'Kaldor Facts' and the decline of Wage Share: An agent based-stock flow consistent model of induced technical change along Classical and Keynesian lines

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Abstract

This paper introduces the classical idea about the so-called *directed* and *induced* technical change (ITC) within a *Keynesian* demand-side and *evolutionary* endogenous growth model in order to analyse the interplay between technical change, long-run economic growth and functional income distribution. The ITC process is analysed within an Agent-Based Stock-Flow Consistent (AB-SFC) model, wherein credit-constrained heterogeneous firms choose both the *intensity* and the *direction* of innovation towards a labour- or capital-saving choice of technique. In the long-run, the model reproduces the so-called 'Kaldor stylised facts' (i.e. a purely labour-saving technical change process), however during the transitional phase the model shows a labour-saving/capital-using innovation pattern, as the aggregate output-capital ratio decreases until it stabilises in the long-run, and the labour share persistently decline as observed during the last decades in many advanced (and developing) economies. Within the present model, we can ascribe these results mainly to the effect exerted by the interplay between directed and biased technical change, the process of wage formation and the dynamics of aggregate demand. In order to stress the effective role of the innovation bias on the model dynamics, the baseline scenario has been compared with a 'counterfactual' scenario wherein 'neutral' technical progress is at work. The main findings are also confirmed by computing a sensitivity investigation on the key parameters shaping innovation and wage formation process.

Keywords Agent-based macroeconomics · Stock-flow consistent models · Induced technical change · Directed innovation · Choice of techniques · Labour share · Growth and distribution.

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1 Introduction

Since the inception of classical political economy the effect of technological progress on long-run economic growth and the distribution of income among social classes has been representing a crucial issue. For many years the bearings for modern theory of economic growth and distribution have been the empirical regularities known as 'Kaldor stylised facts' (Kaldor 1957), and in particular the relative constancy of aggregate output-capital ratio and distributive shares. However, over the last few decades we have observed a persistent decline in the wage share (OECD 2015; IMF 2017) together with moderate growth of real wages (in particular, as compared to the pace of labour productivity growth) and different patterns of output-capital ratio in advanced economies (Piketty 2014; Stiglitz 2016).

Following the 'Complex Adaptive System' approach, extensively applied to economics during the last decades (Arthur et al. 1997; Kirman 2010), and (Delli Gatti et al. 2007), this paper tries to exploit some insight provided by the *classical* interpretation of the *Induced Technical Change* (ITC) hypothesis by introducing it into a *Keynesian* demand-side and *evolutionary* endogenous growth model, so to analyse one of the possible explanations proposed to the persistent observed decline of the wage share. To the purpose, the model focuses on the interplay between labour-saving patterns of technical change, long-run economic growth and functional income distribution without recurring to any distinction between short-run (Keynesian) and long-run (classical) framework[1] as well as on the effect of potential feedback mechanisms between directed and biased technical change, the dynamics of wages and aggregate demand within an artificial simulated economy.

The model is mainly built upon the Post-Keynesian Agent Based-Stock Flow Consistent (AB-SFC) models implemented by (Caiani et al. 2016; Caiani et al. 2018b; 2018c). I introduce within this framework the possibility of *classical-fashioned* 'induced' and 'biased' technical change processes as the heterogeneous consumption-good firms choose both the *intensity* and *direction* of innovation towards labour- or capital-saving choice of techniques, thereby adopting the new production technique depending on a classical *profitability criterion* (Okishio 1961; Shaikh 1978; 1999; 2016; Nakatani 1979; Park 2001).

In this way, while traditional ITC models analytically impose the trade-off between labour or capital productivity improvements, e.g. *via* the so-called 'Invention Possibility Frontier' (IPF) *á-la-Kennedy* (Kennedy 1964), the present model endogenously reproduces the '*innovation bias*' towards the adoption of labour-saving production techniques as an *emergent property* of the evolutionary innovation

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[1]On this ground, for example, (Dumenil and Levy 1999) proposed a '*traverse*' model wherein two different investment behaviours are implemented depending on the time horizon: a Keynesian investment function in the short-run and a classical investment function in the long-run. (Dosi et al. 2015) also propose an interesting analysis of *classical* and *Keynesian* accumulation regimes as different roots of business fluctuations.

process engaged by heterogeneous firms. Moreover, in the long-run the model is also able to reproduce the standard 'Kaldor facts' (i.e. with purely labour-saving technical change), although during the transitional phase a richer dynamics with labour-saving/capital-using innovation pattern emerges, as the aggregate output-capital ratio decreases until it stabilises in the long-run and the wage share persistently decline.

We can ascribe these findings to the directed and biased technical change process and to the negative feedback mechanisms between the increasing adoption of labour-saving production techniques, negatively affecting the aggregate level of unemployment, and the dynamics of wages with consequent contractions of aggregate consumption. In order to stress the effective role of the innovation bias on the model dynamics, the baseline scenario has been compared with a 'counterfactual' scenario with 'neutral' technical progress and with an extensive investigation on some key parameters shaping both innovation and wage formation process.

The paper is organised as follows: after a brief discussion about the related literature (Section 2), Section 3 provides the description of simulation schedule and behavioural rules adopted by the heterogeneous interacting agents, then Section 4 shows the main simulation results and Section 5 proposes a summary of the main findings with some consideration on possible further refinements of the model.

2 Related literature

The social and economic consequences of declining wage (or labour) share, growing capital-output ratio[2] and different patterns of the rate of profit have been brought to the centre of economic debate by Piketty's book (2014) and his analysis about inequalities and capital concentration within advanced economies characterised by weak growth. The declining pattern of aggregate wage share is nowadays at the core of economic and political economy debate about the interplay between technological change, wage bargaining process, institutional factors and distributive shares (see for example (Piketty 2014; Stiglitz 2012)), so as to lead many economists to highlight the evidence for 'new stylised facts' (Stiglitz 2016; Jones 2016).

The Organisation for Economic Co-operation and Development (OECD 2012; 2015) and the International Monetary Fund (IMF 2017) provide a detailed analysis of key factors proposed in literature as the main drivers of falling wage share during the last decades. On this ground, special attention has been devoted to the role of an increasingly faster process of labour-saving technical change and to the discrepancies between productivity growth and real wages pattern, especially within the European Monetary Union and the US.

Within the economic literature, different explanations have been proposed in order to account for the evidence of declining wage share mainly through neoclassical and classical *technology-based* or Post-Keynesian *demand-driven* lenses. From a Post-Keynesian perspective, the increasing role played by 'financialization' in advanced economies have been identified as the main factors accounting for the declining

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[2]See Stiglitz (2016) for a detailed discussion about the definition of capital-output ratio adopted by Piketty and its relation with the Kaldor facts.

wage share (Lavoie and Stockhammer 2013; Stockhammer 2013; Dünhaupt 2017), whereas within the neoclassical stream of literature both theoretical and empirical contributions mainly rely on the hypothesis of different values of elasticity of substitution between production input (labour and capital). Furthermore, other explanations focus either on the effects of changes in labour market institutions, e.g. the shrinking workers' bargaining power (Berthold et al. 2002; Bental and Demougin 2010; Checchi and García-Peñalosa 2010), or on the role played by 'globalization' in explaining the trend of labour share (Brock and Dobbelaere 2006; Doan and Wan 2017; Jayadev 2007). Recently, some contributions highlight the role of structural change as a further source for the decline of labour share in advanced economies from both neoclassical (Alvarez-Cuadrado et al. 2018) and Post-Keynesian/Kaleckian perspectives (Beqiraj et al. 2019).

From an empirical standpoint, many economists within the neoclassical stream of literature try to account for the role of technical change and its direction in affecting the declining labour share (Bentolila and Saint-Paul 2003; Bassanini and Manfredi 2014; Hutchinson and Persyn 2012; Karabarbounis and Neiman 2014). However as anticipated, all of these contributions have been focused on the estimation of an elasticity of substitution between production inputs greater than one as the sole explanation of an increasing 'capital deepening' affecting in turns the labour share.

During the nineties, Acemoglu proposes a revival of the so-called *induced* (ITC) and *directed* technical change hypothesis, stemming from Hicks (1932), by modelling an explicit direction of technical change, i.e. biased towards skilled or unskilled labour (Acemoglu 1998) or towards labour or capital input (Acemoglu 2002; 2003), in order to explain the dynamics of wages and labour share in the US and European countries. Acemoglu proposes an endogenous growth model, similar to the monopolistic competition models implemented by Romer (1989) and Grossman and Helpman (1991) and Howitt and Aghion (1998), by combining the assumption of elasticity of substitution less than one with the endogenous bias of technical change towards labour or capital productivity improvement as the theoretical explanation for labour share fluctuations in the medium-run, whereas in the long-run the model exhibits constant distributive shares in line with the 'Kaldor Facts'.

