in terms of price rigidity for firms is to quickly adopt the average rigidity observed in the market, not being too rigid or too flexible.

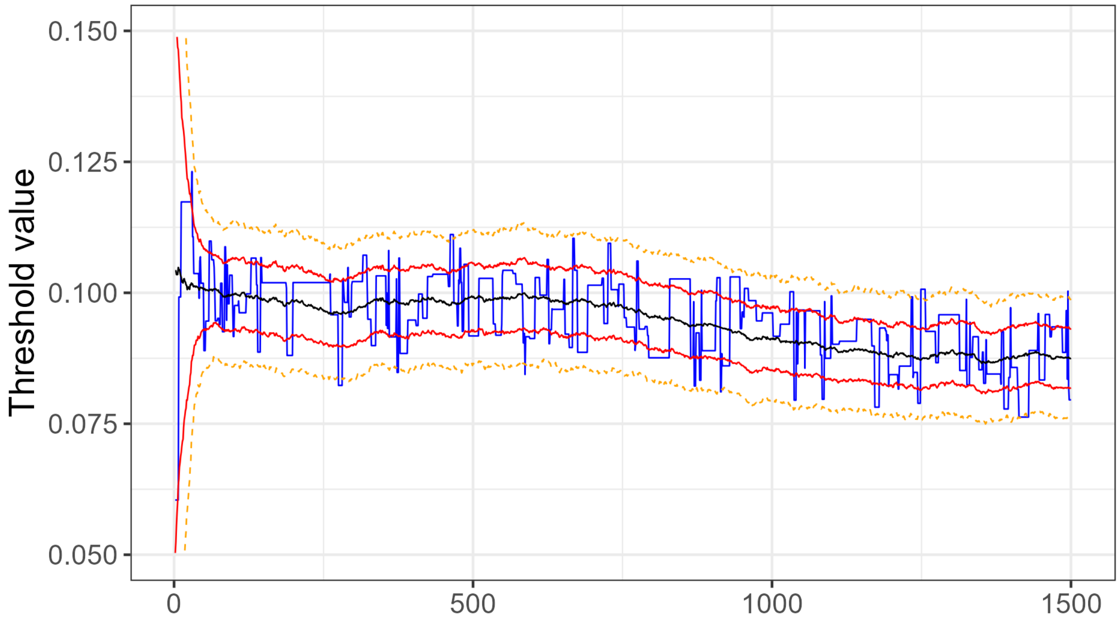


Figure 3.13: Band of inaction of one simulation run

Black= mean among the firms. Red = 1 STD. Orange = 2 STD. Blue = one firm

3.6 Sensitivity analysis

To evaluate how sensible are the results obtained in the prior section, we performed a local sensitivity analysis. This is necessary to observe how important are the values of the calibrated parameters to reproduce the empirical data (micro and macro). All the results of the sensitivity analysis are reported in Appendix 2. This analysis was done with the parameters that were considered more interesting to evaluate.

They are $\alpha, \sigma, \nu, \xi_p, \xi_q, \varphi, \rho_{\pi,h}, \chi, maq$. Respectively, the elasticity of production concerning labor, the relative risk aversion coefficient, the marginal disutility of labor, the price elasticity of the market share, the quality elasticity of the market share, the GDP gap effect over the inflation expectation, the wage indexation, the parameter of the reaction function of the central bank, and the maximum variation of the quality of a consumption good.

First, the sensitivity analysis is performed observing if with the given values of the parameters the results are stable. Unstable parameter sets are those where the model crashed due to the convergence of some values to zero or infinity, making the division operations of the model impossible. Thus, unstable cases are impossible cases and we considered stable even scenarios with possible extreme values.

We always considered the mean (ME) and standard deviation (SD) of the chosen variables for the sensitivity analyses. They were: GDP gap, inflation, wage share, nominal interest, number of firms using each one of the rules, the average percentage of firms' adopting the flex markup heuristic, the average percentage of firms' adopting the fix markup heuristic, and the average percentage of firms' adopting the competitors' price heuristic. To realize the simulations of the sensitivity analysis we used Monte Carlos experiments with 30 simulations, each consisting of 1500. We tested 8 different values for each parameter, defined in the interval $(X_i - X_i/2)$ to $(X_i + X_i/2)$, where X_i is the parameter value obtained in the calibration exercise. For example, in the case of a parameter with a benchmark value of 1, we analyze a sample ranging from 0.5 to 1.5.

The only parameters that leads the model to feature unstable results were α and ξ_p, respectively, the elasticity of production concerning labor and the price elasticity.. The elasticity of production concerning labor (α) is the most important variable of the model. We observed a non-linear behavior of the model depending on the variable being analyzed. The higher the value of (α), the model show a decreasing value of the GDP gap, higher mean inflation rations, nominal interest rate and wage-shares. The standard deviation of the variables increases the higher the value of α. The parameter α considerable changes the distribution of heuristics among the firms. Basically, for the lowest value of α for which the model is stable, the heuristics tend to evenly distributed among the firms. However, the higher the value of this parameter, the higher the participation of rule 3 and, specially, of rule 1, the "flex markup"heuristic. On the opposite side, the "fix markup"heuristic, in environments of higher inflation, tends to lose participation in the firm's population.

The sensitivity analysis of σ, the relative risk aversion coefficient, showed that the higher the value of that parameter, the higher the wage share, the nominal interest rate, and the lower the GDP gap. Following the same tendencies of changes in α, the higher the inflation rate, the higher the participation of the heuristics flex markup and firm's population. However, we observe a decrease in the number of firm's following the competitors' price heuristic.

Different values of the elasticity of demand to prices (ξ_p), also showed important results in terms of the final results of the simulations. In macroeconomic terms, the closer to one the demand elasticity, the lower was the average inflation rate, the standard deviation of inflation, and, hence, the level and standard deviation of interest rate. The only value of ξ_p below 1 showed unstable results.

The results concerning firms' behavior are also interesting, although expected. The lower the ξ_p, the higher the number of firms adopting the flex markup strategy. Increasing the value of ξ_p we have more firms adopting the competitors' price heuristic, but less firm's using the fix markup heuristic.

The variable ξ_q did not show meaningful changes in the macroeconomic variables. However, in terms of the heuristics distribution, surprisingly, the higher the importance of ξ_q, less firms adopted the flex markup heuristic, as would be expected. On the other hand, we observe a increase in the number of firms following the fix markup and the competitors' pricing approaches.

Changes in the maximum variation of the quality of consumption good in a period, $maxp$, also did not have any meaningful effect over any variable. This was quite surprising given that, with given prices, quality is what dictates the competition dynamics among the firms, their profit, and, therefore, the evolutionary process.

Changes in the variable φ, the parameter the sets the GDP gap effect over the inflation expectations, also did not lead to meaningful differences between the variables. In other words, in our modeled environment, the effect of our measure of GDP gap on the expectation of inflation does not seem to make important differences.

In conclusion, with the tested variables, α, σ, and elasticity of demand lead do important differences to the final results of the model, while the other variable did not. The sensibility results showed also that the main variable that is affect by the model parameters is the wage share, with really small results over the other macroeconomic variables, with the only exception being the parameter α. In terms of the heuristics distribution, we observe that, the higher the inflation rate, wage share, nominal interest rate and lower GDP gap, which all tend to correlate in the sensibility analysis, the higher the participation of the flex rule of thumb and the lower the fix markup. The competitors' price did not show a clear tendency to change its participation in the firm's population with changes in the macroeconomic variables. Therefore, we can say that the sensitivity analysis shows evidence that unstable environment's tend to select heuristics where price's are more flexible and where firm's follow more the price of competitor's to set their own prices. Since these strategies make prices more flexible, this tends to reinforce the instability of the model. Also worth to mention, we do not observe that the the parameters related to quality competition where important to change significantly the macroeconomic affects. We also observed that the higher the important of the relative quality to drive firm's competitiveness's, the higher the participation of the "fix" markup heuristic.

3.7 Conclusion

In the present paper, we developed an hybrid ABM-DSGE model that incorporated in a traditional DSGE model many characteristics found in ABMs. The purpose of the paper was to develop a model that allows for the heterogeneity in pricing behavior that is empirically observed to emerge from an evolutionary dynamics driven by competitive forces, selecting the fittest pricing heuristics. The objective was to show that even using a standard model, that assumes a specific macroeconomic environment, the empirically observed pattern of firms can be explained as an evolutionary process with firms using simple heuristics and rules of behavior and having bounded rationality. In other words, the calibration of DSGE models that assumes rational expectations may be capturing some kinds of behavior that can also be explained with an evolutionary approach.

The difference to the standard DSGE model is the existence of firms with limited rationality, the existence of different pricing heuristics, and the possibility that the parameters that conduct the pricing decisions are endogenously time-varying. The process of evolution is driven by an evolutionary switching protocol that has at its core the selection of behaviors that are being more effective by the fittest firms. Fitness in our model is measured by the ability of a firm to generate higher profits compared to others.

We employed the method of simulated moments to calibrate the model and identify a set of parameters that best reproduces the desired statistical moment targets. Through Monte Carlo simulations, we verified that the model yields stable results for macroeconomic variables. We analyzed the behavior of key macroeconomic variables, including inflation, interest rates, GDP, and the functional distribution of income. In the benchmark model, the economy does not exhibit long-term growth due to zero shocks to technology growth. However, the relative quality shocks introduced dynamics in the model, resulting in cyclical behavior.

The simulations demonstrated a cyclical pattern in inflation, with inflation expectations tending to be lower than the actual inflation rate. The nominal interest rate followed the expected behavior, remaining consistently above the inflation rate. Additionally, the GDP gap exhibited a downward trend over time but also displayed cyclical behavior.

However, it is important to note that these stable macroeconomic outcomes occur within an environment where firms continuously analyze and revise their pricing heuristics. As a result, there is no fixed participation of heuristics within the firms' population, and no single heuristic dominates over others, even in the absence of switching costs among different pricing strategies. The heuristic most frequently used was the "flex markup"strategy, followed by the "fix markup"strategy. The least adopted heuristic was the "competitors' price"strategy. The model captured the heterogeneity of firms' pricing strategies observed in empirical studies and demonstrated the persistence of this heterogeneity over time. This aspect of our model provides insights into why persistent pricing heterogeneity exists across firms.

In terms of pricing rigidity, we observe that firms tended to adopt a "adjustment threshold"of 10%. Furthermore, the convergence to this threshold value within the firm population is rapid, as firms that initially adopt values higher or lower than the threshold quickly adapt to a strategy that closely aligns with the average behavior of the population. It is noteworthy that the emergence of sticky prices occurs even in the absence of any cost considerations for firms when adjusting their prices. Therefore, this phenomenon can be regarded as a truly emergent property of the model. Firms that either have fully flexible prices or excessively stable prices experience lower profits or fitness, which compels them to adapt.

We also conducted a sensitivity analysis to evaluate the robustness of our results. The analysis showed that the elasticity of production concerning labor and the relative risk aversion coefficient significantly influenced the model results. Changes in these parameters impacted macroeconomic variables such as inflation, wage share, and nominal interest rate. The analysis also highlighted the importance of the pricing heuristics in unstable environments, where flexible prices and following competitors' prices became more prevalent.

In conclusion, our hybrid ABM-DSGE model successfully incorporated key characteristics of agent-based models into a traditional DSGE framework. By allowing for heterogeneity in pricing behavior driven by evolutionary dynamics, we demonstrated that empirically observed patterns of firms can be explained by simple heuristics and bounded rationality. The calibrated model replicated key macroeconomic variables and exhibited cyclical behavior in response to shocks, despite the absence of long-term growth. The model also highlighted the persistence of pricing heterogeneity among firms and the importance of pricing heuristics in unstable environments. These findings suggest that the incorporation of elements from ABMs can enhance the realism and flexibility of traditional DSGE models, enabling a better understanding of real-world dynamics without compromising their ability to reproduce empirical data.

Chapter 4

Exploring markup heuristics dynamics in an agent-based macroeconomic model

4.1 Introduction

Markups, the difference between a product's cost and its selling price, are of significant importance to both firms and the economy as a whole. Microeconomically, markups determine the income available to firms for wages, interest, and profits (Dolgui and Proth, 2010). At the same time, the decision about markups is nontrivial (Seppecher et al., 2018), because it impacts the competitiveness of consumer goods (Dolgui and Proth, 2010) Macroeconomically, markups play a crucial role in understanding the functional income distribution, inflation, and overall macroeconomic performance. The literature on this subject is extensive and includes studies on profit share, rise and fall of firms, and macroeconomic implications of markups (Eeckhout, 2021; De Loecker et al., 2020; Autor et al., 2020; Syverson, 2019).

Although markups are central to the economy, economists have a limited understanding of what drives them (Blanchard, 2009). This is reflected in the macroeconomic literature, where markups are often treated as exogenous. Agent-based macroeconomic models also reflect this limitation, with many assuming that markups are constant and equal among all firms. There are also macroeconomic ABMs in which markups are endogenous and differ among firms. In some of these models, the aggregate functional income distribution is exogenously imposed, and the markups are endogenous given some variable that explains the competitiveness of the firms, with the rule determining the markups equal for all the firms. This approach has limitations as it does not capture the complexity of the factors that drive markups in the real economy.

The aforementioned literature has provided valuable insights, but it has not given sufficient consideration to certain key stylized facts identified through surveys with firm managers. One such fact is that firms employ different pricing heuristics in setting their prices. The existence of multiple pricing heuristics is well established in the literature on business and operations research (Dolgui and Proth, 2010; Hinterhuber, 2008), yet the question remains as to why firms do not universally adopt what is considered the optimal pricing strategy, namely value-based pricing (Hinterhuber, 2008).

This chapter aims to examine the presence of heterogeneity and interaction in firms' price-setting behavior and how it is affected and affects changes in the functional distribution of income and macroeconomic performance. To accomplish this, we have developed a agent-based macroeconomic model in which firms can utilize four distinct pricing heuristics. These heuristics were derived from the ABM literature and surveys with managers to identify the rules used by firms to set prices. Additionally, we posit that firms are continuously interacting with their environment and learning, seeking more effective heuristics to increase profits and improve competitiveness. As a result, firms are able to adjust their pricing heuristic in response to changes in the macroeconomic environment, with consequent feedback effects on the functional distribution of income and macroeconomic performance.

In Section 2 of this chapter, we conduct a thorough review of the empirical literature on price behavior and summarize the key findings of surveys that have investigated the heuristics used by firm managers to set prices. In Section 3, we present our model, which is a typical macroeconomic ABM with features commonly found in the literature on macroeconomic issues. The agents in the model include producers of consumer goods, a monopolistic producer of capital goods, a banking sector (comprising of a private bank and a central bank), a government, and households. There are various spaces of interaction, including markets for goods, credit, labor, and capital goods. All agents are assumed to be rational and bounded, making decisions based on rules of thumb.

The central agent of the model is the consumer goods firms, which are responsible for investing, researching, hiring labor, contracting credit, and most importantly, making price decisions. The novelty of our model lies in its focus on price adjustments of the firms. These firms may follow four different strategies to set their prices. These pricing rules of thumb were developed considering the different pricing heuristics that are empirically observed and the pricing rules that are commonly considered in ABMs. Consumer goods firms in our model are also permanently learning and adapting their pricing heuristic, looking for behaviors that increase their profit performances. Given that the result of the pricing strategy depends on the firm's interaction with the consumers and the competitors-based pricing, we cannot calculate in advance the distribution of strategies across the population of firms.

In Section 4, we discuss the calibration of the model. First, to obtain a benchmark model, we calibrated the model to reproduce some macroeconomic stylized facts observed for the US economy. The calibration was carried out using the method of simulated moments and solved using a genetic algorithm. To our knowledge, using this algorithm to calibrate agent-based macroeconomic models is an innovation of the dissertation. The statistical moments are the results of Monte Carlo simulations.

In Section 5, we present the results of the benchmark model. Through a detailed analysis, we examine the behavior of key macroeconomic variables and the functional distribution of income in the benchmark model. Additionally, we present results that demonstrate the model's ability to replicate a significant number of stylized facts, both macroeconomic and microeconomic, observed in the US economy. The most important result is the distribution of pricing heuristics among the population of firms. Finally, in Section 6, we offer a succinct conclusion of our findings.

4.2 Empirical evidence

The present chapter focuses on the heterogeneity of pricing heuristics adopted by firms worldwide. As discussed in chapter two, surveys of firm managers across various countries and profiles consistently reveal that firms employ a wide range of theories and strategies to determine their pricing policies.

The most common pricing rules adopted by firms are markup pricing strategies or cost-based approaches. Cost increases, especially raw and labor costs, are considered the most significant drivers of price changes, followed by financial costs, changes in demand, and changes in competitors' prices. For price decreases, the competitor's price is the most influential factor, followed by the cost of raw materials and changes in demand. This survey underscores the importance of incorporating factors beyond the "essence"of cost-based pricing in models, particularly changes in demand and competitors' behavior.

However, given that firms typically use cost-based pricing formulas and their cost dynamics are mostly exogenous to pricing decisions, this evidence suggests that the factors driving price changes may also affect firms' markups. Nonetheless, the surveys offer limited insights into how markups precisely respond to different environmental information or whether certain information is more critical in explaining markup behavior. Therefore, further research is needed to fully understand the relationship between pricing heuristics, markups, and the various factors influencing pricing decisions.

4.3 The model

4.3.1 Introduction

This section presents the description of the ABM that we have developed to study the dynamics of markup pricing strategies and how this co-evolve and affects macroeconomic variables and the functional distribution of income. The present model has features found in several ABMs (Dawid and Delli Gatti, 2018) and we believe that it meets the necessary criteria to examine the effect of various pricing strategies on macroeconomic dynamics. The model has six different agents, firms in the consumption goods sector, a monopolistic firm producing in the capital goods sector, households divided into workers and capitalists, a banking sector, the government, and the central bank.

In the subsequent sections, we will discuss the decision-making processes of the agents and the interactions that occur within the model. The stock-flow relationships of the agents can be found in Appendix C and the initial conditions in D.

The model can be succinctly outlined through the following chronological sequence:

1. Central bank determines the base interest rate.
2. The banking sector remunerates deposits.
3. The banking sector calculates each firm's interest rate.
4. Workers calculate their reservation wage.
5. Consumption goods producers form demand expectations.
6. Consumption goods producers try to innovate.

7. Consumption goods producers estimate the amount of necessary labor and capital given the expected demand, try to hire or fire workers and send investment orders to the capital goods sector
8. Consumption goods producers send orders to the capital goods sector.
9. The capital goods sector, based on the total orders received and the current level of employment, makes decisions to hire or fire workers.
10. The capital goods sector distributes machines to the firms producing consumer goods based on orders received and production levels.
11. Given expected demand and internal availability of production factors, consumption goods firms produce.
12. Consumption goods producers compute the expected unitary cost of production.
13. Consumption goods producers evaluate their performance in terms of profitability in the previous period. If necessary, they review their pricing strategies.
14. Consumption goods producers revise their prices.
15. Government pays unemployment insurance for unemployed workers
16. Government collects taxes.
17. Government decides how much will buy from the consumer goods sector.
18. Workers and capitalists make decisions on how much to consume and save, based on income from labor, unemployment insurance, interest paid by the banking sector, and distributed profits.
19. Workers and the government go to the consumer goods market to spend disposable income allocated for consumption.
20. Firms use sales revenue to pay wages, interest on debt, pay the capital goods producer, invest in R&D, pay dividends, and retain a portion of net profit.
21. Firms may take out loans to pay expenses if necessary.

22. It is computed whether firms go bankrupt or not. A new firm is created with parameters calculated from the average of the surviving firms.

23. Macroeconomic aggregates are calculated.

4.3.2 Output decisions and production

In order to formalize the decision-making process for production, we adhere to the standard model commonly utilized in agent-based macroeconomic models as outlined in previous literature such as(Possas et al., 2001; Dosi et al., 2010; Caiani et al., 2016; Dawid et al., 2019). The output of firms producing consumption goods is determined by their expectations of future demand in the consumption goods market and their production capacity. The expectation of future demand is influenced by adaptive expectations, as proposed by Dosi et al. (2020). That is, expectations are formed by observing the past and extrapolating it to the future. This concept can be represented mathematically by Equation (4.1), which describes how the expectation of demand adapts to changes in the market. In our model, the expectation of future demand for a given firm f is given by the average amount of sales in the last four periods, plus the unattended demand from the previous period. This is represented mathematically as:

$$Z^e_{f,t} = \frac{1}{4}\sum_{i=1}^{4} C_{f,t-i} + \beta Cu_{f,t-1}, 0 < \beta < 1, \tag{4.1}$$

where $C_{f,t-1}$ is the total amount of sales that each firm f made at time t, $Cu_{f,t-1}$ is the unfulfilled demand of period t, β is the adjustment of expectations given the unfulfilled demand of last period and $Z^e_{f,t}$ is the firm expected demand.

The total desired output is represented by the Equation (4.2). The production of stocks is determined by the parameter μ, which determines a percentage of the expected demand that will be produced to become stocks. Finally, firms discount from the total desired output the existing stock $S_{f,t-1}$. We assume that consumer goods do not depreciate. Therefore, the total desired output of the firm is defined as:

$$O^D_{f,t} = Z^e_{f,t} + \mu Z^e_{f,t} - S_{f,t-1}, 0 < \mu < 1, \tag{4.2}$$

where the variable $O^D_{f,t}$ is central because it will determine the firm's total demand for labor and capital. The desired output may be larger than the production capacity because the firms may not be able to have enough labor or capital to produce the desired amount. Thus, the total output will be equal to the firm's production capacity.

The firm capacity of production $O^*_{f,t}$ is given by the total amount of factors of production available to it and their productivity. This is modeled through a Leontief production function (Equation (A.2)).

$$O^*_{f,t} = min\left\{ a_t L^D_{f,t}; \sum_{i=1}^{M} v_t K_{i,f,t} \right\}, a > 0, v > 0, \tag{4.3}$$

where $L^D_{f,t}$ is the total amount of labor directly involved in the production of the goods in firm f, a is the direct labor productivity, $K_{i,j,t}$ is a machine of type i, belonging to firm f in period t, M is the number of machines available to the firm f and v is output-capital ratio of the machines. The parameters a is endogenous in the model and depend on the technology embodied in the machines. We suppose that the machines have a fixed parameter for the capital-output ratio, represented by Equation (4.4), setting how many goods can be produced by one machine in every period:

$$v_t = \frac{O^*_t}{K_t}. \tag{4.4}$$

The machines have also the same capital-labor relation. So, each machine has a parameter for the capital-labor relation, given by:

$$l_{t,i} = \frac{K_{i,t}}{L_{i,t}}. \tag{4.5}$$

The equation for the direct labor productivity embodied in a machine is expressed as:

$$\frac{O^*_{i,t}}{L_{i,t}} = \frac{O^*_t}{K_t}\frac{K_{i,t}}{L_{i,t}} = v_t l_{t,i} = a_{t,i}. \tag{4.6}$$

Considering the Equation (4.6), firms compute the demand for direct labor calculating the average productivity of the $M_{f,t}$ available machines (Equation (4.7)).

$$L^D_{f,t} = \frac{\sum_{i=1}^{M} a_{t,i}}{M_{f,t}} O^*_{f,t}. \tag{4.7}$$

Thus, the labor productivity of the workers directly employed in the production of consumption goods is endogenous and dependent on parameters that reflect the characteristics of the machines used by the firms.

Besides the workers directly employed in production, the firms also employ workers in administrative tasks. This determines the overhead cost of the firm and the demand for indirect labor (L_f^I). As the firms grow, more workers for administrative activities are needed. The total is determined by the total capital stock of the firms through the equation $\kappa M_{f,t}$. Consequently, the total demand for labor at the normal level of capacity utilization is given by:

$$L_f^* = L_f^D + L_f^I = O_{j,t}^D/a + \kappa M_{f,t} = u^* O_{f,t}^*/a + \kappa u^* O_{f,t}^*/v, \kappa > 0. \tag{4.8}$$

The Equation (4.8) is based on Steindl (1979). Therefore, given the expectation of demand, firms will determine their desired output and, as a result, the total demand for machines and labor. However, whether the consumption goods firms will acquire all the factors of production needed will depend on their interactions in the labor market, the capital goods market, and the credit market. If firms have enough capacity for production, their production will be equal to $O_{f,t}^D$. If $O_{f,t}^D$ is greater than $O_{f,t}^*$, they will produce to the limit of their capacity.

4.3.3 Pricing

As discussed in Section (5.2), the firms can follow many pricing strategies. In the present sub-section, we divided the discussion into two points: cost of production and prices.

4.3.3.1 Expected cost of production

Now, we will outline the first step of pricing, which is the calculation of production costs. First, firms determine the total labor cost by multiplying the labor demand, as given by Equation (4.8), with the average wage paid to its workers ($\overline{W_f}$). Then, the firm calculates the expected unitary cost of production by dividing the total labor cost by the expectation of demand, as given by Equation (4.1). Therefore, the expected unitary cost of production is determined as follows:

$$UC_{f,t} = \frac{L_{f,t}^* \overline{W_f}}{Z_{f,t}^e}. \tag{4.9}$$

4.3.3.2 Pricing

In this step, the firm has already decided on which heuristic to adopt to set the final price. All the firms follow a cost-based approach to set prices. The equation they use to calculate their prices is shown below:

$$P^D_{f,t} = (1 + m_{f,t})UC_{f,t}, \tag{4.10}$$

where $P^D_{f,t}$ is the final price set by firm f at time t, $UC_{f,t}$ is the unit cost of production, and $m_{f,t}$ is the fixed markup applied by the firm. The difference between the various pricing heuristics, denoted by $\omega \in \Omega$, where $\Omega \equiv \{1, 2, 3, 4\}$, lies in the method used by the firms to determine the value of $m_{f,t}$.

We model the first pricing heuristic, known as the "demand-determined markup" heuristic, as being dependent on the difference between the desired and observed stock levels of firm f in the previous period. This heuristic has been previously modeled in Caiani et al. (2016); Schasfoort et al. (2017) and considers one information that has been found to be common to be used in pricing strategy among firms in various countries, as indicated by surveys in chapter 2. While demand is not always the primary factor influencing price changes, the motive changes in demand has been deemed at least moderately important by a significant number of firms in surveys. We assume that firms adjust their markup, $m_{f,t}$, based on the following rule:

$$m_{f,t} = (1 + \Theta_{1,f,t}(\mu Z^e f, t - Sf, t - 1))m_{f,t-1}, \tag{4.11}$$

where μ is a constant, $Z^e_{f,t}$ is the desired stock level for a firm f at time t and $\Theta_{1,f,t}$ a parameter that controls the adjustment of the markup given the difference in the desired stock from the current stock. The idea of the first "demand-determined markup" heuristic is that the markup is a variable that also responds to the existing conditions of demand given the capacity constraint. If the total production is getting closer to the production capacity, this means that, for many possible reasons, the firms are unable to expand the supply capacity. This can happen because the capital goods sector is unable to keep up with the demand or because the firm is not finding enough workers. In this case, we suppose that the firm has no alternative but to increase its markup.

The second pricing heuristic, known as the "market share markup" heuristic, is based on the difference in market share between the current and previous periods for firm f. This heuristic has been previously studied in Dosi et al. (2010, 2015a, 2020, 2022). It is modeled as follows:

$$m_{f,t} = (1 + \Theta_{2,f,t}(ms_{f,t-1}/ms_{f,t-2} - 1))m_{f,t-1}, \quad (4.12)$$

where $ms_{f,t}$ represents the market share of firm f at time t and $\Theta_{2,f,t}$ a parameter that controls the adjustment of the markup given the growth of the firm market share. We have seen through the surveys that firms considered the price of the competitors and the overall competitiveness of the market to set their prices. The market share is considered in Dosi et al. (2010) as a proxy for the overall state of the competitiveness of the product of the consumer good's firms, and a variable that can be seen by them. As a result, it is considered by them that the market share drives the markups. We followed the same line of argumentation to justify this pricing heuristic.

The third pricing heuristic we have defined as the "value-based" approach. This heuristic represents firms that adopt value-based pricing strategies based on the perceived value of their products to consumers. By perceived value, we mean the relative cost-benefit of the goods, given their relative quality. This heuristic is particularly supported by business literature that advocates for value-based pricing as being optimal (Hinterhuber, 2008; Liozu, 2017).

In our model, we assume that firms do not face the same constraints that might normally justify the low adoption of value-based pricing, such as costs associated with implementing different pricing strategies or a lack of management capabilities. Therefore, we model this heuristic as follows:

$$m_{f,t} = (1 + \Theta_{3,f,t}(\frac{Q_{f,t-1}}{\overline{Q_{f,t-1}}} - \frac{Q_{f,t-2}}{\overline{Q_{f,t-2}}}))m_{f,t-1}, \quad (4.13)$$

where $Q_{f,t}$ represents the relative quality of the firm's products, $\overline{Q_{f,t}}$ is the average relative quality of all products in the market at time t and $\Theta_{3,f,t}$ a parameter that controls the adjustment of the markup given the difference of the current relative quality from the past relative quality. Firms using this heuristic act parsimoniously to changes in the relative quality of their products, as they are uncertain about the exact value that consumers will place on quality improvements and how much they can charge to capture all of the potential consumer surplus.

The fourth heuristic is based on the "essence"of cost-plus pricing approaches, as described by Amaral and Guerreiro (2019), with the markup being completely independent of competitors' or consumers' behavior. Therefore, regardless of any variable directly observed by the firms such as capacity utilization, demand, stocks, or market share, the markup is permanently fixed given a profit target. This heuristic can be justified based on Lavoie (2014), which presents different possible cost-plus pricing formulas, including the target return pricing. This heuristic assumes that firms define the markup as a function of the profit target rate.

The question is how the target profit rate is determined. Lavoie (2014) presents four possible theories. The Marxian and Kaleckian theories describe the target profit rate as determined by class struggle and the degree of monopoly, respectively. Therefore, the profit rate is not truly exogenous to the environment of the firm, the competitor's behavior, or the interaction between the firm and its employees. We have already considered the profit rate as an endogenous process with the other heuristics. Another explanation, common among Post-Keynesians, is that the profit target is determined by the growth rate of capital. The idea is that the profit target of the firms is determined by the investment plans of the firms. Given the capital structure of the firm, expectations of demand, and the need for retained capital to fulfill the investment plans, the firms set the target profit rate. The issue with this theory is that we do not observe a close link between a firm's profit rate and growth (Bottazzi et al., 2010). The last theory presented by Lavoie (2014) is that the profit target is a function of the interest rate set by the central bank. Therefore, according to Lavoie (2014), the target profit rate is determined outside the system of production. We consider that this theory expresses well the cost essence of theories that state that prices are independent of the competitive environment of the firms. In other words, the "cost-plus essence"of cost-based pricing approaches. Besides, there is evidence that the cost channel of monetary transmission may be significant, indicating that increases in the base interest rate may increase the level of prices (Gaiotti and Secchi, 2006; Tillmann, 2008).

The firms using the "cost-based"essence pricing heuristic only consider their previous profit rate and a profit target, as shown in Equation (4.14):

$$m_{f,t} = (1 + \Theta_{4,f,t}(r_{f,goal} - r_{f,t-1}))m_{f,t-1}. \tag{4.14}$$

The profit rate, r_f, is calculated in relation to the firm's nominal capital stock. The profit target, $r_{f,goal}$, described by the Equation (4.15), is simply the central bank's interest rate plus a *premium*, which is determined as an exogenous parameter. The parameter $\Theta_{4,f,t}$ controls for the adjustment of the markup given the difference in profit target from the current profit. Therefore, firms using this heuristic aim to achieve a profit rate that is sufficient to cover the opportunity cost (the central bank's interest rate) plus a premium. These firms do not consider market conditions or whether their prices are high or low.

$$r_{f,goal} = i_{cb,t-1} + premium_{f,t}. \tag{4.15}$$

In our model, we aimed to incorporate the diversity of pricing strategies observed both empirically and theoretically, as well as the dynamic nature of these strategies. By doing so, we sought to examine how firms behave in an environment characterized by such differences. The primary objective was to assess the survival and dominance of different heuristics within the economy.

The equations representing these heuristics share similar structures, differing mainly in the information utilized to determine markups. The choice of information employed in each heuristic is plausible and supported by empirical evidence, as well as theoretical justifications. The fundamental question is whether one particular heuristic tends to play a more significant role in explaining firms' economic outcomes.

4.3.4 Firms' evolutionary process

To model the switching protocol of heuristics by the firms, we propose that firms consider the profit that is being generated by each heuristic in the economy, as suggested by Jobber and Hooley (1987), who shows that most firms aim to increase profits when setting prices. We assume that firms are monitoring the market and have free access to information concerning the past profit of competitors and the heuristic that was used. These assumptions are strong, but they allow us to consider that information is transmitted quickly in the economic environment, making it harder for less profitable heuristics to persist and accelerating the selection process.

Given the performances of the heuristics, the probability of them being selected follows the seminal model of Brock and Hommes (1997). This heuristic switching protocol was selected for its wide use in the literature studying heuristic heterogeneity in economics, including in the ABM literature (Dosi et al., 2020; Reissl, 2021). Therefore, we assume that the selection of a pricing heuristic is a discrete choice, with their probability of selection ultimately being given by a multinomial logit function.

Equation (4.16) calculates the performance of the cost-based pricing heuristics. The performance is based solely on the rate of profit generated by each pricing strategy. The profit rate is computed by summing the profit of all the firms that were using the heuristic ω at time t, their respective stocks of machines M, and the price of the machines at each time period.

$$U_{\omega,t} = \sum_{j=1}^{8} \frac{Profit_{\omega,t-j}}{M_{\omega,t-j} Pk_{\omega,t-j}}. \tag{4.16}$$

After computing the current performance of the heuristics, firms store it in their memory. Equation (4.17) shows the evolution of each heuristic's performance memory over time. The parameter Λ_1 measures the relative weight of past performance.

$$M_{t,\omega} = \Lambda_1 M_{t-1,\omega} + U_{\omega,t}, 0 < \Lambda_1 < 1. \tag{4.17}$$

Finally, the probability of any of the two heuristics being selected is given by Equation (4.18). The parameter $\Lambda_1 \in (0,1) \subset \mathbb{R}_{++}$ captures the persistence of the heuristics.

$$P(\omega)_t = \Lambda_3 P(\omega)_{t-1} + (1-\Lambda_3)\frac{exp(\Lambda_2 M_{t,\omega})}{Z_t}, 0 < \Lambda_3 < 1. \tag{4.18}$$

with $Z_t = \sum_{\omega=1}^{\Omega} exp(\Lambda_2 M_{t,\omega})$ being a normalization factor, the parameter $\Lambda_2 \subset \mathbb{R}_+$ a measure of the impact of past performance on the heuristic choice and the parameter $\Lambda_3 \in (0,1)$ the persistence of pricing heuristic (the higher this parameter, the higher is the path dependency in terms of the weight of each heuristic rule).

The previous process of strategy evaluation is based on the interaction of firms with their competitors. Even though a firm may be using a given cost-based pricing approach, which is determined by a markup factor heuristic and the evolution of the unit cost of production, firms are constantly monitoring the evolution of the competitive conditions in the market and the performance of competing pricing rules.

Additionally, firms may explore strategies that go beyond the limitations imposed by the initial conditions of the simulation. This is important to avoid the initial conditions of the model affecting the selection of strategies too heavily. No threshold for markup size is imposed, and the average markup of the simulated economy emerges as an endogenous result through selection. Finally, we assume that firms can only revise their heuristics four periods after the last revision.

