Productivity and unemployment: An ABM approach

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Abstract

We investigate the relationship between productivity and unemployment with an ABM approach. In particular, we use the framework of Riccetti et al. (2015) to run computer simulations considering different levels of productivity and analyse the corresponding effects on unemployment.

The simulation results show the emergence of a fluctuating pattern of the unemployment rate, the public deficit and the inflation rate as functions of productivity. The marked pattern of the unemployment rate in the model is empirically validated by the OECD database. This unexpected oscillating behaviour remains in subsequent simplifications of the baseline model. Thus, our approach allows us to explain the productivity-employment linkage as an emergent macroeconomic property of a complex system.

We conclude that economic policies aimed at increasing labour productivity could have unintended side effects on the unemployment rate, the government deficit and the inflation rate, which should be explored and taken into account before the policy is implemented.

Keywords: Productivity; unemployment; macroeconomic dynamics; agent-based models

1. Introduction

Labour productivity is a generally accepted measure of economic efficiency; therefore, it is considered a usual performance indicator for an economy (Mas-Colell et al., 1995). It measures how efficiently labour input is combined with other factors of production, and it depends not only on the personal capacities of workers or the intensity of their effort but also to a large degree on the presence and/or use of other inputs (e.g., capital, intermediate inputs, technical change, economies of scale).

The impact of labour productivity on economic growth and social development has been widely studied (see Atolia et al., 2012, for a review). However, little attention has been paid to the effect that increases in productivity have on employment, presumably due to difficulties in identifying such a causal link. In fact, as shown below, a simple scatter graph of real data[1] allows us to illustrate this uncertain influence. Complications derived from possible countervailing dynamics between employment and productivity were recognized by the International Labour Organization (ILO) as far back as its Employment Policy Convention (Nº 122, 1964). This caused the ILO to aim for "full and productive employment".

[Figure 1 about here]

Figure 1 shows the plot of the unemployment rate versus labour productivity for three countries: Australia, Germany and Japan. Although spurious correlations could be present, meaningful fluctuations clearly appear in all three cases, which might suggest that small increases in labour productivity can produce both upward and downward swings in the unemployment rate. Similar oscillating patterns are present to a greater or lesser degree

[1] We consider yearly data from the OECD for different countries. In the OECD database (https://data.oecd.org/), labour productivity is calculated by the ratio between GDP (measured in USD constant prices using 2010 as the base year) and the total number of hours worked, taking the normalized value 100 at 2010.

in all OECD countries[2]. Furthermore, the significant relative size of the fluctuations can hardly be attributed to random events. As shown in Figure 2, countries in the second and third quartiles (Q2 and Q3) have high residual deviations, ranging from 16% to 25%.

[Figure 2 about here]

Economic theory provides us with different explanations of how the unemployment rate may be affected by a sudden increase or fall in the productivity growth rate associated with technological developments. In the next section, we discuss some of the mainstream arguments related to an array of channels: employment search (Pissarides, 2000), the creation-destruction of sectors (Aghion and Howitt, 1998), technological uncertainty (Manuelli, 2000), the wealth and income distributions (Atolia et al., 2012), worker effort (Leibenstein, 1966, 1975, 1978a, 1978b, 1979; Stigler, 1976) and psychological damage (Darity and Goldsmith, 1996; Goldsmith et al., 1996). However, none of these proposed channels seem to enlighten us properly about the observed fluctuations, probably due to the complexity of the phenomenon (where both institutions and decisions of agents are involved), which makes it difficult to model a relationship directly between employment and productivity.

In this work, we address the uncertain linkage between productivity and employment in an attempt to discover new theoretical explanations within a framework of agent-based modelling (ABM). Agent-based models are useful for simulating social interactions within complex structures with a view to detecting collective behaviour. It is in these computational models that emerging properties and novelties appear, and so such models can be helpful for our purpose here, which also has practical implications. In particular, if our analysis detects nonlinear, oscillating patterns, economic policies aimed at increasing labour productivity could have either positive or negative side effects on the

[2] In https://archive.org/details/ProductivityAndUnemploymentForOCDECountries, data and graphs are shown for a more extensive set of countries than those presented in Figure 1.

unemployment rate, so further exploration should be carried out before such policies are implemented to determine whether we are facing a positive or negative correlation stage.

The paper is structured as follows. In Section 2, we summarize the main theoretical explanations for the employment-productivity linkage and justify the use of agent-based modelling. The specific agent-based framework (introduced in Riccetti et al., 2015) is described in Section 3. In Section 4, we present the results of our simulations, which show a marked fluctuating, nonlinear pattern. Section 5 focuses on providing an empirical validation of this pattern. Finally, we summarize our findings in Section 6.

2. Theoretical approaches and methodological framework

In this section, we review the usual theoretical arguments that attempt to explain the possible relationship between employment and productivity, beginning with the classical theory of employment search (Pissarides, 2000).

According to this theory, workers (with different training, experience and skills) look for adequate and well-paid jobs, while companies require workers with greater productive capacity. Both workers and companies do not have all the necessary information for their respective choices. In line with their own information, workers accept job offers above their reserve wages and reject those offers below them. However, an increase in labour productivity should increase the salary offered by companies and concomitantly reduce the time the average worker needs to find a suitable job. Consequently, an increase in productivity should generate a decrease in the unemployment rate.

However, this decrease in the unemployment rate may not be sustained over time if workers notice increases in wages offered by companies and, consequently, adjust their reserve wages to the new level offered in the economy. Through this dynamic, the unemployment rate would gradually return to the level prior to the increase in productivity in a gradual adjustment process, although the process could take time. This could be one of the reasons why an increase in productivity does not necessarily imply a permanent reduction in unemployment levels. However, other factors, such as reduced search costs due to technological improvements or organizational policies, could have a persistent effect on the unemployment rate.

Changes in the long-term growth rate of the economy may also impact the equilibrium unemployment rate, even without a change in search technology. As Pissarides (2000) remarks, the decision for a company to employ a worker implies comparing the recruitment costs incurred now with the earnings that will accumulate once the worker is hired. Thus, an increase in the economic growth rate would raise future earnings, making current hiring more attractive and leading to a decrease in the unemployment rate. Since productivity correlates positively with the growth rate, it has a negative impact on the unemployment rate.