On similar grounds, in order to account for fluctuations in the distributive shares (Jones 2005) presents a growth model wherein the production function takes different values of the elasticity of substitution for the short and long-run that is, respectively, less than and equal to one.

Before Acemoglu, the ITC hypothesis has been developed along neoclassical lines during the sixties by Kennedy (1964), who proposes a growth model with the so-called 'Invention Possibility Frontier' (IPF) in order to represent the tradeoff between improvements in labour or capital productivity, and then by Samuelson (1965) and Drandakis and Phelps (1966).

Moreover, from quite distant theoretical perspectives, the puzzling question about the interplay between technical change, growth and functional distribution have been also addressed along purely classical (Van Der Ploeg 1987; Foley and Michl 1999; Foley 2003b; 2003a; Zamparelli 2015) or classical/evolutionary (Dumenil and Levy 2003) lines by implementing the ITC approach.

Notwithstanding, if we accept the idea of directed input-saving technical change process, induced by different paces of wages growth and relative input scarcity (so-called 'Habbakkuk Hypothesis'[3]), as one of the main explanation for declining wage share in advanced economies, an interesting puzzling question still remains: that is, why the moderate growth of wages in the early eighties could have not reversed the labour-saving trend of technical change pattern. Blanchard (1997), for example, explained this phenomenon with weaker bargaining power of workers and with lagged factor substitution process triggered by the 'wage push shock' after the seventies, e.g. within many European countries. Recently, Stiglitz and Greenwald (2015) also propose a model with directed technical change by using the Kennedy's IPF in order to show the impact of different values of the elasticity of substitution between labour and capital upon long-run growth, distributive shares and unemployment. They highlight how, in a fixed coefficient scenario (the case analysed within the present model), an excessive labour-saving technical change may have relevant negative effects upon functional income distribution and may also reflect in excessively high levels of unemployment.

The contributions illustrated so far, are built upon purely 'supply-side' and technological-based approach to growth and distribution. Nevertheless, a 'demand-side' Keynesian approach has been increasingly developed by many scholars, in order to account for the effects of aggregate demand on the dynamics of real and financial side of monetary production economies. In this respect, a relatively new and promising literature implementing macroeconomic models with strong interdependence between demand- and supply-side and real and financial side of the economy comes from the Complex Adaptive System approach applied to economics, stemming from Arthur et al. (1997) and Kirman (2010), and Delli Gatti et al. (2007). On these lines, the so-called '*Keynes + Schumpeter*' (K+S) class of models (Dosi et al. 2010; Napoletano et al. 2012; Dosi et al. 2017), the Eurace@Unibi AB-SFC models (Dawid et al. 2012) and the Agent-Based Stock-Flow Consistent (AB-SFC) models (Caiani et al. 2016; Caiani et al. 2018a; Caiani et al. 2018c; 2018b), concentrate the analysis upon the interplay between the evolutionary endogenous growth process, income and wealth distribution, aggregate demand and credit and financial issues. As anticipated in the Introduction, the present model is built upon the AB-SFC models proposed by Caiani et al. (2018c) and Caiani et al. (2018b). Moreover, by introducing the classical-fashioned directed innovation mechanism within the well-established tradition of evolutionary demand-driven endogenous growth, the present contribution proposes an attempt to bridge two different "island empires" Ruttan (1997)[4]: the *directed* technical change process implemented in many purely 'supply-side' growth models and the *localised* evolutionary innovation mechanism implemented within the

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[3]In the early sixties, some contributions in the field of economic history (Salter 1962) and (Habakkuk 1962) suggest the relevance of labour scarcity as a key element accounting for the induced labour-saving technical change, especially in Great Britain and United States in the nineteenth century, also in line with Hicks (1932).

[4]In a seminal paper, (Ruttan 1997) discussed how the ITC, evolutionary, and 'path-dependence' approaches to technical change (defined as "three different island empires") could be interpreted as pieces of a more general theory about the sources of technical change capable to represent a robust framework opposed to the neoclassical one.

Keynesian and Schumpeterian endogenous growth models belonging to the 'K+S' family[5].

3 The Model

3.1 An overview on the main building blocks

The AB-SFC approach adopted here stems from the benchmark model implemented by Caiani et al. (2016) and aims to integrate the Agent-Based tradition developed upon the decentralised matching protocols for interactions among heterogeneous agents (Riccetti et al. 2015) with the Stock-Flow Consistent macro modelling approach stemming from Godley and Lavoie (2006), thus allowing us to explicitly taking into account real- and financial-side stock and flow variables and the supply- and demand-side of our artificial economy.

In particular, I introduce in the direct ancestor model (Caiani et al. 2018b) the following refinements: i) an oversimplified capital-good sector; ii) the possibility for consumption-good firms of undertaking induced and directed/biased technical change process; iii) the household sector has been divided into two classes of agents, i.e. workers and capitalist. Then, the evolutionary technical change process has been modelled by following the two steps procedure implemented in the 'K+S' models (Dosi et al. 2010), although here this process takes place within the consumption-good sector (i.e. with 'disembodied' technical change). As anticipated, we also have a *classical-fashioned* directed technical change process as the heterogeneous consumption-good firms choose both the *intensity* and the *direction* of the innovation towards a labour- or capital-saving choice of technique, and as they decide to adopt the new production technique depending on a classical *profitability criterion* (Okishio 1961; Shaikh 1978; 1999; 2016; Nakatani 1979; Park 2001). This modelling framework allows us to let the '*innovation bias*', that is the bias towards the choice of labour-saving production techniques, be an *emergent property* of the evolutionary technical change process engaged by heterogeneous consumption-good firms. That is, without imposing any analytical trade-off such as the 'Invention Possibility Frontier' (IPF) á-la-Kennedy (Kennedy 1964) implemented in the standard ITC models proposed in literature.

The model is populated by K firms producing a homogeneous capital good, only using labour input, and C consumption firms producing a homogeneous final good over two inputs (labour and capital). Consumption-good firms also innovate their production process in order to save the (relatively) expensive production input and try to obtain some profitability gain (Dumenil and Levy 2003; Foley and Michl 1999;

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[5]Recently, (Acemoglu 2015) also highlights some points of connection between the localised technical change framework, stemming by the Atkinson and Stiglitz 'new view' (Atkinson and Stiglitz 1969), the ITC hypothesis and the directed and biased innovation framework. Dosi and Virgillito (2016) also propose a discussion about the Atkinson and Stiglitz approach by analysing it through '*Schumpeterian*' lenses, thus from a theoretical perspective much closer to the one embraced in the present contribution.

Foley 2003b; Zamparelli 2015; Stiglitz and Greenwald 2015). The household sector is composed by two classes of agents: workers and capitalists. Workers sell their labour force to the capital and consumption firms, and capitalists represent the equity investors (i.e. the firms and banks' equity owners) receiving their income in the form of dividends. All the agents within the household sector consume their income on the final good market and they save the residual amount (in the form of bank deposits or equity investment as capitalists agents). Commercial banks offer deposit accounts to households and firms and endogenously create private money by providing loans to the consumption firms. Our artificial economy also has a government and a Central Bank (see Subsections 3.7 and 3.8). As in Caiani et al. (2018a) we have an endogenous entry/exit process. Thus, the simulation model starts with no firms and banks and they are progressively created during the simulation by means of investment out of capitalists' savings. As in the SIM model, the simplest SFC model implemented by Godley and Lavoie (2006), everything starts with government public expenditure, taking the form of lump-sum transfers distributed across workers and capitalists[6]. This transfers are initially saved by households, and then begun to be invested by capitalist agents for the creation of new firms (primarily) and eventually new banks. After that the production starts and then possibly also the demand for loans by consumption firms to commercial banks. Each period the heterogeneous agents directly interact on each market by means of decentralised matching protocols (Riccetti et al. 2015; Caiani et al. 2016). The demand-side agents observe a random subset of suppliers, whose size is given by a fixed parameter measuring the degree of imperfect information.

3.2 The simulation schedule

1. Capital firms decide the wage to be offered and the selling price for their production;
2. Consumption firms determine the production planning by deciding the desired quantity of output, the desired quantity of labour input, wages, selling prices, the desired amount of resources to be invested in R&D and, eventually, the demand for loans;
3. Commercial banks and consumption-firms interact on the credit market;
4. Consumption firms decide the accumulation plan by computing the desired growth rate of production capacity (and hence the desired quantity of capital goods);
5. Capital and consumption firms interact with workers on the labour market;
6. Capital firms interact with consumption firms in the capital goods market;
7. Workers receive their wages and are employed for production and R&D activities. Capitalist agents receive dividends generated in the previous period;

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[6]This is exactly how Caiani et al. (2018a) initialize the model with a generation process for the stock variables. Thus, the simulation starts with no stock variables as they are progressively created and accumulated over time. As the model entails an endogenous process of firms' and commercial banks' creation, at the beginning of the simulation the Central Bank buys government bonds by providing the legal currency necessary to funds public expenditure.