4.3.5 Machine investment

We rely on the model developed by Possas et al. (2001) to represent the investment decision-making process of consumer goods firms. The firms' investment decisions are based on their desired output levels. The firms first evaluate the capacity of their current stock of machines to determine if they have enough to produce the desired amount of goods. They begin by calculating the depreciation of their machines and scrapping any that have broken down. Following Seppecher (2012), we assume that machines have a predetermined lifespan (LS), but they may break down before or after this period. The machine's lifespan is determined when the machines are produced, and each machine is given a lifetime drawn from a uniform distribution $U(LS-PB, LS+PB)$, where $PB \subset \mathbb{R}_{++}$ is a parameter that controls the interval of periods where the machines can break down. If the firm's production capacity is equal to or less than the desired utilization of installed capacity (u^*), the firm will not expand its production potential. Otherwise, the firm will calculate the number of machines needed to produce the desired output and compare it to the current capital stock. The difference between these two divided by the output-capital ratio (v) gives the number of machines that the firm will order from the capital goods producer (I^D), as shown in the following equation (4.19):

$$I^D_{f,t} = \begin{cases} \frac{O^D_{f,t}}{u^* v} - \sum_{i=1} K_{i,f,t} & ,if \quad O^D_{f,t} > u^* v \sum_{i=1} K_{i,f,t}, \\ 0 & ,if \quad O^D_{f,t} \leq u^* v \sum_{i=1} K_{i,f,t}. \end{cases} \tag{4.19}$$

The consumption goods producer will not necessarily receive the total number of machines ordered in the next period. This will depend on the dynamics of the capital goods sector itself and the total number of orders for new machines. This sector may not be able to produce enough to attend all demand in one period. If the firm does not receive the total number of machines ordered, in the next period it makes again a new order. The new machines received by the firm are added to the capital stock and consumer goods firms pay the machine producer. The total payment of the consumer goods firms to the producer of machines gives the total nominal investment in machines of the economy.

4.3.6 R&D investment

In our model, consumption goods are characterized by heterogeneity in terms of quality, as discussed by Dosi et al. (2022). Specifically, firms engaged in the production of consumption goods undertake research and development activities to enhance the perceived quality of their goods, as perceived by consumers. As noted by Eeckhout (2021), investments in product differentiation is one of the prevalent strategies employed by corporations to attain market power. In line with this perspective, our model posits that firms endeavor to improve the quality of their goods in order to gain market share and increase profits.

Based on Caiani et al. (2016); Dosi et al. (2010), the total investment in R&D is a proportion of firm revenue in the past period, given by the parameter ν. The total nominal investment in R&D can be expressed as:

$$RD_{f,t} = \begin{cases} \nu R_{f,t} & ,if \quad R_{f,t-1} > 0, \\ 0 & ,if \quad R_{f,t-1} \leq 0, \end{cases} \tag{4.20}$$

where $\nu \in \mathbb{R}_+$ is a fixed parameter and $R_{f,t}$ the total revenue of firm f at time t. Following the evolutionary literature, the investment in R&D can be allocated in innovation or imitation activities (Nelson and Winter, 1982; Possas et al., 2001; Dosi et al., 2010).The total amount invested in R&D is allocated between investment in innovation and investment in imitation. The proportion is determined by how far the firm is from the good with the highest quality. The total that in invested in innovation is determined by the Equation (4.21), where the variable $QUAL_{f,t}$ is quality of the good of each firm.

$$RDIn_{f,t} = \left(\frac{QUAL_{f,t} - min(QUAL_{f\in N,t})}{max(QUAL_{f\in N,t}) - min(QUAL_{f\in N,t})} \right) RD_{f,t}. \tag{4.21}$$

The total investment in imitation is given by Equation (4.22).

$$RDIm_{f,t} = RD_{f,t} - RDIn_{f,t}. \tag{4.22}$$

The new investment, already deflated, is added to the previously real accumulated investments ($AR\&D^{i\in\{In,Im\}}_{f,t}$). Here we suppose that the research activity is cumulative, as in Richardson (1996), and that there are scale-related returns to the R&D. If the firm was not successful in the innovation process in the previous period, the investment is not lost, but accumulated to be used in the following period.

To model the innovation process, we utilized as inspiration the work of Dosi et al. (2010). The first one is the process of searching for new technologies. This is formally expressed through a draw from a Bernoulli distribution, described as:

$$\delta_{f,t}^{i\in\{In,Im\}} = 1 - e^{-\eta_1 AR\&D_{f,t}^{i\in\{In,Im\}}}. \tag{4.23}$$

If the outcome of a Bernoulli draw is equal to one, the firm will gain access to a new technology. This means that at each period, firms have the potential to acquire two new technologies, one through innovation activities and one through imitation activities. The parameter η_1 determines the ease with which a firm's research leads to innovations. This parameter, in turn, is determined by the equation $\eta_1 = \frac{1}{\eta_3 GDP_t}$, that is used to normalize the total real investment in R&D to the real GDP. If firms have access to a new technology from the innovation activity, this is determined by:

$$QUAL.I_{f,t} = (1 + b_{i,t})QUAL_{f,t-1}, \tag{4.24}$$

where $b_{i,t}$ are is an independent draw from a Beta(β_1, β_2) distribution over the support $[-0.3, 0.3]$. If firms have access to a new technology from imitation activities ($QUAL.M_{f,t}$), this is given by a random draw from the set $\{QUAL_{1,t-1}, ..., QUAL_{N,t-1}\}$, with:

$$\mathbb{P}(QUAL_i) = \frac{QUAL_{i,t-1}}{\sum_{i=1}^{N} QUAL_{i,t-1}}. \tag{4.25}$$

Finally, if the three options are available to the firms, the final quality of the consumer good from the firm f will be given by

$$QUAL_{f,t} = max(QUAL_{f,t-1}, QUAL.I_{f,t}, QUAL.M_{f,t}). \tag{4.26}$$

Finally, if a firm adopts a new technology, $AR\&D_{f,t}^{In}$ and $AR\&D_{f,t}^{Im}$ become zero.

4.3.7 Accounting, finance and exit conditions of the firms producing consumption goods

In this subsection, we describe the firms' accounting, how this relates to their financial situation and the exit condition of the firms. Again, here we follow the usual approach of the ABM literature that follows the pecking order theory of finance (Caiani et al., 2016; Dosi et al., 2010; Dawid et al., 2019; Possas et al., 2001; Salle et al., 2013; Seppecher et al., 2018; Delli Gatti et al., 2010), which assumes that firms prefer to finance their expenses with internal funds and only if needed with loans or equity .

The only form of income for the firms is the revenue (R) with the sale of consumer goods. The firms have the following expenses: wages (W), investment in R&D (IR), investment in new machines (IM), financial burden (F) and the distribution of profits in the form of dividends (DIV).

The only form of expense that we necessarily observe at all times is the payment of wages. If the revenue net of costs is negative, the firm will not invest in R&D.

We have already described how we determine the total amount of wages and investment in the model. The financial burden ($F_{f,t}$), as in Caiani et al. (2016); Seppecher et al. (2018), is equivalent to the sum of interest and amortization repayments:

$$F_{f,t} = i_{f,t}DS_{f,t} + DS_{f,t}/LS, \tag{4.27}$$

where $DS_{f,t}$ is the debt stock, $i_{f,t}$ the firm's interest rate (detailed below). Amortization is the firm's total debt divided by the maturity period, LS (a fixed parameter equal to the expected lifespan of the machines).

Given the expenses of the firm and its revenue, the firm can generate a cash surplus/deficit (DC), given by the Equation (4.28):

$$DC_{f,t} = R_{f,t} - W_{f,t} - IR_{f,t} - IM_{f,t} - F_{f,t} - DIV_{f,t}. \tag{4.28}$$

The dynamics of firms debt stock is given by the Equation (4.29):

$$L_{f,t} = \begin{cases} (1 - 1/LS)L_{f,t-1} & ,if \quad DC_{f,t} > 0, \\ (1 - 1/LS)L_{f,t-1} - DC_{f,t} & ,if \quad DC_{f,t} < 0, \end{cases} \tag{4.29}$$

where $i_{f,t}$ is the interest rate of each firm, LS is the lifespan of the machines and $L_{f,t}$ the stock of debt. The dynamics of firms financial asset stock is given by Equation (4.30):

$$A_{f,t} = \begin{cases} A_{f,t-1} + DC_{f,t} & ,if \quad DC_{f,t} > 0, \\ A_{f,t-1} & ,if \quad DC_{f,t} < 0, \end{cases} \tag{4.30}$$

where $A_{f,t-1}$ is the new worth of the firms. The heuristic we assume in terms of liabilities management by the firms is simple. If firms have a surplus in cash this is added to the firm cash stock. On the other hand, if the firm has a deficit in terms of cash, the firms obtain a new loan with the monopolist bank, increasing the debt stock.

The firm's decisions and its interaction with different markets affect its balance sheet. On one hand, investment decisions reduce the firm's stock of cash and increase the firm's stock of loans, which needs to be recovered with positive economic results. On the other hand, the continuous increase in the firm's liabilities, with the rise in the stock of debt, can increase the firm's leverage and financial burden. In the limit, the liability can become equal to or greater than the firm's asset, representing the firm's insolvency.

When a firm becomes bankrupt, as indicated by the condition ($L_f/A_f > 1$), it is replaced by a new one. This new firm is provided with a cash investment equal to three times the necessary stock of capital for producing ten consumption goods. The new firm is established with zero debt, no market share, and no accumulated research. The expected demand for its products is set at 10, and the quality of its new product is equivalent to the industry average. The total amount of money transferred to the new firm is deducted from the capitalist's wealth. The markup of the new firm is adjusted to reflect the weighted average of the surviving firms. In the event of a failure, the banking sector will reduce from the total loan stock the loan stock of the bankrupt firm, and the central bank will correspondingly decrease its bank reserves, effectively providing a bailout for the monopolist bank.

4.3.8 Dividends policy

One common assumption in many ABMs, it is often assumed that the interest rates of firms are primarily a distributive variable that determines the amount of money transferred from the firm to the banks, and that interest rates may not be considered in the firm's investment or dividend payment decisions. Additionally, firms in these models may not be credit-constrained.

Research has shown that under these assumptions, significant shocks to monetary policy are relatively ineffective at altering model dynamics (Delli Gatti and Desiderio, 2015). While there is an increase in non-performing loans and bankruptcies, the aggregate effects of such policy shocks are minimal.

To produce meaningful results, it is necessary to incorporate more channels for monetary policy in the model. Schasfoort et al. (2017) explore many of these possible channels for monetary policy. For it, the most effective channel of transmission of the monetary policy is due to the bank lending channel, with the level of the interest rates directly affecting the total credit constraint of banks.

Delli Gatti and Desiderio (2015) develops a set of behavioral equations for firms in which, given the level of interest rates and firms' leverage, the total amount of credit demanded by firms decreases with the size of the financial gap.

In Seppecher et al. (2018) and Seppecher et al. (2019), the monetary policy indirectly affects the firms' investment decisions. Firms only invest if their leverage is below a certain target. Therefore, the monetary policy indirectly affects firms' investment decisions by increasing the debt burden, which can worsen the financial soundness of firms.

In Delli Gatti et al. (2010), following the financial accelerator literature, interest rates directly affect the aggregate behavior of the economy by changing the net worth value of the firms, which is the key input for production and employment.

The literature that has extended the post-Kaleckian model to include financial variables is noteworthy. This literature shows that the interest rate has a direct effect on the financial gap of firms, which affects their creditworthiness and total investment. The interest rate also has an indirect effect on consumption due to the assumption that there are two types of capitalism, with financial capitalists having a lower consumption propensity. For a reference, see Lima and Meirelles (2007) and Nikolaidi and Stockhammer (2018).

In our model, the effect of interest rates on the behavior of firms is manifested through their dividend policy. Following Riccetti et al. (2013, 2015); Seppecher et al. (2019) and Alexandre and Lima (2020), we assume that firms' capital structure decisions are independent of output production and that firms choose a target for their level of indebtedness. We do not assume any credit constraints, so banks accommodate all credit demands by firms given their financial gap. As investment decisions are independent of interest rates and banks always accommodate credit demand, the financial condition of firms does not limit capacity expansion, allowing firms and the economy to converge to the desired utilization capacity.

We assume that the target level of indebtedness influences the dividend policy of firms. If past indebtedness is below the target, firms will increase the distribution of dividends to capitalists, increasing the firm's financial gap and credit demand. If leverage is above the target, firms will decrease the distribution of dividends to increase their cash reserves.

The target leverage is determined by the opportunity cost of different sources of capital, which is defined as follows:

$$L_{T,f,t} = (\gamma \frac{L_{T,f,t-1}}{A_{f,t-1}} + (1-\gamma)\frac{r_{f,t-1}}{r_{f,t-1} + i_{f,t-1}})A_{f,t-1}, \tag{4.31}$$

where $\gamma \in (0,1)$ is the effect of past indebtedness on the current target indebtedness, $r_{f,t-1}$ is the past profit rate of firm f computed as the nominal profit divided by the firm's nominal stock of capital, and $i_{f,t-1}$ is the past interest rate charged by the private bank. The opportunity cost of firms to use retained profits is the profit rate, and the debt cost is the interest rate.

We assume that the target level of indebtedness directly affects dividend distribution. To achieve this, we assume that firms' dividend policies $\gamma_{f,t}$ change according to the following equation:

$$\gamma_{f,t} = \gamma_0(1 + \frac{L_{T,f,t-1}}{A_{f,t-1}} - \frac{L_{f,t-1}}{A_{f,t-1}}), 0 < \gamma_0 < 1, \tag{4.32}$$

where γ_0 is the total amount distributed in dividends if the current indebtedness is equal to the target. In addition to past profits, firms also adjust their dividend distribution based on their desired capital structure. This is reflected in the following Equation (4.33) for dividends ($DIV_{f,t}$):

$$DIVf,t = \frac{\gamma_{f,t}}{5}\sum_{i=1}^{5}(R_{f,t-i} - W_{f,t-i} - IR_{f,t-i} - IM_{f,t-i} - F_{f,t-i}) + (L_{T,f,t-1} - L_{f,t-1}). \tag{4.33}$$

The first term of Equation (4.33) represents the total amount distributed by firms based on their average financial results over the past five periods. The second term states that if the firm had a lower debt level than the target in the past period, this difference will be distributed in dividends. One final condition is that dividends are never negative, as expressed in the following equation:

$$DIV_{f,t} = \begin{cases} DIV_{f,t} & ,if \quad DIV_{f,t} \geq 0, \\ 0 & ,if \quad DIV_{f,t} < 0. \end{cases} \tag{4.34}$$

In summary, if the central bank decreases the base interest rate, this will affect the interest rates of firms, increasing their target level of indebtedness. As a result, firms will increase their distribution of profits and demand for loans. This leads to an increase in capitalists' income and consumption, which in turn increases firms' expected demand, investment, and employment. This mechanism operates as a transmission channel of monetary policy to the real economy, similar to the one observed in models with asset markets. This mechanism is similar to the one observed in models with asset markets, where changes in monetary policy affect the current value of assets, increasing the consumption of asset owners or increasing the value of collateral, thereby increasing firms' borrowing capacity. In the current version of the model, which does not include an asset market, the effect of interest rate changes is transmitted through dividends.

4.3.9 Capital goods sector

The capital goods sector is composed of only one monopolistic firm. We suppose that this sector makes a homogeneous capital good that can be used by all the firms in the consumption goods sector. Also, we assume that for producing capital goods is only necessary labor and that the labor productivity of that sector is a proportion of the consumer goods sector. The timeline of the production of the capital goods is as follows:

1 – The capital goods firm receives orders from the consumer goods sector.

2 – Given the total number of orders and the fixed labor productivity, the firm will try to hire enough workers to meet the demands.

3 – If the firm successfully hires enough workers, it will produce all the machines ordered.

4 – Otherwise, the capital goods firm will produce at the limit of the production capacity and will select which firms will receive the ordered machines given the order queue.

5 – With the total revenue, the capital goods firm pays the workers and distributes the residual of the profits to the capitalist household.

It is assumed that the capital goods firm employs a cost-based pricing strategy to set the price of its machines. To determine the price, the firm first calculates the total production using a fraction of productivity in the consumption goods sector ($frac$). The capital goods demand and productivity are used to determine the total demand for labor in the sector. The total cost of production is calculated by summing the wages of all employees. Dividing the total cost by the total production results in the unitary cost of production per machine. Finally, a markup factor is applied to the unitary cost of production to set the final price. The value of the markup factor is three times the average markup factor of consumption goods firms. Additionally, the wage offered in the capital goods sector is 1.5 times the average of the consumption goods sector. This can be justified due to the monopolistic power held by the sole firm operating in the capital goods sector. The profit generated by the capital goods sector is transferred to the capitalist, and any losses are covered through capital injection by the capitalist.

4.3.10 Households

The households are divided into two groups, workers (w) and capitalists (c). The workers receive income in the form of wages, interest from the accumulated wealth, and unemployment insurance paid by the government to the unemployed workers. We assume that firms can only hire working households. Therefore, capitalist households receive income only in the form of interest and profits. They also differ in terms of the propensities to consume out of income and out of accumulated wealth. Due to the characteristics of the capitalist household, we only have one representative household as the capitalist.

Given the total amount of income and wealth, each household has to decide how much will consume and save, as in the stock-flow consistent models described in Godley and Lavoie (2006). In the present model, households only allocate wealth (We) in the form of bank deposits (D) or cash (M). The consumption by each household is determined by the Equation (4.35):

$$C_{h,t} = \begin{cases} c_c YD_{h,c,t} + w_c We_{h,c,t-1} & , if \quad h \equiv Capitalist, \\ c_w YD_{h,w,t} + w_w We_{h,w,t-1} & , if \quad h \equiv Worker, \end{cases} \tag{4.35}$$

where $c \in (0,1) \subset \mathbb{R}_{++}$ is the propensity of consumption out of disposable income, dependent of the type of the consumer, Y_h is the disposable income of each household and $w \in (0,1) \subset \mathbb{R}_{++}$ is the propensity of consumption out of current wealth. The nominal disposable income of each household can be expressed through the Equation (4.36):

$$YD_{h,t} = \begin{cases} (1 - tx_w)(i_{f,t} D_{h,t-1} + DIV_{h,t-1}) & , if \quad h \equiv Capitalist, \\ (1 - tx_c)(i_{f,t} D_{h,t-1} + W_{h,t}) & , if \quad h \equiv Worker, \end{cases} \tag{4.36}$$

where tx_w is the tax over workers, tx_c the tax over capitalists, $i_{f,t}$ the interest rate that remunerates the wealth allocated in the form of deposits,$D_{h,t-1}$the stock of deposits and $DIV_{h,t-1}$ the total amount of profits distributed to the capitalist household in t-1 in the form of dividends. If the worker is unemployed, substitute $W_{h,t}$ for the unemployment benefit. The value of the benefit is determined by the government.

The law of motion of the wealth stock of each household is given by:

$$We_{h,t} = YD_{h,t} - C_{h,t} + We_{h,t-1}. \tag{4.37}$$

How the wealth is distributed between money and deposits is given by the portfolio preference Equation (4.38) and Equation (4.39). These equations are based on the portfolio equations presented in Godley and Lavoie (2006) and Tobin (1969). The first portfolio Equation (4.38) gives the capitalist and workers' wealth allocation in cash. If the baseline interest rate is zero, the total amount allocated in cash will be $\lambda_0 \in (0,1) \subset \mathbb{R}_+$.

The parameter $\lambda_1 \in \mathbb{R}$ gives the effect of the interest rate level over the portfolio of the households. If $\lambda_1 > 0$, the higher the baseline interest rate set by the central bank, the less the households will apply their wealth in cash, moving their wealth to the private bank to receive higher interest income. Contrary, if $\lambda_1 < 0$, the higher the baseline interest rate set by the central bank, the more the households will apply their wealth in cash. This last effect can be justified if households have a return target for their portfolio.

The total amount of wealth invested in bank deposits, given by the Equation (4.39), is simply one less the percentage allocated in cash.

$$\frac{M_{h,c,t}}{We_{h,t}} = \begin{cases} 0 & ,if \quad \lambda_0 - \lambda_1 i_{cb,t} < 0, \\ \lambda_0 - \lambda_1 i_{cb,t} & ,if \quad 1 \geq \lambda_0 - \lambda_1 i_{cb,t} \geq 0, \\ 1 & ,if \quad \lambda_0 - \lambda_1 i_{cb,t} > 1. \end{cases} \tag{4.38}$$

$$\frac{D_{h,t}}{We_{h,t}} = 1 - \frac{M_{h,t}}{We_{h,t}}. \tag{4.39}$$

4.3.11 Government and aggregate GDP

The government is the simplest agent in the model but plays an important role in stabilizing the economy. It must decide the amount of goods it will purchase from the consumer goods sector. The nominal expenditure of the government follows Equation (5.10):

$$G_t = (1 - \rho(G_{t-1}/Y_{t-1} - 0.2))G_{t-1}, \tag{4.40}$$

where G_t is the nominal expenditure of the government allocated to purchase consumption goods during period t and Y_t is the nominal aggregate GDP. The parameter ρ controls the adjustment of government consumption. The law of motion of the government debt stock follows:

$$B_t = (1 + i_{b,t})B_{t-1} - T_t + G_t - CB.P_t, \tag{4.41}$$

where B_t is the government debt stock, $i_{b,t}$ is the target short-term nominal interest rate by the central bank, T_t the total sum of taxes collected by the government and $CB.P_t$ the net-profit of the central bank.

The aggregate nominal GDP follows the national accounts system, with $Y_t \equiv I_t + C_t + G_t$. Therefore, we assume that the government expenditure behaves counter-cyclically to GDP, as observed empirically (Stock and Watson, 1999), targeting a nominal expenditure of 20% of the GDP.

The government receives income in the form of taxes paid by households. Initially, we assume that all tax rates are equal to 25%. In addition to government consumption and tax collection, the government also pays unemployment benefits to unemployed workers, interest rates to the banking sector, and receives profits or covers losses from the central bank. The unemployment benefit is equal to 40%, as in (Dosi et al., 2010), of the average nominal wage observed in the previous period. The profit of the central bank is generated through the interest paid by the monopolistic private bank. To cover deficits, the government borrows from the banking sector.

4.3.12 The banking sector

We consider the banking sector as a monopolistic private bank and a central bank. The banking sector takes deposits from households and extends loans to firms and the government. We suppose that the supply of credit is endogenous and demand-driven at the current interest rate, as in Lima and Freitas (2007).

There are three types of interest rate in the model. We draw on Dosi et al. (2015a) and Lima and Freitas (2007) to model the interest rate structure. First, and most importantly, there is the base interest rate, which is determined by the central bank. The base interest rate follows a simple Taylor rule, which can be defined as:

$$i_{b,t} = (1 - \upsilon_{cb})(r^* + \phi_1(\pi_{t-1} - \pi^*) - \phi_2(U_{t-1} - U^*) + \pi_{t-1}) + \upsilon_{cb} i_{b,t-1}, \tag{4.42}$$

where $i_{b,t}$ is the target short-term nominal interest rate, $\pi \in \mathbb{R}_+$ the rate of inflation, π^* is inflation target, $r^* \in \mathbb{R}_+$ is the assumed equilibrium real interest rate by the central bank, $\upsilon_{cb} \in (0, 1) \subset \mathbb{R}_+$ is a parameter to express the inertia of the monetary policy, $\phi_1 \in \mathbb{R}_+$ express the reaction of the monetary policy to deviations of in inflation from the inflation target and $\phi_2 \in \mathbb{R}_+$ express the reaction of the monetary policy to deviations of the unemployment rate (U_{t-1}) from an exogenous unemployment target set ($U^* \in (0, 1)$).

The second interest rate of the economy, which the monopolistic private bank sets, is the interest rate that remunerates household deposits. We consider it equal for all households, and it remains as a fixed proportion, lower than 1, of the base interest rate.

The third interest rate is the one charged on the loans from firms. The private bank uses a satisfying pricing procedure to set the interest rate that will charge by the firms. Following Delli Gatti et al. (2010), this interest rate can be defined as:

$$i_{f,t} = (1 + \varphi_{f,t}) i_{b,t}, \tag{4.43}$$

where $i_{j,t}$ is the interest rate charged on a single firm, $\varphi_{f,t}$ a variable markup on the base interest rate $i_{b,t}$. The markup is determined by the creditworthiness of the firms. The creditworthiness of the firms is calculated given their indebtedness. This is obtained by dividing the firm debt stock L_f by its net worth A_f. As in Dosi et al. (2010), given their indebtedness, the firms receive a rating (rat), with $rat \in \{1, ..., 4\}$. For each rating it is applied a different markup, increasing for the indebtedness.

A private bank generates profits through the difference in interest rates, referred to as the spread. The bank manages bank reserves (Br) from the central bank, receives household deposits (D), purchases government bonds (B), and issues loans to private firms (Lo). The cost of financing through deposits is lower than borrowing from the central bank, therefore, the private bank only borrows bank reserves from the central bank when the demand for credit exceeds the total amount of household deposits. Conversely, if the supply of deposits exceeds the demand for credit, the private bank keeps bank reserves at the central bank and earns interest at the base rate.

To model the relationship between the banking sector and the government, we suppose that the private bank accommodates all the government credit demand. For simplicity, the interest rate associated with loans to the government is equal to the base interest rate set by the central bank. The profit of the private monopolist bank ($\prod_{b,t}$) can be expressed as:

$$\prod_{b,t} = \sum_{j=1}^{N} i_{f,t} L_{f,t-1} - i_{b,t} B_{G,t-1} - \tau i_{b,t} \sum_{h=1}^{M} D_{h,t-1} - i_{b,t} (\sum_{j=1}^{N} B_{f,t-1} + B_{G,t-1} - D_{h,t-1}). \quad (4.44)$$

The first two terms are the interest incomes obtained from the total stock of loans to the firms and the government. The third term is the payment of interest to the households, where ($\tau_{b,t}$) is the difference between the interest rate of the deposits to the base interest rate. The fourth term expresses the relation between the private bank and the central bank. If $B_{f,t-1} + B_{G,t-1} > D_{h,t-1}$, then the private bank obtain credit with the central bank equal to the difference. Otherwise, if $B_{f,t-1} + B_{G,t-1} < D_{h,t-1}$, then the stock of deposits of the private bank in the central bank is larger than the stock of loans. In that case, the central bank pays interest to the private bank. Finally, since the monopolistic private bank does not have any other cost, any profit generated is distributed to the capitalist in dividends.

4.3.13 Labor market interaction

In order to determine their labor needs, firms first evaluate their internal labor conditions and project their demand for labor. If the demand for labor exceeds the internal supply, the firms turn to the external labor market to hire new employees. The process of matching firms with available workers involves several steps and was based on Fagiolo et al. (2004). Firstly, companies determine their labor demand based on their expected demand. Then, the total number of workers who will apply for the open positions at the company is determined. Based on the modern theory of labor monopsony (Manning, 2021), the proportion of workers who apply for a company's open positions can be represented by a multinomial logit equation that takes into account the wage offered ($w^{O}_{f,t}$) by the firms as a key variable. Therefore, the total share of the demand labor market of each firm, $ms_{L,f}$, can be represented as:

$$ms_{L,f,t} = \frac{\exp(3w^{O}_{f,t})}{\sum(\exp(3w^{O}_{f,t}))}. \quad (4.45)$$

In the process of matching firms with available workers, households that apply for open vacancies include both unemployed individuals and some employed individuals. The employed individuals who apply for a new job are those for whom the following condition is true:

$$\frac{w_{h,t}}{\sum(w^O_{f,t})/N} < U(0, 0.6). \tag{4.46}$$

This equation states that if the current wage received by the worker ($w_{h,t}$) is below a value drawn from a uniform distribution between 0 and 0.6, when compared to the average wage offered of firms ($w^O_{f,t}$), the employed worker will be included in the pool of workers searching for new employment.

Once the pool of workers who have applied for the open vacancies is determined, they are randomly ordered and a share ($ms_{L,f,t}$) of them apply for the vacancies of the firm f. Once the appropriate workers are found, the firm offers them a job with a wage given by Equation (4.47):

$$w^O_{f,t} = \begin{cases} (1+\psi_1(\frac{L^D_{f,t-1}}{L_{f,t-1}} - 1.02))((1-\psi_2)\overline{W_{f,t-1}} + \psi_2 w^O_{f,t-1}) & ,if \quad \psi_1(\frac{L^D_{f,t-1}}{L_{f,t-1}} - 1.02) < \psi_3, \\ (1+\psi_3)((1-\psi_2)\overline{W_{f,t-1}} + \psi_2 w^O_{f,t-1}) & ,otherwise, \end{cases} \tag{4.47}$$

where $L^D_{f,t-1}/L_{f,t-1}$ is the relation between labor demand, L^D, and labor supply, L, of the firm f in the previous period and $\overline{W_f}$ the average nominal wage of the firm f. The parameter $\psi_1 \subset \mathbb{R}_{++}$ is the reaction of the firms to differences in the labor demand and supply ratio, $\psi_2 \in (0, 1)$ the wage offered inertia and the parameter $\psi_3 \subset \mathbb{R}_{++}$ is the maximum value for the variation in the wage offered. If the labor demand is equal to the labor supply in the past period, the wage offered will decrease, as firms will attempt to negotiate lower wages in the following period. This theory is based in Seppecher et al. (2019).

If the selected workers have a reservation wage lower than the wage offered, they will accept the job offer. The firm will either contract enough workers to fulfill its labor demand or hire all the workers who have accepted the offer.

After the firms try to contract the workers, if some firm still has more than enough work to meet the demand conditions, they lay off employees using ternary criteria to adjust their internal labor supply.

The dynamics of the reservation wage of the workers is defined as:

$$\begin{cases} w^R_{h,t} = w^R_{h,t}(1+\psi_4\pi_{t-1}) & , if \quad e_{i,t-1} = 1 \quad , \\ w^R_{h,t} = w^R_{h,t-1} & , if \quad e_{i,t-1} = 0 \quad , \end{cases} \tag{4.48}$$

where $w^R_{h,t}$ is the reservation wage of the household, $\psi_4 \subset \mathbb{R}_{++}$ is the wage indexation to past inflation π_{t-1} and $e_{i,t-1}$ is their employment status in the last period.

If the worker is employed, his reservation wage is revised upwards by multiplying the past inflation by $\psi 4$. If he is unemployed, he does not adjust his reservation wage to inflation. When the worker enters a new company, which necessarily means that the wage offered was above the reservation wage, the $w^R_{h,t}$ is updated to be equal to the $w^O_{f,t}$ accepted by the workers. We draw this heuristic, with some modifications, from Giri et al. (2019) and Seppecher et al. (2018).

We also assume that the current wage is only revised after the worker has spent 4 periods in the same firm. In that case, the worker will ask for a wage adjustment to be equal to the reservation wage and will only obtain it if the current wage offered of the firm is above it.

It is noteworthy to mention that the dynamics of the labor market and wages are primarily influenced by local interactions. The only variable that is universally acknowledged by all agents is the average wage offered from firms, which may lead to employed workers to seek new employment opportunities, a reasonable assumption given that workers are aware of the wage offers of at least some new job opportunities (Card, 2022). Additionally, it is assumed that firms are the primary entities responsible for setting final wages, and workers can only accept or reject these offers. This is another stylized fact of the labor market (Card, 2022). Furthermore, it is suggested that the main driving force behind increases in real wages and, subsequently, the wage share, is the degree of job turnover in the economy. This phenomenon has been acknowledged as an important aspect of the US labor market (Bartel and Borjas, 1981). Finally, it should be noted that employed workers possess limited bargaining power within their respective firms. The only possibility for them to increase their wages within the firm, given their reservation wage, is if the wage offered from the firm is sufficiently high. However, this will depend on past conditions in the labor market.

4.3.14 Consumption goods market interaction

In the consumer goods market, three types of agents interact with each other: households, the government, and consumer goods firms. The households and the government act as buyers, while the firms function as sellers. Prior to the start of their interactions, the households and the government have already determined their nominal demand for consumption goods. Similarly, the firms have already produced their output, based on their demand expectations or their production capacity constraints.

To determine how to distribute the nominal demand among the firms, we use a model that assesses the competitiveness of each firm. The competitiveness of a firm at any given time is denoted by $E_{f,t}$ and is computed using Equation (5.6).

$$E_{f,t} = \frac{(Q_{f,t-1}/\overline{Q})^{\alpha_1}}{(P_{t-1}/\overline{P})^{\alpha_2}(1 + Cu_{f,t}/C_{f,t-1})^{\alpha_3}}. \tag{4.49}$$

The Equation (5.6) is closely related to the equation utilized by Silverberg (1987) and utilized also in Possas et al. (2001), which is an index of the firm's competitiveness. The parameters in the set $\{\alpha_1, ..., \alpha_3\} \in \mathbb{R}_+$ are the elasticity of competitiveness to the relative quality of the goods, to the relative prices, to the size of price changes and delivery delays. The main differences concern the existence of heterogeneous consumption goods. Since the goods have different qualities, in the numerator we have the relative quality of the goods, as in Dweck et al. (2020).

Previous studies have employed a competitiveness index as an input in a replicator model to simulate the evolution of market share, with variations in the manner in which competitiveness is modeled (Dosi et al., 2010, 2022). In our model, which draws from the framework established by Dawid et al. (2019), we deviate from the use of a replicator model. Instead, we considered the competitiveness index in the context of a "Smoothed Best Replies"model (Safarzyńska and van den Bergh, 2010). Therefore, we assume that the current market share of firms is determined by two components: a logit equation that is dependent on the firms' competitiveness index, and the past market share, as presented in Equation (5.7).

$$ms_t = \upsilon_{ms} \frac{exp(E_{f,t-1})}{\sum_{f=1}^{N} exp(E_{f,t-1})} + (1 - \upsilon_{ms}) ms_{t-1}. \tag{4.50}$$

Equation (5.7) proposes that the market share of a firm is mainly influenced by its relative competitiveness and an inertial component, where past market share influences current market share. The parameter $\upsilon_{cb} \in (0,1) \subset \mathbb{R}_+$ is used to express this inertia. Through the Equation (5.8), we have that the higher the relative quality and the lower the relative price of a good, the higher the market share of a firm will be. Equation (5.8) further shows that a firm's market share is higher when it offers higher quality and lower prices than its competitors. These characteristics reflect aspects of competition in markets with heterogeneous goods, where firms compete through the development of new goods and prices. For more details on these markets and their dynamics, refer to Metcalfe (1998) and Melo et al. (2016).

How the aggregate nominal demand is allocated across the firms is determined through the following Equation (5.8):

$$DN_{f,t} = ms_t AggD_t, \tag{4.51}$$

where $AggD_t = G_t + \sum C_{c,t} + \sum C_{w,t}$, the total aggregate nominal demand in the consumption goods' market. This is given by the total amount allocated in consumption by the workers, capitalists and government. And the real demand of each firm, in terms only of goods, is nothing more than the firm aggregate nominal demand divided by its price:

$$D_{f,t} = \frac{DN_{f,t}}{P_{f,t}}. \tag{4.52}$$

4.4 Simulation protocol and empirical validation

We use Monte Carlo simulations to analyze the dynamic behavior of our model. In these simulations, we model an economy with 200 firms and 6,000 workers. The methodology employed to ensure stock-flow consistency, in line with the Post-Keynesian stock-flow consistent models (Caverzasi and Godin, 2015), as well as initial values of the model's variables, are detailed in Appendix (C) and (D), respectively. To establish appropriate parameter values and ensure that the model reproduces commonly observed empirical regularities, we first conduct a calibration exercise using the "method of simulated moments"(Delli Gatti et al., 2017; Fagiolo et al., 2019). This method involves searching for a set of input values that can generate a set of output values measured through statistical moments of the simulations. These output values can be statistical moments observed empirically or values considered reasonable by the modeler. The objective function for the calibration problem using the method of simulated moments is:

$$\hat{\theta} = argmin_{\theta}[\mu^*(\theta) - \mu_R]' W^{-1}[\mu^*(\theta) - \mu_R], \tag{4.53}$$

where θ is the parameter vector governing the outputs of the simulations, $\mu^*(\theta)$ is the vector of statistical moments obtained using a specific vector of parameters, μ_R is the vector of statistical moments observed empirically or the target for the statistical moments and W is a weight matrix.