This result is sensitive to changes in some of the assumptions of the model. For example, Aghion and Howitt (1998) highlight in their Schumpeterian model of growth with the R&D sector that technological development does not happen uniformly in all sectors and tends to eliminate obsolete jobs while creating new ones. As a result, it is the difference in increases in job creation and destruction rates that ultimately determines whether the unemployment rate increases or decreases.

Manuelli (2000) provides an alternative short-term explanation. In his model, a technological innovation in the development stage that is not yet viable negatively affects the market value of current companies, which causes companies to reduce investment and job creation pending the availability of the innovation. Therefore, the unemployment rate increases. However, when this technology becomes available, companies will begin to invest in it and create more jobs to implement it, thus generating a decrease in the unemployment rate. For Manuelli, this was one of the reasons why, in the mid-1970s, stock markets were depressed and unemployment increased. The markets were warning about the arrival of new technologies that would make current technologies obsolete. These novel technologies (related to information technology and computer science) began to reach their later development stages at some point in the 1980s, which led to a decrease in unemployment and an increase in productivity over time.

Finally, let us mention the work of Atolia et al. (2012), who examine the consequences of a change in productivity in the evolution of the wealth and income distributions over time. These authors find that although the long-term results for the aggregate economy are independent of the change in productivity, the short-term responses can be quite sensitive. A sharp productivity increase leads to an immediate rise in production, while a continuous ongoing change leads to the opposite dynamic, where both employment and production decrease.

On the other hand, behavioural economics provides us with explanations of the inverse relationship, that is, from the unemployment rate to productivity. In particular, X-efficiency theories seek to explain how higher unemployment rates lead to lower productivity. Since recessions are characterized by high unemployment rates (creating a floating form of labour reserve or a reserve army of labour, in the words of Karl Marx), salaries tend to decrease. X-efficiency theories suggest that low perceived salaries can produce X-inefficiency in production, that is, workers tend to reduce their effort and productivity (Leibenstein, 1966, 1975, 1978a, 1978b, 1979; Stigler, 1976). When workers think they have received unfair treatment (such as a lower salary than they deserve), they respond by neutralizing any economic benefits gained from cutting salaries. As a consequence, lower salaries do not necessarily translate to lower costs for the firm, and thus, a higher unemployment rate tends to produce lower labour productivity.

Similar results can be derived from empirical evidence in behavioural economics: being unemployed long-term can cause serious psychological damage to workers (low selfconfidence, depression, loss of will and so on), which, in turn, can permanently undermine workers' productivity and their job searches (Darity and Goldsmith, 1996; Goldsmith et al., 1996). Therefore, sustained high rates of unemployment can damage the productivity of the whole economy in the long term, creating a vicious circle.

In summary, we conclude that the relationship between (un)employment and productivity can be addressed from different theoretical approaches. However, the complexity of the phenomenon, where both institutions and decisions of agents are involved, makes it difficult to find a satisfactory theoretical explanation for the fluctuating patterns observed in the real data. In this work, we propose the adoption of an alternative methodological approach using agent-based models.

Agent-based modelling (ABM) is a multidisciplinary methodology that deals with the study of socio-economic systems whose aggregate properties at the macro-level can be properly explained as emerging from a set of decentralized relationships between heterogeneous agents at the micro-level, revealing non-trivial connections at the micro-macro levels (Pyka and Fagiolo, 2007; Rixen and Weigand, 2014). This way to model a system is known as "bottom-up". This methodology is highly encouraged when studying a complex system. In this case, closed-form solutions tend to be impossible to obtain either due to the analytical intractability of the model, to the difficulties in observing or measuring some of the variables under consideration or to the presence of qualitative variables.

Despite its novelty, agent-based modelling has attracted growing interest as a theoretical tool for studying complex systems in social sciences (see Klein et al., 2018, for some statistics), mainly in economics (see Farmer and Foley, 2009; Dawid and Neugart, 2011), where its use has become widespread (see Tesfatsion, 2001, for an early overview of ABM in economics and Tesfatsion, 2002, for a standardization of good practices). Some recent papers in economics are Riccetti et al. (2018) on endogenous macroeconomic crises; Silvestre et al. (2019) on endogenous macroeconomic growth; Assenza et al. (2018) on fiscal policymaking; Giri et al. (2019) on monetary policymaking; Mazzocchetti et al. (2018) on loans/mortgages and business cycles; Bookstaber et al. (2018) on the vulnerability of the financial system; Fatas-Villafranca et al. (2019) on market structure based on demand-side factors; Seppecher et al. (2018) on price setting; Dehghanpour et al. (2018) on electrical markets; Günther and Stummer (2018) on innovation diffusion of consumer computers; and O'Donoghue and Somerville (2018) on risk aversion.

In recent years, some general agent-based frameworks have been introduced to computationally simulate artificial economies, which can be used for further explorations. For example, EURACE (Deissenberg et al., 2008) was designed to simulate the European economy. In other research, Howitt (2008) introduces a Keynesian macro model from heterogeneous microeconomic behavioural rules operating in various sectors; Dosi et al. (2006) present an evolutionary macroeconomic model with Keynesian features focused on industrial R&D as a core driver of economic growth; and Riccetti, Russo and Gallegati[3] (2015) develop a general (dis)equilibrium macroeconomic microfounded framework with heterogeneous agents (households, firms and banks), which directly interact in different markets (goods, labour, credit and bank deposits) according to a common general and decentralized matching process.