8. Consumption firms undertake the innovation process and compare the new ran-
    dom technique with the one inherited from the previous period. Then they
    produce the final good;
9. Government decides the tax-rate and the public expenditure planning;
10. Bonds are issued by Government and then purchased by commercial banks
    on the bonds market. The residual amount of bonds, not purchased by private
    banks, is absorbed by the Central Bank;
11. Households pay taxes on their income and receive the tax-exempt transfers by
    the Government. Then, they compute the desired consumption and interact with
    the consumption firms;
12. Firms compute their profits and net worth and the taxes to be paid in the next
    period. Consumption firms also compute the dividends to be distributed in the
    next period to the equity investors (capitalists);
13. Entry/exit process. Capitalists invest and eventually create new firms and banks.

3.3 Capital-good firms

We have $k = 1, \ldots, K$ firms (capital sector) producing each period a certain quan-
tity of intermediate capital goods, $y_{k,t}^K$, depending on the demand requested by the
consumption-good firms as capital input. Thus we have

$$y_{k,t}^K = a_{K,t} N_{k,t}^D \qquad (1)$$

with $a_{K,t}$ indicating the labour productivity for workers employed in the capital pro-
duction process[7] and $N_{k,t}^D$ indicating the desired quantity of labour needed in order
to produce the capital output. Thus, they demand a certain quantity of labour input as
follows

$$N_{k,t}^D = \frac{y_{k,t}^K}{a_{K,t}} \qquad (2)$$

and decide the quantity of capital output to be produced, $y_{k,t}^K$, depending on the
desired quantity requested by the consumption goods firms,

$$y_{k,t}^K = y_{c,t}^{KD}. \qquad (3)$$

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[7]Labour productivity in capital sector adaptively evolves at time t accordingly to the average labour pro-
ductivity of consumption-good sector in $t - 1$, that is $a_{K,t} = \Phi_{l,t-1}$ (similarly to Dosi et al. (2019)).
This oversimplified specification of capital-good sector together with the choice of having an innovation
process taking place only within the consumption-good sector (i.e. with purely 'disembodied' technical
change), are motivated by the aim of the paper, that is the analysis of the role of intensity and direc-
tion of technical change within final-good sector. Nevertheless, we ought to explicitly clarify how purely
evolutionary-fashioned models should crucially take into account both the role of *embodied* technical
change and the effect and the dynamics of product innovations together with process innovations. The
present model proposes just a first attempt to analyse the biased effect of process innovation and its
direction upon growth and distributive dynamics in the light of recent empirical evidences. Therefore, an
extension in those directions will be included within further developments of the present model.

Capital firms adopt an adaptive wage rule depending on the wage offered in the previous period and on the difference between labour demanded and labour effectively employed in the previous period (Caiani et al. 2018c), as follows:

$$
w_{k,t} = \begin{cases} w_{k,t-1}(1 - U[0, \delta]), & \text{if } N_{k,t-1}^D - N_{k,t-1} = 0 \text{ with } Pr(u_t) = 1 - e^{-u_{t-1}v} \\ w_{k,t-1}(1 + U[0, \delta]), & \text{if } N_{k,t-1}^D - N_{k,t-1} > 0 \end{cases}
$$
(4)

If firms were not satisfied, that is labour demanded is greater than the employed one in $t - 1$, they have a positive probability $Pr(u_t)$ of upward revising the offered wage. This probability is inversely related to the level of unemployment in the economy u_t, with a positive (fixed) parameter v indicating the strength of their relation (the lower v the higher the probability of reducing the wages).

Then, the capital firms adopt this simple pricing rule

$$
p_{k,t} = (1 + \mu_k)\frac{w_{k,t}}{a_{K,t}}
$$
(5)

with a (fixed) mark-up μ_k over the unit labour cost.

3.4 Consumption-good firms

3.4.1 Production, prices and wages

We have $c = 1, \ldots, C$ heterogeneous firms producing a homogeneous consumption good over two inputs (labour and capital) assuming a fixed coefficient Leontief production function, as follows

$$
y_{c,t} = \min\{u_{c,t}\varphi_{kc,t}y_{c,t}^K; \varphi_{lc,t}N_{c,t}\}
$$
(6)

with $u_{c,t}$ indicating the degree of capacity utilisation, $\varphi_{kc,t}$ and $\varphi_{lc,t}$ being, respectively, the capital and labour productivity, whereas $y_{c,t}^K$ and $N_{c,t}$ are the capital and labour input. Consumption-good firms may improve the inputs' productivity ($\varphi_{kc,t}$ and $\varphi_{lc,t}$) by means of the R&D activity, and they adopt a new production technique depending on a *profitability criterion*, that is if the expected profit rate related to new innovation is greater than the actual one (see Subsection 3.4.2). Once the firm has chosen the production technique, it can compute the desired output and the desired quantity of labour (for simplicity, hereafter we refer again to t and $t - 1$ as the actual and previous period) given, respectively, by

$$
y_{c,t} = u_{c,t}\varphi_{Kc,t}y_{c,t}^{KD} = \varphi_{lc,t}N_{c,t}^D
$$
(7)

and

$$
N_{c,t}^D = u_{c,t}^D y_{c,t}^K \frac{\varphi_{kc,t}}{\varphi_{lc,t}}.
$$
(8)

Each period, consumption firms adaptively revise prices and their expectations about selling, as follows:

$$
\text{if } \overline{y}_{c,t} \geq \overline{y}_{c,t-1}^e : \begin{cases} \overline{y}_{c,t}^e = \overline{y}_{c,t-1}^e(1 + U[0, \delta]) \\ p_{c,t} = p_{c,t-1}(1 + U[0, \delta]) \end{cases}
$$
(9)

$$\text{if } \overline{y}_{c,t} \leq \overline{y}^e_{c,t-1} \text{and } y^{tot}_{c,t-1} > \overline{y}_{c,t-1} : \begin{cases} \overline{y}^e_{c,t} = \overline{y}^e_{c,t-1}(1 - U[0,\delta]) \\ p_{c,t} = p_{c,t-1}(1 - U[0,\delta]) \end{cases} \tag{10}$$

$$\text{if } \overline{y}_{c,t} \leq \overline{y}^e_{c,t-1} \text{and } y^{tot}_{c,t-1} = \overline{y}_{c,t-1} : \begin{cases} \overline{y}^e_{c,t} = \overline{y}^e_{c,t-1} \\ p_{c,t} = p_{c,t-1} \end{cases} \tag{11}$$

where $\overline{y}_{c,t-1}$ indicates the output sold in the previous period and $y^{tot}_{c,t} = y_{c,t-1} + inv_{c,t}$. The desired output can be computed as $y^D_{c,t} = y^e_{c,t}(1 + \theta) - inv_{c,t}$[8].

Moreover, the selling price is greater than (or equal to) the unit labour cost plus a mark-up[9].

Finally, also consumption firms adopt an adaptive wage rule, as follows:

$$w_{c,t} = \begin{cases} w_{c,t-1}(1 - U[0,\delta]), \text{ if } N^D_{c,t-1} - N_{c,t-1} = 0 \text{ with } Pr(u_t) = 1 - e^{-u_{t-1}v} \\ w_{c,t-1}(1 + U[0,\delta]), \text{ if } N^D_{c,t-1} - N_{c,t-1} > 0 \end{cases}$$
$$\tag{12}$$

3.4.2 Innovation

Each period firms C undertake an evolutionary innovation process and they decide to adopt the new random technology only by comparing its expected profit rate with the actual one Okishio (1961), Shaikh (1978), Nakatani (1979), Shaikh (1999), Park (2001), and Shaikh (2016).

The innovation process starts after the decision about the desired investment in the R&D activity, which is a (fixed) share γ of the expected sales (Silverberg and Verspagen 1996; Dosi et al. 2010) and (Caiani et al. 2019), as follows:

$$IN^D_{c,t} = \gamma \overline{y}^e_{c,t} p_{c,t}. \tag{13}$$

Then, the innovation process takes place in two steps as in the 'K+S' tradition (Dosi et al. 2010). In a first step, firms compute a Bernoulli experiment in order to determine whether the R&D activity has been successful, so we have:

$$Pr_{IN_t} = 1 - e^{-vINc,t} \tag{14}$$

and this probability is affected by the amount of resources invested in innovation.

Then, we have a second step whereby new production techniques are obtained through a multiplicative stochastic process reproducing the idiosyncratic learning of new capabilities accumulated by heterogeneous firms (Dosi et al. 1993; Dosi et al. 2016). We have two independent random draws for the growth rate of capital productivity and the growth rate of labour productivity:

$$\varphi^+_{kc,t+1} = \varphi_{kc,t}(1 + \hat{\varphi}_k) \tag{15}$$

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[8]The desired quantities (here of labour and output) could be lower then the effective ones, so we could have that $N^D_{c,t} \geq N_{c,t}$ and $y^D_{c,t} \geq y_{c,t}$.