The statistical moments considered in the calibration process included cross-correlations of various macroeconomic variables with GDP, the standard deviation of those variables, as reported in Stock and Watson (1999), and the average value of the base interest rate, inflation, and aggregate unemployment. The cross-correlations of macroeconomic variables with GDP is a very usual data utilized in the literature to validate ABMs (see, for example, Assenza et al. (2015); Rolim et al. (2023); Caiani et al. (2016)). The empirical statistical moments considered to calibrate the model (cross-correlations and standard deviation), represented in the vector $\mu^*(\theta)$, included the aggregate GDP [1], aggregate consumption [2], aggregate investment [3], government real consumption [4], unemployment rate [5], aggregate capacity utilization [6], aggregate labor productivity [7], inflation rate [8], real wage rate [9], base interest rate [10], and aggregate functional distribution [11]. The periodicity of the variables considered in Stock and Watson (1999) is quarterly, and the cross-correlations range from -6 to +6 relative to the current value of GDP. Therefore, we considered a total of 157 statistical moments, including 143 cross-correlations and 11 standard deviations, plus the three average results.

The matrix W was constructed to balance the contribution of each type of statistical moment to the model. Elements in the diagonal matrix of W were set according to the relative importance of each type of statistical moment in the total set of moments. For cross-correlations, the respective value on the W diagonal was 143/157. For standard deviations, the value was 11/157, and for the averages, 3/157.

For the purpose of computing statistics, we are using the periods of the generated time series starting from period 250. The calibration exercise included simulations with a total of 1000 periods. In Table (4.1), we have parameters free to calibrate and the parameter space used to calibrate the model.

Parametric space			
Parameter	Name	Min value	Max value
PB	Lifespan of the machines	2	10
γ_0	Dividend policy	0.1	0.9
ψ_1	Variance of offer wages	0.5	2
ψ_2	wage offered inertia	0.5	1
ψ_3	Max. variance of offer wages	0.03	0.15
ψ_4	Inflation indexation	0.4	1
Θ	Markup adjusment	0.05	2
w_c	Workers propensity to consume out of disposable income	0.8	1
w_w	Workers propensity to consume out of wealth	0	0.5
c_c	Capitalist propensity to consume out of disposable income	0.4	0.6
c_w	Capitalist propensity to consume out of wealth	0.05	0.2
ϕ_π	Central bank reaction to inflation	0.1	2
ϕ_u	Central bank reaction to unemployment	0	0.5
υ_{cb}	Monetary policy inertia	0.2	0.95
Λ_1	Memory parameter	0.5	0.9
Λ_2	Effect of performance over probability of selection	0.5	8
Λ_3	Persistence of the heuristic	0.5	0.9
ρ	Government reaction	0	2
λ_0	Allocation in deposits if base interest rate is zero	0.2	0.6
λ_1	lambda_cash_capitalist	-2	2
$frac$	Productivity multiplayer of the capital goods sector	0.25	4
α_q	Quality elasticity	0	6
α_p	Price elasticity	0	6

Table 4.1 - Range of the possible values of the calibrated parameters

The calibration optimization problem was solved using a search-based genetic algorithm (for an introduction, McCall (2005)). The steps of the algorithm are as follows:

1- Generation of a random population of parameter sets within the given parameter space

2- Computation of the fitness value of the population (using the value of the objective function)

3- Selection of the parameter sets that will reproduce and survive to the next simulation based on their fitness values and a hyperparameter called elitism

4- Recombination and mutation of the selected parameter sets (recombination creates new individuals using the values of the fittest ones, while mutation randomly substitutes some parameters with values from random parent individuals)

5- Repeat steps 2 to 4 until the value of the fittest parameter set does not change through a certain number of simulation rounds or until a limit of simulation periods is reached.

This algorithm has the advantage of being able to explore the entire parameter space and find global maximums/minimums of the objective function without being too computationally expensive. Additionally, it does not require a prior solution (like Bayesian methods of calibration), but a suggested solution can be incorporated into the initial population.

The values of hyperparameters adopted to implement the genetic algorithm are in Table (4.2).

Hyper-parameters	
Name	Value
Population	15
Runs	7
Crossover	0.6
Mutation	0.2
Elitism	1

Table 4.2 - Hyper-parameters of the Genetic Algorithm

Due to the high computational cost of running the model, to calibrate the model we only consider a discrete range of values that could be chosen in lieu of a continuous range. For each parameter was considered a maximum and a minimum possible value. The interval between these two values was equally divided in 15 parts. The points that divided the parts of the intervals resulted in the uniform discrete distribution of each parameter. Necessarily, populations of parameters set for the genetic algorithm were drawn from the uniform discrete distributions of the parameters.

To calculate the statistical moments for each combination of parameters tested, the average of five simulations was taken. The initial population of parameters at the beginning of the calibration process was sampled using the Latin Hypercube method, in order to ensure an even distribution of samples.

After calibrating the model using a genetic algorithm, a local analysis was conducted by applying a local search algorithm. This was done to determine if using the parameters in the vicinity of those selected by the genetic algorithm improves the calibration of the model. The final values for the stocks and parameters of the baseline simulation are:

Description	Value
Adjustment of expectations given the unattended demand	0.2
Market share inertia	0.5
Desired stock (% of demand expectation)	15%
Direct labor productivity	105
Indirect labor parameter given stock	0.01
Desired degree of utilization of production capacity	0.8
Parameters that control the adjustment of the markup given the rule used	1.5821
Premium of the profit target	5%
Parameter past performance memory	0.6143
Parameter that control for the relative weight of past performance	7.4643
Parameter that controls the persistence of the heuristics	0.8714
Percentage of investment in R&D	0.05
Firm search capabilities parameters	1/(0.001 GDP)
Effect of past indebtedness on the current target	0.9
Total amount distributed in dividends if the current indebtedness is equal to the target	0.3857
Life span of the machines	40
Workers' propensity to consume out of disposable income	0.9429
Workers' propensity to consume out of wealth	0.3571
Capitalists' propensity to consume out of disposable income	0.4857
Capitalists' propensity to consume out of wealth	0.0929
λ_0 (Allocation in deposits if base interest rate is zero)	0.2
λ_1 (sensitivity of wealth allocation to interest rate)	0.2857
Income tax, wealth tax, interest tax	25%
Adjustment of government consumption	
0.4285 % of the base Interest rate on deposits	50%
Assumed equilibrium real interest rate	0
Central bank reaction to inflation	0.3714
Central bank reaction to unemployment	0.25
Monetary policy inertia	0.8429
Neutral real interest rate	0.025
Reaction of the firms to differences in the labor demand and supply	2
Maximum variation of wage offered	0.0643
wage offered indexation	0.9286
Inflation indexation of the wages	0.7
Competitiveness elasticity to relative quality	2.5714
Competitiveness elasticity to relative price	2.5714
Competitiveness elasticity to delays	6
Competitiveness elasticity to relative price changes	6
Competitiveness elasticity to any price changes	6
Market share inertia	0.9

Table 4.3 - Parameters of the benchmark model

After determining the benchmark model, according to the methodology of Vandin et al. (2022), we evaluated whether the number of simulations was sufficient to ensure that the results for the time series of “GDP,” “unemployment rate,” “inflation rate,” and “wage share” fell within a 95% confidence interval, with a margin of error of no more than 5% of the average result or, in the case of variables measured in percentages, below 5 percentage points. Our analysis determined that 30 Monte-Carlo simulations were sufficient to guarantee this level of confidence. Therefore, using 100 simulations was considered sufficient to produce robust results and conclusions.

Furthermore, also in accordance with the methodology of Vandin et al. (2022), we applied the Kolmogorov-Smirnov test to the baseline model, and evidence was found that the time series of GDP, unemployment rate, and wage share in difference, and inflation rate in level, were ergodic. This suggests that the number of periods considered in the simulations was adequate to analyze the model in its steady state. However, it is worth noting that while the model may exhibit stable tendencies, they may be positive or negative over time.

All these validations techniques are statistical analysis. This means that they are techniques to analyses if a sufficient number of simulations of a certain length are enough to observe differences that are statistically significant. This does not necessarily mean that the model is in equilibrium, as would be defined with a model solved analytically. What we defined in our model as the steady-state is that the time-series of “GDP,” “unemployment rate,” “inflation rate,” and “wage share” are stable and ergodic. When the model fulfilled these conditions it was considered that the results were robust enough statistically to be analyzed. These conditions may occur even with some of the models’ variables showing stable tendencies.

Table (5.4) presents the average standard deviations of 100 simulations comparing the calibrated baseline model with empirical values. Overall, the standard deviations of the simulations are lower than those observed in reality. This is likely due to the fact that the model only considers two stochastic processes, namely, the quality innovation and lifespan of the firm’s machines. The hierarchy of variables in the model, ordered by their standard deviations from highest to lowest, is consistent overall with empirical observations. The aggregate investment has the highest standard deviation, followed by aggregate consumption, GDP, and government consumption. Consumption has higher volatility than GDP in the model because the government, which has a participation in the GDP close to 20% in the simulations, has a low standard deviation compared to what is observed empirically.

The aggregate unemployment rate and capital utilization have equal standard deviations in the simulations, which is different from what is seen empirically. In reality, it is known that firms' reaction to decreases in demand is to first decrease the number of hours of the employed workers, then to do temporally layoffs, with the workers being fired being really the last option. These mechanisms are not considered in the simulated model, which explains the standard deviation.

The inflation rate, real wage rate, and base interest rate have all lower volatility in relation to what is seen empirically, but the order of the most volatile to the least is respected in the model.

	Obs [1]	Empirical [2]	[1]/[2]
GDP	0.41	1.66	0.25
Consumption	0.49	1.26	0.39
Investment	2.81	4.97	0.57
Government.Cons	0.15	2.49	0.06
Unem.rate	0.49	0.76	0.64
Cap.Util	0.49	3.07	0.16
Labor prod.	0.23	1.05	0.22
Inflation	0.11	1.44	0.08
Real wage rate	0.10	1.10	0.09
Base interest rate	0.12	1.47	0.08

Table 4.4 - Average standard deviation of the detrended time-series generated by the simulations compared with empirical results

Figures (4.1) and (4.2) presents the average cross-correlation of GDP with other variables using the calibrated model, along with error bars representing two standard deviations. While the algorithm was not able to calibrate the model such that the empirical results fall within the interval of two standard deviations, the model is able to capture the signal and direction of the cross-correlations well. The only exception where the signal was not adequate is in the case of the cross-correlation of the base interest rate.

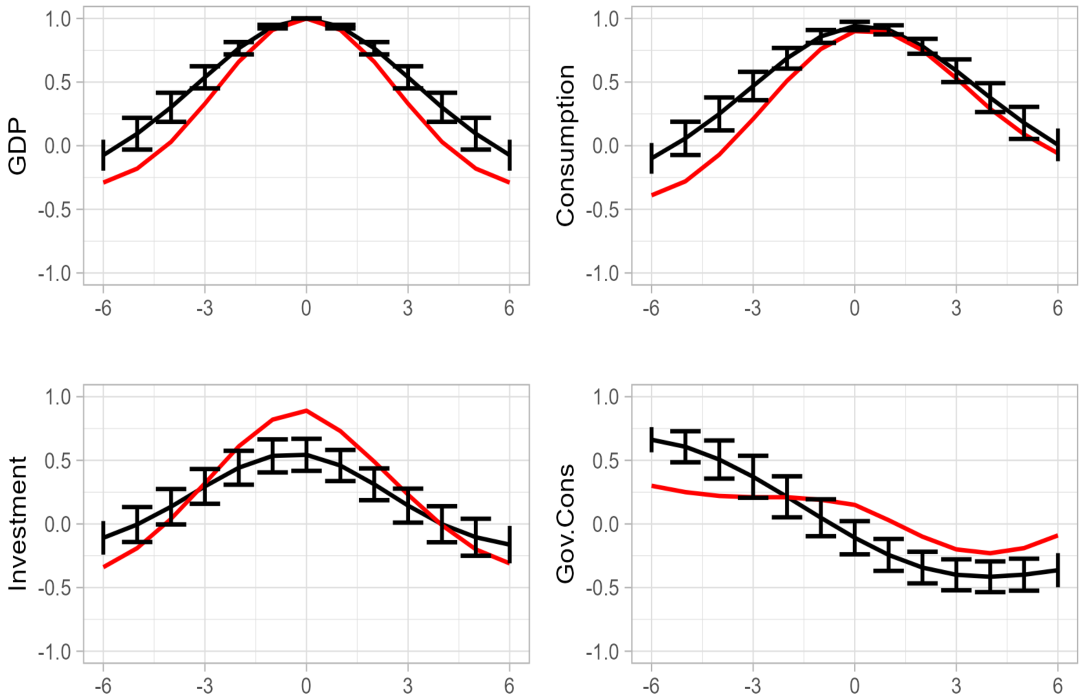


Figure 4.1: (a) Cross-correlations structure for output

Note: Bpf: bandpass-filtered (6,32,12). GDP, consumption, investment and gov.cons series are taken in logarithm. Bars are 2 standard deviations of 100 Monte Carlo average cross-correlations

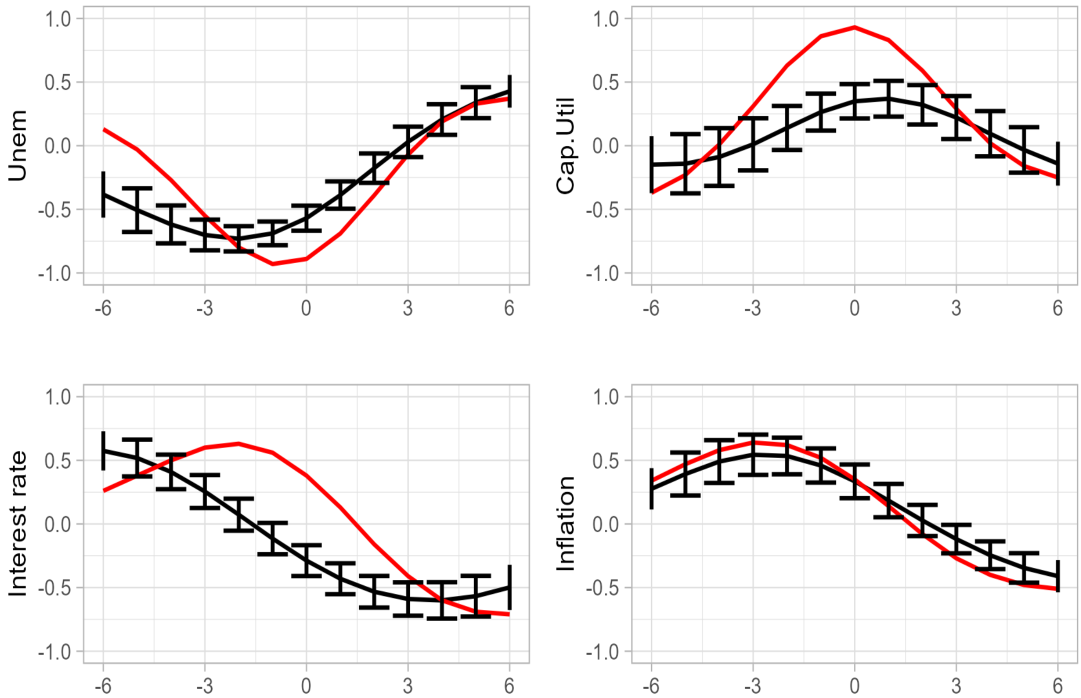


Figure 4.2: (b) Cross-correlations structure for output

Note: Bpf: bandpass-filtered (6,32,12). GDP, consumption, investment and gov.cons series are taken in logarithm. Bars are 2 standard deviations of 100 Monte Carlo average cross-correlations

4.5 Results

In the following section, the results of the model are presented. The section is divided into three parts. Firstly, the macroeconomic results are presented, highlighting the model's ability to replicate stylized facts observed in the US economy and the behavior of the simulated economy at the macro level. Second, the microeconomic results are examined. Finally, an analysis of the evolution of heuristics within the model over time is provided. In the accompanying figures, the average results of 100 simulations are represented in black, with one standard deviation from the average shown in red, and the results of a single simulation run are illustrated in blue. The transient phase is considered up until period 500.

4.5.1 Macroeconomic results

As depicted in Figure (4.3), the total production fluctuates throughout the simulations and does not exhibit any upward trend, which is consistent with the assumption of no productivity growth of capital goods. On the contrary, Figure (4.3.a) shows an average decrease in aggregate GDP and stable standard deviations. In Figure (4.3.b), we present the cyclical behavior of investment (represented in black), consumption (in red), and government expenditure (in blue) in one simulation run. As observed in empirical data, investment is the most volatile component of GDP. Government expenditure would typically be the second most volatile component; however, as previously mentioned, in the calibrated model, government expenditure has a lower standard deviation.

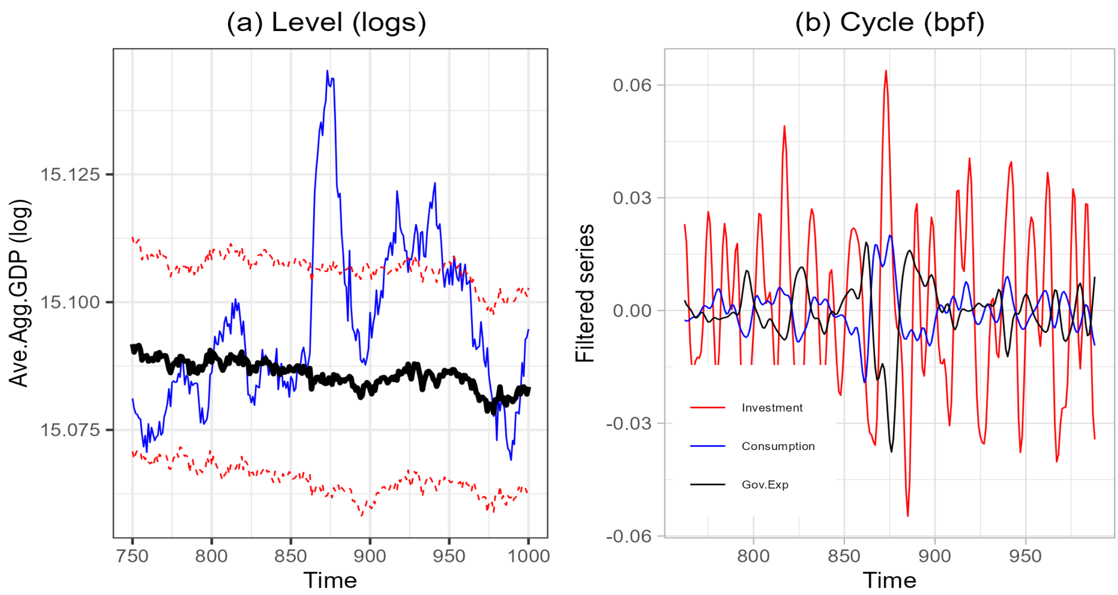


Figure 4.3: GDP dynamics

Black = mean. Red = 1 STD. Blue = one run.

As illustrated in Figure (4.4), the inflation rate remains stable in the long-run across the simulations. This can be inferred by examining the average results, represented by the black line, and the constant standard deviations, shown by the red lines. When examining a single simulation, it is observed that inflation fluctuates and exhibits periods of significant increases and decreases.

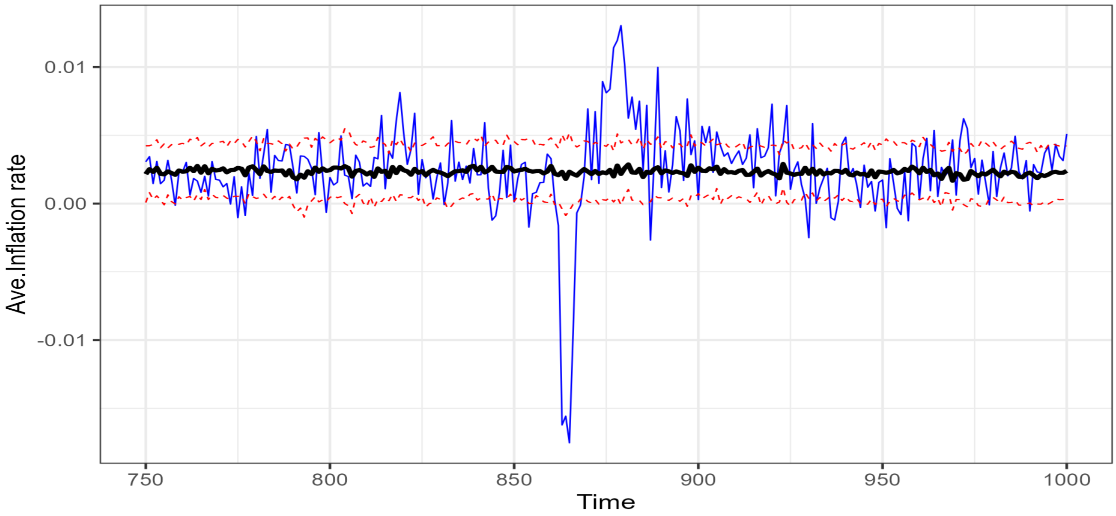


Figure 4.4: Inflation rate

Black = mean. Red = 1 STD. Blue = one run.

As expected, the baseline interest rate also displays a cyclical behavior, with an average that remains slightly above the average inflation rate, as can be seen in Figure (4.5). Additionally, the interest rate exhibits periods of increased volatility between the simulations.

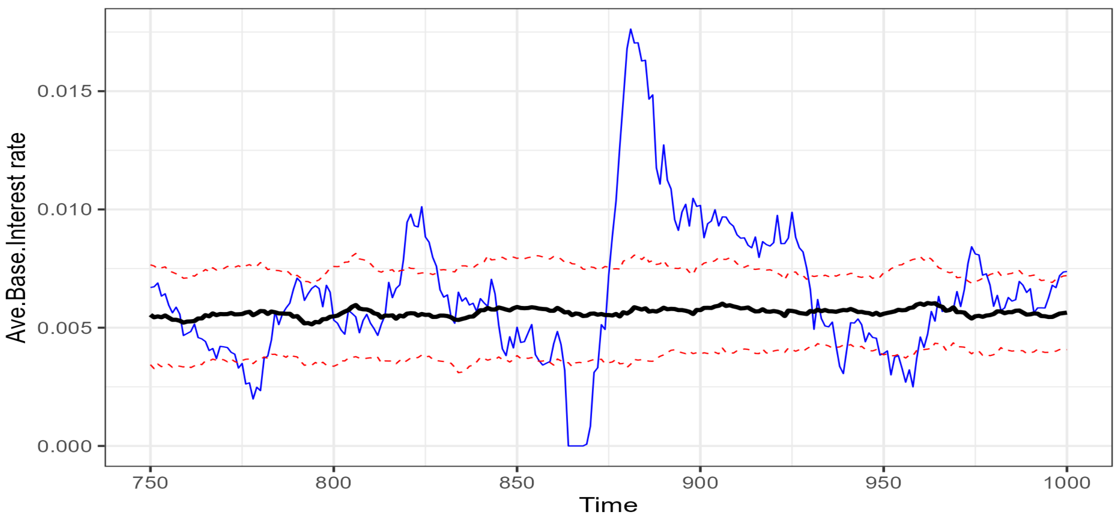


Figure 4.5: Baseline interest rate

Black = mean. Red = 1 STD. Blue = one run.

In the case of the unemployment rate, as depicted in Figure (4.6), a transient period is observed until period 500, characterized by a cyclical behavior. Subsequently, on average, the unemployment rate gradually increases over time. At the end of the simulations, the unemployment rate fluctuated between 12% and 14%, as determined by the one standard deviation. However, when examining the results of a single simulation, represented by the blue line in Figure (4.6), a cyclical behavior of the unemployment rate is observed.

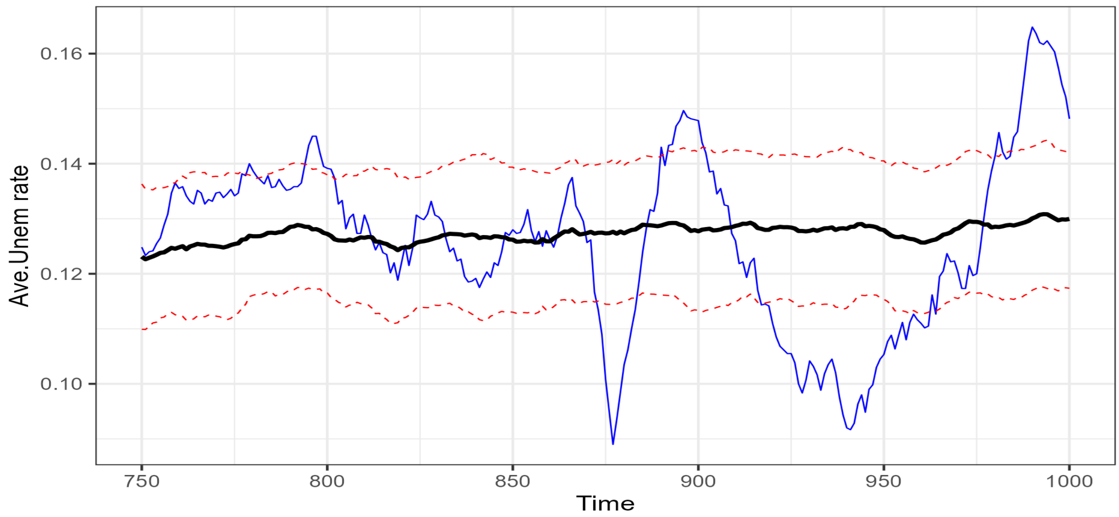


Figure 4.6: Unemployment rate

Black = mean. Red = 1 STD. Blue = one run.

Another notable result that demonstrates the model's ability to produce stable results is the relationship between capitalist wealth and GDP, as well as the government debt to GDP. After the initial transient period, on average, the government debt continues to increase, but this trend gradually decreases over time. At the end of the simulations, this relationship has a mean value close to 2 and a standard deviation of 0.125. The average change rate measured by a moving average of 12 periods of the government debt in relation to GDP decreases over time, approaching 0 at period 1000. This indicates a stable behavior. The same observation can be made for the stock of capitalist wealth in relation to GDP, which also exhibits a stable result using the same criteria. The mean value of this relationship at period 1000 is slightly above 1 and has a standard deviation close to 0.1, as seen in Figure (4.7).

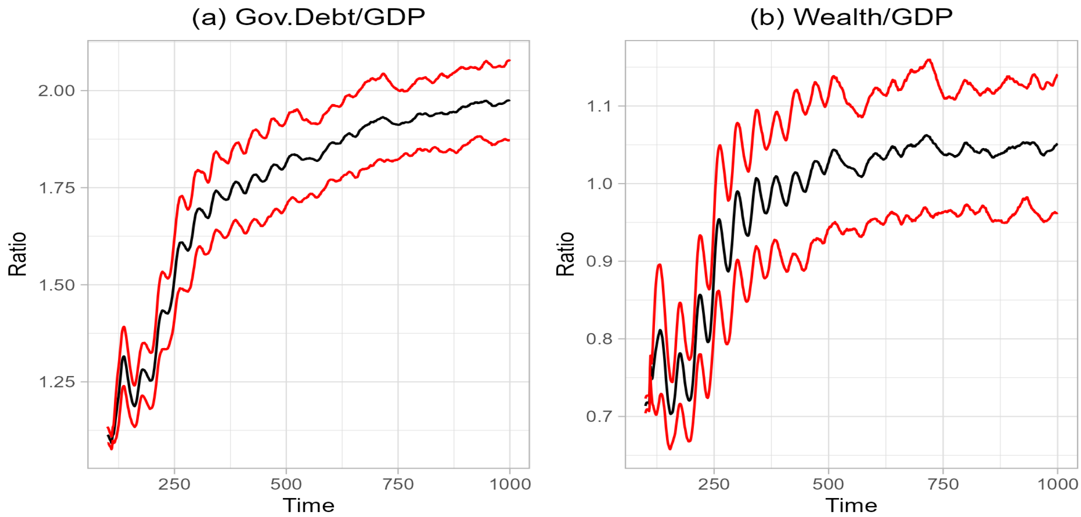


Figure 4.7: Wealth and debt stocks

Black = mean. Red = 1 STD

The wage share of the model, as presented in Figure (4.8), exhibits, on average, a tendency to increase over time. The standard deviation also tends to increase over time. When examining the results of a single simulation, it is observed that the tendency is not monotonic, with the simulations showing cyclical behavior.

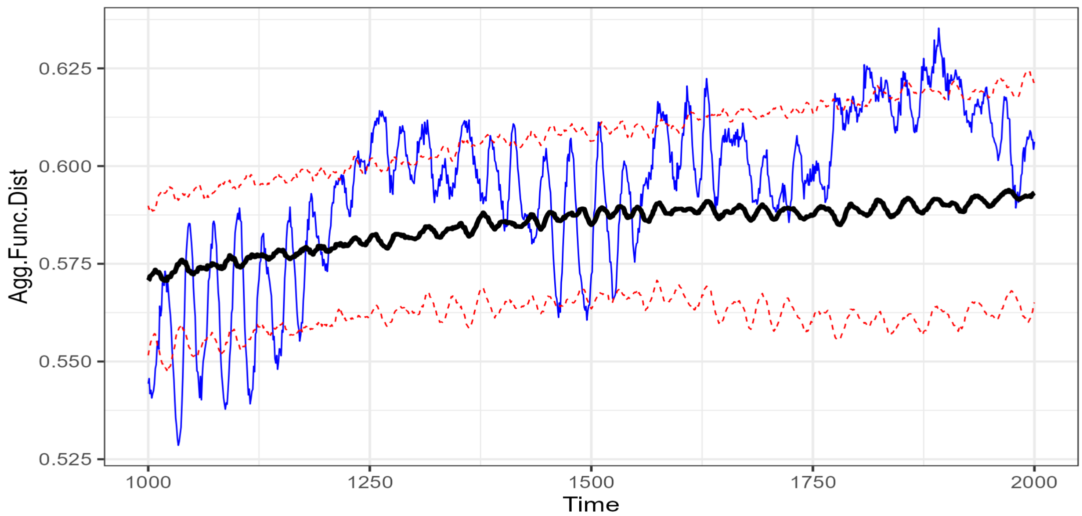


Figure 4.8: Wage share

Black = mean. Red = 1 STD. Blue = one run.

In conclusion, while the model demonstrates stability in terms of financial ratios, inflation, and interest rate, macroeconomically, a long-term trend of decreasing GDP, wage share, and increasing unemployment is observed. These results can be understood with the microeconomic information about the models.

4.5.2 *Microeconomic results*

In the current subsection, we present the primary microeconomic results of the model, demonstrating its ability to replicate important micro stylized facts and to exhibit the micro environment in which firms compete.

As depicted in Figure (4.9), we present the weighted average of the indebtedness of the economy, calculated from 100 simulations. The indebtedness of each firm is weighted by its market share. A cyclical behavior of the participation of debt in the balance sheet of firms in the economy is observed, with this value remaining between 0.63 and 0.67. When examining a single simulation, as shown in Figure (4.9), the level of indebtedness of firms in the economy follows a cyclical pattern.

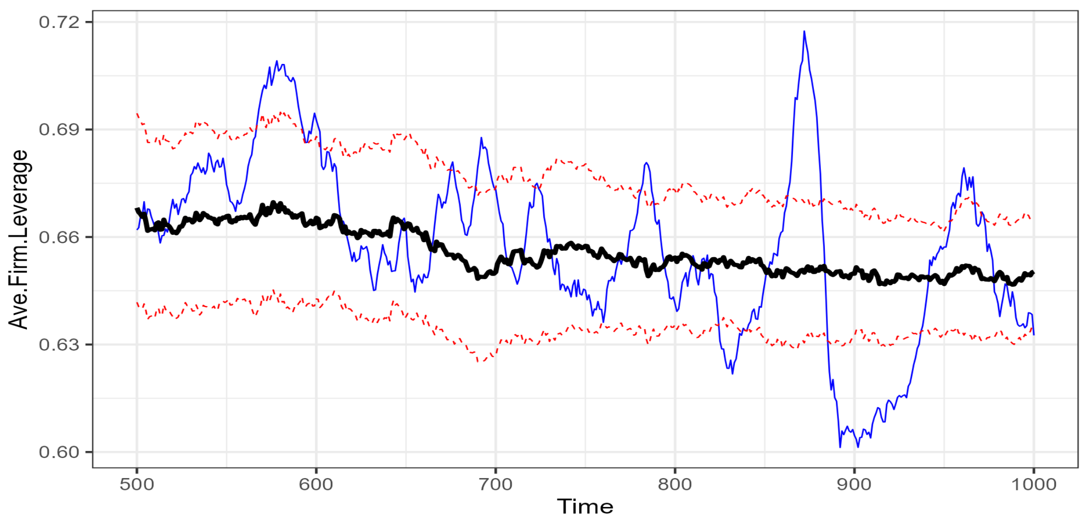


Figure 4.9: Weighted average of indebtedness

Black = mean. Red = 1 STD. Blue = one run.

Additionally, the number of bankrupt firms, which is significant due to its impact on the selection of heuristics, is on average 1 per period in the simulations. However, as seen in Figure (4.10), when examining the results of a single simulation run, spikes in the number of bankrupt firms can be observed.

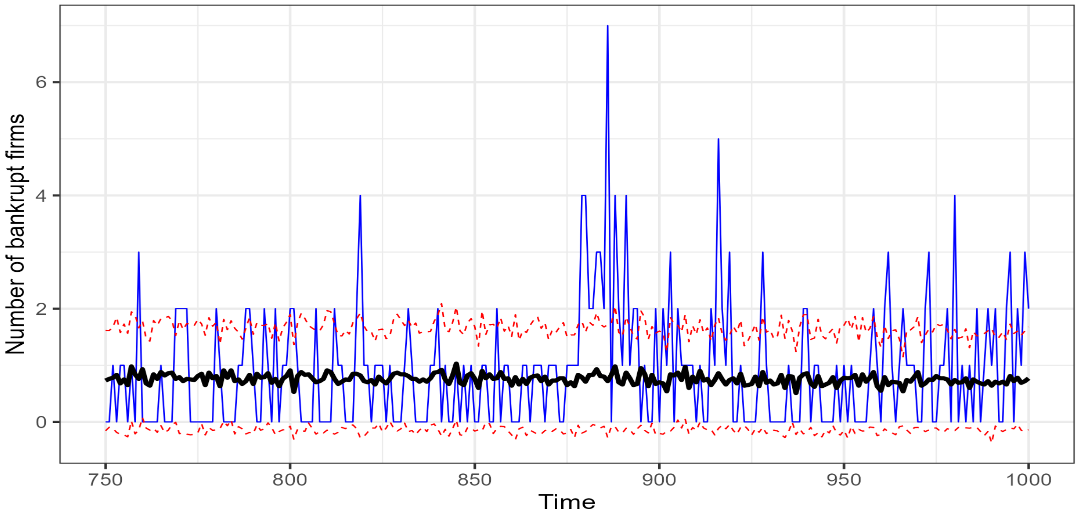


Figure 4.10: Number of bankrupt firms

Black = mean. Red = 1 STD. Blue = one run.

As depicted in Figure (5.13), our model's simulation results demonstrate a mean value and one standard deviation of the Herfindahl-Hirschman (HH) Index, as well as the average value of the firm with the highest market share at different periods. Initially, all simulations commence with a highly competitive market, where all firms possess identical goods, prices, and market shares. However, through the implementation of different pricing strategies and investments in product differentiation, an increase in market concentration is observed over time. As seen in Figure (5.13), firms exhibit varying degrees of competitiveness in terms of market share. Despite this, the final degree of market concentration in the steady state is low, with the HH index being slightly above 0.0051 and the average value of the maximum market share being above 0.8% at the end of the simulations.