In particular, the Riccetti-Russo-Gallegati framework has many useful features (it has a low number of specifications, flexibility, and consistency; it endogenously creates business cycles in which real and financial aspects interact; it allows computational experiments about policy intervention to be performed; etc.) that make it especially suitable for different purposes. The framework has thus been used in Riccetti et al. (2013a) to explore the effects of banking regulation (credit exposure and lending concentration) on macroeconomic dynamics (banking stability); Riccetti et al. (2013b) to study how

[3] A first draft of this paper was published in 2012 (MPRA Paper from University Library of Munich, Germany).

unemployment benefits affect macroeconomic dynamics; Russo et al. (2014) to explain the interplay between inequality and financial fragility; Russo et al. (2016) to evaluate the convenience of applying the trivial solution to the problem studied in the previous paper, that is, introducing consumer credit to avoid financial fragility; Riccetti et al. (2016a) to study the role of dividends distributed by firms and banks on financial instability and macroeconomic dynamics; Riccetti et al. (2016b) to analyse the effect of stock market volatility in the real economy; Russo (2017) to show how the social structure affects macroeconomic dynamics; and Giri et al. (2019) to study the relationship between monetary policy and large-scale crisis events.

3. The Riccetti-Russo-Gallegati model

In this paper, we draw on a computational agent-based model that allows us to identify the potential impact of labour productivity on the unemployment rate. In particular, we take the well-established Riccetti-Russo-Gallegati model (2015) as our primary framework. This model provides a macroeconomic microfounded setting that is highly suitable for our purpose, with heterogeneous agents who interact in markets driven by a decentralized matching mechanism.

Accordingly, we consider an economy populated by individuals ($i = 1,2, \dots, H$), firms ($f = 1,2, \dots, F$), banks ($b = 1,2, \dots, B$), a central bank and a government, which interact over a time span $t = 1,2, \dots, T$ in four markets: credit market (firms and banks), labour market (firms and individuals), goods market (individuals and firms) and deposit market (banks and individuals). All agents are supposed to be boundedly rational, thus following simple rules of behaviour in an incomplete and asymmetric information scenario. The interaction structure of all markets is based on the same matching protocol. First, agents from the demand side (firms in the credit market, firms in the labour market, individuals in the goods market, and banks in the deposit market) observe a random subset of potential counterparts, whose size depends on a parameter $0 < \chi \leq 1$ (which proxies the degree of imperfect information). Then, the agents choose the most suitable partners according to some market-specific criteria.

The sequence of events occurring in each period t is detailed below (see Riccetti, Russo & Gallegati, 2015, for a full description of the model).

1. *Central bank*. The bank decides the nominal interest rate i_t^{CB} as well as the amount of money M_t to be lent to banks trying to reduce the aggregate excess supply or demand in the credit market in the previous period.

2. *Credit market*. Firms demand credit from banks ($B_{f,t}^d$) in relation to their net worth $A_{f,t}$ and leverage target $l_{f,t}$ (which is updated in each period according to the profits $\pi_{f,t-1}$ and the inventories $\hat{y}_{f,t-1}$). Banks set their credit supply ($B_{b,t}^d$) depending on their net worth $A_{b,t}$, deposits $D_{b,t}$ and central bank credit $m_{b,t}$. The interest rate charged by bank b on firm f at time t is given by $i_{b,f,t} = i_t^{CB} + \hat{\imath}_{b,t} + \bar{\imath}_{f,t}$, where $\hat{\imath}_{b,t}$ is a bank-specific component and $\bar{\imath}_{f,t}$ is a risk premium on firm target leverage.

   Firms choose the banks offering the lowest interest rates. At the end of the matching process, some banks may lend all available credit, while others may remain with some residual money. Similarly, some firms may obtain the required credit, while others may remain credit constrained.

3. *Labour market*. Workers propose a wage $w_{i,t}$ updated according to their occupational status in the previous period (upward if employed, downward if unemployed). The government hires a randomly selected fraction g of individuals (the remaining part is available for working in the firms). Firm's f labour demand depends on available funds $A_{f,t} + B_{f,t}$ (net worth and bank credit).

   Firms hire $n_{f,t}$ workers with the lowest proposed salaries. After the matching process, some firms satisfy their labour demand, while others hold back residual cash; at the same time, some people may remain unemployed. Employed people pay income taxes to the government.

4. *Public deficit*. Given the wage expenditure for public workers and the taxes collected in the previous period (coming from private incomes and wealth), the government calculates its deficit (or surplus) and updates the overall debt. Banks buy government securities to use up excess liquidity. The central bank purchases the remaining securities.

5. *Goods market*. Firms produce consumption goods on the basis of hired workers: $y_{f,t} = \phi n_{f,t}$, where $\phi \geq 1$ is a productivity parameter. They put into the goods market their production from the current period and the inventories from the previous period $\hat{y}_{f,t-1}$ and update the price $p_{f,t}$ in line with $\hat{y}_{f,t-1}$.

   Individuals decide their desired consumption $c_{i,t}^{d}$ on the basis of their wages $w_{i,t}$ and net wealth $A_{i,t-1}$. Individuals acquire goods from the cheapest supplier. At the end of the matching process, some individuals satisfy their desired consumption, while others may remain with residual cash (savings); on the other hand, some firms sell all their production, while others may accumulate inventories.

6. *Deposit market*. Individuals deposit their savings in banks, asking for a minimum interest rate $i_{i,t}^{D}$, updated from the previous period (upward if $i_{i,t-1}^{D}$ was obtained, downward if not). Banks offer an interest rate $i_{b,t}^{D}$ on deposits according to the funds required.

   Individuals deposit all their available money in a single bank that offers the highest interest rate if it is higher than $i_{i,t}^{D}$. Otherwise, at an interest rate below the desired one, individuals do not deposit their savings.

7. *Wealth evolution*.

   a. Firms calculate profits $\pi_{f,t}$, and surviving firms repay their debt to banks, pay taxes, and distribute dividends to individuals.

b. Banks calculate profits. Individuals lose (part of their) deposited money in case of bank defaults. Surviving banks pay taxes and distribute dividends to individuals.
c. Individuals update their wealth, on which they pay a capital levy.

8. *Replacement of bankrupt agents*. New participants replace bankrupt agents (firms or banks with negative net worth) according to a one-to-one replacement. The money needed to finance new participants is first subtracted from individuals' wealth and, if it is not enough, it is provided by the government.

From the point of view of economic theory, this is a stock-flow consistent macroeconomic model with post-Keynesian characteristics and an acyclic public sector with limited participation (the public sector sets taxes, gives employment and provides financial aid to bankrupt agents). On the other hand, the financial structure of companies adjusts in line with dynamic trade-off theory and includes short-term loans (within the period).