The desired quantity of (fixed) capital stock is computed depending on the accumulation decision (see Subsection 3.4.3).

[9]That is, we have $p_{c,t} \geq (1 + \mu_c)(\frac{w_{c,t}}{\varphi_{lc,t}})$ with μ_c indicating the mark-up over the unit labour cost.

and

$$\varphi_{lc,t+1}^{+} = \varphi_{lc,t}(1 + \hat{\varphi}_l) \tag{16}$$

with $\hat{\varphi}_k \sim U[-\delta_{IN}, \delta_{IN}]$ and $\hat{\varphi}_l \sim U[-\delta_{IN}, \delta_{IN}]$.

Thus, we have the same symmetric support for both random draws. As stated above, the adoption of the new production technique depends on a *profitability criterion*, i.e. it is adopted only if

$$r_{c,t+1}^{+} > r_{c,t}. \tag{17}$$

The profit rate is given by the ratio between the firm's profit[10] and the stock of capital, as follows:

$$\frac{\Pi_{c,t}^{*}}{K_{c,t}} \equiv r_{c,t} = \frac{p_{c,t}y_{c,t} - w_{c,t}N_{c,t} - p_{kc,t}y_{c,t}^{K} - IN_{c,t} - i_{c,t}^{l}L_{c,t}}{p_{kc,t}y_{c,t}^{K}} \tag{18}$$

with $p_{c,t}y_{c,t}$ indicating the revenues obtained by selling production in the previous period, $w_{c,t}N_{c,t}$ and $p_{kc,t}y_{c,t}^{K}$ indicating, respectively, the costs of the production factors and $i_{c,t}^{l}L_{c,t}$ being the repayment for loans obtained before production process (see Subsection 3.4.4).

After some substitution we obtain the profit rate inherited from t and the potential profit rate expected from the adoption of the new random technique $(\varphi_{kc}^{+}, \varphi_{lc}^{+})$ in $t+1$, as follows

$$r_{c,t} = \frac{u_{c,t}\varphi_{kc,t}[p_{c,t} - \frac{w_{c,t}}{\varphi_{lc,t}}(1 + \gamma)]}{p_{kc,t}} - 1 - \frac{i_{c,t}^{l}L_{c,t}}{p_{kc,t}y_{c,t}^{K}} \tag{19}$$

and

$$r_{c,t+1}^{+} = \frac{u_{c,t+1}^{D}\varphi_{kc}^{+}[p_{c,t} - \frac{w_{c,t}}{\varphi_{lc}^{+}}(1 + \gamma)]}{p_{kc,t}} - 1 - \frac{i_{c,t}^{l}L_{c,t}}{p_{kc,t}y_{c,t}^{K}} \tag{20}$$

with $\frac{w_{c,t}}{\varphi_{lc,t}} = \omega_{c,t}$, $\frac{w_{c,t}}{\varphi_l^{+}} = \omega_{c,t+1}^{+}$ indicating, respectively, the wage share of c without and with the adoption of the new production technique. Thus, firms compare (17) the 'old' and the 'transient' profit rate within a 'real competition' framework (Shaikh 1999; Park 2001) and Shaikh (2016).

Moreover, consumption-good firms facing productivity gaps with respect to the sectoral average (Φ_x) may try to catch-up with the leading competitors by exploiting sectoral spillover effects[11] Varspagen and De Loo (1999), as follows:

$$\varphi_{xc,t+1} = \varphi_{xc,t} + U[0, \Phi_{x,t} - \varphi_{xc,t}] \text{ if } \varphi_{xc,t} < \Phi_{x,t} \tag{21}$$

with $x = \{l, k\}$.

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[10] As in Caiani et al. (2016) and Caiani et al. (2018c), we refer to $\Pi_{c,t}^{*}$ as the Operating Cash Flow, that is the firm's profit excluding the variation of the inventories (see Subsection 3.4.4).

[11] A more sophisticated specification for firms' imitation process could be taken into account for further extensions of the present model. For example, instead of approximating general sectoral spillover effects *via* the difference with the sectoral average of productivity, we could explicitly discriminate among leader and laggard firms by letting the latter to imitate those firms that are closer in terms of technological distance, as in Dosi et al. (2010) and Dosi et al. (2019).

3.4.3 Investment and capital accumulation

Consumption firms compute each period their desired rate of growth of productive capacity depending on their profitability and their capacity utilisation compared to their 'normal' rates (as in Caiani et al. (2016) and Caiani et al. (2018c)), as follows

$$g_{c,t}^D = \lambda_1 \frac{r_{c,t-1} - \overline{r}}{\overline{r}} + \lambda_2 \frac{u_{c,t}^D - \overline{u}}{\overline{u}} \qquad (22)$$

with λ_1 and λ_2 representing, respectively, the investments' sensitivity to the profit rate and to the capacity utilisation, while $u_{c,t}^D$ is the desired capacity utilisation[12], and $\overline{r}$ and $\overline{u}$ indicate, respectively, firms' 'normal' profit and capacity utilisation rates[13]. Thus we have both a *Classical* and a *Kaleckian* engine for the investment decision undertaken by consumption firms depending, respectively, on the weight given to the profit rate and on the weight given to the desired degree of capacity utilisation.

After the accumulation decision, C computes the desired nominal investment, $i_{c,t}^D$, as the number of capital units needed due to the obsolescence of capital (given a fixed depreciation rate δ and a given life span for machines) and/or fill the possible gap between the current and the desired capacity. Then, the desired real investment will be $I_{c,t}^D = i_{c,t}^D p_{kc,t}$.

3.4.4 Financing demand, profits and net worth

Each consumption-good firm may finance its production activity by means of internal funds, that is its net worth $A_{c,t}$, and/or, if necessary, by means of external funds, that is a desired quantity of loans[14], $L_{c,t}^D$, with an interest rate $i_{c,t}^l$ (see Subsection 3.6).

The demand for loans requested to the banking sector depends on the cost of the desired quantity of productive inputs and on the disposable internal funds, as follows

$$L_{c,t}^D = \begin{cases} w_{c,t} N_{c,t}^D + p_{kc,t} y_{c,t}^{KD} - A_{c,t}, & \text{if } w_{c,t} N_{c,t}^D + p_{kc,t} y_{c,t}^{KD} > A_{c,t} \\ 0, & \text{otherwise.} \end{cases} \qquad (23)$$

The desired quantity of loans could differ from the effective amount obtained, that is we could have $L_{c,t}^D \geq L_{c,d}$, due to an unsatisfactory amount of loans to be supplied by the banks or due to an individual credit rationing (as production activity has the priority on the R&D expenditure).

Firms' profits are given by the difference between revenues and expenditure:

$$\Pi_{c,t} = p_{c,t} \overline{y}_{c,t} + \Delta INV_{c,t} - w_{c,t} N_{c,t} - p_{kc,t} y_{c,t}^K - IN_{c,t} - i_{c,t}^l L_{c,t}. \qquad (24)$$

where $\Delta INV_{c,t}$ indicates the variation of inventories, and firms' net worth evolves according to the following law of motion:

$$NW_{c,t} = NW_{c,t-1} + \Pi_{c,t-1}^* - T_{c,t}^\pi - DIV_{c,t}. \qquad (25)$$

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[12] Depending on the desired output $y_{c,t}^D$, that is $u_{c,t}^D = min(1, \frac{y_{c,t}^D}{y_{c,t}^K \varphi_{kc,t}})$.

[13] Assumed to be constant and equal across firms. Caiani et al. (2018b) and Caiani et al. (2018c) calibrate the values of these 'normal' rates by computing the steady-state solution of the aggregate model.

[14] For simplicity, we assume that each loans lasts only one period.

When the operating cash flows are positive ($\Pi^*_{c,t-1} > 0$), firms pay taxes on their profits ($T^\pi_{c,t}$) and distribute dividends ($DIV_{c,t}$) to equity owners (capitalists), as follows

$$T^\pi_{c,t} = \begin{cases} \tau_t \Pi^*_{c,t}, & \text{if } \Pi^*_{c,t} > 0 \\ 0, & \text{otherwise.} \end{cases} \qquad (26)$$

and

$$DIV_{c,t} = \begin{cases} \rho(\Pi^*_{c,t} - T^\pi_{c,t}), & \text{if } \Pi^*_{c,t} > 0 \\ 0, & \text{otherwise.} \end{cases} \qquad (27)$$

with τ_t indicating the tax-rate decided by the government (see Subsection 3.8).

3.5 Households

We have $h = 1, \ldots, H$ households (workers and capitalists) consuming their income on the consumption goods market, saving in the form of bank deposits and paying taxes over their income. Only workers sell their labour force to consumption- and capital-good firms, whereas capitalists only own firms and banks receiving dividends as a share of their profits.