This outcome is at odds with the empirical trend of increased market concentration as noted in Autor et al. (2020), our model does not exhibit this behavior. Our model does not exhibit this behavior because, as explained in Terranova and Turco (2022), our model lacks the key ingredients that generate market concentration in ABMs, namely the absence of knowledge spillovers and persistent differentiated capital goods. Our model incorporates knowledge spillovers in the product innovation and evolutionary process and the capital goods are homogeneous for all firms. This enables firms that are lagging behind to eventually catch up to market leaders and prevents the emergence of highly oligopolized markets.

Incorporating homogeneous capital goods and the absence of knowledge spillovers in the model is essential in preventing the emergence of firms that dominate the market solely due to their size. This ensures that pricing competition based on pricing heuristics remains relevant, and the statistics of the importance of certain heuristics in the population of firms do not need to take into account the size effect of firms. It ensures that the market competition remains fair and open, preventing the formation of oligopolies.

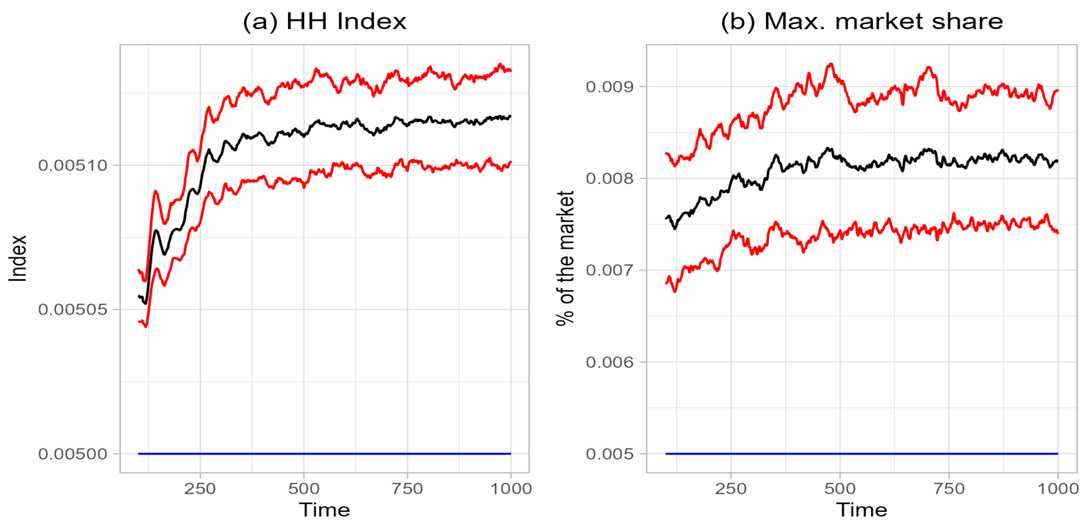


Figure 4.11: Average of the Herfindahl–Hirschman (HH) Index and max market share

Black = average. Red = one SD. Blue = perfectly competitive market

The model is able to replicate a microeconomic stylized fact of a right-skewed distribution of firm size (as proxied by market share) with upper-tails composed of a few larger firms, as can be observed in Figure (4.11) using results from one simulation. This stylized fact has been previously documented in Figure (4.11) using results from one simulation. This stylized fact has been previously documented in Bottazzi and Secchi (2003).

The model also reproduces the lumpiness of investment, as established in Doms and Dunne (1998). By examining Figure (4.12), we can observe the distribution of the ratio of new machines to total machines, with the majority of firms not investing in new machines every period, while a small number of firms acquire a significant amount of new machines, which is consistent with the empirical evidence. These stylized facts highlight the ability of the model to accurately capture key features of the real-world economy.

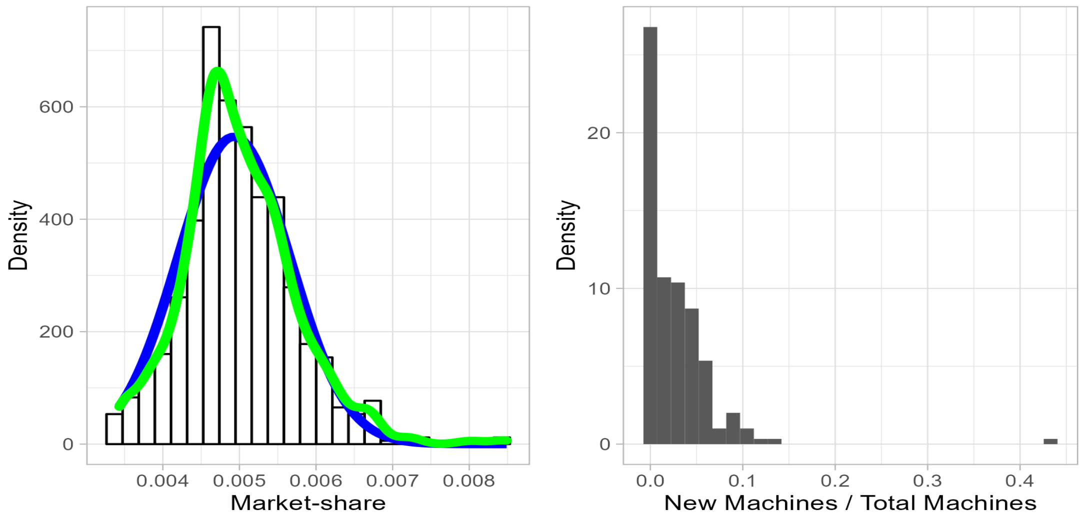


Figure 4.12: Stylized microeconomic facts

Bars: frequency. Blue: Normal distribution. Green: Density function

Additional stylized facts that are verified in the model, as seen in Figure (4.13), include the pro-cyclicality of firms' investment in R&D (Wälde and Woitek, 2004; Barlevy, 2007) and the pro-cyclicality of firms' stock of debt to GDP (Jordà et al., 2017; Hiebert et al., 2018). In both cases, these variables are leading indicators of GDP. The pro-cyclicality of firms' stock of debt is also a stylized fact of business cycles (Azariadis, 2018).

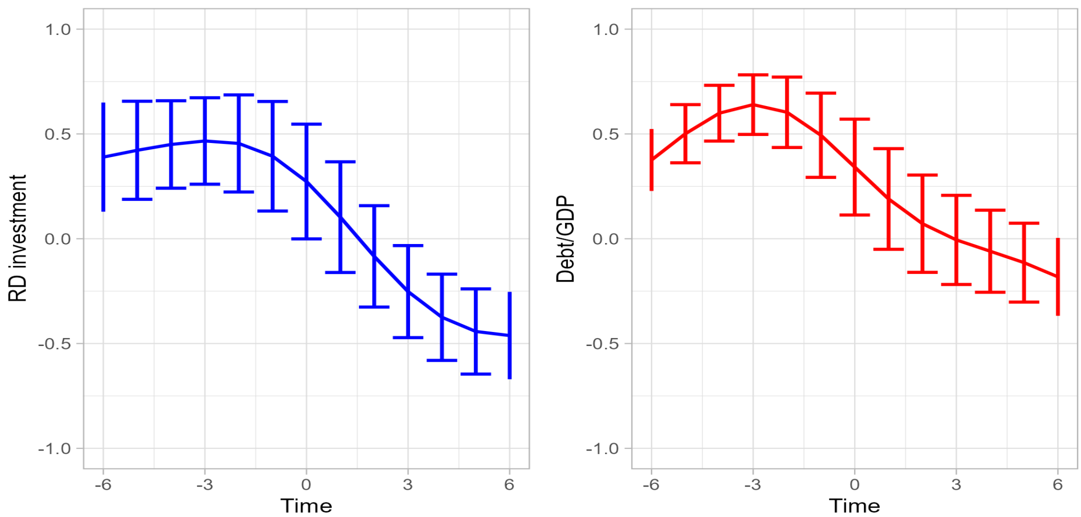


Figure 4.13: Cross-correlation of R&D investment (blue) and debt to GDP ratio (red)

Bars = one standard deviation

In Figure (4.14), we can see the average result of our simulations (in black) indicating an increase in the average markup of firms over time. There is a considerable amount of variation among the simulations, with an interval of one standard deviation ranging from 0.55 to 0.65 at the last period. When observing the results of individual simulations, we observe a high degree of volatility and the possibility of significant decreases or increases in firms' markup. This suggests that while the average trend is of an increasing markup, observing the individual results of the simulations shows that the economies may deviate for long periods from this trend, with the average markup moving for a long period in a different direction.

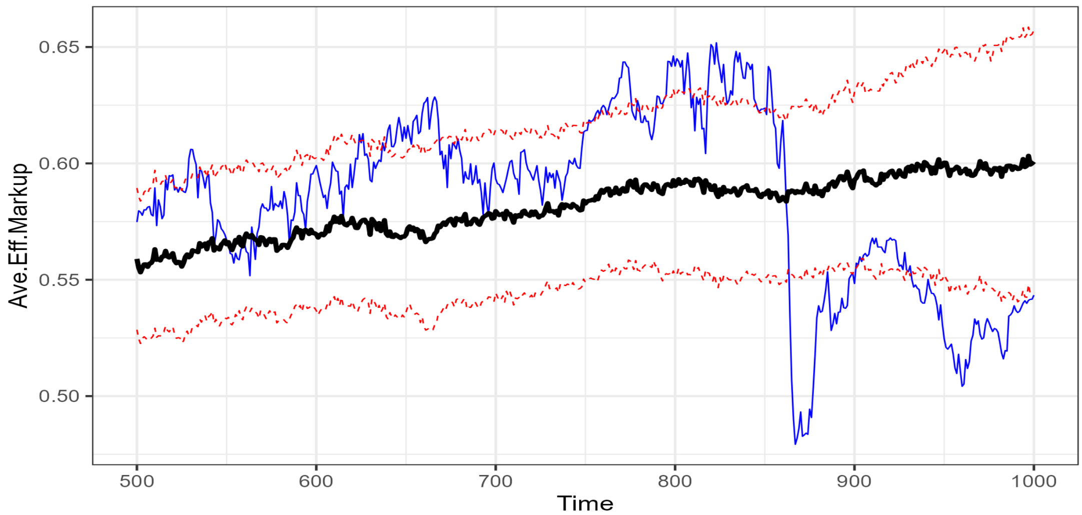


Figure 4.14: Average markup

Black = average. Red = one SD. Blue = perfectly competitive market

The result of the average trend of markup in the simulations explains many of the tendencies seen at the macro level, given the demand-driven nature of the developed model. The continuous increase in the average markup means a continuous decrease in the wage share, GDP, and an increase in the unemployment rate.

4.5.3 Heuristics dynamics results

In this subsection, we examine the dynamics of the heuristics employed by firms in the model. In Figure (4.15), we present the distribution of firms that use one of the heuristics during a single simulation. From this figure, we can draw two main conclusions. Firstly, we observe that the strategy of setting markup based on a profit rate quickly disappears from the population of firms, with only a small number of firms adopting this strategy for short periods of time before it is phased out again. In other words, the strategy we considered the true "essence" of the cost-based approach is completely dominated by the others. Secondly, we observe a high degree of volatility in the participation of the other three heuristics in the firm population, with the adoption of a particular rule fluctuating between less than 15% and more than 50% of firms at different times.

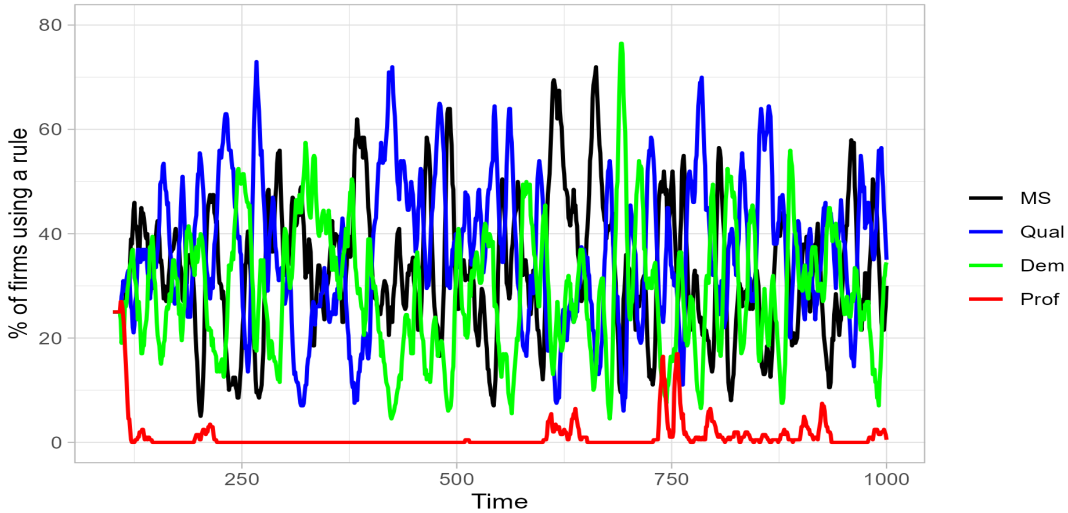


Figure 4.15: Distribution of markup rules over one simulation

MS = market share heuristic. Qual = Quality heuristic. Dem = Demand heuristic. Prof = Profit heuristic

Furthermore, in Table (4.5), we present the participation of the heuristics in the population of firms across 100 simulations (considering the average results from period 100 onward). On average, 36% of firms employed the quality heuristic, 32% the market share heuristic, 31% the demand heuristic, and only 0.1% the profitability heuristic to set markup. We also observe a high standard deviation in these results, with an average of 14% (with the exception of the profitability strategy).

Additionally, from period 500 onward in the simulations, on average, 10% of firms changed the heuristic being used in every time step. Given the low number of bankruptcies in the simulations, this indicates that the most significant process of adaptation in the simulated economy is due to a within-firm process, with firms adopting what appears to be better strategies, rather than through market selection (bankrupt firms swapping heuristics). This within-firm adaptation process being more important than the market selection process is observed empirically for other firm behaviors (Dosi et al., 2015b; Bottazzi et al., 2010)

	Mean	SD
Market share	0.32	0.14
Quality	0.36	0.14
Profitability	0.01	0.02
Demand	0.31	0.14

Table 4.5 - Mean participation of the heuristics in the population of firms from period 100 onward in 100 simulations

Figure (4.16) illustrates the average participation of various pricing heuristics in the firm population, determined by 100 simulations. The data indicates that the quality heuristic consistently demonstrates the highest average participation among the firms. The market share heuristic is the second most frequently used strategy, followed by the demand heuristic. On the contrary, the profitability strategy is observed to have minimal participation within the firm population.

Based on the average utilization of these heuristics, it can be inferred that the most successful pricing strategy is the quality strategy, followed by the market share strategy, and then the demand strategy. In contrast, the profitability strategy is comparatively less successful.

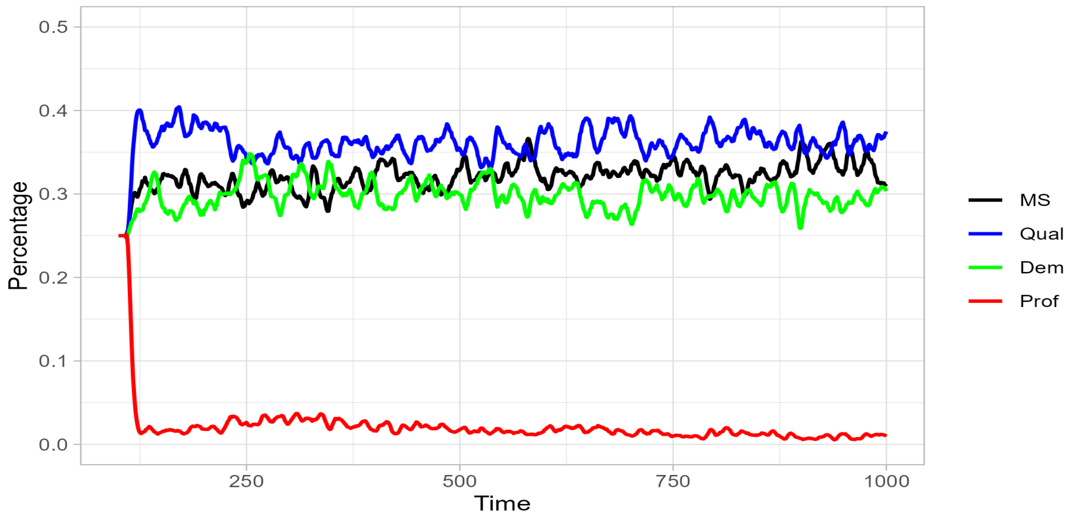


Figure 4.16: Distribution of markup rules over one simulation

MS = market share heuristic. Qual = Quality heuristic. Dem = Demand heuristic. Prof = Profit heuristic

These findings are of particular interest compared to the economic theory and surveys presented in the first section of the article. The quality heuristic, which is most closely aligned with the value-based pricing strategy recommended by economic and business literature, is observed to be the most effective. However, it is important to note that this heuristic does not completely dominate other strategies. A significant number of firms continue to use heuristics that take into account demand conditions and competitiveness, as these strategies did not result in lower profit rates for the firms. On the other hand, the profitability heuristic is consistently associated with lower profit rates, as firms using this strategy tend to decrease prices without taking into account market information, leading to lower revenue and thus lower profits. In Figure 4.17 we can observe the average profit rate of the firms using each one of the heuristics. Therefore, our simulations reveal the persistence of heterogeneity in pricing heuristics among firms, with all strategies that take into account market conditions still capable of generating profit rates sufficient for survival.

The heuristic "profit"shows evidence to be self-defeating. This strategy would be plausible to be adopted and thrive among the firms if the lower profit targets would lead to lower prices and an increase in market share sufficient enough to compensate the lower prices, generating higher profits. However, the lower prices are not compensated for by higher market shares given the calibration of the model. Because of that, the adoption of a pricing strategy based on the "profit heuristic"with a profit target below the average observed in the market becomes self-defeating.

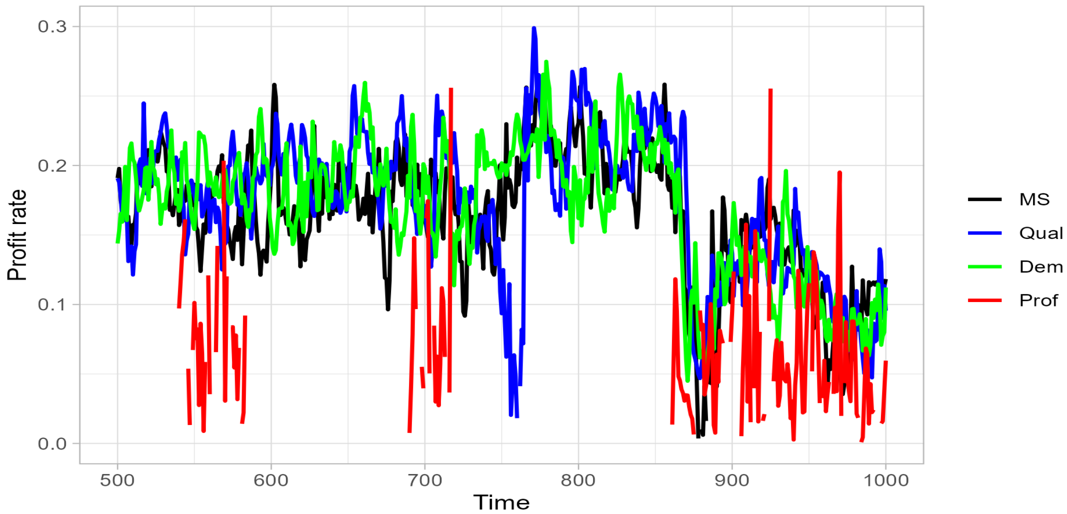


Figure 4.17: Average profit rate of the firms using each heuristic in one simulation

MS = market share heuristic. Qual = Quality heuristic. Dem = Demand heuristic. Prof = Profit heuristic

We also investigated the relationship between the adoption of pricing heuristics and the economic cycle. Specifically, we examined whether there is a co-evolution of the macroeconomic environment with the microeconomic environment. Figure (4.15) illustrates that the participation of certain heuristics among firms appears to follow a cyclical pattern.

To further investigate this relationship, we analyzed the cross-correlations of the detrended participation of the heuristics in the firm's population with the detrended aggregate GDP. As shown in Figure (4.18), the participation of the heuristics in the firm's population is moderately correlated with GDP. Furthermore, the participation of the heuristics in the firm's population is a leading variable for GDP. For all the heuristics, the participation between periods -6 and -3 has the highest correlation (either positive or negative) with the current GDP. The "quality" heuristic demonstrates the strongest correlation with GDP.

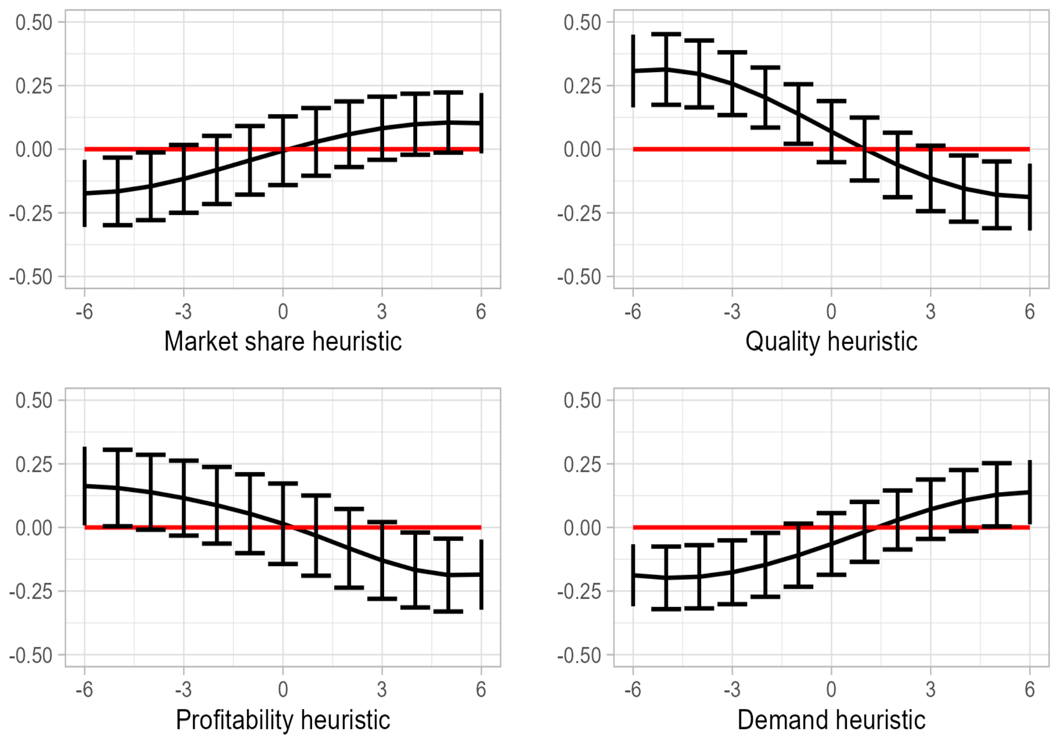


Figure 4.18: Cross-correlation of heuristic participation with the GDP

Bars = one standard deviation

Moreover, the participation of the heuristics among the firm's population also appears to affect the markup level of the economy. Specifically, the participation of the heuristics in the firm's population is a leading variable for the average markup level, as can be seen in Figure (4.19). This suggests that the choice of heuristics among firms can have a significant impact on both the micro and macroeconomic environment.

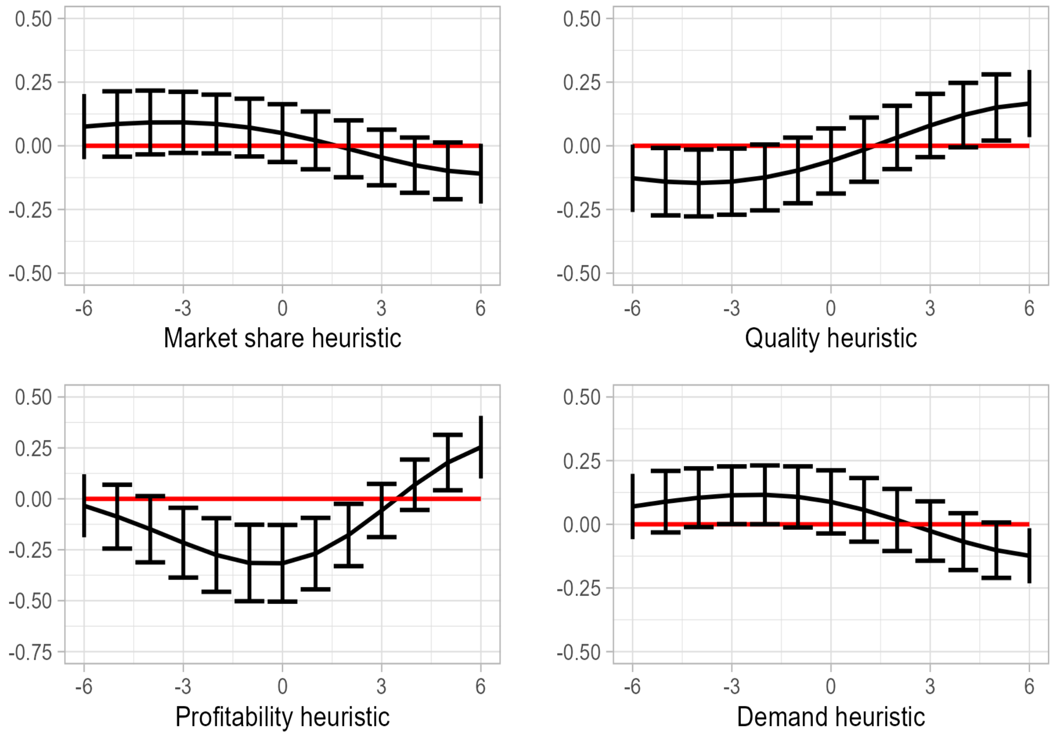


Figure 4.19: Cross-correlation of heuristic participation with the markup

Bars = one standard deviation

These results are in line with the empirical results that find a negative correlation between markup and GDP in the business cycle (Rotemberg and Woodford, 1991, 1999; Bloch and Olive, 2001). In our model this happens because the of the switch between different pricing heuristics during the business cycle. It is challenging to establish causal mechanisms in ABMs due to their complexity. However, we can observe that when more firms adopt the "quality" heuristic, we see a decrease in the average markup of the economy. This means that firms that adopt this strategy start to continuously decrease their markup in order to become more competitive if the quality of their goods does not improve as much as the average. Since a low number of firms innovate in every period, the majority of firms using the "quality" heuristic tend to decrease their markup, with only a few increasing prices by a larger amount. This leads to an increase in the wage share of the economy. Given the wage-led nature of the model, this decrease in markups increases real consumption in the economy and stimulates investment in new machines and the employment of more workers. As we have seen, it is also in this period that the debt stock of firms increases together with the investment in R&D to improve quality. With the multiplier effect of consumption and the accelerator effect of investment, we see an economic boom.

The positive correlation of the current GDP with the participation of the "market share"and "demand"heuristics in periods +1 to +6 suggests that these strategies benefit during the growth phase of the cycle. However, as shown in Figure (4.19), an increase in the participation of these two heuristics leads to an increase in the overall markup of the economy, which can potentially reverse the economic cycle. This means that even though these heuristics increase the firm's fitness during the growth phase, when its participation increases in the firm's population, it leads to a rise in overall markups, which can ultimately slow down or reverse the economic cycle.

Together with other mechanisms in the model, such as the dividend policy of the firms and the behavior of the central bank, the firms' pricing behavior contributes to the business cycle. Moreover, different phases of the cycle seem to benefit different pricing heuristics. This leads to a co-evolutionary process, with firms' behavior affecting the macro environment and vice-versa. The economic cycle keeps repeating, with firms adopting heuristic rules that increase markup in some periods and decrease in others.

4.6 Conclusion

The aim of the present chapter was to discuss pricing heuristics in an agent-based macroeconomic model. We first presented that surveys show the presence of a remarkably persistent heterogeneity in how firms set prices. This heterogeneity involves the main pricing rules and formations considered. We also described that the business literature also identifies the remarkably persistent heterogeneity when considering cross-section analysis among firms. This contradicts theories that argues that firms would only utilize one pricing strategy, the value-based strategy, in which price is decoupled from costs and is related to how consumers value the goods relative to others.

The question at present is whether this observed heterogeneity is due to firms not yet having learned what the optimal strategy is and still needing time to adapt, or if the heterogeneity will be persistent over time, with no heuristic tending to dominate in the population of firms.

To study this, we developed an agent-based macroeconomic model. In the model, firms can adopt four different pricing heuristics focused on reproducing different strategies for the markup. These pricing rules are based on the evolution of demand, the evolution of competitiveness (based on the firms' market share), the relative quality of the firms, and the profit target.

We calibrated the model using the simulated moments method, considering macroeconomic data from the US presented in Stock and Watson (1999), and using a genetic algorithm to solve the calibration exercise. The model is able to satisfactory reproduce a wide array of macroeconomic and microeconomic stylized facts for the US, making the results obtained with it robust empirically.

The main conclusion of the study is that persistent heterogeneity in pricing strategies among firms is observed. While the heuristic considered optimal by the business and economic literature is the most frequently used, other heuristics continue to be significant. There is no evidence that all firms will eventually adopt the optimal heuristic, as inferior strategies can still result in satisfactory profits. The only heuristic not selected by firms is the "profitability"heuristic, which did not generate sufficient profits. The persistence of heterogeneous pricing behavior among firms in a model where pricing decisions are endogenous and firms are completely free to choose among different behaviors in an agent-based macroeconomic model is a novelty in the literature.

We also demonstrated evidence that the evolutionary behavior of firms, with them continually trying to adopt pricing strategies that improve their fitness, influences the business cycle of the model. We found that the participation of heuristics among firms correlates with the business cycle. At the beginning of the cycle, the "quality"heuristic is favored, leading to lower average markups and driving growth. However, during periods of higher GDP, heuristics based on market share and demand become more advantageous, resulting in increased markups, decreased wage share, and GDP. Given the calibration of the model and the reproduction of many stylized facts, we have evidence that the business cycles observed empirically may also be explained by the strategic and adaptive pricing behavior of firms.

It should be acknowledged that the model has limitations. First, even though we enriched the model to consider different pricing heuristics, they are still relatively simple. We assume that firms only consider one piece of information at every period to set markups, while in reality, firms may use more than one piece of information to set prices, as modeled in Oliveira et al. (2020). Furthermore, the pricing equations do not account for any asymmetry in the pricing strategies identified in pricing surveys, where certain information may be more important depending on its signal. We also did not incorporate the possibility that firms incorporate the dynamics of the unitary cost of production in the markups, as was done in Rolim et al. (2023). Despite these limitations, the model provides robust empirical evidence for the persistent heterogeneity in firms' pricing strategies and their correlation with the business cycle.

Chapter 5

To follow or to lead: An agent-based model of price stickiness and its macroeconomic consequences

5.1 Introduction

Price stickiness refers to the tendency for prices to remain unchanged for extended periods of time, despite changes in economic conditions that might otherwise be expected to lead to price adjustments. This phenomenon has been documented in many modern economies and is a key feature of many macroeconomic models.

There are several theories that attempt to explain why prices are sticky, and the mechanisms underlying this phenomenon are still the subject of ongoing research. One influential theory suggests that the existence of implicit contracts between firms and their customers or suppliers can contribute to price stickiness.

Implicit contracts are agreements that are not explicitly written down or legally binding but are understood to exist based on the repeated interactions between firms and their trading partners. For example, a supplier may have an implicit contract with a customer that the supplier will continue to provide a certain product at a certain price as long as the customer continues to place orders. Similarly, a customer may have an implicit contract with a firm that the customer will continue to purchase a certain product at a certain price as long as the firm continues to offer it under reasonable conditions.

The aim of this chapter is to examine the evolution of price stickiness in an economy where firms may be punished by consumers when adjusting prices, using an agent-based macroeconomic model. Our model simulates the interactions between firms and consumers, enabling us to explore how changes in the economic environment impact on the frequency, duration, and size of price changes and their effect on overall economic performance. This analysis seeks to shed light on the relationship between firms and consumers and its role in the emergence and dynamics of price stickiness, using an evolutionary agent-based macroeconomic model approach. Additionally, the study aims to provide insight into the potential macroeconomic consequences of such arrangements.

The chapter is organized into several sections. Following the introduction, the subsequent section provides a literature review of empirical evidence of microeconomic patterns of price stickiness, drawn from micro-data and surveys with firm managers. The third section presents a critical review of the prevailing mainstream theories on the existence of price stickiness. Our article also posits that an evolutionary perspective can theoretically explain the emergence of price stickiness. Sections 5 and 6 outline the model and its calibration process, respectively, while section 7 presents the results, highlighting the stylized facts and the outcomes in terms of price stickiness. In section 8, we present the results of different experiments to demonstrate the robustness of the model to different configurations of parameters, as well as the economic implications of different economic policies. Finally, the conclusion provides a summary of the findings.

5.2 *Empirical evidence*

In this section, we will outline the primary stylized facts that we aim to replicate in the current chapter. These details and literature reviews were already presented in chapter two. The first group of stylized facts was obtained through micro-data of consumer price indexes. We specifically selected the values obtained with micro-data of the consumer price index of the United States, since all the other macroeconomic stylized facts analyzed are also for the American economy.

The majority of the empirical micro-data results used as a benchmark were collected in Nakamura and Steinsson (2008). They include the frequency of regular price changes (which excludes discounts), the implied price duration, the size of price changes (when increase and decrease), and the percentage of price changes. We also considered the statistics of the percentage of price changes considered small, as presented in Klenow and Kryvtsov (2008).

The second source of stylized facts are the surveys with firm managers. In chapter two, we provided an extensive literature review that included surveys with firm managers in developed and emerging countries to understand how firms set prices and the main sources of price stickiness. The literature shows that the majority of the firms follow a cost-based pricing approach. The main explanations given for price stickiness are stability of costs, implicit contracts, and coordination failures.

Additionally, studies that used micro-data have observed that firms tend to change prices idiosyncratically, followed by internal shocks rather than macroeconomic shocks that are common to all firms. Many articles have also identified the importance of implicit contracts. Firms attempt to maintain stable prices to retain loyal customers and avoid customer punishment for breaching implicit contracts.

This information about the price-setting behavior of firms was considered to justify the formalization of our model and provided information to calibrate the model. We developed a model where firms follow a cost-based pricing approach, where they can keep their prices stable. Firms do not change the final price given any change in their costs or markup. This stability is a choice that can evolve over time. The statistical moments obtained from the micro-data of the consumer price index were used as quantitative variables to observe if the model replicates these stylized facts.

5.3 Theory

5.3.1 Theories of rigid prices

Price stickiness has been a central topic in modern macroeconomics, particularly since the 1980s, when the New-Keynesian literature emerged. The New-Keynesian literature has focused on understanding the causes of price stickiness and it's macroeconomic consequences. This is because the existence of price stickiness has important implications for the functioning of an economy and the effectiveness of the monetary policy.

Empirical evidence suggests that price stickiness is a widespread phenomenon in modern economies, and this has motivated researchers to study the underlying mechanisms that can lead to this phenomenon. By understanding the causes of price stickiness, economists can better understand how changes in monetary policy can affect the economy. In particular, the existence of price stickiness suggests that monetary policy may not be neutral, meaning that changes in the money supply or interest rates can have real effects on the economy. The present section discussed briefly some of the main theoretical developments since the

1970s that try to explain why prices do not tend to vary frequently. For an extensive discussion of articles that try to understand this, starting from the article of Mills (1927), see Wolman (2007),Nakamura and Steinsson (2013),Rotemberg (2005) and Melmies (2010).