4. Computer simulations of the agent-based model

We run a series of computer simulations for the same parameter setting as the baseline model (Riccetti et al., 2015). Accordingly, we consider $H = 500$ individuals, $F = 80$ firms, $B = 10$ banks, and a time span of $T = 150$ periods, and we analyse the results for the last 50 periods (so the first 100 are used to initiate the model). However, unlike the RRG model, we do not fix the value of the productivity parameter ϕ (set to 3 in the seminal work). Instead, we vary it from $\phi = 2$ to $\phi = 12$ (with a step size of 0.01), keeping all other parameters constant, and we carry out 500 realizations (with different random seeds) for each value of productivity.

The simulation results are displayed in Figure 3 and show the emergence of fluctuations in the graph of the unemployment rate as a function of productivity.

[Figure 3 about here]

This unexpected behaviour seems to resemble the oscillations observed to a greater or lesser extent in all OECD countries, and consequently, the RRG model could provide us with theoretical explanations. Similar fluctuating patterns are also obtained when both the public deficit and the inflation rate versus productivity are plotted (see Figures 4 and 5, respectively). Therefore, increases in productivity have an ambiguous effect on the virtual economy generated by the computational framework considered, suggesting that small increases in labour productivity might produce upward or downward swings in the unemployment rate, in the government deficit and in the inflation rate.

[Figure 4 about here]

[Figure 5 about here]

To identify the relevant factors that produce such nonlinear, oscillating dynamics, we analyse simpler versions of the RRG baseline model. In particular, we sequentially remove different components from this primary framework[4]. First, we take $\chi = 1$, which implies that perfect information is assumed in all four markets (PI version) and whose simulations produce similar figures as those from the baseline model. Second, we set $M_t = 0$; that is, we additionally consider that there is no credit supply from the central bank (NCB-PI version), which again does not change the qualitative results.

Continuing with our top-down strategy, we now remove the credit market (by setting $B^d_{b,t} = 0$ for each bank b) and the deposit market (by fixing $i^{CB}_t = 0$, which implies $i^D_{b,t} = 0$ for each bank b). Somewhat surprisingly, the new reduced model with no credit market, no deposit market, no central bank and perfect information (NCM-NDM-NCB-PI version) still preserves the same patterns as those obtained from the original framework

[4] We are interested in finding reduced versions of the Riccetti-Russo-Gallegati model that preserve the oscillating pattern and so allow us to study the relationship between productivity and (un)employment. However, other results produced by the full model (from financial contagion to large crises) could be not reproduced by these simpler versions.

(as shown in Figure 6). The removed components can reduce or amplify the size of fluctuations, but they are not directly responsible for the oscillations.

[Figure 6 about here]

As commented in the previous section, the government plays a symbolic, passive role in the RRG baseline model, only hiring gH workers in each period and collecting taxes but choosing neither the fraction g nor the tax rates on income and wealth. Although no significant influence on the results is expected, we have simulated the NCM-NDM-NCB-PI version for different sizes of the public sector ($g = 0.1, 0.2, 0.3, 0.4, 0.5$) and adjusted tax rates. Figure 7 clearly shows the persistence of fluctuating patterns regardless of the size of the public sector. We see that variations in the unemployment level are the only relevant logical effect of resizing the public sector on the reduced model.

[Figure 7 about here]

At this point, labour and goods markets are the only components that remain unchanged from the RRG baseline model. However, even when we modify the rules on updating the wages $w_{i,t}$ demanded by individuals and the prices $p_{f,t}$ set by firms, similar evolutions are obtained (for example, considering adaptive or replicator-type updating algorithms), which suggests that the oscillating behaviours are due to nonlinear interactions between the heterogeneous agents involved (in particular, individuals and firms). Note that the oscillations cannot be explained by transient dynamics or random shocks but rather are persistent results in all versions of the RRG model considered. Consequently, we conclude that the fluctuating patterns exhibited by the unemployment rate, government deficit and inflation rate in terms of productivity are emergent properties of the baseline computational model.

Broadly speaking, emergent properties refer to systemic features that are entirely unexpected from micro-level specifications and arise from the collaborative functioning of a system but do not belong to any one part of that system. In other words, an emergent property of a complex system arises from the nonlinear interaction among its parts, none of which show this property, and so it cannot be predicted from their components, despite a thorough knowledge of the features of, and laws governing, its parts (Gros, 2008). Examples of emergent properties, which can arise from simple agent-based models with few interconnected components, include the layout of cities, the brain, ant colonies, flocks of birds and complex chemical systems. The intrinsic non-linearity of complex systems often makes their analytical treatment difficult, so that computational modelling is the usual methodological framework to identify and deal with emergent properties.

In our case, the NCM-NDM-NCB-PI model (with only two types of agents: individuals and firms) generates unexpected oscillations of the unemployment rate, the government deficit and the inflation rate as functions of productivity, as happened with the original RRG model. Therefore, the nonlinear interactions between individuals and firms (which produce complex dynamics and the emergence of fluctuating patterns) could be the main explanation for the dubious linkage between productivity and employment observed in real data. Other elements of the baseline model (banks, government, central bank, credit market, deposit market, etc.) can modulate the frequency and amplitude of oscillations, but they would be directly caused by two agents (individuals and firms) interacting in two markets (goods and labour). This mutual influence produces co-evolutions that are difficult to anticipate, resulting in the emergence of intricate patterns.

5. Empirical validation of the emergent pattern

As stated in the previous section, the extensive computer simulations carried out show the emergence of a marked pattern in the graph of the unemployment rate as a function of productivity (see Figure 3). Now, we address the issue of its potential empirical validation. First, it is worth pointing out three substantial constraints, some of which (common, to a greater or lesser degree, among theoretical models) can be addressed with a variety of technical procedures.