3.5.1 Workers

Workers update each period their reservation wage depending on their occupational status, as follows

$$w_{w,t} = \begin{cases} w_{w,t-1}(1 + U[0,\delta]), & \text{if employed in } t-1 \text{ with } Pr(u_t) \\ w_{w,t-1}(1 - U[0,\delta]), & \text{if unemployed in } t-1 \end{cases} \qquad (28)$$

with $Pr(u_t) = e^{-u_{t-1}v}$ indicating a positive probability of increasing the wage claims (as for consumption firms).
Workers gross income is given by

$$y_{w,t} = w_{w,t} + i^d_{b,t} D_{w,t} + TF_t \qquad (29)$$

with $i^d_{b,t} D_{w,t}$ indicating the interest rate gained from bank deposits[15] and TF_t representing the tax-exempt transfer received by government[16].

3.5.2 Capitalists

Capitalists gross income is given by

$$y_{m,t} = DIV_{m,t} + i^d_{b,t} D_{m,t} \qquad (30)$$

with $DIV_{m,t}$ indicating the dividends received by the firms/banks they own and $i^d_{b,t} D_{m,t}$ being the interests on their deposits.
Capitalists may save their wealth ($NW_{m,t}$) either as deposit accounts $D_{m,t}$ or as equity investment $A_{m,t}$ in firms/banks' ownership. The choice between these two

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[15]For simplicity we assume the same interest rate offered by the banking sector.
[16]These transfers represent the public expenditure in this model, as in Caiani et al. (2018a), see Subsection 3.8.

assets depends on a certain degree of liquidity preference ($LP_{m,t}$) [17] endogenously determined depending on the rate of return gained from the two types of asset available. Thus, capitalists compute the desired level of wealth depending on their disposable income and the desired consumption, as follows

$$NW^D_{m,t} = NW_{m,t-1} + y^{DISP}_{m,t} - C^D_{m,t} \tag{31}$$

then they obtain the desired level of deposits and equity as

$$D^D_{m,t} = NW^D_{m,t} - (A^D_{m,t} - A_{m,t-1}) \tag{32}$$

and

$$A^D_{m,t} = \max\{A_{m,t-1}, (1 - LP_{m,t})NW^D_{m,t}\} \tag{33}$$

with $A^D_{m,t} - A_{m,t-1}$ indicating the desired investment in equity, which is bounded to be non-negative (Caiani et al. 2018a). As for the other desired variables in the model, we could also have that $C^D_{h,t} > C_{h,t}$ (with $h = m, w$), and in the case of capitalist agents this means that $NW^D_{m,t} < NW_{m,t}$. In this case deposits act as a buffer stock variable with $A_{m,t}$ remaining at the planned level.

The disposable income for a generic agent within the household sector (worker or capitalist) is given by

$$y^{DISP}_{h,t} = (1 - \tau_t)y_{h,t} \tag{34}$$

with $h = w, m$ and τ_t indicating the tax-rate in the current period.

Each period, households also decide the desired quantity of consumption depending on their current disposable income and their wealth (i.e. bank deposits), as follows

$$C^D_{h,t} = \alpha_{1h}y^{DISP}_{h,t} + \alpha_{2h}D_{h,t} \tag{35}$$

with $0 < \alpha_{1h} < 1$ and $0 < \alpha_{2h} < 1$ and $\alpha_w > \alpha_m$.
Thus, the desired savings are

$$S^D_{h,t} = y^{DISP}_{h,t} - C^D_{h,t} \tag{36}$$

3.6 Banks

We leave the banking sector functioning as well as the Government and the Central Bank behaviour exactly as in Caiani et al. (2018a). Thus, we have $b = 1, \ldots, B$ banks collecting deposits from households and firms (i.e. capitalists' deposits), offering an interest rate $i^d_{b,t}$ (which is a constant fraction of the discount rate i_t fixed by the Central Bank), they endogenously create means of payment by providing credit to consumption-good firms and they may purchase government bonds.

The probability of receiving credit by banks depends on the firms' leverage

$$Pr(L_{c,t}) = e^{-\iota \frac{L^D_{i,t}}{A_{i,t}}} \tag{37}$$

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[17] See Caiani et al. (2018a), for a detailed description of how capitalists compute their liquidity preference. In the original model, the household sector is not composed by both workers and capitalists so households as a whole act as consumers, workers and equity owners. On the contrary, in the present model only capitalist agents may invest in equity asset.

$$i_{c,t}^l = \chi \frac{L_{c,t}^D}{A_{c,t}} + i_t \tag{38}$$

with i_t indicating the discount rate fixed by Central Bank.

The desired supply of loans depends on banks' net worth

$$L_{b,t}^{SD} = \mu_1 A_{b,t} \tag{39}$$

and the maximum amount that a bank may provide to each firm is a maximum share of its supply ($\zeta L_{b,t}^{SD}$).

Commercial banks have a minimum amount of reserves to be held by the Central Bank as a proportion of their deposits

$$R_{b,t}^{min} = \mu_2 D_{b,t} \tag{40}$$

receiving a fixed interest rate i_{res}.

Then, banks may also spend the remaining amount of liquidity by purchasing government bonds $B_{b,t}$, yielding an interest rate i_t^b [18].

Thus, banks' profit is given by

$$\Pi_{b,t} = \sum_{c=1}^{C} i_{c,t} L_{c,b,t} + i_t^b B_{b,t} + i_{res} R_{b,t} - BD_{c,b,t} - i_t^d D_{b,t} - i_t L_{b,t}^{cb} \tag{41}$$

with $BD_{c,b,t}$ indicating the 'bad debt', that is the non performing loans due to firms' defaults.

Also banks' profits are subject to taxation, and then net profit are eventually distributed to the equity owners as for firms (see Eqs. 26 and 27).

3.7 Central Bank

We have a Central Bank offering cash advances (CA_t) requested by commercial banks, holding their reserves ($R_{CB,t}$), and eventually purchasing the residual amount of government bonds ($B_{CB,t}$).

Central Bank also computes its profits and we assume that they are automatically distributed to government, so we have

$$\Pi_{CB,t} = i_t^b B_{CB,t} + i_t CA_t - i_{res} R_{CB,t}. \tag{42}$$

3.8 Government

Government receives taxes from household sector (capitalists and workers) and from firms and banks, thus

$$T_t = \sum_{h=1}^{H} \tau T_{h,t}^y + \sum_{c,\pi^*>0}^{C} \tau T_{c,t-1}^\pi + \sum_{b,\pi>0}^{B} T_{b,t-1}^\pi. \tag{43}$$

Government public expenditure is represented by tax-exempt transfers equally distributed to the households ($TF_t = \frac{G_t}{H}$). As in Caiani et al. (2018a), the initial level

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[18] As in Caiani et al. (2018a) banks randomly access the bond market with a probability of purchase them, depending on the riskiness of the economy (i.e. the debt-on-GDP ratio): $Pr(b_t) = e^{-i \frac{B_t}{Y_t}}$.

of public expenditure (G_0) and the initial tax rate are revised following a relatively simple adaptive rule:

$$\text{if } d_t \geq d^{max} \text{ and } G_t^D \leq G_{t-1} : \begin{cases} G_t = G_{t-1}(1 - U[0, \delta]) \\ \tau_{t+1} = \tau_t(1 + U[0, \delta]) \end{cases} \quad (44)$$

$$\text{if } d_t \geq d^{max} \text{ and } G_t^D > G_{t-1} : \begin{cases} G_t = G_{t-1} \\ \tau_{t+1} = \tau_t(1 + U[0, \delta]) \end{cases} \quad (45)$$

$$\text{if } d_t < d^{max} \text{ and } G_t^D \leq G_{t-1} : \begin{cases} G_t = G_{t-1}(1 - U[0, \delta]) \\ \tau_{t+1} = \tau_t(1 - U[0, \delta]) \end{cases} \quad (46)$$

$$\text{if } d_t < d^{max} \text{ and } G_t^D > G_{t-1} : \begin{cases} G_t = G_{t-1}(1 + U[0, \delta]) \\ \tau_{t+1} = \tau_t \end{cases} \quad (47)$$

thus depending on the difference between effective (d_t) and maximum fiscal target (d^{max}) and desired (G_t^D) and past levels of public expenditure (G_{t-1}). Following (Caiani et al. 2018a), G_t^D is given by the initial level of public expenditure (G_0) adjusted for the average level of consumption price and productivity, i.e. $G_t^D = G_0 \Phi_t P_t$.