The first commonly accepted explanation for staggered prices is the existence of costs for firms to adjust prices (Wolman, 2007). According to this theory, there are three implications. Firstly, if there is a cost to changing individual prices, prices will not change continuously. Secondly, individual prices will change more frequently when the benefits of adjusting the price are high or the costs are low. Thirdly, due to inflation, the benefits of adjusting prices increase over time and therefore the frequency of price adjustment should be high when the inflation rate is high and low when the inflation rate is low. Many studies have been motivated by menu cost models of costly price adjustments, focusing on these implications.

A formal explanation of price rigidity with fixed, lump-sum, cost, was first presented by Barro (1972). This article introduced a model in which firms face a fixed, lump-sum, cost to adjust their prices regardless of the direction or magnitude of the price adjustment. Therefore, a (s,S) type adjustment policy (Leahy, 2016). In this type of policy, the firm sets a ceiling and a floor for price variations, only adjusting the price if the desired target price exceeds the predetermined range. In this model, a monopolized market is considered where the monopolist faces permanents drops in demand depending on the frequency of the price adjustments. Barro (1972) shows how the optimal adjustment range depends on the lump-sum adjustment cost and the variation in the firm's demand determined by stochastic shocks in a given period.

Barro (1972) led to many studies that analyze the price dynamics of firms in different environments. Sheshinski and Weiss (1977),Sheshinski and Weiss (1983),Kuran (1986) and Danziger (1983) examine the relationship between inflation and the cost of adjusting prices. Unlike earlier works such as Barro (1972), these articles focus on the impact of expected inflation, considering different scenarios to model inflation and inflation expectations, on the frequency and magnitude of price adjustments and their welfare effects. In general, the authors argue that inflation can decrease the adjustment costs.

Rotemberg (1982) innovated the study of staggered prices by considering the effects from a macroeconomic viewpoint and developed a model with staggered prices, demonstrating that this economy is characterized by fluctuations in aggregate output as a response to nominal shocks. Rotemberg (1982) argues that changing prices is costly due to administrative costs, such as updating price lists and informing dealers, as well as the implicit cost of customer dissatisfaction with large price changes. Given that firms have rational expectations with perfect information, it may be optimal for a monopolistic firm to maintain the old price. Unlike previous literature, Rotemberg (1982) assumes that the cost of price adjustment is a function of the square of the price change. This assumption is justified on the basis that customers may prefer small and frequent price changes rather than infrequent and large price changes.

Another common way of modeling the causes of price rigidity is through the use of staggered contract decisions. Contracts are not adjusted at the same time and are fixed for extended periods, such as a year, especially wages, according to the authors who first developed this approach. Based on this argument, Phelps and Taylor (1977),Taylor (1979) and Fischer (1977) were among the first to study the implications of staggered contracts for wages and prices for inflation and monetary policy.

These articles do not offer micro-empirical evidence for the existence of staggered contracts or justify it from optimal micro-behavior of some agents. The argumentation of the structural models presented is usually narrative and gets close to the argument of the existence of "implicit contracts". In Phelps and Taylor (1977), it is argued that keeping prices constant for a period is important to save the time of customers in learning the firm's price offer, reducing the incentive to inquire elsewhere. Also, firms may regard it as profitable on average in attracting buyers to remove the risk of price disappointment. Fischer (1977) does not even offer a narrative for the existence of staggered prices, only affirming that "though the transaction costs of frequent price setting and wage negotiations must be part of the explanation"(Fischer, 1977, p. 194).

Later on, Phelps and Taylor (1977) and Taylor (1979) were cited in Calvo (1983) to justify perhaps the most quoted article on price rigidity. The model presented in Calvo (1983) differs by deriving the existence of rigid prices due to the behavior of a firm with rational expectations. The argument of the paper is that prices are rigid due to staggered contracts, and these contracts do not have a fixed time to be revised, but a random, stochastic, time. Prices are rigid because they can only be adjusted when a signal is received exogenously. Therefore, firms do not have the flexibility to adjust prices, but they fix the price for an interval with a stochastic length.

The Calvo (1983) model has been widely adopted in the macroeconomic literature and is still widely used today, along with the Rotemberg (1982) model, to understand and explain price rigidity. These two models gave rise to an enormous theoretical and empirical literature that tries to identify the causes of price changes as "time-dependent" and "state-dependent", first defined in (Dotsey et al., 1999).

Advancements in the theories of sticky prices, along with their real and welfare consequences, were incorporated into what is now known as the "New Keynesian Synthesis" (Romer, 1993) or "approach" (Goodfriend and King, 1997). Many of these elements, given their empirical relevance and potential macroeconomic impact (Mankiw, 1985; Akerlof and Yellen, 1985), were combined with elements of the New Keynesian School in Real Business Cycle models, leading to the development of the Dynamic Stochastic General Equilibrium (DSGE) models used to study business cycles (De Vroey and Duarte, 2013).

The development of DSGE models that incorporated staggered price models of the 80s, especially the Calvo model, had significant results in economic policy. From that time to today, many policymakers still use models that cite these articles to justify the develop macroeconomic models with staggered prices (Alice et al., 2017; Sergi, 2020; Sbordone et al., 2010; Dotsey, 2013). Although both models are important, the Calvo specification tends to be more broadly used in DSGE models. According to Goodfriend and King (1997), although the Rotemberg's specification is more attractive from a microeconomic perspective, since firms are likely to adjust prices when they suffer large shocks or given the inflation rates, state-dependent models were proved to be difficult to be incorporated in complete macroeconomic models. Caplin and Leahy (1991) observes that although the model could lead to different results, many simplifications are necessary to characterize imperfect competition equilibrium with costly price adjustments. For this reason, Goodfriend and King (1997) affirms that the New Keynesian models have emphasized time-dependent models like the Calvo. According to De Vroey and Duarte (2013), the Calvo model was perceived to be a convenient way to bring price stickiness to DSGE models.

Other explanations have been proposed for the price rigidity or sluggishness of adjustments during the rise of the New Keynesian approach (Melmies, 2010), but they did not have the same broad impact as the previous two explanations. These explanations include coordination failures (Ball and Romer, 1991; Stiglitz, 1984), the existence of kinked demand curves (Stiglitz, 1984; Kimball, 1995), and quality effects (Stiglitz, 1984). The literature on coordination failures and kinked demand curves can be related as both suggest the presence of strategic complementarities in the pricing behavior of firms (Nakamura and Steinsson, 2013). Despite being compelling, these explanations have not been widely adopted in macroeconomic models with sticky prices. Furthermore, they have been criticized for a lack of empirical evidence to support the existence of strong price strategic complementarities (Nakamura and Steinsson, 2013).

Recently, there has been an increasing emphasis on the importance of firms' relationships with customers (Nakamura and Steinsson, 2011; Kleshchelski and Vincent, 2009). The notion that the pricing policies of firms are indirectly determined by implicit contracts between the firm and its customers, in which the firm guarantees the stability of prices, is not novel. In fact, this idea was used to justify the existence of rigid prices in microeconomics by Phelps and Taylor (1977).

The existence of implicit contracts can be attributed to the presence of "customer markets"as opposed to "auction markets". In customer markets, firms act as price setters and quantity takers, whereas in auctions, the quantity is predetermined, and the price is determined by demand (Okun, 1975). Additionally, given that firms have the freedom to set prices as they wish, and the market does not have a single unique price like in auctions, firms selling the same good can offer it at different prices. This creates a cost for customers, the cost of searching for the best offer. If consumers do not have the resources to collect and process all the information, this gives firms monopolistic power.

On the other hand, customers have some bargaining power. Current customers signal that the given price is an acceptable deal (Okun, 1975). By committing to maintaining this price, the firm encourages customers to return to buy in the future or, at least, use past information to evaluate today's offers. Hence, past offers influence current demand. This stability of prices by firms to retain customers is what is referred to as the firm's implicit contract with customers. If firms increase prices, this can be seen as a breach of the contract, raising the cost of acquiring customers and causing them to search for alternative firms offering similar goods.

The customer market is related to the concept of fairness. When Okun (1975) cites that customers accept to purchase a certain good at a given price, this implies that the conditions offered are perceived as fair. This also relates to the fair market rules (Okun, 1975). For instance, if firms increase their prices due to an increase in costs, customers may view this increase as "fair" and not a violation of the implicit contract, thus continuing to demand from the same firms. Conversely, if the price increase is considered unfair, customers can penalize the current firm by seeking alternatives from competitors.

The first model to describe a customer market was introduced by Phelps and Winter (1970), where an industry model was developed and firms intertemporally maximize profits based on their current monopolistic power, and market share decreases for prices above the market average. Okun (1975) discusses the macroeconomic effects of an economy with customer markets in terms of GDP and inflation. Both of these articles do not provide microeconomic evidence for the existence of these markets or proof that they exist using a neoclassical microfoundation, but they provide a narrative hypothesis for their existence.

This theoretical hypothesis that customer's markets may lead to stable prices from the 1970s and 1980s was supported by data from the 2000s. As observed from numerous surveys with firms, the existence of implicit contracts is one of the primary explanations cited by firm managers for price rigidity. This was also noted in Melmies (2010) in an evaluation of a large number of manager surveys. This has motivated the development of new research to theoretically justify these findings.

Kleshchelski and Vincent (2009) develops a general equilibrium model in which firms consider the size of their customer base in their intertemporal profit optimization exercises. It is shown that cost pass-through is a non-monotonic function of the size of switching costs. Nakamura and Steinsson (2011) deals with the issue of the existence of a customer model, assuming in a general equilibrium model that customers have consumption habits in the goods market and also know that their actions will affect the total demand of the firms in the future. The article shows that various forms of price rigidity are possible outcomes of the model, with firms committing to the customers that they will not increase the price in the future.

In a model developed in Rotemberg (2011), consumers can perceive the actions of a firm towards them as benevolent or not. This molds their behaviors, with them possibly becoming angry or regretting their purchases. As a result, firms are shown to adopt a policy of rigid prices and price discrimination. Rotemberg (2005) presents a model in which consumers are concerned about the fairness of prices and only react negatively when they perceive them to be unfair. This results in price rigidity. It suggests that the frequency of price adjustments should depend on variables observable to consumers across the economy. Rotemberg (2005) argues that this model can shed light on why inflation does not drop immediately after monetary tightening.

Another explanation developed recently that explains the existence of sticky prices is due to sticky information (Mankiw and Reis, 2002, 2010). The basic premise of this literature is that information diffuses slowly in the economy and that the agents observe a noise information. So, while there are agents that update prices using updated and correct informations, others use old or wrong information. In a model where firms use imperfect information to set prices, Mankiw and Reis (2002) show that properties of the model are more consistent with mainstream views about monetary policy. With this assumption the model reproduces a pattern of inflation that resembles the one of Fischer (1977). The key difference is that the stickiness is generated not because of contracts, but because of the sticky information. Still, the article has it's limitations. Mainly, it is assumed that all the firms adjust prices at every period. A fact not observed empirically.

5.3.2 An evolutionary hypothesis

The majority of the literature reviewed in the previous section, specifically the self-proclaimed New-Keynesian literature from the 1980s, endeavors to explain the occurrence of sticky prices utilizing the dominant methodological microfoundation that has become the standard in much of the macroeconomic literature of that era until present times. This framework is characterized by the utilization of models with representative agents and rational expectations (Duarte and Lima, 2012), which assume a high level of knowledge and rational capabilities on the part of the agents in the models. This approach is also applicable to recent models that aim to explain the emergence of sticky prices due to fairness considerations or implicit contracts.

The present essay addresses the issue of the existence of sticky prices and its macroeconomic ramifications through an evolutionary approach (Nelson and Winter, 1982; Nelson et al., 2018; Dopfer, 2005). Microeconomically, the study of prices from this perspective is deemed valid given the substantial body of literature that suggests that prices are not simply the result of a market-clearing process, but rather arise from a process of coordination and decision-making by firms. In this sense, the evolutionary approach has the potential to offer unique perspectives on this phenomenon. Furthermore, although the study of pricing dynamics is a central part of microeconomics, its examination from a macroeconomic viewpoint is also valid. This is due to two main reasons.

Firstly, limiting the examination of this topic to an industrial or sectoral level overlooks the potential impact of the frequency and magnitude of price adjustments on the aggregate economy, which may result in different macroeconomic dynamics and outcomes. Moreover, ignoring the influence of the macroeconomic environment on the pricing policies of firms disregards historical examples of inflation and hyperinflation, where the macroeconomic environment and the pricing policies of firms have displayed positive feedback loops with each other, as demonstrated empirically in Araujo (2019).

Secondly, incorporating the empirical regularities discussed in the chapter two are crucial for providing policy recommendations with agent-based macroeconomic models. In recent years, numerous agent-based macroeconomic models have been developed to address issues related to monetary policy and inflation (Salle et al., 2013; Dosi et al., 2015a; Schasfoort et al., 2017; Giri et al., 2019). However, unlike the New-Keynesian literature and recent DSGE models, these macroeconomic ABMs do not address the underlying causes of persistent sticky prices.

The evolutionary approach presents an alternative microfoundational perspective for the microeconomic behavior of economic agents (Nelson and Winter, 1982; Nelson et al., 2018). This approach is based on the theories of bounded rationality by Simon (Simon, 1955, 2005). Bounded rationality assumes that economic agents have limited access to information and limited computational capabilities to process it, hindering their ability to make optimal decisions due to the complexity of the environment they operate in. As a result, agents are not able to optimally maximize a behavioral function, but rather are driven by specific goals that are deemed satisfactory. In a choice situation, agents consider only a small number of decision options, typically limiting their choices to those that were recently used and fresh in memory (Simon, 2005). Additionally, agents may not rationalize their decisions, but rather follow habits or rules of thumb. The evolutionary perspective can be seen as favoring a behaviorist view of the firm, rather than a marginalist view (Winter, 1971). The theorizing of economic agents' decisions in this literature involves modeling their behavior and decision-making processes.

The definition of firms, based on Nelson and Winter (1982), is that they are organizations engaged in the production of goods and services for external customers, with the aim of achieving a satisfactory level of profit. These firms are characterized by a set of routines, which form a significant part of their problem-solving repertoire Dosi and Nelson (2010). These routines are the regular and predictable behaviors of the firm and define much of what is typical in business Helfat (2018). The routines involve receiving signals from the environment and explaining how the firm responds to specific environmental circumstances Dosi and Nelson (2010). A collection of routines forms the organizational competencies and capabilities of the firms Winter (2000). An organizational capability, according to (Winter, 2000), is a set of routines that enables organizational managers, given input flows, to make decisions for producing outputs of a specific type. According to academic literature in the field of strategic management (Dutta et al., 2002; Johansson et al., 2012), pricing policy should not be viewed as a routine activity, but rather as a complex array of routines that requires involvement from multiple areas of the firm, therefore, a capability, that includes human capital, systems capital, and social capital. Human capital refers to the trained personnel who are responsible for pricing, while systems capital encompasses the flow of information and interconnections between various parts of the firm, including input costs and managers. Social capital, which is the most challenging component to accumulate, involves aligning the entire firm, including customers, to adapt to changes in pricing. It is considered the most difficult capability to accumulate because of the unpredictable nature of customer reactions to price changes.

The routines of firms are specific to each firm and are ingrained in the memory of the organizations. They can be considered the "genes"of the firm. The differences in routines of firms help explain why firms differ significantly in various aspects of their behavior and why this heterogeneity is persistent over time (Dosi and Nelson, 2010).

To explain the persistence of heterogeneity in routines and competencies over time in firms, the evolutionary approach posits that the economic theory of firm behavior must be part of a broader evolutionary theory of the competitive process in market economies (Helfat, 2018). Firms are in a constant state of competition in a market economy, utilizing various capabilities to achieve the common goal of obtaining profit. Pyka and Nelson (2018) emphasizes the significance of three types of competition among firms that influence their economic outcomes: product innovation, in which firms constantly strive to create new products considered superior by consumers compared to those of their competitors; process innovation, with firms continuously seeking to innovate production methods to produce the same goods more efficiently; and, inter-mediating both, there is the price competition, with firms offering higher quality goods being able to charge higher prices and firms with cheaper production methods either maintaining their profit margins or offering lower prices.

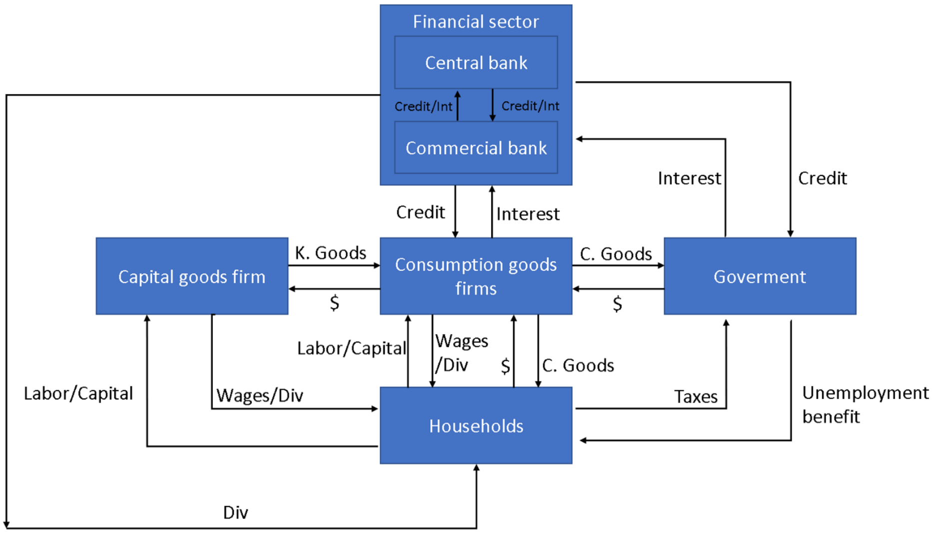
The competitive process compels firms to continuously innovate and search for inventions that may provide a competitive advantage. It also pushes lagging firms to imitate their competitors. Firms that lag behind in terms of competitiveness may fail and disappear. Thus, the ongoing competition process selects the firms, and thus, sets of routines, with higher fitness, but also drives the persistence of heterogeneity among firms (Silverberg et al., 1988; Dosi and Nelson, 2010; Helfat, 2018). This dynamic competition among firms was referred to by Dosi and Nelson (2010) as the Schumpeterian competition process.

The evolutionary literature has long emphasized the study of how technologies, viewed as capabilities, emerge and diffuse among firms, considering this to be the primary driver of competition among firms. This premise was based on the assumption that firms that invested more in innovation would be more efficient, have higher profits, and grow faster. However, numerous empirical studies have demonstrated that this relationship is weak (Bottazzi et al., 2008, 2010). Dosi et al. (2010) argues that the connection between efficiency, innovation, and firm growth is largely mediated by the degree of behavioral freedom, which encompasses capabilities that extend beyond investment in R&D, such as pricing strategies. Indeed, evidence from the strategic management literature suggests that pricing capabilities, although often receiving less attention from firm boards, can be a significant source of competitive advantage for firms and contribute to improved performance (Liozu and Hinterhuber, 2013; Liozu et al., 2014).

Our proposed model hypothesizes that the phenomenon of price stability arises from a market selection process, rather than being driven by factors such as menu costs or fixed contracts. Our assumption is that firms have the capacity to adjust prices without incurring physical costs or managerial costs at any given time, but lack the information or capability to optimally determine when and by how much to do so in response to market conditions. This differs significantly from models that posit firms have the capacity to optimally compute price changes. Empirical evidence suggests that the main explanation given by firms for rigid prices is due to stable costs, the existence of implicit contracts and coordination failures. Our hypothesis is that this reflects a routine internalized by firms in response to selective pressure, rather than an optimal behavior based on rational expectations. In other words, firms have internalized the notion that maintaining stable prices over time improves their performance in terms of profit. Below, we present the model we propose to formalize these ideas.

5.4 The model

The ABM developed to study the importance of price rigidity is a reformulated version of the model set forth in the previous chapter. The main changes in that model were in the pricing model adopted by the firms and in the heuristic mechanism that drives the firm's pricing rigidity. The structure and the interactions between the agents are summarized in Figure (5.4).



As in the previous essay, the model comprises six agents, namely firms in the consumption goods sector, a monopolistic firm producing in the capital goods sector, households divided into workers and capitalists, a banking sector, the government, and the central bank. In the subsequent subsections, we thoroughly examine all of the decisions made by these agents and explore their interrelationships. We offer detailed explanations of newly added model blocks while summarizing unchanged blocks, which are further elaborated in the preceding chapter. Those seeking more information regarding the stock-flow relations of the agents are encouraged to consult Appendix A. Additionally, details regarding the acquisition of initial conditions may be found in Appendix C. The model can be described and summarized through the following timeline:

1. Central bank determines the base interest rate.
2. The banking sector remunerates deposits.
3. The banking sector calculates each firm's interest rate.
4. Workers calculate their reservation wage.
5. Consumption goods producers form demand expectations.
6. Consumption goods producers try to innovate.
7. Consumption goods producers estimate the amount of necessary labor and capital given the expected demand, try to hire or fire workers and send investment orders to the capital goods sector.
8. Consumption goods producers send orders to the capital goods sector.
9. The capital goods sector, based on the total orders received and it total labor stock, makes decisions to hire or fire workers.
10. The capital goods sector distributes machines to the firms producing consumer goods based on orders received and production levels.
11. Given expected demand and internal availability of production factors, consumption goods firms produce.
12. Consumption goods producers compute the expected unitary cost of production.
13. Consumption goods firms review their price strategies in terms of stickiness.
14. Consumption goods firms revise their desired prices.
15. Consumption goods firms decide whether or not to adjust their prices given their pricing strategy.
16. Government pays unemployment insurance for unemployed workers.
17. Government collects taxes.
18. Government decides how much will buy from the consumer goods sector.

19. Workers and capitalists make decisions on how much to consume and save, based on income from labor, unemployment insurance, interest paid by the banking sector, and distributed profits.

20. Workers and the government go to the consumer goods market to spend disposable income allocated for consumption.

21. Firms use sales revenue to pay wages, interest on debt, pay the capital goods producer, invest in R&D, pay dividends, and retain a portion of net profit.

22. Firms may take on loans to pay expenses if necessary.

23. It is computed whether firms go bankrupt or not. A new firm is created with parameters calculated from the average of the surviving firms.

24. Macroeconomic aggregates are calculated.

5.4.1 Pricing

5.4.1.1 Expected cost of production

We assume that firms adopt a cost-based approach to set prices, which is supported by ample evidence from surveys. Accordingly, firms first calculate their production costs and then multiply them by a markup factor. The first step in this pricing process is to determine production costs. Specifically, firms compute the total labor cost by multiplying their labor demand (L^*) by the average wage paid to their workers ($\overline{W_f}$). Subsequently, the firm derives the unit cost of production by dividing the total labor cost by the expected demand ($Z^e_{f,t}$). In sum, the expected unitary cost of production is calculated as follows:

$$UC_{f,t} = \frac{L^*_{f,t}\overline{W_f}}{Z^e_{f,t}}. \tag{5.1}$$

5.4.1.2 Desired price

In the second step, the firm set its desired price. We follow the customer-based literature for this (Phelps and Winter, 1970; Klemperer, 1995), which is also utilized in the ABM literature (Dosi et al., 2010). We assume that firms have some degree of monopolistic power over their pool of customers, imposing on them a markup. The market power is determined by the market share of the firms, assumed to be known by them.

Therefore, we model that the markup is a function of the market share of the previous period, as in Dosi et al. (2010). Defining Θ as the markup adjustment term given the market share $ms_{f,t}$ of the firms, the markup equation for this heuristic is given by Equation (5.2):

$$m_{f,t} = m_{f,t-1}(1 + \Theta \frac{ms_{f,t} - ms_{f,t-1}}{ms_{f,t-1}}), \Theta_{f,t} > 0. \tag{5.2}$$

Having determined the markup, firms following this heuristic set the desired price as:

$$P^D_{f,t} = (1 + m_{f,t})UC_{f,t}. \tag{5.3}$$

5.4.1.3 *Desired price vs. observed price*

We have already examined the two initial phases of price-setting by the firms. We created the last step to account for the possibility that prices are rigid and not adjusted at all periods. This step specifies that firms will only readjust their prices to the desired level if the discrepancy between it and the previous observed price surpasses a certain threshold, η, that we call "adjustment threshold"or "band of inaction."

This second step was inspired by the (s,S) models of sticky prices (Leahy, 2016; Dhyne et al., 2011). The difference is that this literature considers that firms can calculate the optimal price of their goods. Here we suppose that firms have the desired prices. Another difference is that in the literature on the (s,S) models, the band of inaction is justified because of adjustment costs. In the current model, it is assumed that firms do not incur any internal adjustment costs. Rather, firms adaptively learn over time the level of price stability that enables them to achieve satisfactory profits. This learning process is characterized by firms continuously monitoring their profit outcomes under different levels of price rigidity and adjusting their behavior accordingly. Specifically, firms seek to strike a balance between the benefits of adjusting prices to reflect changes in costs and demand and the costs associated with coordination failures and implicit contracts. We formalize the third step in the decision of price adjustment as:

$$P_{f,t} = \begin{cases} P_{f,t-1} & ,if \quad |\frac{P^D_{f,t}}{P_{f,t-1}} - 1| \leq \eta_{f,t}, \\ P^D_{f,t} & ,if \quad |\frac{P^D_{f,t}}{P_{f,t-1}} - 1| > \eta_{f,t}. \end{cases} \tag{5.4}$$

The parameter $\eta \in \mathbb{R}_+$ is specific to each firm, and we assume that initially it is uniformly distributed across firms, following the distribution $U(0.01, 2)$. The higher the parameter η, the less likely the firm will change its price. This will fundamentally depend on the desired price volatility, which, in turn, will depend on the evolution of the relative quality of goods, average price, labor productivity, and nominal wage. Therefore, the frequency of price adjustment will also depend on macroeconomic conditions, as empirically verified. The more volatile the desired markup, cost of production, and productivity, the more frequently the prices will change.

5.4.2 Heuristic change

In the current model, firms adopt an evolutionary algorithm as a means of acquiring new heuristics, following the principles articulated by Alchian (1950) in his seminal work on uncertainty. The algorithm embodies two essential features: a continuous exploration process, which introduces new strategies into the population, and an exploitation process, which facilitates the diffusion of profitable strategies throughout the firm population. This model is rooted in the works of Seppecher (2012),Seppecher et al. (2018), and Silverberg and Verspagen (1994), which model the learning mechanism as open-ended dynamic (Dosi et al., 2005), with the potential for the discovery of truly novel innovations always present. Despite this open-ended nature, it is postulated that the innovations produced are locally oriented, as evidenced by empirical observation in most organizational innovations (Massini et al., 2002).

The exploration process is driven by the Equation (5.5). At every period firm changes the value of the parameter $\eta_{f,t}$.

$$\eta_{f,t} = \eta_{f,t-1} + U(-0.02, 0.02); \eta_{f,t} > 0. \tag{5.5}$$

The evolution of the adjustment threshold is determined through a random selection from a uniform distribution over the range of [-0.02,0.02]. This approach aligns with the literature (Seppecher, 2012; Seppecher et al., 2019) and does not involve the assumption of any form of interaction among competitors during the innovation process. Furthermore, firms can explore strategies that surpass the limitations imposed by the initial conditions of the simulation. This approach is deemed valuable in order to prevent the initial conditions from having a disproportionate influence on the selection of strategies.

In the case of the second dimension of the evolution process, which is the diffusion of the values of $\eta_{f,t}$, this occurs through the process of entry and exit of firms from the market and through the abandonment of strategies by some firms. This process is presented in a parsimonious manner, as in the model of Seppecher (2012). Firms may change their strategies and adopt the value of $\eta_{f,t}$ from one of their competitors in two cases: bankruptcy, when the firm's debt-ratio (Debt/Asset) exceeds 1, or when the firm's market share falls below $0.01/N$, with N being the number of firms in the simulation. If a firm decides to revise its heuristic, the firm selects a value of η_f from within the population of firms, with the probability of selecting η_j from firm j proportional to firm j's market share. Thus, the market acts as a mechanism for selection, and the values of η_t that are more favorable for firm survival are more likely to persist and spread among the population of firms. This leads to the evolution of market behavior, with the most successful behavioral rules becoming more prevalent over time. The average adjustment threshold of the firms in the simulated economy is an endogenous result that emerges through selection. It is not imposed any limit to the "band of inaction", with firms being free to adopt a $\eta = 0$ if they deem it the best option.

5.4.3 Consumption goods market interaction

In the market for consumption goods, three distinct agents interact and play pivotal roles in shaping the market dynamics. These agents are households (divided into workers and capitalists), the government, and consumer goods firms. The former two serve as buyers, the customers, while the latter acts as a seller.

Prior to this interaction, households and the government have already determined their nominal demand for consumption goods. On the other hand, consumer goods firms have already produced goods to the best of their ability given their demand expectations and production limitations.

To determine the distribution of nominal goods among firms, a model is followed that calculates the competitiveness of each firm. The competitiveness of a firm, represented by $E_{f,t}$, at a particular time, is given by Equation (5.6).

$$E_{f,t} = \frac{(\frac{Q_{f,t-1}}{\overline{Q}})^{\alpha_1}}{(\frac{P_{t-1}}{\overline{P}})^{\alpha_2}(1+(\frac{P_{f,t-1}}{P_{f,t-2}}-1)^2)^{\alpha_3}(1+\alpha_4 I_{\{|P_{f,t-1}/P_{f,t-2}|>1\}})(1+\frac{Cu_{f,t}}{C_{f,t-1}})^{\alpha_5}}. \quad (5.6)$$

The Equation (5.6) is strongly related to the equation used by Silverberg (1987) and also in Possas et al. (2001). The parameters in the set $\alpha_1, ..., \alpha_5 \in \mathbb{R}_+$ represent the elasticity of competitiveness with respect to the relative quality of the consumption goods, their relative prices, changes in their prices, the relative size of changes in their prices, and delivery delays, respectively.

In relation to Silverberg (1987), the current model differs in two significant ways. Firstly, the model takes into consideration the heterogeneity of consumption goods, and secondly, it accounts for the presence of implicit contracts. Regarding the former, the relative quality of goods is included in the numerator to account for differences in the quality of goods, as in Dweck et al. (2020).

The second difference is that in the denominator of Equation (5.6), we have two terms that penalize firms for price changes. This novel feature reflects the extensive literature that highlights the existence of implicit contracts between firms and their customers, as previously discussed in the chapter two and previous sections (Correa et al., 2018; Anderson and Simester, 2010; Young and Levy, 2010; Rotemberg, 2005; Blinder, 1991). Recalling, this literature draws attention, from theoretical models, to the fact that there is an implicit contract between consumers and companies. Through price stability, firms maintain the loyalty of their customer base. Companies that adopt pricing policies with frequent adjustments have less customer loyalty and are penalized by consumers who have made recent purchases. Anderson and Simester (2010) conducted a field experiment to examine customers' reactions to observing a retailer sell a product at a lower price after they have purchased it. The experiment found that customers react by making fewer subsequent purchases from the retailer, with the article characterizing this as a boycott of the customers to punish the firm. This effect was found to be strongest among the most valuable customers, who purchased recently and at the highest prices. Leibbrandt (2020) similarly found that firms avoid price discrimination and overpricing low-value customers in order to maintain the loyalty of high-value customers.

In a field experiment, Anderson and Simester (2010) observed customers' responses to a retailer selling a product at a lower price after their purchase. The study discovered that customers reacted by making fewer future purchases, which was seen as a customer boycott to punish the retailer. This effect was most prominent among valuable customers who had recently made high-priced purchases. Leibbrandt (2020) also found that firms refrain from price discrimination and overpricing low-value customers to retain the loyalty of high-value customers.

We considered two terms to evaluate the existence of implicit contracts. In the case of the first one, the size of the punishment is relative, depending on the size of the adjustment. In the second term, we use an indicator function. If $|P_{f,t-1}/P_{f,t-2}| > 1$, then $I = 1$, otherwise, $I = 0$. Therefore, with the indicator function, independently of the size of the price adjustment, firms will suffer a loss in competitiveness, which is driven by the parameter α_4. In previous studies such as Silverberg (1987) and Possas et al. (2001), the competitiveness index has been utilized as an input in a replicator dynamics model to formalize the evolution of the market share of the firms. Other works have made similar efforts, but with variations in how competitiveness is modeled (Dosi et al., 2010, 2022). Our model, which is based on Dawid et al. (2019), deviates from these approaches by considering the competitiveness index in the context of a "Smoothed Best Replies" model, which is a commonly used model in evolutionary literature to describe changes in individual states (Safarzyńska and van den Bergh, 2010).

The market share of firms in our model is determined by two factors: a logit equation dependent on the competitiveness index, and the past market share, as specified in Equation (5.7).

$$ms_{f,t} = \upsilon_{ms} \frac{exp(2E_{f,t-1})}{\sum_{f=1}^{N} exp(2E_{f,t-1})} + (1 - \upsilon_{ms}) ms_{f,t-1}. \tag{5.7}$$

In the Equation (5.7) we suppose that the market share is mainly driven by the relative competitiveness and an inertial component of the market share, with the past market share influencing the current market share. It can be inferred that a firm's market share will be higher if it has a higher relative quality and a lower relative price. By considering these factors, we have accounted for several key aspects of competition in markets with heterogeneous goods, where firms compete through product development and pricing strategies. The dynamics of such markets are comprehensively described in Metcalfe (1998) and formalized in Melo et al. (2016).

The parameter $\upsilon_{cb} \in (0, 1)$ expresses the market share inertia, which is a common feature in consumer market models and can explain why firms may exhibit periodic market power. If $vms = 0$, the current consumption would be solely determined by the present state of $E_{f,t}$, and changes in prices would have no long-term effect on a firm's market share. The gradual shift in consumers' decisions toward the consumption of a particular good is a direct result of changes in competitiveness. The existence of consumption habits and the influence of past experiences with suppliers contribute to this gradual process, as modeled in the consumer market literature.

How the aggregate nominal demand is allocated across the firms is determined through the following Equation (5.8):

$$DN_{f,t} = ms_t AggD_t, \tag{5.8}$$

where $AggD_t = G_t + \sum C_{c,t} + \sum C_{w,t}$, the total aggregate nominal demand in the consumption goods market. This is given by the total amount allocated in consumption by the workers, capitalists, and government. And the real demand of each firm, in terms only of goods, is nothing more than the firm aggregate nominal demand divided by its price:

$$D_{f,t} = \frac{DN_{f,t}}{P_{f,t}}. \tag{5.9}$$

Due to the indivisibility of consumer goods, it is common that $DN_{f,t} > D_{f,t} * P_{f,t}$. To address this discrepancy, the consumer goods market engages in ten rounds of negotiations. In each round, the unspent $AggD_t$ is recalculated and reallocated among firms that have a price, $P_{f,t}$, lower than the remaining demand.

5.4.4 Government and aggregate GDP

The government is the more straightforward agent in the model but has an important stabilizing role. It has to decide how many goods it will try to buy from the consumption goods sector. The expenditure is independent of the past income but responds to the current state of the economy. The nominal expenditure of the government follows the Equation (5.10).

$$G_t = (1 + \pi_{t-1})(1 + \rho_u(U_{t-1} - 0.05))G_{t-1} \tag{5.10}$$

If the unemployment rate $U_{h,t}$ is different from 5%, the government starts to adjust its real expenditure, targeting an unemployment rate of 5%. We assume that the fiscal policy and monetary policy are coordinated and both have the same policy target. Defined the total expenditure of the government, the aggregate nominal GDP follows the national accounts system, with $Y_t \equiv I_t + C_t + G_t$. The government receives income in the form of taxes that are paid by the households. Income tax rates are equal to 25%.