First, we must keep in mind the pure theoretical character of the Riccetti-Russo-Gallegati model, where all processes are oversimplified and without a sufficient degree of freedom to make empirical adjustments. Second, empirical data provide statistics about productivity indirectly through a proxy variable (the ratio between GDP and the total number of hours worked), whereas in the theoretical model, it is represented by the parameter ϕ, measured in units produced per individual in each period. Therefore, the agent-based model and real data do not deal with the same information. In addition, when the productivity parameter ϕ is changed, computer simulations run independently (what is plotted in Figures 3-7 is the average unemployment rate in the steady state for each value of ϕ, representing economies only differentiated by their productivity), unlike in the case of real data generated by temporal observations from each country, which can also be influenced by changes in other economic variables.

However, despite these difficulties, we carry out an empirical validation based on identifying which families of mathematical functions can reproduce the main features of the pattern generated by the theoretical model. In particular, we find that Figure 3 features a damped oscillation evolution[5] (which could be expressed by $\Psi(x) = ae^{-bx}\sin(cx + d)$ as usual) combined with a slightly increasing linear trend ($\Gamma(x) = ex + f$). Estimating these parameters, we obtain $a = 0.0617$, $b = 0.215$, $c = 3.57$, $d = 0.769$, $e = 0.00675$ and $f = 0.0833$, with $R^2 = 0.902$, meaning that the function provides a fairly good adjustment to the theoretical pattern, as shown in Figure 8.

[5] The emergence of damped oscillations may be related to the property of self-organized criticality, typically observed in complex systems that exhibit the "sandpile effect". In our model, low *relative* changes in productivity would be absorbed (with no impact) by the economy until they reached a critical value, after which they would then produce a significant influence on the process.

[Figure 8 about here]

Surprisingly, the proposed structure also successfully adjusts to observed statistics. In Figures 9, 10 and 11, we show real data and the estimated curve for Australia, Germany and Japan, respectively. The estimations for Australia and Germany exhibit a one-hump shape (left-skewed for Australia and right-skewed for Germany), while a double-hump curve appears for Japan. The R^2 values (0.829, 0.884 and 0.941, respectively) confirm a high goodness of fit in all three cases.

[Figure 9 about here]

[Figure 10 about here]

[Figure 11 about here]

In Table 1, we provide detailed results on the proposed estimation for the OECD countries (the first row shows the results from the theoretical model). Despite the abovementioned difficulties, the characteristic pattern inferred from the theoretical model gives quite satisfactory empirical estimations. In particular, the R^2 values from nonlinear estimation are significantly higher than those from linear regression in all cases, thus indicating substantially improved explanatory power.

[Table 1 about here]

6. Conclusion

In this paper, we have drawn on a well-established computational agent-based model (introduced in Riccetti et al., 2015) to identify the potential impact of changes in labour productivity on the unemployment rate. The RRG model provides a macroeconomic microfounded framework that is highly useful for this purpose, with heterogeneous agents that interact in markets driven by a decentralized matching mechanism. Unlike the baseline model where the productivity parameter (ϕ) was set to 3, we vary it between 2 and 12, keeping all other parameters as set out in the seminal work.

The simulation results show the emergence of fluctuations in the graph of the unemployment rate, the public deficit and the inflation rate as functions of productivity. As a consequence, increases in productivity have an ambiguous effect on the economy and can produce ups or downs in the three macroeconomic variables considered, which could explain the indeterminate effect of labour productivity on the unemployment rate observed in real data. In particular, the marked pattern of the unemployment rate in the model is empirically validated by the OECD database, with quite satisfactory results achieved for all countries.

This unexpected oscillating behaviour remains in subsequent simplifications of the RRG baseline model with no credit market, no deposit market, no central bank and perfect information. Furthermore, we verify the irrelevant role that the public sector and the rules for updating salaries and prices (the final components of the simplest version that were unchanged from the baseline model) play in the fluctuating patterns obtained. We thus conclude that oscillating behaviour must be due to nonlinear interactions between the heterogeneous agents involved (in particular, individuals and firms).

Consequently, we infer that the fluctuating patterns exhibited by the unemployment rate, the government deficit and the inflation rate in terms of productivity are emergent properties of a complex system. In such a way, the nonlinearity present in the interactions between individuals and firms (producing complex dynamics and the emergence of intricate patterns) seems to play the central role in the explanation of the oscillations (the frequency, regularity and amplitude of which could be influenced by many other factors) of the unemployment rate as a function of labour productivity observed in real data.

As a final and practical outcome, we conclude that economic policies aimed at increasing labour productivity could have unintended side effects on the unemployment rate, the government deficit and the inflation rate, so further exploration should be carried out before such policies are implemented to determine, for each case, whether we are facing a positive or negative correlation stage.