In each period, government may has a budget surplus SUR_t or deficit DEF_t, so we have

$$DEF_t = G_t + i_{t-1}^b B_{t-1} - T_t \quad (48)$$

with public debt defined as

$$B_t = B_{t-1} + DEF_t - SUR_{t-1}. \quad (49)$$

Finally, the interest rate on public bonds depends on the debt-on-GDP ratio and on the Central Bank's discount rate, as follows:

$$i_t^b = \chi_b \frac{B_t}{Y_t} + i_t. \quad (50)$$

4 Simulation results

The model has been ran for 1000 time periods and for 100 Monte Carlo (MC) simulations[19] following a baseline calibration for both parameters and initial conditions (see Table 4 in Appendix). The burn-in period has been excluded from the presentation of simulation results, so that the artificial time series cover a time-span of $T = \{200:1000\}$, with each period corresponding to a quarter. The baseline setup has been identified relying on both the calibration proposed for its direct ancestor models (Caiani et al. 2018a) and (Caiani et al. 2018b) and the attempt to reproduce realistic simulated values that can be comparable with empirical data related to some representative advanced economies.

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[19]The model has been implemented by using Python programming code as for his ancestor model (Caiani et al. 2018b). Statistics on the simulated time series has been computed by means of R econometric environment.

Table 1 Average empirical and simulated data for some macroeconomic variables

Variable (%) (years)	US	Germany	Italy	France	MC Average baseline (std error)
Real GDP growth rate (1970-2019)	0.007	0.005	0.004	0.005	0.005 (0.001)
Unemployment (1970-2019)	0.06	0.07	0.09	0.09	0.07 (0.005)
Labour productivity growth (1970-2019)	0.002	0.002	0.002	0.001	0.003 (0.0002)
Debt/GDP (1995-2017)	1.05	0.69	0.90	1.28	1.32 (0.003)
R&D/GDP (1995-2017)	0.03	0.02	0.02	0.01	0.03 (0.0001)
Wage share (1977-2010)	0.59	0.66	0.65	0.65	0.74 (0.001)
Δ Wage Share (1977-2010)	-8.9	-7.9	-12.5	-14.1	-9.1 (0.002)

Empirical data on real GDP and labour productivity growth, unemployment, debt-on-GDP ratio and R&D investment on GDP have been collected from the Organisation for Economic Co-operation and Development (OECD) database (https://data.oecd.org/) and refer to the period 1970-2019. We use quarterly data for both empirical and simulated real GDP and labour productivity growth. Empirical data on the variation of aggregate wage share have been collected from the EU-Klems database (http://www.euklems.net/), related to the time-span 1977-2010.

To this purpose, Table 1 provides a comparison between simulated[20] and empirical data allowing us to reasonably draw on the proposed baseline setup of the model. Table 1 shows data on real GDP growth rate, average unemployment rate, public debt-to-GDP ratio, labour productivity growth, R&D expenditure over GDP, aggregate wage share, computed as the ratio between gross labour compensation and value added, and its (%) variation for four advanced economies (i.e. US, Germany, Italy and France).

Furthermore, following (Dosi et al. 2010) and (Caiani et al. 2016) we also provide another minimum indirect empirical validation in order to check for the ability of the model to reproduce a collection of macroeconomic stylised facts and empirical regularities[21] (Table 2). Table 3 shows the cross-correlation values related to the cyclical component of some key macroeconomic variables across 100 MC runs. Cyclical and trend components of the artificial time series have been obtained by

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[20] Simulated data are average values across 100 MC runs under the baseline calibration for 200 time periods (i.e. 50 years), that is for the time span $T=\{800:1000\}$.

[21] See Fagiolo et al. (2019) for a detailed discussion about the well-established procedures adopted in literature for direct and indirect validation of computational agent-based models (ACE). The ability of the model in reproducing empirical regularities has been indeed identified as one of the key step in order to stress the reliability of the baseline calibration of an ACE.

Table 2 Stylised facts and statistical regularities reproduced by the simulation model under the baseline scenario

Standard Macroeconomic SF	Long-run 'Kaldor' SF
Procyclical real consumption	Growing labour productivity
Procyclical real investment	Increasing 'capital deepening'
Procyclical real wages	Roughly stable profit rate
Countercyclical unemployment rate	Roughly stable output-capital ratio
Procyclical labour productivity ('*Smith effect*')	
Labour productivity-wages correlation ('*Ricardo effect*')	
Endogenous self-sustained growth	
	New SF
	Declining wage share
	Persistent unemployment

applying the Hodrick-Prescott (HP) filter[22] to the simulated data generated by the model. As we can see, real consumption, and real wages are coincident and strongly pro-cyclical, whereas real investment and unemployment are coincident and counter-cyclical (Stock and Watson 1999; Napolatano et al. 2006). Inventories and R&D investment on GDP ratio are coincident and cyclical, whereas public expenditure on GDP ratio is coincident and countercyclical probably indicating that public expenditure increases when GDP grows but less than proportionally (as in the ancestor model (Caiani et al. 2018a)). Moreover, cross-correlation between aggregate labour productivity and, respectively, real GDP and real wages show both *Kaldorian/Smithian* and *Ricardian*[23] mechanisms boosting the dynamics of aggregate labour productivity within the present model.

Figure 1 represents the trend component of artificial time series related to some key macroeconomic variables (across 100 MC runs) providing an overview on the model dynamics. As we can see the model is able to reproduce a self-sustained endogenous growth process, as shown by the exponential growth of real-GDP, real consumption and aggregate labour productivity (Y/L), which in turns follows the pattern of real-GDP (i.e. the so-called 'Kaldor' or 'Smith effect').

Indeed, the analysis of the interplay between technical change and the process of capital accumulation, together with the dynamics of real wages and labour productivity, is pivotal to understand the main features of our model at both micro and macroeconomic level.

The main result provided by the simulation model, is the endogenous emergence of a strong and persistent declining pattern of aggregate wage share (i.e. total labour costs over total output or aggregate real wage-labour productivity ratio) due to the

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[22]We set the smoothing parameter $\lambda = 1600$, as indicated in literature for quarterly data (Ravn and Uhlig 2002).

[23]For a detailed discussion about the so-called 'Smith' and 'Ricardo effect' in shaping technical progress dynamics in capitalist economies see Sylos-Labini (1983).

Table 3 Cross-correlation structure of some macroeconomic variables under the baseline scenario

Variable	t-4	t-3	t-2	t-1	t	t+1	t+2	t+3	t+4
Lab. prod.	-0.120	-0.109	-0.058	0.022	0.357	0.157	0.139	0.095	0.069
(s.e.)	(0.008)	(0.008)	(0.008)	(0.009)	(0.009)	(0.009)	(0.008)	(0.008)	(0.007)
Consumption	-0.056	-0.061	-0.037	0.0187	0.421	0.002	-0.001	-0.038	-0.043
(s.e.)	(0.008)	(0.007)	(0.007)	(0.006)	(0.008)	(0.008)	(0.007)	(0.006)	(0.007)
Investment	-0.046	-0.034	0.024	0.129	0.592	0.015	-0.010	-0.043	-0.053
(s.e.)	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)	(0.008)	(0.006)	(0.007)	(0.006)
Unemployment	0.019	-0.003	-0.060	-0.162	-0.601	-0.017	0.029	0.070	0.085
(s.e.)	(0.006)	(0.007)	(0.006)	(0.006)	(0.009)	(0.007)	(0.005)	(0.007)	(0.006)
Public Exp.-GDP	0.078	0.042	-0.048	-0.219	-0.887	-0.172	0.003	0.087	0.112
(s.e.)	(0.007)	(0.008)	(0.008)	(0.009)	(0.005)	(0.009)	(0.009)	(0.008)	(0.006)
Inventories	-0.206	-0.195	-0.128	0.017	0.513	0.418	0.332	0.229	0.140
(s.e.)	(0.007)	(0.008)	(0.009)	(0.009)	(0.008)	(0.007)	(0.008)	(0.009)	(0.009)
Real Wages	-0.059	-0.071	-0.057	-0.048	0.182	0.021	0.022	0.013	0.022
(s.e.)	(0.007)	(0.007)	(0.009)	(0.009)	(0.006)	(0.010)	(0.009)	(0.009)	(0.008)
Lab. Prod. (wages)	-0.112	-0.096	-0.052	0.031	0.618	0.109	0.028	-0.016	-0.034
(s.e.)	(0.006)	(0.006)	(0.006)	(0.007)	(0.015)	(0.007)	(0.006)	(0.006)	(0.007)
R&D Exp.	-0.114	-0.106	-0.063	0.042	0.569	0.125	0.176	0.012	0.073
(s.e.)	(0.009)	(0.008)	(0.010)	(0.009)	(0.012)	(0.009)	(0.008)	(0.009)	(0.010)

Cross-correlation structure (across 100 MC runs) between some macroeconomic variables and real-GDP and between labour productivity and real wages under the baseline scenario. The cyclical component has been obtained by applying the HP filter to the artificial time series with a smoothing parameter $\lambda = 1600$. We show values related to the lag structure $t = \{-4; +4\}$. MC simulations standard errors in parenthesis.

different paces of wages and labour productivity growth (Fig. 1). Thus, by definition when real wages grow at a slower (faster) pace with respect to labour productivity, aggregate wage share decreases (increases).