In addition to consumption and tax collection, the government also pays unemployment benefits to unemployed workers, interest rates to the banking sector, and receives profits or covers losses from the central bank. The unemployment benefit is equal to 40% of the average nominal wage observed in the past period. The profit of the central bank is generated through the interest paid by the monopolistic private bank. To cover deficits, the government borrows from the banking sector.

5.4.5 The other blocks of the model

In the present subsection, we summarize the model blocks that have not changed from the previous version in the precing chapter.

5.4.5.1 Output decisions and production

In our model, the decision-making process for production follows a standard model commonly used in ABMs. The output of firms producing consumption goods is determined by their expectations of future demand and their production capacity (Possas et al., 2001; Dosi et al., 2010; Caiani et al., 2016; Dawid et al., 2019; Rolim et al., 2022; Oliveira et al., 2020). Following Dosi et al. (2020), expectations of demand are formed based on observing the past and extrapolating it to the future. Given these expectations, the total desired output takes into account the expected demand, a percentage of that demand that will be produced as stocks, and existing stocks. The firm's production capacity is modeled through a Leontief production function that takes into account the available factors of production and productivity. The actual production will depend on the availability and accessibility of the necessary factors of production, such as labor and capital, in the relevant markets and the firm's capacity. If the desired output is greater than the firm's capacity, it will produce to the limit of its capacity.

5.4.5.2 Machine investment

We rely on the model developed by Possas et al. (2001) to formalize how consumer goods firms make investment decisions. We assume that consumer goods firms evaluate their current stock of machines, net of the depreciated machines, and calculate how many new machines are needed to produce the desired output. They order these machines from a capital goods producer and pay for them only after they are received. The number of machines received depends on the dynamics of the capital goods sector and the total number of orders for new machines. These new machines are added to the firm's capital stock, and the total payment made by all firms to the machine producer is the total nominal investment in machines for the economy.

5.4.5.3 Labor market dynamics

Firms determine their labor needs by evaluating internal conditions and projecting demand. If demand exceeds internal supply, firms turn to the labor market. The process of matching firms with available workers involves several steps, including determining labor demand, estimating the number of workers who will apply for open positions based on the wage offered, and randomly selecting a share of those workers to apply to a specific firm. This model is based on the modern theory of labor monopsony (Manning, 2021) and the matching model developed by Fagiolo et al. (2004). The wage offered by the firm is a key variable in this process and is represented by a multinomial logit equation. The higher the wage offered, the higher the share of workers that apply for this firm. The pool of workers who have applied for open vacancies is determined by considering all unemployed and employed individuals who apply for new positions. Every unemployed person applies for one vacancy, and employed individuals will only apply depending on their wage in relation to the average wage being offered. Once workers are found by the firms, they offer them a job at an internal reference wage determined by the firm's wage policy. The workers will accept the job if the wage offer is higher than their reservation wage. Job turnover, or the rate at which workers are leaving and being hired for new jobs, can play a key role in determining the level of real wages and the wage share in the model. When there is high job turnover, employers may have to offer higher wages to attract and retain workers, which can lead to increases in real wages and wage share. This relationship has been acknowledged by economists and researchers, such as Bartel and Borjas (1981).

5.4.5.4 R&D investment

Our model posits that firms engaged in the production of consumption goods undertake research and development (R&D) activities to enhance the perceived quality of their goods as perceived by consumers, in order to gain market share and increase profits. According to Eeckhout (2021) and Pyka and Nelson (2018), companies commonly use investments in creating products perceived as better by the consumers as a way to gain market share. The R&D investment block is based on Dosi et al. (2022). As in Caiani et al. (2016); Dosi et al. (2010), the total investment in R&D is a proportion of the total revenue of each firm. Following the evolutionary literature (Nelson and Winter, 1982; Possas et al., 2001; Dosi et al., 2010), the investment in R&D is divided into innovation or imitation activities, and the proportion is determined by how far the firm's good is from the good with the highest quality. The model also describes the process of searching for new technologies, which basically replicates the model of Dosi et al. (2010).

5.4.5.5 Accounting, finance and exit conditions of the firms producing consumption goods

In this subsection, we examine the accounting practices of firms and their relationship to their financial situation and exit conditions. The model describes how firms make decisions and interact with different markets, affecting their balance sheet. The only form of income for the firms is the revenue from consumer goods sales. The firms have the following expenses: wages, investment in R&D, investment in new machines, financial burden, and the distribution of profits in the form of dividends.

The result of the income and expenses gives the firm's cash surplus or deficit. If the firm has a surplus, this is added to the total assets. On the other hand, if it has a deficit, this is financed with an increase in total loans. In the limit, the liability can become equal to or greater than the firm's asset, representing the firm's insolvency.

When a firm becomes bankrupt, it is replaced by a new one. The new firm is provided with a cash investment equal to three times the necessary stock of capital for producing ten consumption goods, and it is established with zero debt, the market share of the broken firm, and no accumulated research. The quality of its new product is equivalent to the industry average. The total amount of money transferred to the new firm is deducted from the wealth held by the capitalists. The markup of the new firm is adjusted to reflect the weighted average of the surviving firms.

In the event of a firm failure, the banking sector will deduct from the total loan stock the stock of loans from the bankrupt firm, and the central bank will correspondingly decrease its bank reserves, effectively providing a bailout of the monopolist bank.

5.4.5.6 Dividends policy

In our model, the dividend policy is a key variable. Following Riccetti et al. (2013, 2015); Seppecher et al. (2019) and Alexandre and Lima (2020), it is assumed that firms have a target level of indebtedness. The target is determined by the opportunity cost of different sources of capital, which is defined as a function of past indebtedness, the past profit rate of the firm, and the past interest rate charged by the private bank. The target level of indebtedness directly affects dividend distribution, with firms increasing dividends if leverage is below the target and decreasing dividends if leverage is above the target. The model assumes that firms' capital structure decisions are independent of output production and that banks always accommodate credit demand. Additionally, it assumes that the financial condition of firms does not limit capacity expansion, which would happen if credit constraints were present. This allows firms and the economy to converge to the desired utilization capacity. The mechanism for transmitting monetary policy shocks to the real economy in this model is through dividends, where the monetary policy affects the consumption decisions of capital owners through changes in dividends, similar to what is observed in models with asset markets.

5.4.5.7 Capital goods sector

The capital goods sector is composed of a single monopolistic firm that produces a homogeneous capital good that can be used by all firms in the consumption goods sector. The production process involves receiving orders from the consumer goods sector, hiring enough workers to meet the demands, and producing the machines ordered. In cases where the firm is unable to hire enough workers, it will produce at the limit of its production capacity and select which firms will receive the ordered machines based on an order queue. The firm employs a cost-based pricing strategy to set the price of its machines. This includes calculating the total production using a fraction of the productivity in the consumption goods sector, determining the total demand for labor in the sector, and summing the wages of all employees to calculate the unit cost of production per machine. A markup factor is then applied to the unitary cost of production to set the final price. The wage offer in the capital goods sector is 1.5 times the average of the consumer goods sector, which can be justified by the monopolistic power held by the sole firm operating in the capital goods sector. The profits generated by the capital goods sector are transferred to the capitalist, and any losses are covered through capital injection by the capitalist.

5.4.5.8 Households

In this model, households are divided into two groups: workers and capitalists. The workers receive income as wages, interest from accumulated wealth, and unemployment insurance from the government. Capitalist households only receive income from interest and profits. Both groups have different propensities to consume out of income and accumulated wealth. The households must decide how much to consume and save, and can only allocate wealth in the form of bank deposits or cash. The consumption and disposable income equations, the law of motion of the wealth stock of each household, and the portfolio equations are based on Godley and Lavoie (2006) and Tobin (1969).

5.4.5.9 The banking sector

The banking sector is composed of a single monopolistic private bank and a central bank. The private bank takes deposits from households and extends loans to firms and the government, and the central bank sets the base interest rate through a Taylor rule. It is assumed that the availability of credit is determined by demand at the current interest rate, similar to the approach presented in Lima and Freitas (2007). We draw on Dosi et al. (2015a) and Lima and Freitas (2007) to model the nominal interest rate structure. There are three types of nominal interest rates in the model: the base interest rate set by the central bank, the nominal interest rate on household deposits set by the private bank as a fixed proportion of the base interest rate, and the nominal interest rate on loans to firms, set by the private bank based on the creditworthiness of the firms. The creditworthiness of firms is determined by their indebtedness, and firms are given a rating based on their level of indebtedness, with a different markup applied to each rating. The private bank generates profits through the difference in interest rates, referred to as the spread, and manages bank reserves, household deposits, government bonds, and loans to private firms. The private bank only borrows bank reserves from the central bank when the demand for credit exceeds the total amount of household deposits.

5.5 *Simulation protocol and empirical validation*

We analyze the dynamic behavior of our model through Monte Carlo simulations in this study. The model consists of 200 firms and 6000 workers and follows the Post-Keynesian stock-flow consistent framework of Caverzasi and Godin (2015). The initial values of the model and the methodology for ensuring stock-flow consistency are explained in Appendix (C).

To set proper parameters and confirm that the model replicates empirical regularities, we first calibrate it using the method of simulated moments (Delli Gatti et al., 2017; Fagiolo et al., 2019). The objective function for the calibration using the method of simulated moments is represented by Equation (5.11):

$$\hat{\theta} = argmin_{\theta}[\mu^*(\theta) - \mu_R]' W^{-1}[\mu^*(\theta) - \mu_R], \tag{5.11}$$

where θ is the parameter vector governing the outputs of the simulations, $\mu^*(\theta)$ is the vector of statistical moments obtained using a specific vector of parameters, μ_R is the vector of statistical moments observed empirically or the target for the statistical moments and W is a weight matrix.

In the calibration process, we consider statistical moments that include cross-correlations between macroeconomic variables with the GDP and the standard deviation of these variables Stock and Watson (1999). These moments, commonly used to validate ABMs Assenza et al. (2015); Rolim et al. (2023); Caiani et al. (2016), include aggregate real GDP, aggregate real consumption, aggregate real investment, real government consumption, unemployment rate, aggregate capacity utilization, aggregate labor productivity, inflation rate, real wage rate, and the base interest rate. The periodicity of the variables is quarterly, and the cross-correlations range from -6 to +6 relative to the current value of the real GDP. Apart from the standard deviation and cross-correlation, we also calibrated the model for the means of the inflation rate, the base interest rate and the unemployment rate. We also considered microeconomic variables in the calibration exercise. The empirical facts utilized to calibrate the model were based on Nakamura and Steinsson (2008) and Klenow and Kryvtsov (2008). We considered the average frequency of price adjustment by the firms, the proportion of price changes that are increased, the average size of price increases, the average size of price decreases, and the percentage of adjustments that are classified as small (below 5%). As a result, we consider 162 statistical moments, including 143 cross-correlations, 11 standard deviations, 3 average aggregate results, and 5 microeconomic statistics related to pricing.

The matrix W is created to evenly balance the contribution of each type of statistical moment to the calibration exercise. The elements in the diagonal of W are set based on the significance of each type of moment in the overall set of moments. For cross-correlations, the value in W is 143/162, for standard deviations, it is 11/162, for averages it is 3/162, and for the microeconomic statistics, 5/162.

We compute statistics starting from the period 250 of the generated time series, and the calibration exercise involved simulations for 1000 periods. In Table (5.1), we show the parameters that were subject to calibration and the parameter space used.

Parametric space			
Parameter	Name	Min value	Max value
PB	Lifespan of the machines	2	10
γ_0	Dividend policy	0.1	0.9
ψ_1	Variance of offered wages	0.5	2
ψ_2	Wage offered inertia	0.5	1
ψ_3	Max. variance of offer wages	0.03	0.15
ψ_4	Inflation indexation	0.4	1
Θ	Markup adjusment	0.05	2
w_c	Workers propensity to consume out of disposable income	0.8	1
w_w	Workers propensity to consume out of wealth	0	0.5
c_c	Capitalist propensity to consume out of disposable income	0.4	0.6
c_w	Capitalist propensity to consume out of wealth	0.05	0.2
ϕ_π	Central bank reaction to inflation	0.1	2
ϕ_u	Central bank reaction to unemployment	0	0.5
υ_{cb}	Monetary policy inertia	0.2	0.95
ρ	Government reaction	0	2
λ_0	Allocation in deposits if base interest rate is zero	0.2	0.6
λ_1	lambda_cash_capitalist	-2	2
$frac$	Productivity multiplayer of the capital goods sector	0.25	4
α_1	Competitiveness elasticity to relative quality	0	6
α_2	Competitiveness elasticity to relative price	0	6
α_3	Competitiveness elasticity to relative price change	0	20
α_4	Competitiveness elasticity to any price changes	0	0.2

Table 5.1 - Range of the possible values of the calibrated parameters

The calibration optimization problem was solved using a search-based genetic algorithm (McCall, 2005; Scrucca, 2013). The values of hyper-parameters adopted to implement the genetic algorithm are in Table (5.2).

Hyper-parameters	
Name	Value
Population	15
Runs	6
Crossover	0.6
Mutation	0.2
Elitism	1

Table 5.2 - Hyper-parameters of the Genetic Algorithm

Due to the high computational cost of running the model, to calibrate the model we only consider a discrete range of values that could be chosen in lieu of a continuous range. For each parameter was considered a maximum and a minimum possible value. The interval between these two values was equally divided into 15 parts. The points that divided the parts of the intervals resulted in the uniform discrete distribution of each parameter. Populations of parameters set for the genetic algorithm were drawn from the uniform discrete distributions of the parameters.

To calculate the statistical moments for each combination of parameters tested, the average of five simulations was taken. The initial population of parameters at the beginning of the calibration process was sampled using the Latin Hypercube method, in order to ensure an even distribution of samples.

After calibrating the model using the genetic algorithm, a local analysis was conducted by applying a local search algorithm. This was done to determine if using the parameters in the vicinity of those selected by the genetic algorithm could improve the calibration of the model. The parameter values used in the baseline simulation are shown below:

Description	Value
Adjustment of expectations given the unattended demand	0.2
Market share inertia	0.5
Desired stock (% of demand expectation)	15%
Direct labor productivity	105
Indirect labor parameter given stock of machines	0.01
Desired degree of utilization of production capacity	0.8
Parameter that controls the adjustment of the markup given the rule used	0.6071
Percentage of investment in R&D	0.05
Firm search capabilities parameters	1/(0.001 GDP)
Effect of past indebtedness on the current target	0.9
Total amount distributed in dividends if the current indebtedness is equal to the target	0.2143
Life span of the machines	40
Workers' propensity to consume out of disposable income	0.9857
Workers' propensity to consume out of wealth	0
Capitalists' propensity to consume out of disposable income	0.4714
Capitalists' propensity to consume out of wealth	0.1571
λ_0 (Allocation in deposits if base interest rate is zero)	0.6
λ_1 (sensitivity of wealth allocation to interest rate)	-1.4286
Income tax, wealth tax, interest tax	25%
Adjustment of government consumption	0.5714
% of the base Interest rate on deposits	50%
Assumed equilibrium real interest rate	2.5%
Central bank reaction to inflation	0.5071
Central bank reaction to unemployment	0.5
Monetary policy inertia	0.6286
Neutral real interest rate	0.025
Reaction of the firms to differences in the labor demand and supply	2
Maximum variation of wage offer	0.09
Wage offer indexation	0.6571
Inflation indexation of the wages	0.7
Competitiveness elasticity to relative quality	3.8571
Competitiveness elasticity to relative price	2.1428
Competitiveness elasticity to delays	6
Competitiveness elasticity to relative price change	11.4285
Competitiveness elasticity to any price changes	0.0714
Market share inertia	0.9

Table 5.3 - Parameters of the benchmark model

After determining the benchmark model, in accordance with the methodology of Vandin et al. (2022), we evaluated if the number of simulations was sufficient to ensure that the results for the time series of “GDP”, “unemployment rate”, “inflation rate”, and “wage share”fell within a 95% confidence interval, with a margin of error of no more than 5% of the average result or, in the case of variables measured in percentages, below 5 percentage points. Our analysis determined that 100 Monte-Carlo simulations were sufficient to guarantee this level of confidence. Therefore, using 100 simulations was deemed sufficient to produce robust results and conclusions.

Additionally, in accordance with the methodology of Vandin et al. (2022), we applied the Kolmogorov-Smirnov test to the baseline model, and evidence was found that the time series of GDP, unemployment rate, and the wage share in difference, and inflation rate in level, were ergodic. This suggests that the number of periods considered in the simulations was adequate to analyze the model in its steady state. However, it is worth noting that while the model may exhibit stable tendencies, they may be positive or negative over time.

Table (5.4) displays the average standard deviations of our simulations with the benchmark specification obtained with the calibration exercise. The results indicate that the standard deviations of the model components are generally lower than those observed empirically, except for the aggregate investment. Additionally, the hierarchy of the variables in terms of higher to lower standard deviations is consistent with empirical observations, particularly for the aggregate macroeconomic variables such as aggregate consumption, government spending, aggregate GDP, and aggregate consumption.

The standard deviations of the aggregate unemployment rate and capital utilization are lower than what is observed empirically. Furthermore, the labor productivity, inflation rate, real wage rate, and base interest rate all exhibit considerably lower volatility in the simulated model compared to empirical observations.

Figures (5.1) and Figure (5.2) present the average cross-correlation of GDP with other macroeconomic variables using the calibrated model. Error bars are included in the figures to represent two standard deviations. Despite the fact that the calibrated model failed to reproduce the empirical results within the interval of two standard deviations, it successfully captures the signal and direction of the cross-correlations. However, it should be noted that there is one exception, which pertains to the behavior of government expenditure. In the model, the government’s behavior is counter-cyclical to GDP and helps to stabilize

	Obs [1]	Empirical [2]	[1]/[2]
GDP	1.23	1.66	0.74
Consumption	0.97	1.26	0.77
Investment	6.88	4.97	1.38
Goverment.Cons	1.31	2.49	0.53
Unem.rate	0.69	0.76	0.91
Cap.Util	0.62	3.07	0.20
Labor prod.	0.34	1.05	0.32
Inflation	0.19	1.44	0.13
Real wage rate	0.20	1.10	0.18
Base interest rate	0.31	1.47	0.21

Table 5.4 - Comparison of Average Standard Deviation of Detrended Time-Series from Simulations and Empirical Data

aggregate unemployment. In contrast, empirical evidence suggests that government expenditure has a low correlation with GDP. Nevertheless, the behavior of the government was retained in the model in order to generate lower unemployment rates, which in turn contributed to generating positive inflation rates. It is anticipated that future versions of the model will be able to reproduce the stylized fact of unemployment rates remaining below 10% while also incorporating a government expenditure variable with low correlation to GDP.

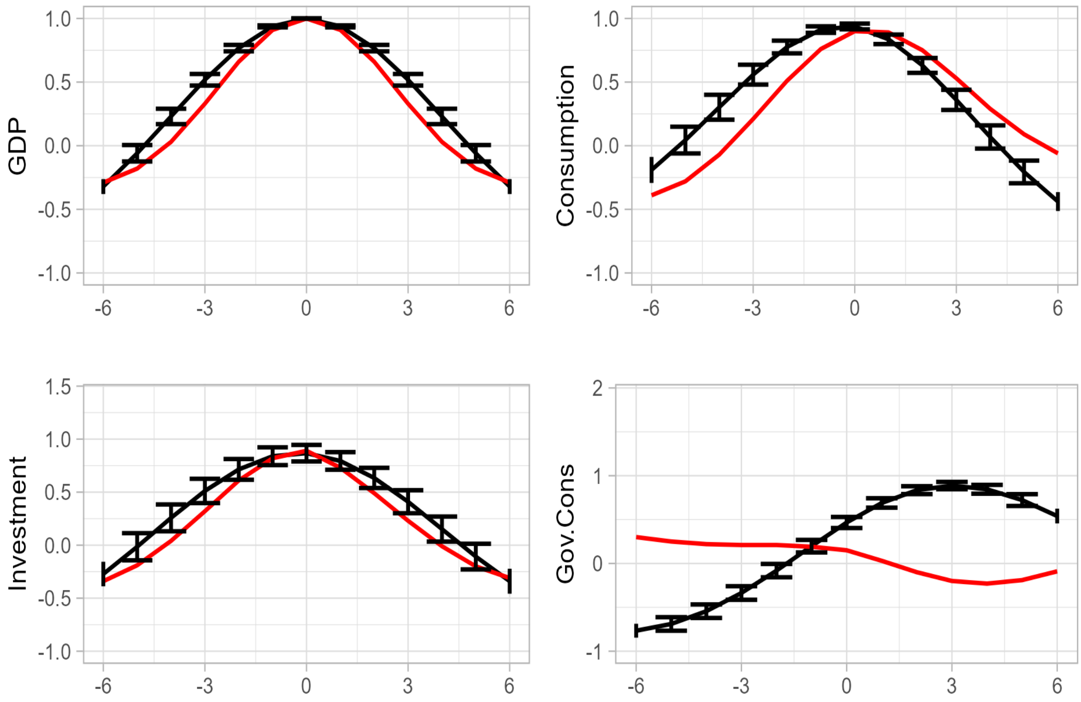


Figure 5.1: (a) Cross-correlations structure for output

Note: Bpf: bandpass-filtered (6,32,12). GDP, consumption, investment and gov.cons series are taken in logarithm. Bars are 2 standard deviations of 100 Monte Carlo average cross-correlations

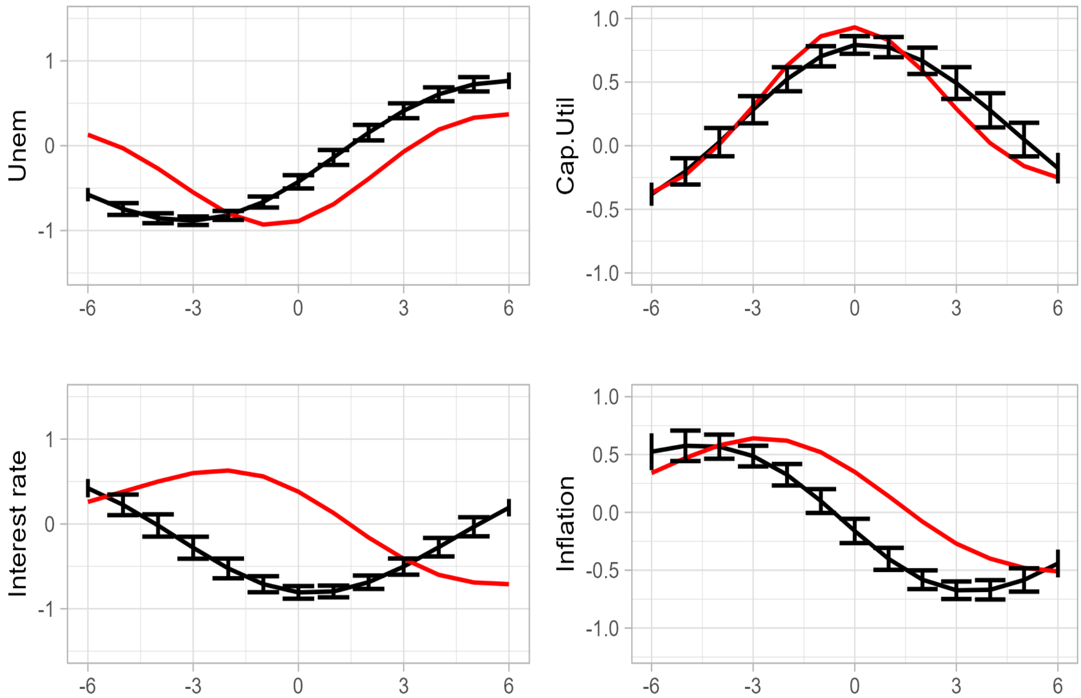


Figure 5.2: (b) Cross-correlations structure for output

Note: Bpf: bandpass-filtered (6,32,12). GDP, consumption, investment and gov.cons series are taken in logarithm. Bars are 2 standard deviations of 100 Monte Carlo average cross-correlations

We conducted a sensitivity analysis of the calibration exercise with the aim of assessing the impact of varying values of the parameters α_3 and α_4 on $\hat{\theta}$ of Equation (5.11), the objective function of the calibration exercise. The results of the analysis are presented in Figures (5.3) and (5.4). It is worth noting that a lower value of θ implies a better combination of parameters to reproduce the selected statistical moments. The sensitivity analysis is performed through interpolation of the results obtained from multiple simulations conducted using the genetic algorithm during the calibration exercise.

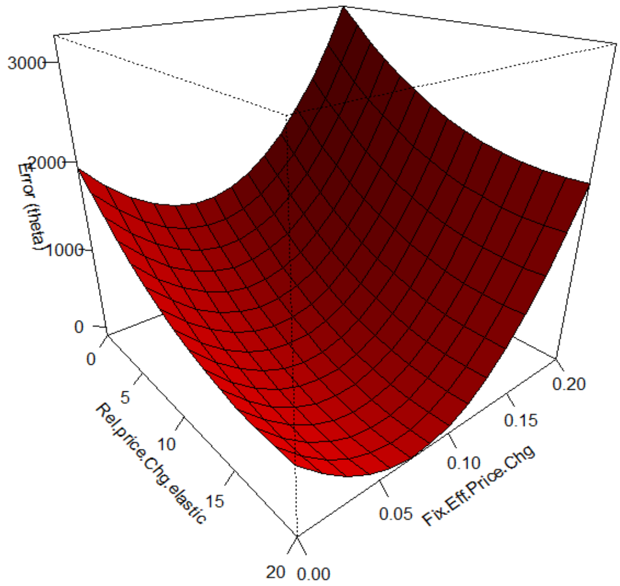


Figure 5.3: Local sensitivity analysis of the effects of the parameters related to pricing, α_4 and α_5, over the error of $\hat{\theta}$

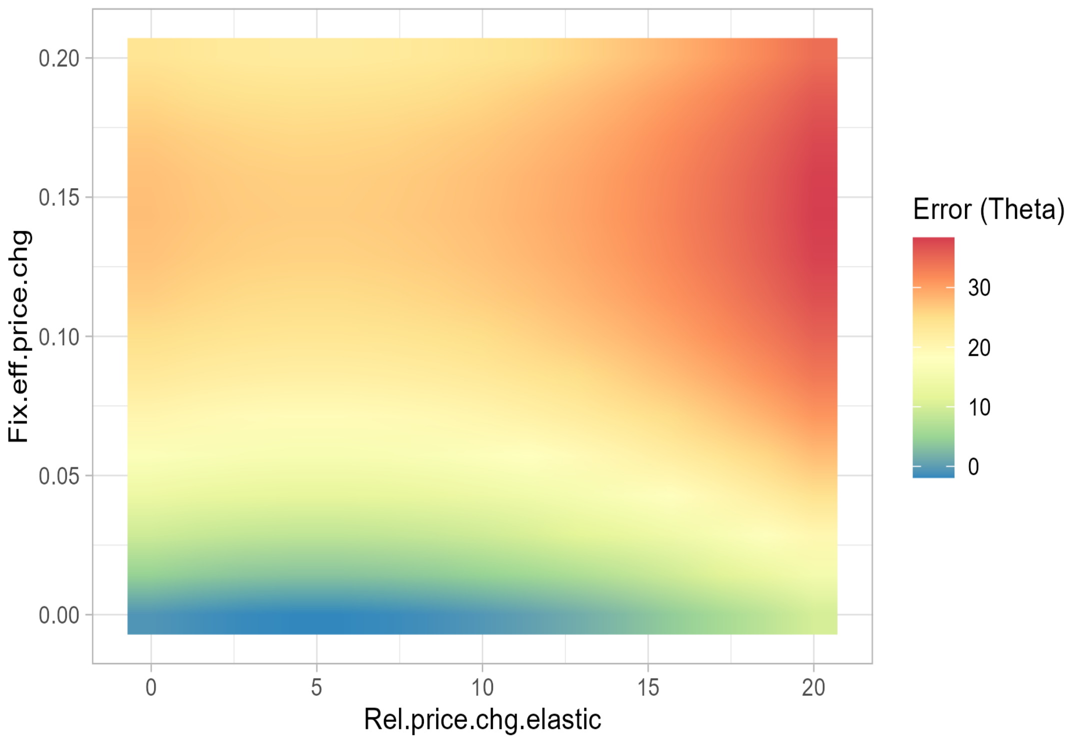


Figure 5.4: Local sensitivity analysis of the effects of the parameters related to pricing, α_3 (relative effect) and α_4 (fix effect), over the error term ($\hat{\theta}$)

Figures (5.3) and (5.4) provide empirical evidence to support the proposition that incorporating positive values for the parameters that penalize firms for adjusting pricesenhances the fitness of the model in replicating empirical data to some extent. The sensitivity analysis demonstrates that an appropriate range for the parameter α_3 is between 0 and 10, while the corresponding range for α_4 is narrower, ranging from 0 to a maximum of 0.025. The values of these parameters selected by the algorithm in the benchmark simulation were $\alpha_3 = 4.2858$ and $\alpha_4 = 0.0142$. Thus, the calibration exercise indicates that the parameter set that best reproduces stylized facts, including microeconomic phenomena related to pricing, corresponds to a low sensitivity of customers to price changes, reflecting the role of implicit contracts in the model. This finding is noteworthy since it suggests that even small changes in customer sensitivity to price changes can have significant impacts on the model.

In the experimental section, we demonstrate that it is not necessary to consider positive values for α_3 and α_4 to achieve a stable price environment over time, with firms adopting heuristics that lead to stable prices even with $\alpha_3 = \alpha_4 = 0$, indicating that this property may emerge from the model itself. Nonetheless, incorporating positive values for the parameters related to implicit contracts has contributed to a better fit of the model to empirical observations.

5.6 Results

5.6.1 Macroeconomic results

As illustrated in Figure (5.6.1.a), the aggregate production level exhibits fluctuations across the simulation period and does not exhibit any upward trend, which aligns with the assumption of no productivity growth of capital goods. Also, Figure (5.6.1.a) portrays a stable and cyclical behavior of the aggregate GDP, with consistent standard deviations. Figure (5.6.1.b) further depicts the cyclical patterns of investment (depicted in black), consumption (in red), and government expenditure (in blue) across a single simulation run. Notably, the investment component of GDP displays significantly more volatility, followed by government expenditure and consumption, in accordance with the observed empirical patterns.

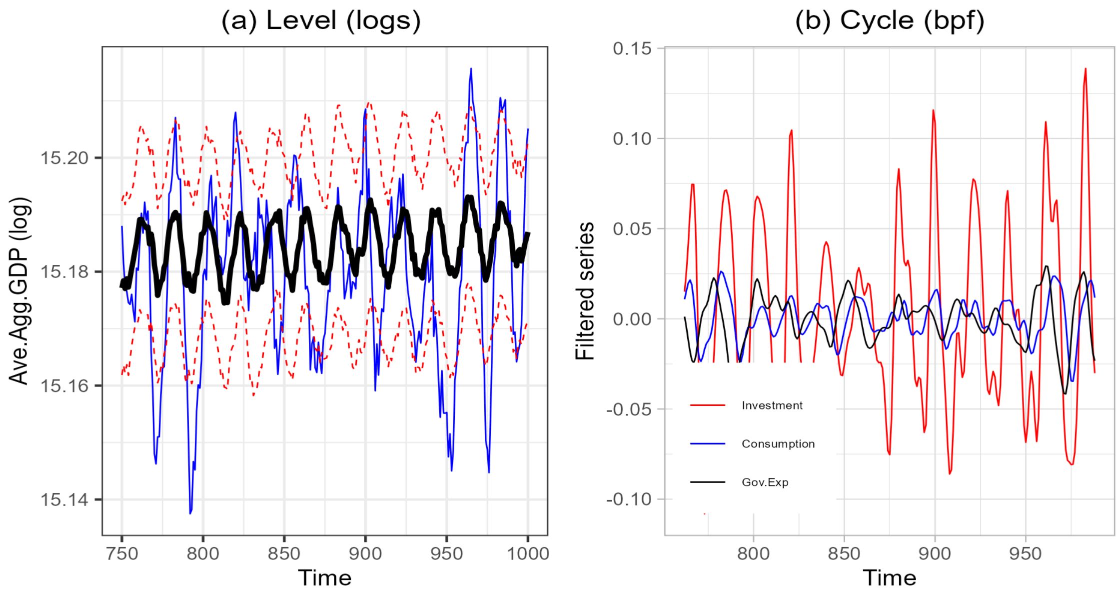


Figure 5.5: GDP dynamics

Black = mean. Red = 1 STD. Blue = one run.

As depicted in Figure (5.6), the inflation rate shows a stable behavior in the long run across the simulations, oscillating around 0.0075, quarterly, or 0.03, annually. This is inferred by analyzing the average results, represented by the black line, and the constant standard deviations, depicted by the red lines. Nonetheless, the examination of a single simulation shows that inflation fluctuates, displaying periods of notable increases and decreases.

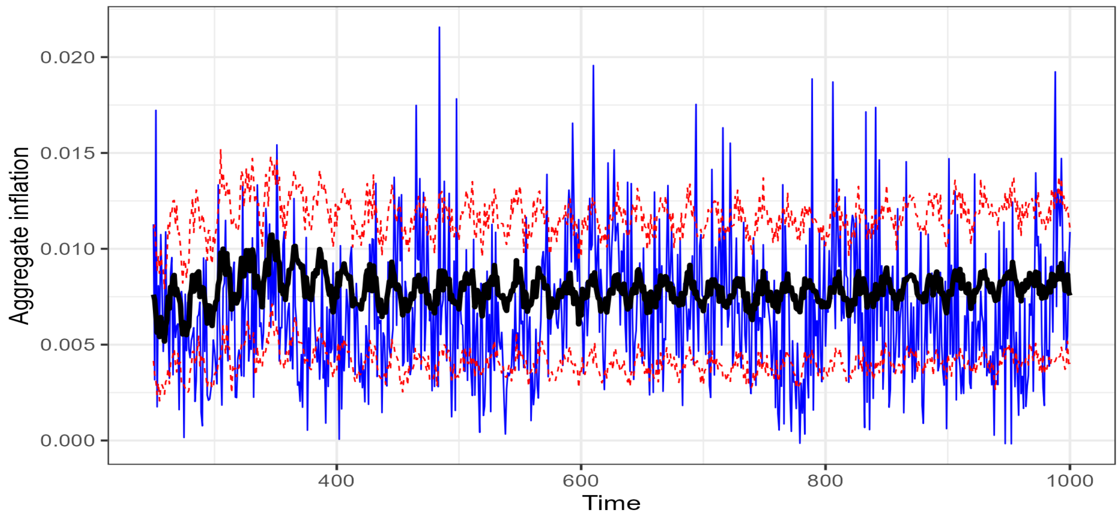


Figure 5.6: Inflation rate

Black = mean. Red = 1 STD. Blue = one run.

Consistent with the model, Figure (5.7) reveals that the baseline interest rate follows a cyclical pattern, with an average value slightly exceeding that of the average inflation rate. Moreover, the interest rate displays episodes of heightened variability across the different simulation runs.