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Figures and Tables

	Fitness (R^2)		Nonlinear Model's Parameters $y = ae^{-bx}\sin(cx+d)+(ex+f)$					
Country	Linear	Nonlinear	a	b	c	d	e	f
Theory	5.99E-01	9.02E-01	6.17E-02	2.15E-01	3.57E+00	7.69E-01	6.75E-03	8.33E-02
AUS	1.34E-03	8.29E-01	7.16E+00	9.82E-03	1.15E-01	4.32E+01	7.55E-02	-1.37E-01
AUT	5.74E-01	8.59E-01	3.76E+00	1.97E-02	4.90E-01	2.46E+01	8.03E-02	-2.82E+00
BEL	8.68E-02	5.68E-01	-3.11E+07	1.83E-01	8.26E-01	-1.07E+01	-3.48E-02	1.15E+01
CAN	4.46E-02	6.62E-01	1.63E+02	5.94E-02	1.88E-01	3.04E+01	-6.08E-02	1.34E+01
CHE	4.71E-01	9.59E-01	6.08E+04	1.27E-01	-6.70E+01	-1.98E+01	1.04E-01	-5.81E+00
CHL	1.40E-01	6.57E-01	1.09E+01	2.10E-02	-1.02E-01	-7.88E+00	-4.93E-02	1.22E+01
CZE	5.12E-01	7.38E-01	-2.70E+04	1.21E-01	1.18E+00	3.08E+00	-1.59E-01	2.20E+01
DEU	4.18E-01	8.84E-01	3.18E-10	-2.31E-01	1.29E-01	9.25E+01	1.76E-01	-6.37E+00
DNK	3.01E-02	6.43E-01	1.81E+01	2.58E-02	8.24E-01	3.09E+01	7.56E-02	-1.22E+00
ESP	6.76E-01	9.47E-01	1.44E+04	5.18E-02	1.38E-01	3.60E+01	-9.47E+00	1.01E+03
EST	2.15E-01	4.66E-01	3.51E-01	-2.07E-02	3.47E-01	5.47E+01	-7.69E-02	1.69E+01
FIN	5.91E-01	6.60E-01	6.07E+03	1.02E-01	1.13E+00	2.76E+01	-1.00E-01	1.82E+01
FRA	5.16E-01	7.79E-01	3.36E-03	-5.28E-02	1.14E+00	-2.19E+01	3.07E-01	-2.20E+01
GBR	7.14E-02	5.07E-01	-3.28E-08	-1.78E-01	6.74E-01	4.47E+01	1.77E-02	3.61E+00
GRC	3.56E-02	5.78E-01	1.03E-01	-4.37E-02	4.14E-01	-6.09E+00	1.65E-01	-9.68E-01
HUN	1.51E-01	5.35E-01	1.89E-02	-5.06E-02	8.56E+01	1.37E+01	9.38E-02	-2.09E-01
IRL	2.20E-01	8.76E-01	7.58E+01	2.79E-02	9.56E-02	7.28E+01	-5.53E-02	1.67E+01
ISL	1.51E-01	8.94E-01	2.47E-01	-2.25E-02	3.57E-01	4.16E+01	1.02E-01	-5.68E+00
ISR	3.73E-01	8.78E-01	-4.65E+04	1.15E-01	2.80E-01	6.68E+01	-2.05E-01	2.74E+01
ITA	7.95E-05	3.88E-01	3.08E+01	-6.89E-03	1.62E-01	1.37E+01	1.13E+00	-4.33E+01
JPN	7.15E-01	9.41E-01	-1.19E-01	-2.47E-02	1.61E-01	4.03E+01	4.07E-02	5.62E-02
KOR	4.08E-02	4.36E-01	7.03E+00	3.23E-02	1.41E-01	7.43E+01	-8.57E-03	4.30E+00
LUX	7.56E-03	4.24E-01	1.33E-06	-1.31E-01	-4.24E+00	1.00E+02	9.19E-02	-3.99E+00
MEX	5.83E-02	2.14E-01	-3.27E+09	2.24E-01	8.08E-01	1.47E+01	-1.80E-02	5.72E+00
NLD	4.75E-01	8.18E-01	2.27E-07	-1.57E-01	-4.80E+01	4.45E+01	2.72E-01	-2.23E+01
NOR	2.51E-01	4.11E-01	9.24E-02	-1.32E-02	6.74E-01	-1.23E+01	5.73E-02	-2.17E+00
NZL	2.18E-01	8.41E-01	4.58E+01	3.44E-02	1.89E-01	2.40E+01	2.32E-03	5.73E+00
POL	7.01E-01	9.50E-01	5.07E+01	2.83E-02	2.18E-01	6.58E+01	-2.86E-01	3.85E+01
PRT	8.12E-01	8.73E-01	-7.14E-09	-1.90E-01	3.83E+00	2.35E+02	5.86E-01	-4.73E+01
RUS	7.84E-01	9.27E-01	2.45E+07	2.52E-01	3.93E+00	-1.65E+02	-1.04E-01	1.68E+01
SVK	1.93E-01	8.19E-01	9.14E+01	4.22E-02	1.80E-01	1.95E+01	-1.50E-01	2.77E+01
SVN	8.00E-02	4.11E-01	5.26E-09	-1.95E-01	1.06E+00	3.22E+01	6.21E-02	1.16E+00
SWE	3.93E-01	7.58E-01	9.75E-01	1.39E-04	-8.42E+01	-6.96E+00	1.08E-01	-3.80E+00
TUR	2.44E-03	7.12E-01	-5.30E+11	2.58E-01	5.39E-01	5.17E+01	9.96E-02	-1.67E+00
USA	6.51E-03	4.53E-01	6.49E-09	-2.05E-01	4.01E-01	5.02E+01	-4.18E-02	9.16E+00

Table 1: Results of the estimated curve for each country

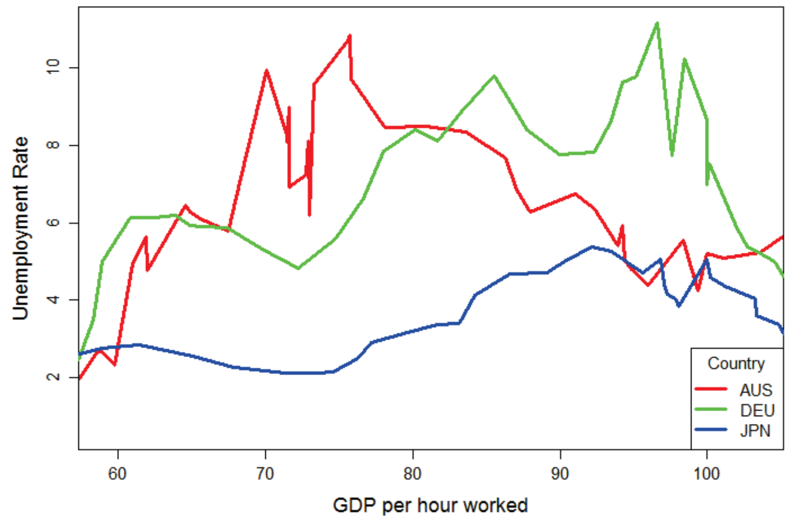

Figure 1: Unemployment rate versus labour productivity

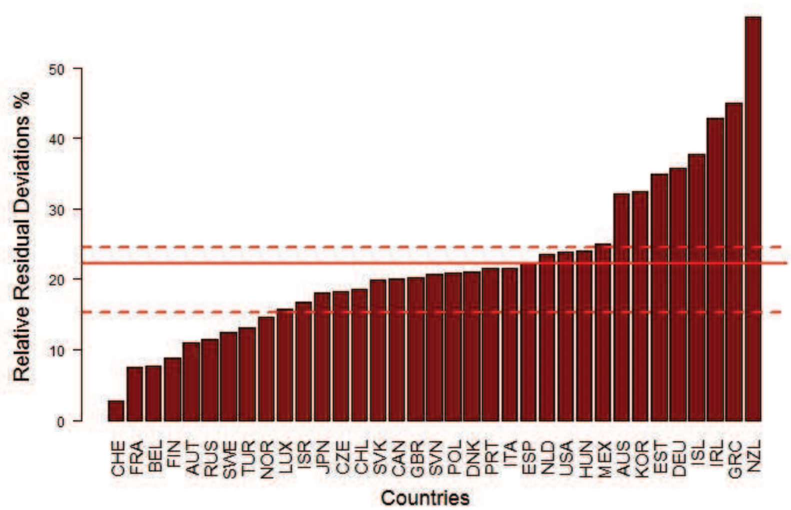

Figure 2: Relative deviations from linear regression (the solid line represents the average, and the dashed lines show the first and third quartiles)