However these patterns may be driven by the predominance of two different economic forces shaping the process of technical change: i) the Schumpeterian evolutionary dynamics leading to 'virtuous circles' of innovation, production and employment; ii) the process of capital accumulation and the increasing adoption of labour-saving production techniques with the growing 'capital deepening' observed in many advanced economies during the last decades. Thus, on the one hand, firms are encouraged to improve their inputs' productivity *via* R&D investments, thereby hiring a certain amount of workers for both innovation and production activities in order to increase their selling performances and conquer greater market shares. Therefore higher levels of R&D investments result in higher probability of innovating (14), so that more productive firms are also capable to reduce their selling prices and improve their competitiveness *vis-à-vis* other firms. From a macroeconomic standpoint, these phases of 'virtuous circles' triggered by innovation and production processes, as well as by higher sales expectations, may also reflect in positive feedback mechanisms for the overall economy in terms of higher aggregate employment.
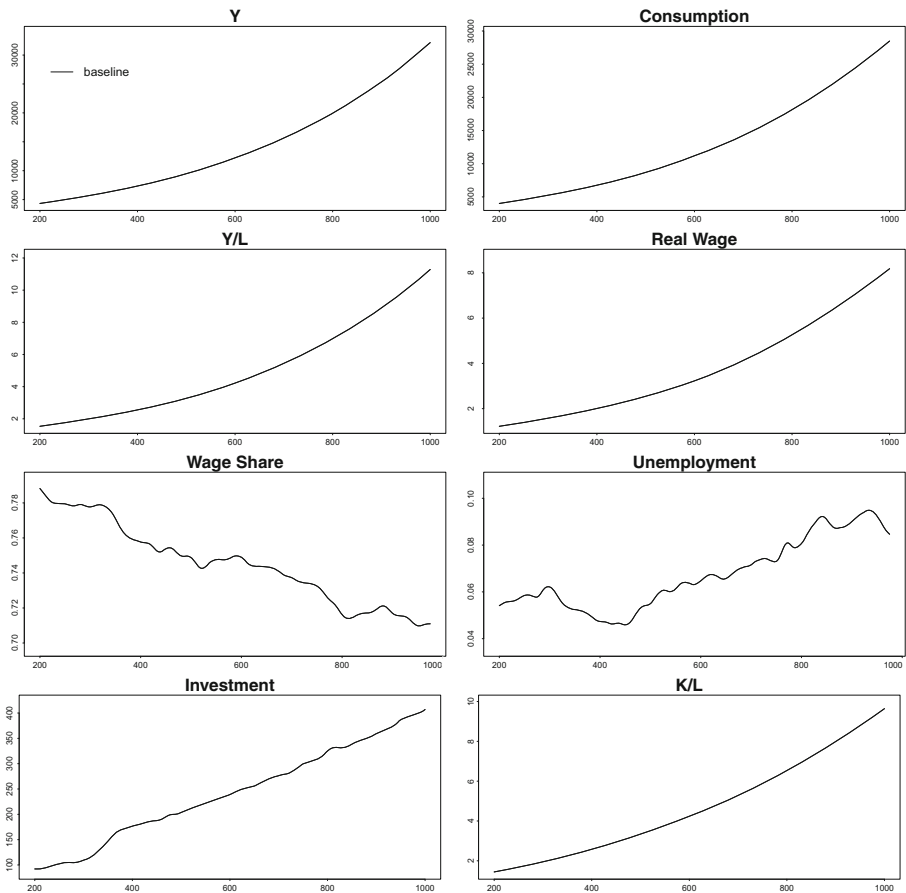
Fig. 1 Average trend (continuous lines) and standard deviations (dashed lines) across 100 MC runs for the time-span $T = \{200{:}1000\}$ related to real GDP, real consumption, average labour productivity, average real wages, wage share, unemployment rate, real investment and capital-labour ratio ('capital deepening')

Of course, some firm may suffer from potential productivity gaps and may have difficulty selling their production output and increasing their profit margins. However, in those cases firms may try to catch up with leading firms by imitating their production techniques (21). All in all, the Schumpeterian evolutionary dynamics may lead more productive firms to survive whereas less productive firms may go bankrupt due to the lower willingness of commercial banks to grant credits (see in Fig. 4 the dynamics of credit and firms survival) and to potential constraints to selling their products with a consequent excessive stockpiling process.

Nevertheless, on the other hand firms also increasingly accumulate capital stock and try to refine their production process through technological changes aimed at minimising input costs and increasing their profitability, thereby progressively improving labour productivity, so that a greater amount of output can be produced by
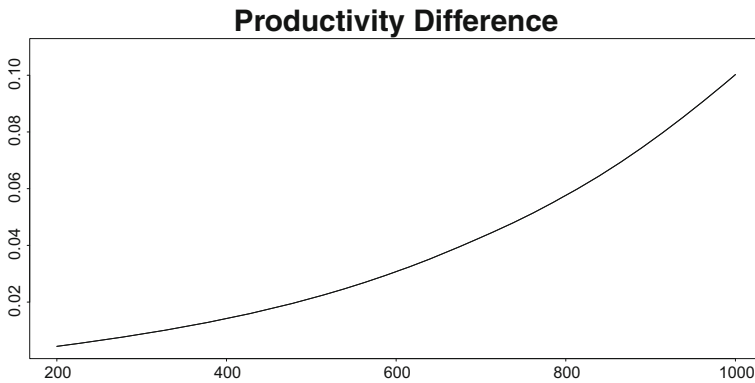
Fig. 2 Percentage difference between average labour productivity and capital productivity, i.e. the difference between the inputs' productivity chosen from the random draws depending on the profitability criterion. Continuous and dashed lines indicate, respectively, average trend and trend of standard deviation across 100 MC simulations

using less workers[24]. This mechanism is displayed in Fig. 1, showing the exponential growth of aggregate output-labour ratio and the increasing 'capital deepening'. The predominance of these two opposite forces, that is virtuous innovative circles and excessive labour-saving innovation patterns, also affects wage dynamics. Indeed although more productive firms, achieving greater market shares and larger size in terms of internal financing and net worth, are able to hire a greater amount of workers for R&D and production activities, the adoption of increasingly labour-saving production techniques may lead to higher levels of unemployment. This in turns affects the strength of workers' bargaining power as their wage claims are negatively affected by higher levels of aggregate unemployment (28). This negative feedback mechanism may be further exacerbated if capital-good firms fail in absorbing those workers fired by consumption-firms. Indeed, the increasing accumulation process of capital stock engaged by consumption-firms generate higher levels of capital demand that may not be continuously fulfilled due to possible capital shortage. Therefore, capital-good firms try to hire increasing amount of workers in order to satisfy the requested demand of capital goods, even though there are not automatic compensation mechanisms ensuring the success of this process[25]. However, we ought to mention an important *caveat* on this point. During the last decades we observed a sectoral shift of output and employment shares from manufacturing to service sectors in both advanced and development countries. This process of 'structural change' has been also identified as a further source for the decline of wage share (De Serres et al. 2001)

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[24]In this respect, these findings are also consistent with the results provided by the ABM implemented by Delli Gatti et al. (2006) where they analyse the interplay between R&D investment, labour-saving technical change, capital accumulation, wage-profit dynamics and financial factors in order to shade a light on 'Kaldor facts' and Goodwin-like growth cycles.