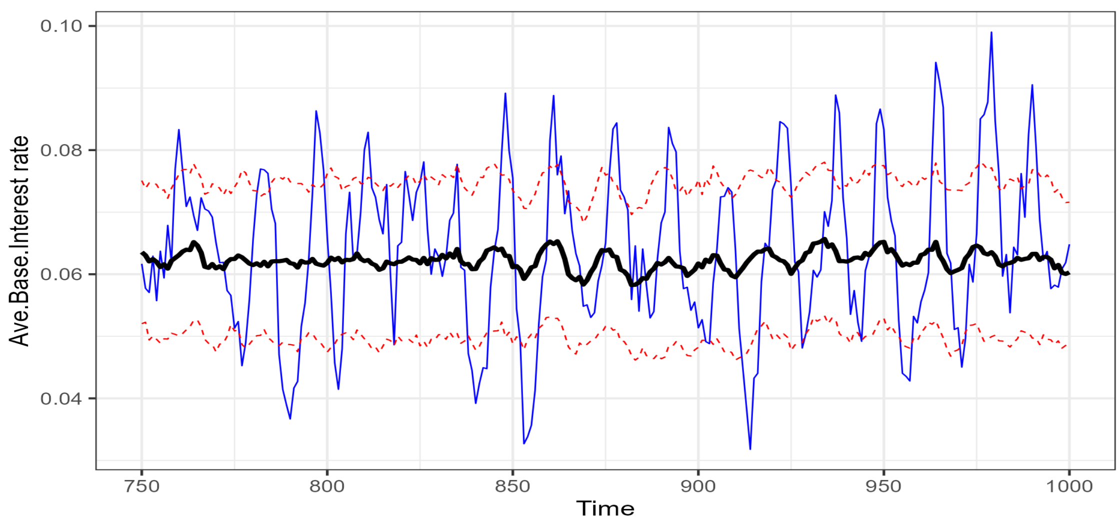


Figure 5.7: Baseline interest rate

Black = mean. Red = 1 STD. Blue = one run.

The unemployment rate fluctuates around the target stipulated by the fiscal and monetary authorities, with and standard deviation of approximately 1%. When examining the results of a single simulation, represented by the blue line in Figure (4.5.1), a cyclical behavior of the unemployment rate is observed.

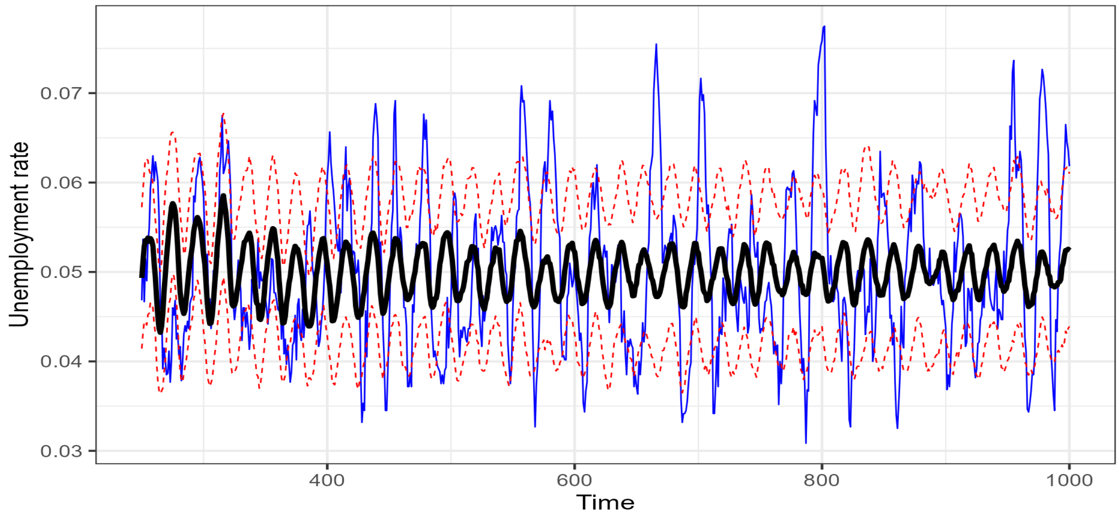


Figure 5.8: Unemployment rate

Black = mean. Red = 1 STD. Blue = one run.

In terms of the primary stocks of the model, namely government debt to GDP and capitalist wealth to GDP, we observe that in both cases, they tend to remain stable, as demonstrated in Figure (5.9). The simulations yield an average value of government debt to GDP of 2.2 and wealth to GDP fluctuating around 1.55. These findings support the notion that the model generates stable outcomes, not only in terms of macroeconomic variables but also with respect to significant ratios that are commonly employed to evaluate the stability of the economic system.

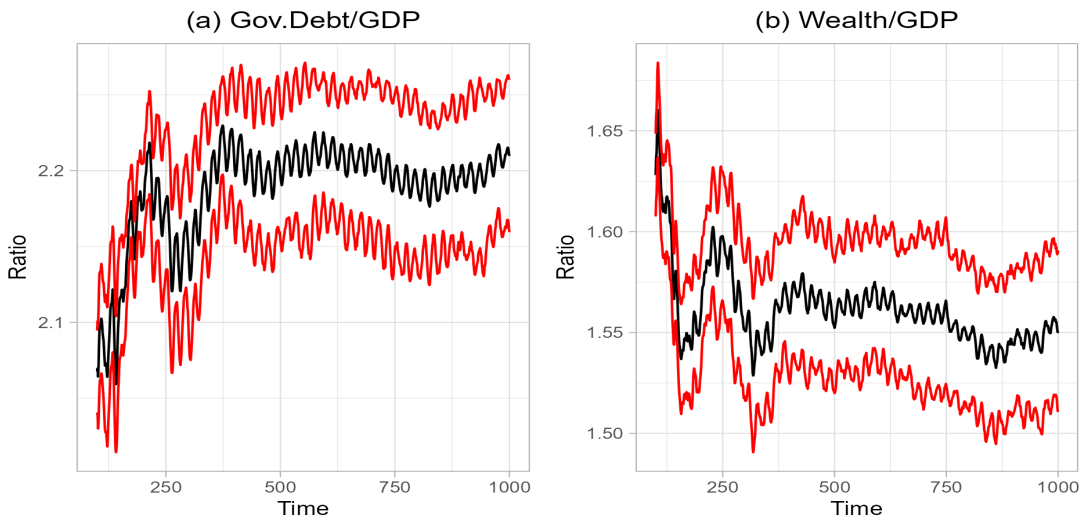


Figure 5.9: Wealth and debt stocks

The wage share of the model, as presented in Figure (5.10), on average, exhibits a tendency to be stable, fluctuating around 0.5. Given that we considered a markup of the firms of 1, obtaining a markup factor of 2, and that the aggregate markup is constant in this model version, the result for the wage share was expected.

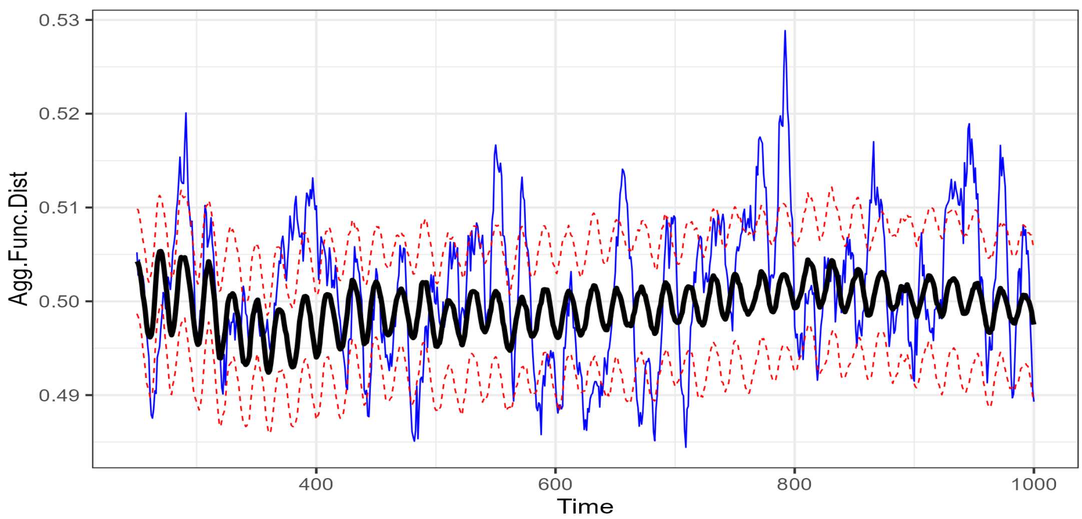


Figure 5.10: Wage share

Black = mean. Red = 1 STD. Blue = one run.

In conclusion, our model exhibits a notable degree of stability across several key macroeconomic variables. These include wealth and debt ratios, inflation, and interest rates. Additionally, a stable long-term trend for the GDP, wage share, and unemployment is observed. However, it is important to note that despite this overall stability, all of these variables display a cyclical behavior pattern, persistently fluctuating over time. Thus, while the model generates consistent and predictable outcomes, the cyclical patterns observed may have implications for economic policy and decision-making.

5.6.2 Microeconomic results

In this subsection, we showcase the fundamental microeconomic outcomes of the model, highlighting its capacity to replicate critical micro-stylized facts and to demonstrate the competitive environment in which firms operate.

The Figure presented in (5.11) displays the weighted average indebtedness of the economy, obtained from 100 simulations, where each firm's level of indebtedness is weighted by its market share. The results indicate that the participation of debt in the balance sheet of firms in the economy exhibits a cyclic behavior, with the value fluctuating between 0.55 and 0.625. Further examination of individual simulations shows that the level of indebtedness of firms in the economy follows cyclical patterns, characterized by extended periods of high indebtedness, followed by shorter periods of stable lower levels of indebtedness.

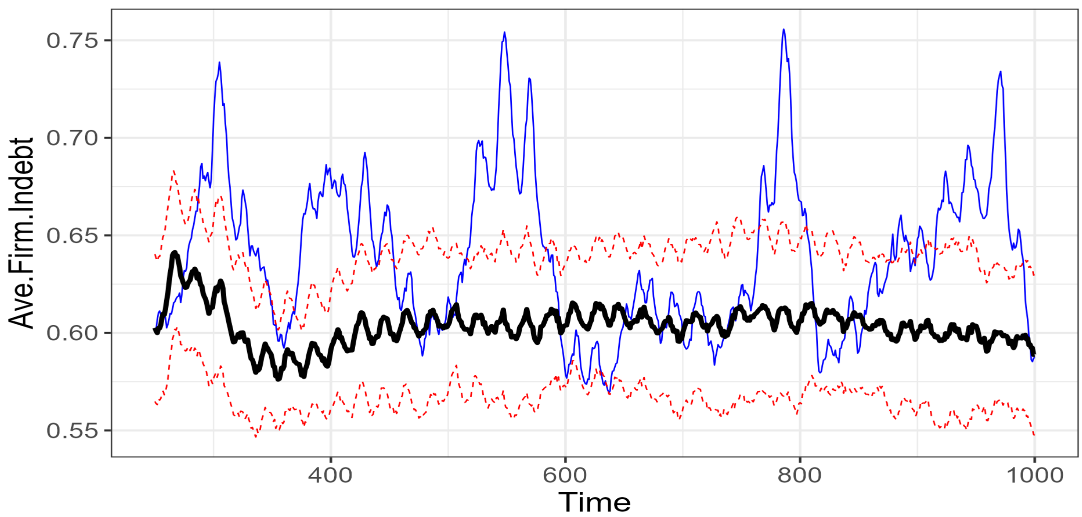


Figure 5.11: Weighted average of indebtedness

Black = mean. Red = 1 STD. Blue = one run.

In addition, it is noteworthy to mention that the model exhibits an average of 12 bankrupt firms per period, which is an important value given its impact on the selection of pricing heuristics. This represents approximately 0.5% of the firms that go bankrupt in every simulation step, leading them to innovate and adopt new price heuristics. Although the average number of bankrupt firms per period shows an increasing trend, the standard deviation remains stable. However, it is important to emphasize that in some simulation runs, as shown in Figure (5.12), the number of bankrupt firms remains relatively constant.

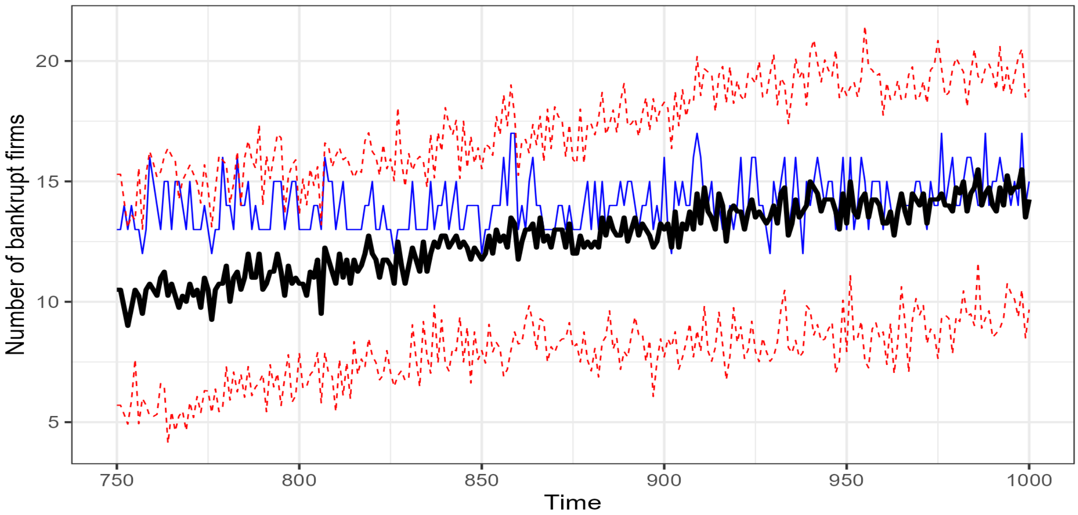


Figure 5.12: Number of bankrupt firms

Black = mean. Red = 1 STD. Blue = one run.

The simulation results on market concentration, presented in Figure (5.13), reveal important insights regarding the evolution of market structure over time. Initially, the market is highly competitive with all firms possessing identical goods, prices, and market shares. However, through investments in product differentiation and pricing strategies, an increase in market concentration is observed over time. The considered figure shows the mean value and one standard deviation of the Herfindahl-Hirschman Index (HH) and the average value of the firm with the highest market share at different periods. Firms exhibit varying degrees of competitiveness in terms of market share. Despite this, the steady-state equilibrium shows low levels of market concentration, with the HH index being close to 0.0053 and the average value of the maximum market share being above 1.2% at the end of the simulations.

Our model does not have key features that generate market concentration in ABMs, as discussed in Terranova and Turco (2022). Specifically, our model does not include knowledge spillovers and persistent differentiated capital goods, which are crucial for generating dominant firms that dominate the market based on their size alone. This approach avoids the need to account for the size effect of firms when analyzing the statistics of the prevalence of certain heuristics in the population of firms.

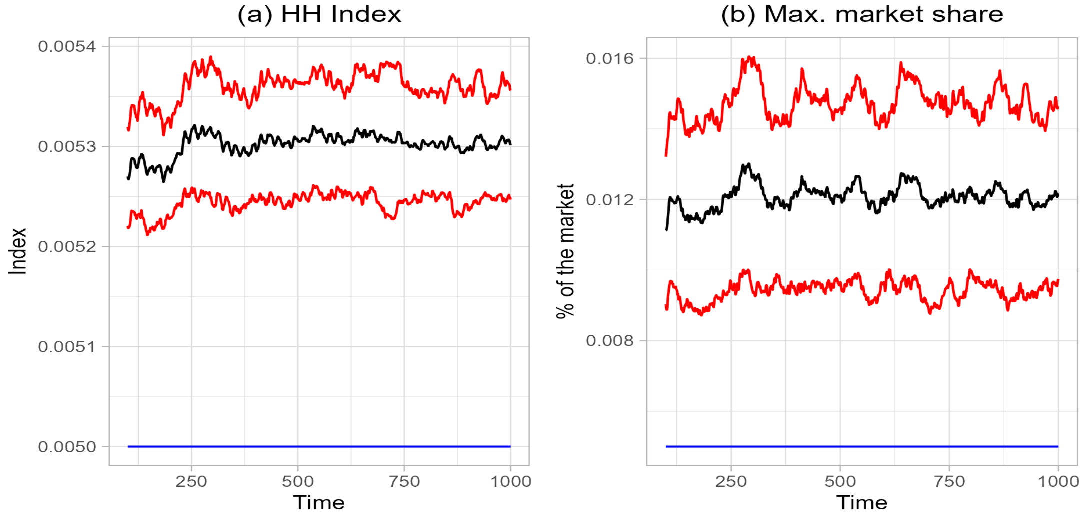


Figure 5.13: Average of the Herfindahl–Hirschman (HH) Index and max market share

Black = average. Red = one SD. Blue = perfectly competitive market

The model demonstrates the ability to replicate a widely recognized microeconomic phenomenon, known as a skewed distribution of firm size Bottazzi and Secchi (2003), as measured by market share. This stylized fact is illustrated in Figure (5.14), which is based on the outcomes of a single simulation. The distribution displays a leptokurtic shape with positive skewness, with a significant number of firms positioned towards the lower end of the market share spectrum, as depicted in Figure (5.14a). The competitiveness of firms, normalized by the maximum competitiveness, as modeled by Equation (5.6), results in a skewed distribution shown in Figure (5.14b). This distribution has a mean value of 0.347, indicating that most firms have substantially lower competitiveness levels than the firms at the frontier of competitiveness.

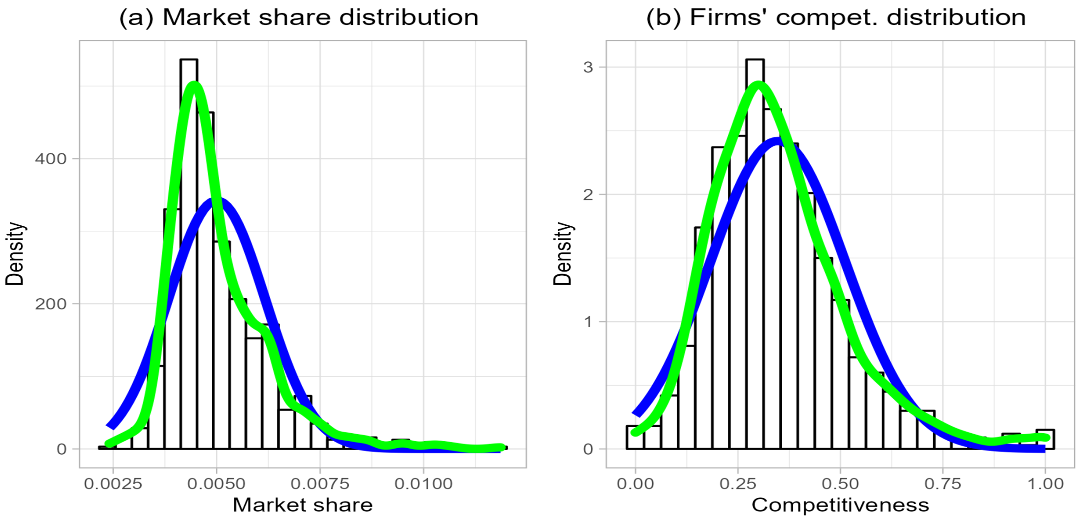


Figure 5.14: Market share and competitiveness distributions

Bars: frequency. Blue: Normal distribution. Green: Density function

Furthermore, the model reproduces the lumpiness of investment, as established in Doms and Dunne (1998). By examining Figure (5.15), we can observe that the model accurately reflects a real-world economy, as most firms do not invest in new machines every period, but a small number of firms acquire a significant amount of new machines.

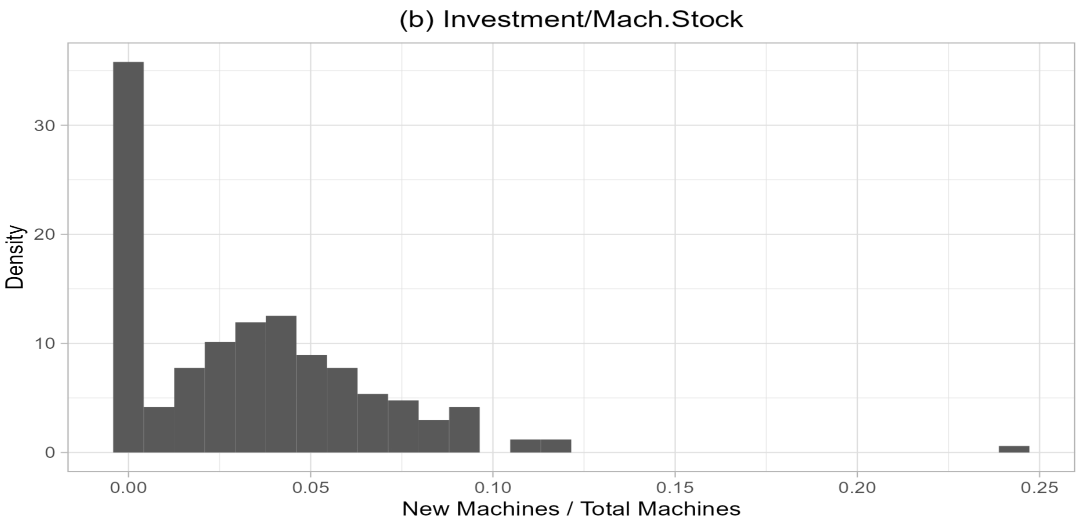


Figure 5.15: Distribution of firm's investing in new machines

The model's findings demonstrate additional stylized facts, as depicted in Figure (5.16). These facts comprise the pro-cyclicality of firms' investment in R&D (Wälde and Woitek, 2004; Barlevy, 2007) and the pro-cyclicality of firms' debt-to-GDP ratio (Jordà et al., 2017;

Hiebert et al., 2018). Notably, both variables are considered leading indicators of GDP. Moreover, the pro-cyclical pattern of firms' stock of debt is a well-documented stylized fact in the context of business cycles (Azariadis, 2018).

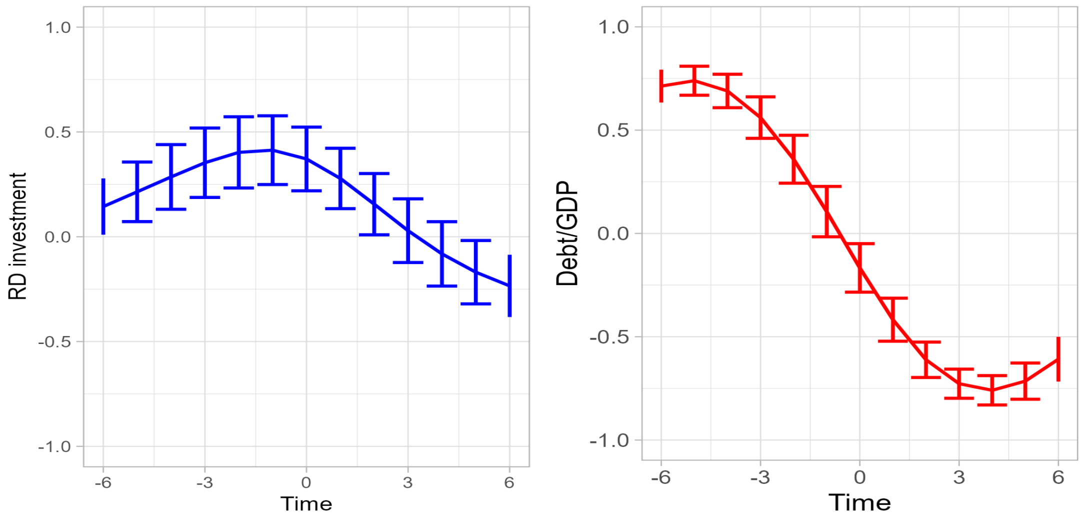


Figure 5.16: Cross-correlation of R&D investment (blue) and debt to GDP ratio (red)

Table (5.5) displays the statistical moments related to pricing behavior at the microeconomic level. These moments are derived from simulation data and compared against empirical observations. The parameters of interest include the frequency of price changes, the implied price duration, the proportion of price increases following changes, the magnitude of price increases, the magnitude of price decreases, and the proportion of small changes.

According to Table (5.5), the benchmark model indicates a high degree of price stickiness, with an implied price duration of 21 months. Additionally, 84% of the observed price changes resulted in price increases. The average magnitude of price increases was found to be 8.4%, while the average magnitude of price decreases was only 2.9%. Furthermore, 58% of the price adjustments were classified as small (below 5%).

Upon comparison of our findings to empirical data, we observe that prices exhibit greater stability than is typically observed. Additionally, the majority of price changes are increases, with the magnitude of price decreases considerably lower than what is commonly observed.

Our analysis reveals a positive correlation between the frequency of price changes and inflation (0.63), as well as between the average size of price adjustments and the rate of

Microeconomic statistical moments				
Parameter	Average	SD	Empirical value	Reference
Frequency of price changes	0.047	0.002	0.12 (monthly)	Nakamura and Steinsson (2008)
Implied price duration	21.483 (months)	1.004	8 (months)	Nakamura and Steinsson (2008)
Price increases when prices changed	0.84	0.008	0.60	Nakamura and Steinsson (2008)
Value of price increases	0.084	0.005	0.073	Nakamura and Steinsson (2008)
Value of price decreases	-0.029	0.0014	- 0.105	Nakamura and Steinsson (2008)
Fraction of small changes	0.58	0.024	0.44	Klenow and Kryvtsov (2008)

Table 5.5 - Simulated microeconomics moments vs. stylized facts

inflation (0.71). These findings are in accordance with previous research by Nakamura and Steinsson (2008) and Klenow and Malin (2010), who identified a positive correlation between the size of price increases and inflation. However, Nakamura and Steinsson (2008) found no relationship between the frequency of price adjustments and inflation. Araujo (2019) demonstrated that different macroeconomic environments in the same region can lead to varying frequencies of price adjustments over time. This highlights the dynamic nature of the frequency of price adjustments and its potential to significantly vary over time.

The contribution of this essay lies in its effort to reproduce these stylized facts within the macroeconomic ABM literature. To the best of our knowledge, this is a novel approach that adds to the growing list of stylized facts that can be replicated by ABMs (Haldane and Turrell, 2019; Fagiolo et al., 2019).

Finally, Figure (5.17) displays the average threshold results obtained from 100 simulations. The parameter of interest is the "adjustment threshold", which determines the pricing heuristic in terms of price rigidity, as given by Equation (5.4). The average value of this parameter is 15%, with a constant standard deviation of approximately 1 percentage point.

This result explains the emergence of price stability in the model. The increase in the average value of the "adjustment threshold", coupled with the constant standard deviation, indicates a selection of pricing heuristics where firms have higher "bands of inaction". It is important to note that this is a result of the calibrated model. Hence, the set of parameters that best replicate numerous macro and micro-stylized facts is one that favors firms adopting a pricing heuristic that promotes price stability.

The benchmark model considered a initial value of the "adjustment threshold"for the firm's drawn from a uniform distribution U(0.01,0.2). However, we conducted tests using different initial values for the "adjustment threshold", based on the parameter set obtained from the calibration exercise, to understand the impact of different initial values of this parameter on the model's outcomes. These tests included setting the "adjustment threshold"equal to zero for all firms. In all the cases we consistently observed that average value of "adjustment threshold"converging to values higher than 15%, evidencing the robustness of the result obtained.

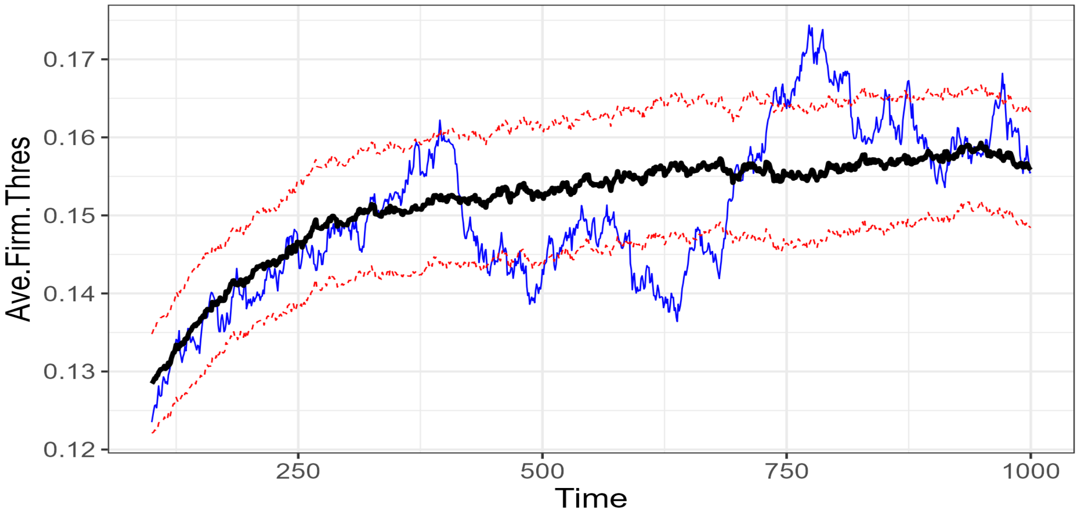


Figure 5.17: Average threshold

Black = mean. Red = 1 STD. Blue = one run.

5.7 Experiments

This section presents the results of a series of experiments conducted using the developed ABMs. The empirical robustness of the model is evident from its ability to explain several macroeconomic and microeconomic empirical regularities. Based on this robustness, we realized experiments and compared the results with those of the benchmark model. Our objective was to investigate the sensitivity of the model to changes in essential parameters related to the competitiveness cost of firms in terms of prices, and the impact of policy interventions on the economy as a whole.

The experiments were designed to provide insights on the behavior of the model under different scenarios and the effects of changes in key parameters on macroeconomic outcomes. Observing the sensitivity of the model to parameter changes is essential to understanding its applicability and limitations. Furthermore, examining the impact of policy interventions allowed us to evaluate the effectiveness of various policy options and their implications on the overall economy.

The first set of experiments, detailed in section (5.7.1), involved varying parameters related to consumer behavior. We examined various combinations of parameters driving firms' competitiveness to observe if the degree of price adjustment significantly affects the price threshold of firms. Additionally, we investigated whether changes in price and quality elasticity influence the behavior of firms and the overall economic performance.

The second set of experiments, presented in section (5.7.2), focused on policy interventions. Specifically, we tested changes in parameters relating to the reaction degree of the central bank to deviations of inflation from the inflation target and the reaction of government spending to deviations of the unemployment rate from the target. The objective was to understand the potential effects of these interventions on the overall economic performance, particularly in terms of output, inflation, employment, and microeconomic behavior.

5.7.1 Price competitiviness

In this section, we present the results of various experiments that consider changes in key parameters that explain the competitiveness of producers of consumer goods. The primary objective of these experiments was to observe how the macroeconomic performance and microeconomic behavior of the firms are affected by different parameter values. These changes in parameters may be viewed as changes in customer behavior, where customers place varying weights on the qualities and prices of goods, as well as the pricing policies of firms. The results are presented in Table 5.6.

To compare the experimental results with those of the benchmark model, we calculated ratios. The rows labeled "Mean.Rat"in Table (5.6) present the mean results of 50 experimental simulations divided by the mean results of 50 simulations using the benchmark set of parameters. The "SD.Rat"rows provide the ratio of the average standard deviation of the 50 experiment simulations against the average standard deviation of the 50 benchmark simulations. The seeds used to do the computer simulations were the same in the benchmark model and simulations, guaranteeing that the difference seen in the results is only driven by the changes in the parameters.

Finally, the "P.Value"column indicates the level of significance of the Welsh test, which compares whether the average results of the experimental population are significantly different from the mean results of the benchmark simulations. In other words, measure the statistical significance of the difference seen in "Mean.Rat".

The first experiment under consideration investigates a scenario where implicit contracts do not exist in the economy, thus leading to a lack of consumer punishment for firms' behavior in terms of frequency and size of price adjustments. This was modeled by

Experiment	Variable	Inflat.	Unem.	GDP	Wage share	Indebt.	Thresh.
No implicit contract ($\alpha_3 = \alpha_4 = 0$)	Mean.Rat SD.Rat P.value	0.979 0.831 0.238	1.001 0.826 0.39	0.998 1.039 0.061 *	1.001 0.97 0.495	1.006 0.9 0.124	0.991 0.898 0.3
Stronger implicit contract ($\alpha_3 = 8.571, \alpha_4 = 0.0428$)	Mean.Rat SD.Rat P.value	1.026 0.991 0.178	0.999 0.975 0.37	1.001 1.189 0.331	0.999 1.121 0.216	0.997 0.855 0.472	0.996 1.179 0.732
Higher elast.rel. price ($\alpha_2 = 9.471$)	Mean.Rat SD.Rat P.value	1.035 0.905 0.061 *	1.001 1.039 0.302	1.016 1.363 0 ***	0.986 1.181 0 ***	0.998 0.998 0.566	0.997 1.007 0.756
Lower elast.rel. price ($\alpha_2 = 2.367$)	Mean.Rat SD.Rat P.value	1.049 1.139 0.02 **	1.001 1.01 0.614	0.997 1.152 0.005 ***	0.999 1.09 0.503	0.997 0.98 0.455	0.999 1.063 0.886
Null elast.rel. price ($\alpha_2 = 0$)	Mean.Rat SD.Rat P.value	1.059 1.28 0.01 **	1.001 0.757 0.6	0.996 1.157 0 ***	0.989 0.993 0 ***	1.004 1.146 0.377	0.95 1.098 0 ***
Higher elast.rel. quality ($\alpha_1 = 4.414$)	Mean.Rat SD.Rat P.value	0.981 0.938 0.303	0.998 0.889 0.111	1.008 1.316 0 ***	0.99 0.992 0 ***	1.012 0.735 0.001 ***	1.012 1.102 0.227
Lower elast.rel. quality ($\alpha_1 = 1.103$)	Mean.Rat SD.Rat P.value	1.025 0.796 0.153	1.001 1.017 0.543	0.998 1.106 0.02 **	1.003 0.908 0.003 ***	0.995 0.841 0.137	0.994 1.109 0.526
Null elast.rel. quality ($\alpha_1 = 0$)	Mean.Rat SD.Rat P.value	1.076 0.959 0 ***	1.001 0.828 0.663	0.999 1.295 0.16	1.002 0.915 0.1	0.989 0.891 0.002 ***	0.989 1.202 0.317

Table 5.6 - Experiments with the elasticities of price competitiviness

setting α_3 and α_4 to zero.

The results from Table (5.6) indicate that, when compared to the benchmark model, the average results are not significantly different, except for GDP. The only variable that displayed a considerable difference was the inflation rate, which yielded a ratio of 0.979. We also do not observe any significant change in the average value of the "adjustment threshold"of the firms (in collum "Thresh"). No significance either statistically or in terms of magnitude. This finding suggests that the existence of sticky prices is an emergent property of the model, without necessitating the consideration of implicit contracts for the emergence of price rigidity. The selection process of heuristics leads to the selection of those that make prices more inflexible, resulting in advantageous outcomes for firms in terms of profit, competitiveness, and market share. Price strategic complementarities, which make it advantageous to firms do not pass every change in the unitary cost of production to their customers, maintain price stability, and foster greater competitiveness and market share for firms. What we can say is that the existence of implicit contracts reinforce these effects.

Another unexpected finding was that the standard deviation of variables was considerably lower than the benchmark. This can be explained by the reduction in the number of variables used as inputs to explain the competitiveness of products in Equation (5.6). Not considering the components of the implicit contracts leads to smoother changes in the relative competitiveness of the products over time, reducing the volatility of market shares, production, and sales of firms.

These results can be contrasted with those where implicit contracts have a stronger effect, modeled by setting α_3 to 8.571 and α_4 to 0.0428. In this case, there is again no evidence that suggests that the average results of the experiment differ from those of the benchmark specification. Only the inflation rate ratio exhibited a value different from 0.01, in module, from 1, with a ratio of 1.026. Therefore, the stronger the implicit contracts in the model, the higher the average inflation rate, contrary to what one would expect based on the literature. This outcome can be explained by the higher punishment imposed on firms when they change prices, leading to greater volatility in changes in market shares. This, in turn, creates higher volatility in the labor market, with firms increasing rates of hiring and firing. In our model, the key variable explaining how firms attract new workers is by increasing their reference wages, making wages more volatile in the model. These changes in wages directly affect the inflation rate, as wage costs are passed through to prices.