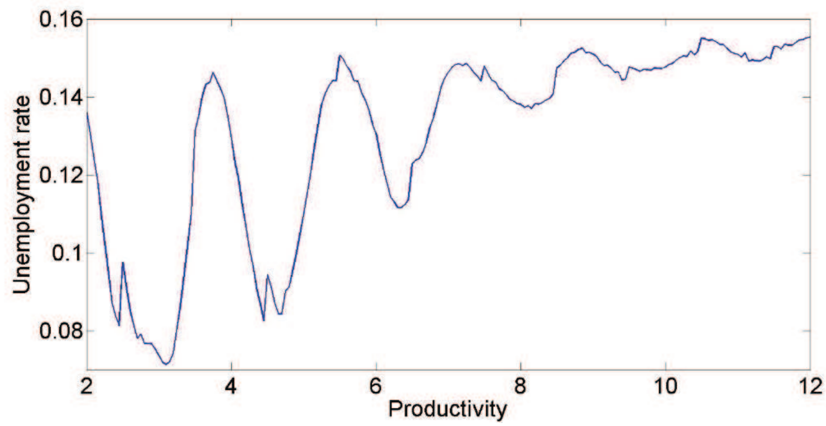

Figure 3: Unemployment rate as a function of productivity

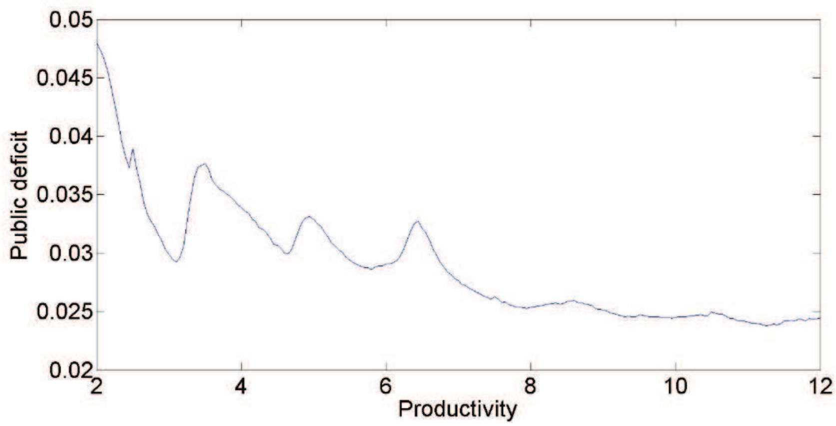

Figure 4: Government deficit versus productivity

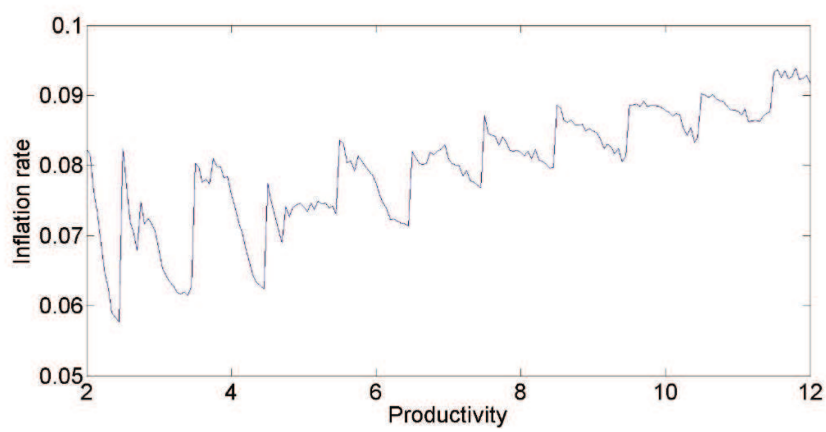

Figure 5: Inflation rate versus productivity

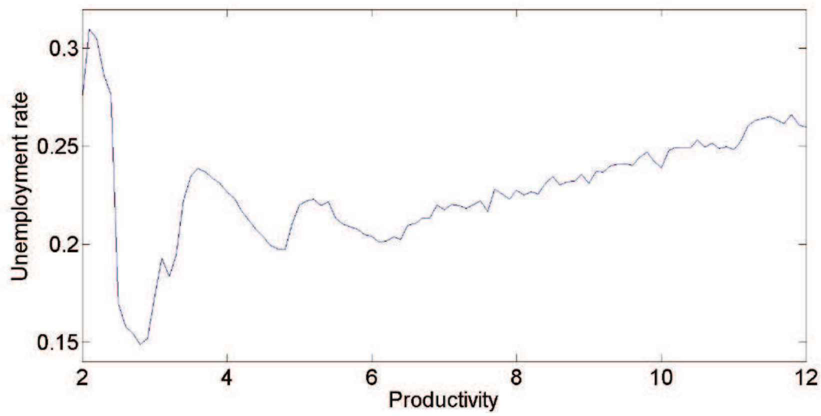

Figure 6: NCM-NDM-NCB-PI model

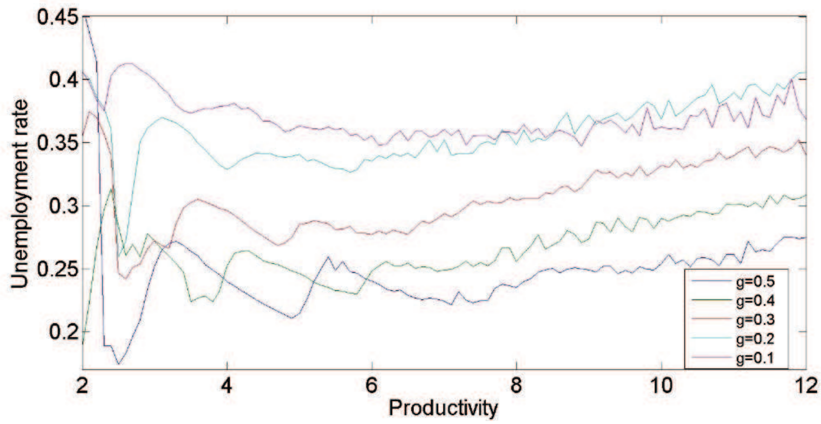