Analyzing the experiments conducted to verify the effect of the "competition elasticity to relative prices", we observed several variables that displayed significant deviations from the benchmark model. These results are present in rows 3, 4, and 5 of Table (5.6). Notably, the inflation rate, the aggregate GDP, wage share, and the average adjustment threshold of firms were affected. Across all experiments, the average inflation rate was observed to be higher, with the effect being most pronounced in experiments with a lower elasticity. Furthermore, the adjustment threshold of firms was significantly lower in experiments with an elasticity of price equal to zero. This finding suggests that as the relative prices become less critical in determining goods' competitiveness, the adjustment threshold of firms declines, resulting in higher inflation rates.

Another observation from the experiments is that higher elasticity to relative prices corresponds to higher aggregate GDP in the economy. Additionally, across all experiments, the average wage share was lower, indicating that the firms' pricing behavior influenced the distribution of income in the economy.

Regarding the standard deviation of the variables, we noted that all experiments exhibited overall higher volatility than the benchmark model. This finding indicates that the effect of the parameter α_2 in the system is not linear, with a point closer to the benchmark resulting in a more stable system. Conversely, values of α_2 that are outlying away from this point correspond to higher volatility in the model.

The experiments conducted with the parameter α_1, which represents the elasticity of competitiveness to the relative quality of goods, indicate that certain variables are significantly impacted by varying values of this parameter. The results can be seen in rows 6, 7, and 8 of Table (5.6). Notably, the average inflation rate was observed to be higher (lower) as the value of α_1 decreased (increased). Additionally, the adjustment threshold of firms was found to be lower (higher) when the elasticity to relative quality was lower (higher). These results suggest that the consumer perception of quality differentiation plays an important role, with economies where this perception is higher tend to exhibit more stable prices.

The experiments also revealed that firms have higher levels of indebtedness when the elasticity to relative quality is lower. This relationship is primarily explained by the behavior of inflation; lower inflation rates lead to lower average interest rates for firms, incentivizing them to increase their use of borrowed capital. On the other hand, higher elasticity to relative quality leads to higher inflation rates and higher average interest rates, discouraging firms from relying on borrowed capital and resulting in lower indebtedness. While the average GDP and wage share showed some evidence of being different in certain experiments, the differences were considered relatively small.

The primary outcome of the price experiments is that implicit contracts are not essential for the emergence of price policies that lead to price stability. Even in the absence of such contracts, firms tend to opt for adjustment thresholds that are similar to those observed in the benchmark, with price adjustments being very infrequently. Moreover, the value of these thresholds does not vary significantly even when the impact of implicit contracts is stronger. Therefore, we can consider the price stickiness as a truly emergent property, generated by coordination failures. Indeed, in Blinder (1994), firms report that coordination failures are more important to explain price stickiness than the existence of implicit contracts.

The outcome of the experiments also showed that variations in the fundamental parameters related to good competitiveness can exert notable effects on key macroeconomic variables, notably inflation and GDP rates. Crucially, these variations also have a significant impact on the overall volatility of the economy.

5.7.2 Policy experiments

This section details the policy experiments conducted in the study. The focus was on exploring the impact of variations on the parameters of policy makers in relation to the benchmark specification. Specifically, the experiments investigated changes in both monetary and fiscal policies. Two distinct cases were analyzed for each policy type. For monetary policy, the experiments involved examining scenarios where the central bank responds strongly or weakly from deviations from the inflation target. Similarly, for fiscal policy, the experiments assessed how variations in government spending to deviations from the unemployment target affect the economic environment. The findings of these experiments are presented and summarized in Table 5.7

Initiating with the investigation of monetary policy, our analysis indicates that the actions of the central bank wield a significant impact on various macroeconomic indicators. Our findings reveal that a higher reaction of the central bank to inflation deviations leads to a significant increase in the average inflation rate, while a dovish stance results in the opposite effect.

Moreover, our analysis demonstrates that the unemployment rate, GDP, and wage share exhibit significant deviations from the benchmark, although the outcomes are comparable to those witnessed in the benchmark for both alternative scenarios. In terms of indebtedness, our experiment shows that a lower response of the central bank to inflation leads to increased indebtedness among firms. This trend can be attributed to lower interest rates that result from a reduced central bank response, which raises the debt targets of

Experiment	Variable	Inflat.	Unem.	GDP	Wage share	Indebt.	Thresh.
Lower CB	Mean.Rat	0.984	1	0.999	1.001	1.035	1.008
reaction	SD.Rat	1.099	1.006	1.501	1.202	1.307	1.312
($\phi_1 = 0.35$)	P.value	0.442	0.763	0.226	0.225	0 ***	0.45
Higher CB	Mean.Rat	1.031	1.001	1.002	0.998	0.976	0.995
reaction	SD.Rat	0.823	0.932	0.897	0.769	0.646	0.94
($\phi_1 = 3.15$)	P.value	0.081 *	0.304	0.024 **	0.01 **	0 ***	0.61
Lower gov.	Mean.Rat	0.988	1.002	0.997	1.007	1.009	1.021
spending	SD.Rat	0.649	1.075	0.981	1.063	0.703	1.425
reaction	P.value	0.469	0.123	0 ***	0 ***	0.005 ***	0.077 *
($\rho_u = 0.4285$)							
Higher gov.	Mean.Rat	1.675	0.942	2.772	0.777	0.908	0.908
spending	SD.Rat	3.191	3.828	548.772	26.772	2.121	1.052
reaction	P.value	0 ***	0 ***	0 ***	0 ***	0 ***	0 ***
($\rho_u = 1.714$)							

Table 5.7 - Policy experiments

firms.

Finally, we do not observe any significant evidence indicating that monetary policy influences the average price adjustment threshold of firms, although the effect is positive for a lower central bank reaction and negative for a higher central bank response. This observation potentially explains the mechanism underlying why the average inflation rate is greater in the experiment featuring a hawkish central bank.

In addition, we would like to emphasize that beyond the mean outcomes, the standard deviation of the time-series indicated important differences. As indicated in Table (5.7), our analysis illustrates that the central bank plays a crucial role in stabilizing the economy. A hawkish reaction of the central bank to inflation deviations results in lower standard deviation values for all the selected macroeconomic variables. For instance, in this scenario, the standard deviation ratio of the unemployment rate was 0.93, and that of GDP was 0.89.

Conversely, a reduced central bank reaction to inflation deviations results in higher overall volatility of the selected macroeconomic variables, firm indebtedness, and average price adjustment threshold. In the experiment featuring a lower central bank reaction, the standard deviation ratio of the unemployment rate was 1.006, and that of GDP was 1.501. These findings emphasize the importance of the central bank's response to inflation deviations in promoting macroeconomic stability, but at a negative cost in terms of average inflation.

Regarding the fiscal policy experiments, our observations reveal that government spending decisions have a significantly higher impact on the economy than monetary policy. All the selected variables were significantly affected in at least one of the experiments. When the government has a lower reaction to differences in the unemployment rate from the target, the main affected variables were the inflation rate and the adjustment threshold of firms. This scenario led to a lower inflation rate and a higher adjustment threshold, while the standard deviation of the price adjustment threshold increased, with a ratio of 1.42. The unemployment rate was not significantly affected, and the average GDP showed a slight decrease while the wage share displayed an increase.

In terms of the increase in the government spending reaction proportional to the increase in the central bank reaction, the effects were substantial. The mean ratio of the inflation rate was 1.6, unemployment rate 0.94, GDP 2.77, wage share 0.77, indebtedness 0.9, and average threshold 0.9. The standard deviation of the variables more than doubled, and that of GDP skyrocketed to 548. Overall, our model suggests that fiscal policy can decrease the average unemployment rate through spending and increase the average GDP. However, this policy comes at the cost of an increase in the inflation rate and a decrease in the wage share. Interestingly, this policy leads to more flexible prices, with the mean ratio of the price adjustment threshold being 0.9.

Comparing the results of the monetary and fiscal policy experiments, we note that fiscal policy is observed to have a more substantial impact on the economy than monetary policy, as all selected macroeconomic variables were significantly affected in at least one of the experiments. In contrast, monetary policy experiments displayed some variations in results, with only certain macroeconomic indicators being significantly impacted.

Secondly, we observe that both policies have similar effects on the mean of the selected macroeconomic variables, with higher reaction levels leading to higher inflation rates, GDP and lower wage shares, and firms' indebtedness. Moreover, we find that the increasing values of inflation feeds back into the microeconomic behavior of firms. In particular, firms with lower price adjustment thresholds are selected when the reaction level of the policymakers is high, whereas firms with higher price adjustment thresholds are selected when the reaction level of the policymakers is low. This would be expected for the fiscal policy, but not for the monetary policy.

In terms of the standard deviations, the experiments show that the effects of the policy interventions exhibit opposite effects. The higher the reaction of the central bank, the lower the standard deviation of the the economic variables. On the other hand, the higher the reaction of government spending, the higher the volatility of the economic system. This suggests that, if coordinated, monetary policy and fiscal policy could be used in complementary ways to ensure that economic targets are achieved while keeping the stability of the system.

In summary, our experiments provide valuable insights into the complexities of the macroeconomic system and the potential impacts of policy interventions on the economy. The key findings are that the monetary policy and, especially, the fiscal policy do affect the macroeconomic environment and the microeconomic behavior that is selected by the agents. The higher the reaction of the government and central bank, the lower the average price adjustment threshold of the firms, increasing the inflation rate. The monetary policy and fiscal policy have the same effects on the system when considering the mean results of the macroeconomic variables, but exhibit opposite effects when considering the volatility. Our findings can inform policymakers and researchers in designing effective policies that promote economic growth and, more importantly in terms of the results, stability.

5.8 Conclusion

In this essay, we address the issue of price stickiness by utilizing a agent-based macroeconomic approach. First, after emphasizing the stylized facts presented in the chapter two that we wanted to emphasize in the current essay, we conducted a survey of the theoretical literature that incorporated the phenomenon of rigid prices in macroeconomic models dating back to the 1970s. Our survey revealed that the DSGE models places significant emphasis on explanations based on rigid contracts to obtain models with price stickiness and assumes a high degree of rationality of firms in setting prices.

We offer a different explanation, suggesting that pricing rigidity may result from an evolutionary process of selection of pricing heuristics. Our hypothesis is that firms employing more rigid pricing strategies tend to be selected through the Schumpeterian competition process. This hypothesis underscores the importance of considering the long-term adaptive and survival strategies of firms in understanding the dynamics of pricing in market economies. To our knowledge, the explanation of pricing behavior, particularly the price stability of firms, as an evolutionary process represents a novelty in the field.

To evaluate the validity of our hypothesis, we developed a agent-based macroeconomic model that incorporates consumer antagonism towards price changes and allows firms to choose from a range of pricing heuristics, ranging from fully flexible to highly inflexible. Using the method of simulated moments, we calibrated the model to reproduce cross-correlations and standard deviations of macroeconomic data and microeconomic moments related to prices in the US economy.

To our knowledge, the reproduction of microeconomic statistical moments related to prices is a novel contribution to the agent-based macroeconomic literature. Our results demonstrate that the model is able to reproduce many stylized facts of the US economy, not only those related to the calibration exercise. We found that the parameters that best fit the empirical data are those in which consumer antagonism towards price changes is low. Given the structure of the model, this result suggests that customers may not need to attribute high importance to price changes, modeled through implicit contracts, for this to have meaningful results over the model dynamics. In the benchmark model, we observed that the "adjustment threshold"converged to 15%. This result remains robust across different starting values for the parameter, even in the extreme case where all firms begin the simulation with an "adjustment threshold"of zero.

Subsequently, we conducted various experiments with the model by modifying the values of parameters related to firm competitiveness and policy. In the firm competitiveness experiments, we observed that the presence of implicit contracts is not necessary to observe the selection of heuristics with stable prices. The fact that sticky prices emerge in the absence of implicit contracts highlights its status as a truly emergent property of the model.

Regarding policy experiments, we found that they do impact the price behavior of firms and the macroeconomic dynamics of the model, particularly in terms of volatility. We observed that as the reaction of economic policy to deviations from key variable targets increases, firms tend to adopt heuristics that promote more flexible prices.

The present research study offers insights for future investigations in the domain of macroeconomics, particularly with regard to the application of agent-based macroeconomic modeling. The results of this study can serve as a foundation for the development and enhancement of future ABMs that aim to comprehensively capture the intricate dynamics of pricing in market economies and the impact of monetary policy. Future research may explore the asymmetrical nature of the drivers of price adjustments, particularly in scenarios where prices are increasing or decreasing. The findings presented in this study can serve as well as a reference point for future macroeconomic agent models that aim to more accurately replicate stylized facts of pricing.

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Appendix

Appendix A

The central planner coordination problem with multiple production plants

In order to obtain the optimal result for the economy in an environment where several firms produce consumer goods, let us first assume that the quality of all goods is identical. Therefore, all goods are homogeneous. Thus, the problem of coordinating multiple production plants becomes an issue that involves only profit maximization. Assuming that there is a central planner who manages the production activities of all plants seeking to maximize aggregate profit, as if all the multiple production plants were part of one vertically integrated firm, the problem is:

$$\prod = \sum_{i=1}^{N} Y_i - w \sum_{i=1}^{N} L_i. \tag{A.1}$$

Subject to restrictions:

$$Y_i = AL_i^{\alpha}, \tag{A.2}$$

$$w = \gamma Y^{\sigma} L^{\nu}, \tag{A.3}$$

$$Y_i = S_i Y = ((p_i/p)^{-\xi_p}(q_i/q)^{\xi_q})/(\sum_{i=1}^{N}(p_i/p)^{-\xi_p}(q_i/q)^{\xi_q})Y, \tag{A.4}$$

$$Y = \sum_{i=1}^{N} Y_i, \tag{A.5}$$

$$L = \sum_{i=1}^{N} L_i, \tag{A.6}$$

$$P = (\sum_{i=1}^{N} P_i)/N. \tag{A.7}$$

Following Costa (2018), we consider that the coordinator of the firms adopts a two-step process to set the prices of the firms. In the first step the costs of production are minimized.

This problem for a single plant of production can be defined as:

$$\mathscr{L} = wL_i + \lambda(Y_i - AL_i^{\alpha}). \tag{A.8}$$

With first order condition being:

$$w = \lambda \alpha Y_i / L_i. \tag{A.9}$$

The total cost of production (TC) of an individual firm, given (A.9), is:

$$TC_i = wL_i = w\lambda\alpha Y_i/w = \lambda\alpha Y_i. \tag{A.10}$$

Therefore, the marginal cost of an individual firm is:

$$MC_i = dTC_i/dY_i = \lambda\alpha. \tag{A.11}$$

Equalizing (A.9) with (A.11), we have the usual result find with New-Keynesian models, where the marginal cost of the firms is equal to the wage share of the firms revenue:

$$wL_i/Y_i = MC_i. \tag{A.12}$$

The second step of the central coordinator is to maximize the aggregate profit. Given Equation (A.11), the profit equation of an individual firm is given by:

$$\Pi_i = P_iY_i - TC_i = P_iY_i - MC_iY_i = (P_i - MC_i)Y_i. \tag{A.13}$$

And substituting Equation (A.4) in (A.13), we have:

$$\Pi_i = (P_i - MC_i)SiY/N. \tag{A.14}$$

Making the assumption that the number of firms is sufficiently large to:

$$d(\sum_{i=1}^{N}(p_i/p)^{-\xi_p}(q_i/q)^{\xi_q})/dp_i \approx 0. \tag{A.15}$$

The first-order condition of Equation (A.14) is:

$$\begin{aligned} d\Pi_i/dP_i = S_iY/N + (P_i - MC_i)Y/NdS_i/dp_i = 0,\\ (P_i - MC_i) = -S_i/(dS_i/dp_i),\\ (P_i - MC_i) = P_i/\xi_p,\\ P_i = \xi_p/(\xi_p - 1)MC_i. \end{aligned} \tag{A.16}$$

And with this result we get to the also usual New-Keynesian result, although using a demand equation sligly different from the Dixit-Stigltz aggregator, where the optimal individual price depends of the marginal-cost and the price elasticity of demand. For the markup to be positive, we must necessarily have $\xi_p > 1$.

If we make the assumption that all production plants are symmetrical and that the real wage is equal for all plants, we have that, for any two plants i and f:

$$MC_i = MC_f, \quad Y_i = Y_f, \quad L_i = L_f, \quad P_i = P_f.$$

Considering the firms symmetrical, given A.5, A.6, A.7 we have:

$$Y = \sum_{i=1}^{N} Y_i = NY_i. \tag{A.17}$$

$$L = \sum_{i=1}^{N} L_i = NL_i. \tag{A.18}$$

$$P = \sum_{i=1}^{N} P_i/N = NP_i/N = P_i. \tag{A.19}$$

Substituting Equation (A.12) in the Equation (A.16), considering the symmetry among the firms, we have:

$$\begin{aligned} P_i = \tfrac{\xi_p}{\xi_p - 1}\tfrac{wL_i}{Y_i},\\ P = \tfrac{\xi_p}{\xi_p - 1}\tfrac{wL}{Y}. \end{aligned} \tag{A.20}$$

Isolating w and equalizing A.20 with A.3, we have:

$$\frac{PY}{L}\frac{\xi_p - 1}{\xi_p} = \gamma Y^{\sigma} L^{\nu}. \tag{A.21}$$

From A.2 and considering the symmetry condition we know that:

$$Y = AL^{\alpha}N^{1-\alpha}. \tag{A.22}$$

Substituting the prior result in A.21, we finally get to the aggregate equilibrium of production:

$$Y^* = (\frac{P}{\gamma}\frac{\xi_p - 1}{\xi_p}(N^{\frac{\alpha-1}{\alpha}}A^{\frac{-1}{\alpha}})^{-1-\nu})^{\frac{\alpha}{(1+v)(\sigma)}}. \tag{A.23}$$

In the model we consider that the households form a expectation of future consumption based on this result.

Appendix B

Sensitivity Analysis Tables of Chapter 3

	1	2	3	4	5	6	7	8	9
1	Parameter value	0.53	0.68	0.83	0.98	1.13	1.28	1.43	1.58
2	Stability	Unstable	Unstable	Stable	Stable	Stable	Stable	Stable	Stable
3	Mean GDP gap			0.01	0	-0.02	-0.07	-0.08	-0.06
4	SD GDP gap			0	0	0.01	0.02	0.02	0.01
5	Mean Inflation			0	0.01	0.02	0.06	0.07	0.05
6	SD Inflation			0	0	0.01	0.04	0.04	0.02
7	Mean Wage-Share			0.17	0.41	0.62	0.67	0.69	0.71
8	SD Wage-Share			0.01	0.01	0.03	0.06	0.06	0.04
9	ME Nom Interest			0	0.01	0.09	0.27	0.31	0.21
10	SD Nom Interest			0	0	0.03	0.09	0.09	0.05
11	ME Rule 1			0.34	0.36	0.44	0.54	0.52	0.45
12	SD Rule 1			0.02	0.02	0.02	0.03	0.03	0.03
13	ME Rule 2			0.33	0.32	0.25	0.10	0.09	0.18
14	SD Rule 2			0.02	0.02	0.02	0.04	0.03	0.03
15	ME Rule 3			0.33	0.32	0.30	0.36	0.39	0.38
16	SD Rule 3			0.02	0.02	0.02	0.04	0.03	0.03

Table B.1 - Sensitivity analysis of α : Elasticity of production with respect to labor

	1	2	3	4	5	6	7	8	9
1	Parameter value	1.3	1.67	2.04	2.41	2.78	3.15	3.52	3.89
2	Stability	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
3	Mean GDP gap	0	0	0	0	0	-0.01	-0.01	-0.01
4	SD GDP gap	0	0	0	0	0	0	0	0
5	Mean Inflation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6	SD Inflation	0	0	0	0	0	0	0	0
7	Mean Wage-Share	0.46	0.49	0.51	0.53	0.54	0.55	0.55	0.55
8	SD Wage-Share	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
9	ME Nom Interest	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.05
10	SD Nom Interest	0	0	0.01	0.01	0.01	0.01	0.01	0.01
11	ME Rule 1	0.35	0.37	0.38	0.38	0.38	0.39	0.39	0.4
12	SD Rule 1	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
13	ME Rule 2	0.32	0.32	0.31	0.31	0.31	0.3	0.3	0.3
14	SD Rule 2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
15	ME Rule 3	0.32	0.32	0.31	0.31	0.31	0.31	0.31	0.31
16	SD Rule 3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table B.2 - Sensitivity analysis of σ : Relative risk aversion coefficient

	1	2	3	4	5	6	7	8	9
1	Parameter value	0.51	0.65	0.8	0.94	1.09	1.23	1.38	1.52
2	Stability	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
3	Mean GDP gap	0	0	0	0	0	0	0	0
4	SD GDP gap	0	0	0	0	0	0	0	0
5	Mean Inflation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6	SD Inflation	0	0	0	0	0	0	0	0
7	Mean Wage-Share	0.5	0.52	0.52	0.53	0.53	0.53	0.53	0.53
8	SD Wage-Share	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
9	ME Nom Interest	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
10	SD Nom Interest	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
11	ME Rule 1	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.38
12	SD Rule 1	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.03
13	ME Rule 2	0.32	0.31	0.31	0.31	0.31	0.31	0.31	0.31
14	SD Rule 2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
15	ME Rule 3	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
16	SD Rule 3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table B.3 - Sensitivity analysis of ν : Marginal disutility of labor

	1	2	3	4	5	6	7	8	9
1	Parameter value	0.85	1.1	1.34	1.58	1.83	2.07	2.32	2.56
2	Stability	Unstable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
3	Mean GDP gap		0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01
4	SD GDP gap		0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Mean Inflation		0.00	0.01	0.01	0.01	0.01	0.01	0.01
6	SD Inflation		0.00	0.00	0.00	0.00	0.01	0.01	0.01
7	Mean Wage-Share		0.19	0.38	0.49	0.56	0.62	0.66	0.69
8	SD Wage-Share		0.00	0.01	0.01	0.02	0.02	0.02	0.02
9	ME Nom Interest		0.01	0.02	0.03	0.04	0.04	0.05	0.05
10	SD Nom Interest		0.00	0.00	0.01	0.01	0.01	0.01	0.01
11	ME Rule 1		0.35	0.36	0.38	0.39	0.39	0.40	0.40
12	SD Rule 1		0.02	0.02	0.03	0.03	0.03	0.03	0.03
13	ME Rule 2		0.33	0.32	0.31	0.30	0.30	0.30	0.30
14	SD Rule 2		0.02	0.02	0.02	0.02	0.02	0.02	0.02
15	ME Rule 3		0.32	0.31	0.31	0.31	0.30	0.30	0.30
16	SD Rule 3		0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table B.4 - Sensitivity analysis of ξ_p : Price elasticity

	1	2	3	4	5	6	7	8	9
1	Parameter value	4.89	6.28	7.68	9.07	10.47	11.87	13.26	14.66
2	Stability	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
3	Mean GDP gap	-0.01	0	0	0	0	0	-0.01	-0.01
4	SD GDP gap	0	0	0	0	0	0	0	0
5	Mean Inflation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6	SD Inflation	0.01	0	0	0	0	0	0	0
7	Mean Wage-Share	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
8	SD Wage-Share	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
9	ME Nom Interest	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.04
10	SD Nom Interest	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
11	ME Rule 1	0.41	0.4	0.39	0.38	0.38	0.37	0.37	0.37
12	SD Rule 1	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.02
13	ME Rule 2	0.29	0.3	0.3	0.31	0.31	0.32	0.31	0.31
14	SD Rule 2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
15	ME Rule 3	0.29	0.3	0.3	0.31	0.31	0.31	0.31	0.32
16	SD Rule 3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table B.5 - Sensitivity analysis of ξ_q : Quality elasticity

	1	2	3	4	5	6	7	8	9
1	Parameter value	0.08	0.1	0.12	0.14	0.16	0.18	0.2	0.23
2	Stability	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
3	Mean GDP gap	-0.01	-0.01	-0.01	0	0	0	0	0
4	SD GDP gap	0	0	0	0	0	0	0	0
5	Mean Inflation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6	SD Inflation	0	0	0	0	0	0	0	0.01
7	Mean Wage-Share	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
8	SD Wage-Share	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
9	ME Nom Interest	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03
10	SD Nom Interest	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
11	ME Rule 1	0.38	0.38	0.38	0.38	0.38	0.38	0.39	0.39
12	SD Rule 1	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.03
13	ME Rule 2	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
14	SD Rule 2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
15	ME Rule 3	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
16	SD Rule 3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table B.6 - Sensitivity analysis of φ : GDP gap effect over the inflation expectation

	1	2	3	4	5	6	7	8	9
1	Parameter value	0.05	0.06	0.08	0.09	0.11	0.12	0.14	0.15
2	Stability	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
3	Mean GDP gap	0	-0.01	-0.01	-0.01	-0.01	0	0	-0.01
4	SD GDP gap	0	0	0	0	0	0	0	0
5	Mean Inflation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6	SD Inflation	0.01	0.01	0	0	0	0	0	0
7	Mean Wage-Share	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
8	SD Wage-Share	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
9	ME Nom Interest	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
10	SD Nom Interest	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
11	ME Rule 1	0.41	0.40	0.39	0.39	0.38	0.37	0.37	0.37
12	SD Rule 1	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02
13	ME Rule 2	0.29	0.30	0.30	0.31	0.31	0.31	0.31	0.31
14	SD Rule 2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
15	ME Rule 3	0.29	0.30	0.30	0.31	0.31	0.31	0.31	0.31
16	SD Rule 3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table B.7 - Sensitivity analysis of $maxq$: Maximum growth of quality

Appendix C

Stock-flow matrix

Flow	Workers	Capitalist	FirmC	FirmK	Bank	Central bank	Gov
Wage	+W		-Wc	-Wk			
Dividends		+Div	-Div.c	-Div.k	-Div.b		
Taxes	-Tw	-Tc					+T
Transfer	+Tr						-Tr
Private Consumption	-Cw	-Cc	+C				
Public Consumption			+G				-G
Investment.Mach.			-I.Mq	+I.Mq			
Investment.RD		+I.RD	-I.RD				
Central bank profit						-CB.P	+CB.P
Loan interests			-i $_l L$		+i $_l L$		
Bond interests					+i $_b B$		-i $_b B$
Deposits interests	+i $_d Dw$	+i $_d Dc$			-i $_d D$		
Interbank interests					-i $_{il} IL$	+i $_{il} IL$	
Change in cash	$+ \Delta Mw$	$+ \Delta Mc$	$+ \Delta Mfc$			$- \Delta M$	
Change in loans			$- \Delta L$		$+ \Delta L$		
Change in bonds					$+ \Delta B$		$- \Delta B$
Change in deposits	$+\Delta Dw$	$+ \Delta Dc$			$- \Delta D$		
Change in interbank loans					$- \Delta IL$	$+ \Delta IL$	

Table C.1 - Income and expenditure matrix

Stock	Workers	Capitalist	FirmC	FirmK	Bank	Central bank	Gov
Cash	+Mw	+Mc	+Mfc			- M	
Loans			-L		+L		
Bonds					+B		-B
Deposits	+Dw	+Dc			-D		
Bank reserves					-BR	+BR	

Table C.2 - Stock matrix

Appendix D

Initial conditions

The purpose of this annex is to outline the procedures used to establish the initial conditions of the model, which ensure stock-flow consistency at the beginning of the simulations. Initially, an unemployment rate of 30% (U_i) was assumed, where i is the sub-index of the initial value of the variables. This high rate was chosen to ensure low pressure in the labor market, making the model less volatile at the beginning of the simulation. The total number of workers, L, considered in the simulations was 6000 and the total number of firms, N, was 200. The output-capital ratio (v) considered was 3.5, and the capital-labor (l) ratio was 30. By multiplying both ratios, the direct labor productivity, a_i, is obtained. As previously noted, firms also utilize indirect labor, which is dictated by the parameter κ and the number of machines. Assuming that firms are utilizing their capital capacity at their target, u^*, the technical coefficient of the firms can be determined as:

$$L_{f,i} = \frac{O^*_{f,i}}{a} + \kappa \frac{O^*_{f,i}}{v} = Tec.Coef f_{f,i} O^*_{f,i} = Tec.Coef f_{f,i} \frac{O_{f,i}}{u^*}. \tag{D.1}$$

Given the technical coefficients and the assumption that firms are homogeneous at the beginning, possessing the same number of workers, and that the expected demand aligns with the production capacity given by the number of workers, we can derive:

$$Z^e_{f,i} = O_{f,i} = (1 - U_i) \frac{L}{N} u^* Tec.Coef f_{f,i}. \tag{D.2}$$

Considering the initial level of production, all firms begin with $M_i = O_{f,i}/v$ capital machines. It should be noted that since the firms possess all the necessary machines to produce, the labor demand of the capital goods sector is zero. Assuming that initial prices are equal among all firms, with $P_{f,i} = 10$ and an equal markup of $m_{f,i} = 0.6$, the initial wage for all employed workers is:

$$W_i = \frac{P_{f,i}}{(1+m_{f,i})Tec.Coef_{f,i}}. \quad \text{(D.3)}$$

In view of the initial wage, the initial value of the unemployment insurance is $UI = 0.4W_i$. The fraction of the wage paid in unemployment benefits was based on the research of Dosi et al. (2010). We assume that all workers do not have any accumulated wealth at the beginning of the simulations and that markets are clearing, thus the nominal supply equals the nominal demand. The nominal aggregate supply is given by $AggS_i = \sum(P_{f,i}O_{f,i})$. Given the wages and unemployment benefits, the total nominal demand of the workers is:

$$AggC_{w,i} = \sum C_{w,t} = (1-tx_w)c_w(W_i(1-U_i) + 0.4W_iU_i)L. \quad \text{(D.4)}$$

We assumed that the total government consumption at the beginning is equal to 10% of the $AggS_i$. Hence, the nominal aggregate demand from the capitalist is:

$$AggC_{c,i} = AggS_i - 0.1AggS_i - AggC_{w,i}. \quad \text{(D.5)}$$

Considering the price equation, and assuming that all transactions with firms and the private bank result in capitalists receiving income net of wages and taxes, either in the form of interest on deposits or dividends, the total amount of income received by capitalists is:

$$YD_{c,i} = (1-tx_c)(AggS_i - L * U_i * W_i). \quad \text{(D.6)}$$

With the consumption equation of the capitalist, we can determine the value of capitalist wealth prior to the initial time as:

$$We_{h,c,i-1} = (AggC_{c,i} - c_cYD_c)/w_c. \quad \text{(D.7)}$$

And the initial wealth as:

$$We_{h,c,i} = YD_{c,i} - AggC_{c,i} + We_{h,c,i-1}. \quad \text{(D.8)}$$

From Table (C), since the workers do not have accumulated wealth, it can be inferred that the only net worth agent in the system is the capitalist and the only agent with a negative balance is the government. Therefore, $We_{h,c,i} = B_i$, meaning that the stock of wealth is equal to the stock of government bonds. With the parameters α_0, α_1 and the assumption that at the beginning of the simulations the base interest rate is $ib, i = (1 + r)(1 + \pi) - 1$, the stock of initial cash of the capitalists, Mci, and deposits Dc_i can be determined.

The initial cash retained and loans of the firms are equal and a function of the initial price of the capital goods and the initial number of machines. The initial price of the capital machines is:

$$Pk_i = (1 + 3m_{f,i})(1.5W_i)/(frac * a) \tag{D.9}$$

And, the total stock of cash and debt of the firms:

$$Lo_i = Mfc_i = N * M_i * Pk_i \tag{D.10}$$

The sum of Mc_i and Mfc_i gives the initial total stock of money, M. This is equal to the initial stock of bank reserves, Br. To verify the accuracy of the computation, Br_i must also be equal to $Lo_i + B_i - Dc_i$. With these initial assumptions, the model is stock-flow consistent.

Appendix E

A code package to quick develop ABMs in R

A considerable part of the effort in the current dissertation was devoted to developing an R package of codes that can quickly implement and run large-scale agent-based models (or dynamic systems in cases of models with structural equations). The present Appendix is a short description of the package developed using the R language. R is generally considered slow programming language compared to other, such as C++. However, it is a relatively easy language to learn to program, and it has a thriving community of statisticians, programmers, mathematicians, and economists willing to help. The community's growth and the widespread use of R among economists led to the decision to develop this package. It is common to find economists who are interested in the topic of agent-based models, but who decide not to delve deeper into the subject or initiate a research in the field due to the barrier involved in learning new programming languages. The aims to develop a code package dedicated to the development of ABMs was to provide an easy tool for anyone who is already familiar with R to start developing their own models. The code can be downloaded from GitHub (https://github.com/n-schiozer/). All the functions' codes are commented, and they are open to being edited by anyone. Any suggestions or constructive criticisms are welcome.

E.1 The creation of the model

R is a language that runs much faster when operations are carried out using matrix operations. Much of the slowness observed in R is due to the extensive and unoptimized use of for-loops by users. Given this, the package developed a way to formalize ABMs following the idea of intensively using matrix operations. The agents in the model can be seen as a set of matrices, and most of the operations in ABM can be represented as matrix operations or functions applied to matrices.

The creation of the model involves three steps, two of which are obligatory, and one is optional. The first step involves writing all the functions that will operate sequentially at every time-step of the simulation. The functions do not need to have all the variables necessary to run as input. The only requirement is that the return function that generates the output must have the exact name of a variable that is being used in the model. For example, if a function is developed to set the total amount of sales for the firms, inside of the return function, we must have a variable defined as “firm@sales”. The first part of the variable’s name defines the type of agent, and the second part defines the name of a specific variable related to the agent. Apart from the requirement of the return function, the package user is free to model whatever they want inside the function, using any operations, auxiliary functions, or packages that the R world allows.

Each function must be added to a list using a function called “addABMfun.”When the model is run or the function “checkmodelstructure”is executed, the model is checked for the presence of simultaneous causality. If circular causality is observed, the model checks will warn the user and stop. If not, the user is shown all the functions of the model and the sequence in which they will be solved.

The second step in creating the model is to create the agents using the “createagent”function. With these functions, we create a type of agent and all the matrices related to that agent. We also need to specify the initial conditions of the matrices and the number of agents. The model’s functions must be created before creating the agents because the code scans the function to determine the number of lags needed for each state variable of the agents.

The third optional step is to create lists of objects for the agents. Unlike matrices, the lists can change in size during the simulations. Therefore, they must be used with caution to avoid bugs and slowness. To create lists, you must specify their names, the number of lists, and the initial lists. For example, we used lists of objects for the firms in our simulations, defining lists of employees and machines. Before running the model, we created lists specifying the number of machines of each firm and their technical characteristics. With the purchase of new machines and the breakdown of old ones, the lists are constantly changing in size.

E.2 Running the model

The main function of the package is called “simulationMULTABM”. It receives several inputs such as the number of simulation periods, the list of created functions, the list of objects which includes matrices and lists, the number of simulations to be run, whether to run the simulations in parallel, a list with variable names to be saved, and whether the model should be run with debugging or not.

The results of the simulations are saved in a list named “results”. For instance, in list 1, you can find all the sales results made by each firm in every period of the first simulation. Using these lists, you can plot graphs, calculate statistics of the simulations, or employ the results in other functions such as calibrating the model or conducting sensitivity analysis with other R packages.

E.3 Debbuging

There is a debugging feature in the code. If debugging is enabled, the functions check for errors such as infinite or missing values or unavailable values at each time step during the simulation. The debugging feature also looks for explosive behavior. If a list of variables names is provided, the debugging feature considers explosive behavior if any of the variables double from one period to the next (hence, caution must be taken when selecting the variable type). When an error is detected, a message is displayed to the user indicating which function generated the error and the type of error. It is also possible to perform microbenchmarking with the debugging feature, which analyzes the time taken by each function to run at the end of the simulation, indicating which functions are the most time expensive in the model.