Figure 7: Different sizes of the public sector

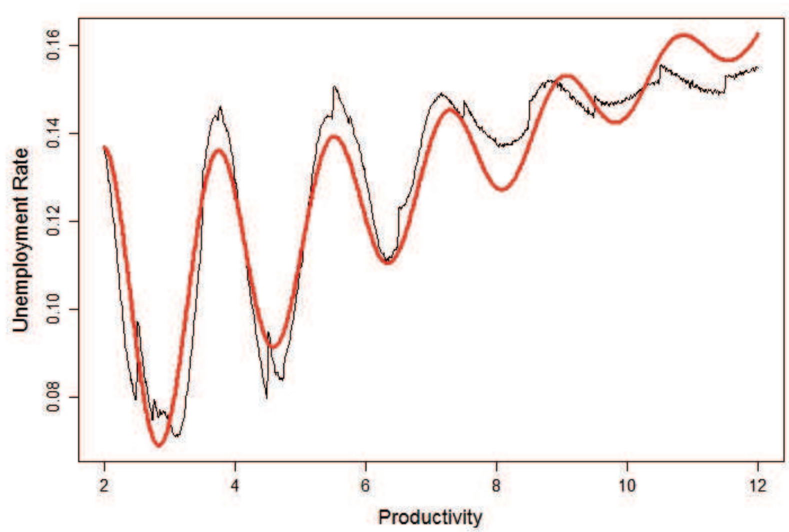

Figure 8: Theoretical pattern and mathematical adjustment

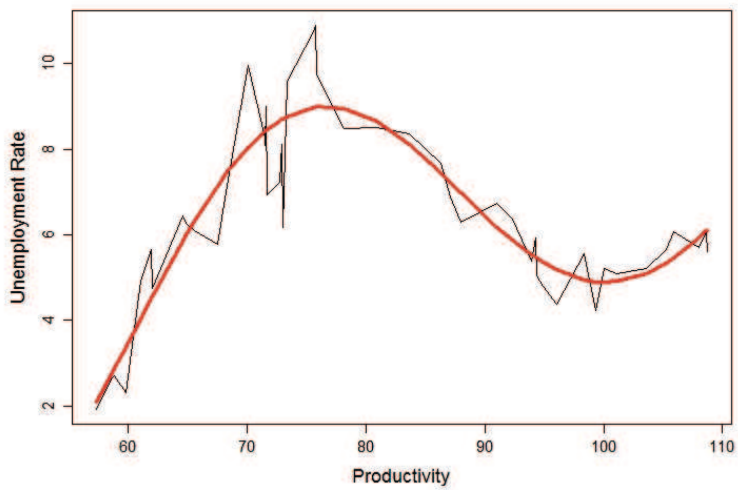

Figure 9: Estimated pattern for Australia

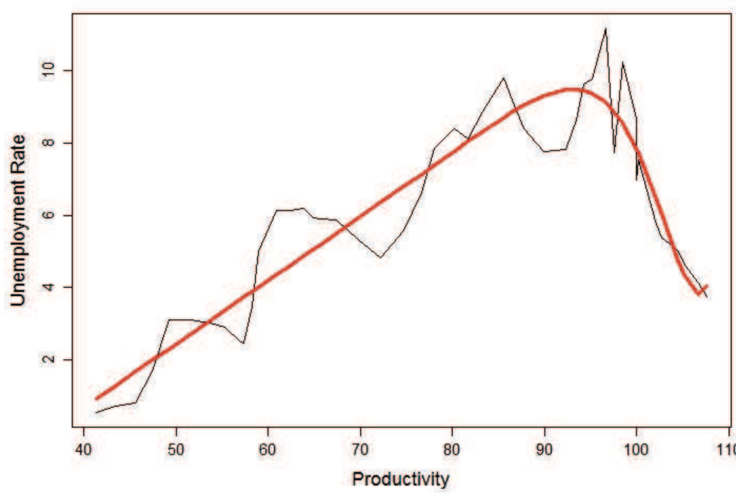

Figure 10: Estimated pattern for Germany

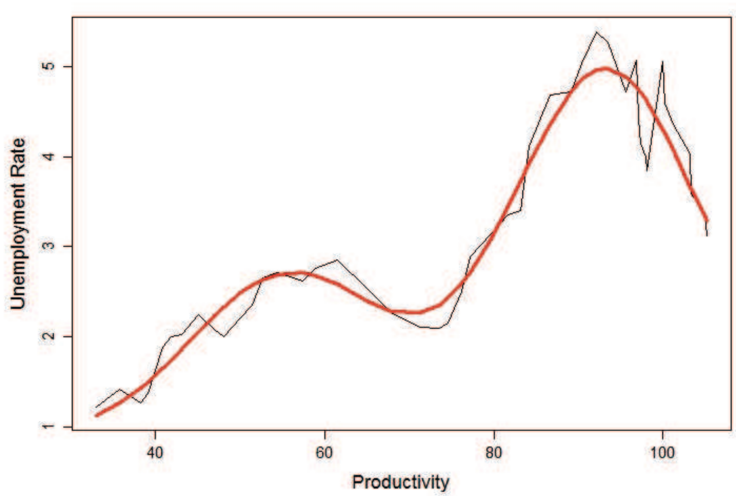

Figure 11: Estimated pattern for Japan