[25]See Vivarelli (2015) and Calvino and Virgillito (2018) for a detailed survey about different 'compensation' mechanisms proposed in literature in order to explain the interplay between innovation and employment.
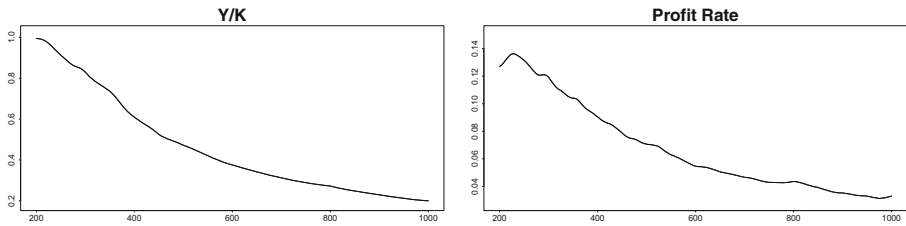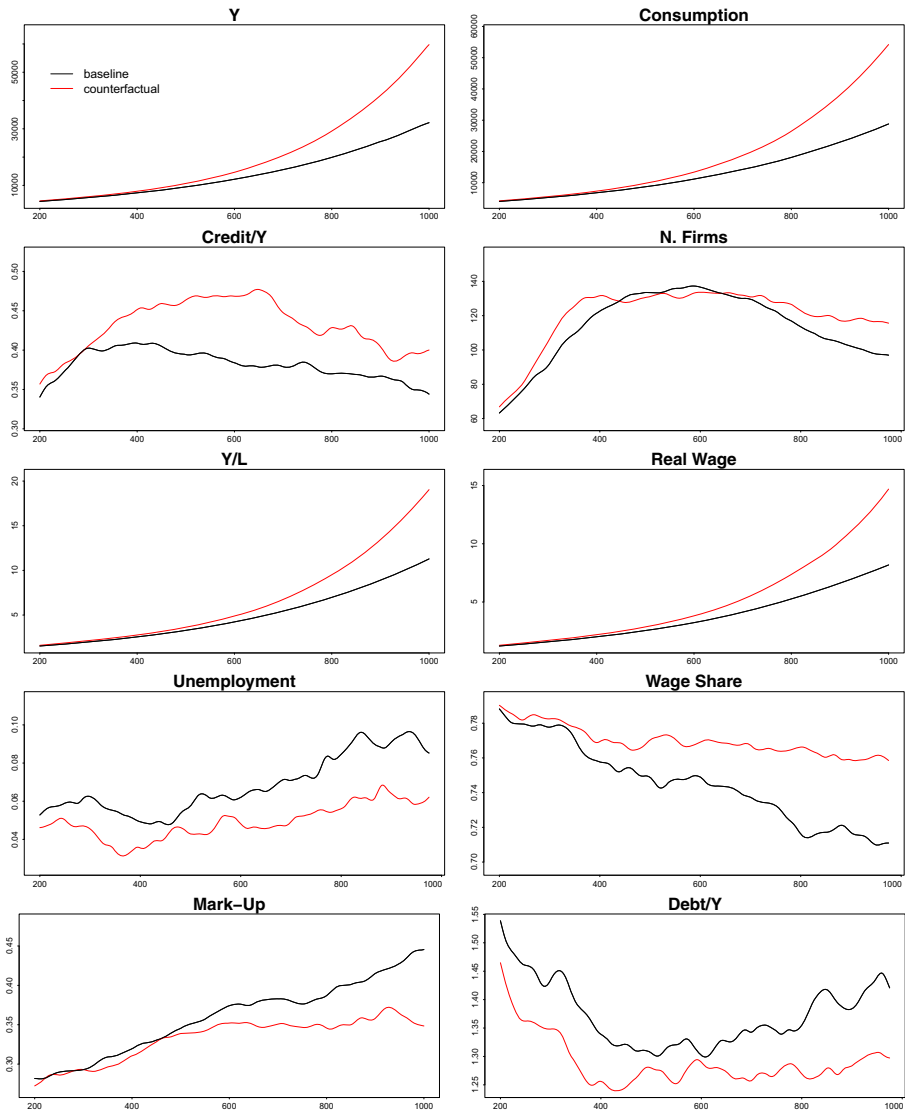
Fig. 3 Average trend (continuous lines) and standard deviations (dashed lines) across 100 MC runs for 1000 time periods (time-span $T = \{200:1000\}$) related to the aggregate output/capital ratio and the average profit rate

and (Beqiraj et al. 2019). Thus, by modelling a single final-good sector within the present model we cannot study the effect of potential employment shifts across sectors due to different growth rates of productivity, i.e. the so-called 'Baumol-Bowen effect' (Baumol 1967), and 'capital deepening', triggered in turns by different intensity of labour-saving technical change in different sectors (as in Acemoglu and Guerrieri (2008), Alvarez-Cuadrado et al. (2018), Ngai and Pissarides (2007), and Young (2004) and Zuleta and Young (2013)), and the dynamics of demand composition between service and manufacturing goods (Beqiraj et al. 2019). This could be an interesting point to be addressed in further versions of the present model.

Let us now discussing the results related to the patterns of technical change shaping firms' adoption of production techniques. As anticipated, firms do not innovate to the same extent on labour- and capital-productivity, i.e. we have *directed* and *biased* technical progress. Indeed, the pattern of the difference between average labour and capital productivity ($\varphi_{lt} - \varphi_{kt}$) displays the endogenous emergence of an '*innovation bias*' from the choice of techniques made by consumption firms (Figure 2). This bias towards labour-saving innovations is driven by the classical profitability criterion (17) through which firms can discriminate among different production techniques, obtained as different random draws from the same symmetric support (14 and 15). Hence, we let emerge the 'innovation bias' from the evolutionary innovation process without imposing any IPF *á-la-Kennedy* as in the standard model of directed technical change (see Section 2). This allows us to overcome one of the main critiques to the standard ITC models, that is the independence of the shape of IPF on the bias along the path of technical change (Nordhaus 1973; Ruttan 1997).

As pointed out by Stiglitz and Greenwald (2015) in their model of directed technical change, a *learning-to-learn* process is at work, so that the factor-biased technical change process may feed upon itself as firms become more skilled at learning how to save the labour input.

Moreover, as stated above in the long-run the model is also able to reproduce the so-called 'Kaldor Stylised Facts', as we have an exponential growth of the output-labour ratio (i.e. aggregated labour productivity), real wages and capital-labour ratio (i.e. the so-called 'capital deepening') (Fig. 1). According to the standard Kaldor facts, in the long-run we should also have roughly stable: average profit rate and output-capital ratio (i.e. aggregated capital productivity) as shown in Fig. 3. However, during the overall simulation these variables show a richer dynamics. The

Fig. 4 Average trend (continuous lines) and standard deviations (dashed lines) across 100 MC runs for 800 time periods ($T = \{200:1000\}$). I analyse two different scenarios: the 'baseline' scenario (black line) and a 'counterfactual' scenario wherein I implement a 'neutral' technical change process (red line). The trend component of the simulated time series has been obtained by applying the HP filter with a smoothing parameter $\lambda = 1600$

average firms' profit rate displays a decreasing pattern for long time periods until it stabilises and the same holds for the aggregate output-capital ratio. Indeed, the rate of profit represents a crucial variable either for firms' choice of technique and for their investment planning (22). According to Eq. (17) consumption firms

discriminate among different productivity improvements depending on expected profitability. However, many economic factors may lead to a 'fallacy of coordination' underling the aggregate pattern of the profit rate due to the relevant feedback mechanisms among technical change, wages, capital accumulation and the profit rate (Dumenil and Levy 2003; Shaikh 2016). First of all, firms are profit-oriented agents and increasingly try to improve labour productivity by means of R&D activities in order to reduce the quantity of workers needed to expand their production and improve their profit margins. However, as discussed above, an excessive labour-saving trajectory of technical change may be detrimental for the dynamics of wages as both firms and workers have a certain probability of reducing the offered and requested wage depending on the aggregate unemployment level in our economy (12) and (28). The weakening of wage dynamics has a twofold consequence: on the one hand, it increases firms' profit margins *via* reductions of labour cost; ii) on the other hand, it weakens workers' purchase power by shrinking aggregate consumption, and hence the aggregate demand, as workers belong to the class with the higher propensity to consume. A decline in aggregate consumption may lead, in turn, a greater number of consumption-good firms to suffer from worse selling performances and lower revenues. This may reduce, in turns, firms' internal financing capacity and trigger higher loans demand to commercial banks (whose willingness to accord loan requests depends on firms leverage and thus on firms' net worth), by downward affecting their investment planning (22). Moreover, as shown by the real investment artificial time series (Fig. 1), the ongoing capital accumulation process boosts the growth of firms capital stocks so to further deteriorating profit margins and hence the rate of profit. As anticipated, we also observe a decreasing output-capital ratio until it stabilises in the long-run, providing support for purely labour-augmenting technical change (i.e. *Harrod-neutral)* in the long-run but for labour-saving/capital-using technical change during the transitional phase. This pattern is also driven by the accumulation of capital stock and the inflation of capital-good prices. Indeed, consumption firms may reduce their selling prices due to increasing productivity gains whereas in our model capital firms cannot undertake innovation activity in order to improve their production process, so that they are more constrained in reducing their selling price for competitiveness purposes[26].

On this ground, the simulation results are quite in tune with the recent debate about different patterns of output/capital ratio (Piketty 2014; Stiglitz 2016) and firms profitability at micro and industrial level (Shaikh 2016), observed in many advanced economies before and after the Great Recession (2007). The model is not able to take into account the theoretical and empirical issues concerning

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[26]Empirical evidences about the role of decreasing capital-goods prices on the pattern of 'capital deepening' in many advanced economies during the last decades (see, for example, Karabarbounis and Neiman (2014)), should be taken into account. However, the oversimplified modelling of capital sector within the present model represents a harsh constraint. As anticipated, the theoretical reasoning for this oversimplified modelling of capital sector lies in the aim of the present contribution. That is, to shed a light on the causes and the effects of biased and directed labour-saving technical change on growth and distribution. To the purpose, a 'disembodied' innovation model wherein the decision about intensity and direction of technical change takes place within the same production sector represents a first step in this direction.

'rent-seeking' behaviours[27] and other crucial economic factors driving the divergence between output-capital and output-wealth ratios, highlighted among others by Stiglitz (2016). Nevertheless, we look at the decreasing pattern of our simulated output-capital ratio as the result of capital accumulation process *vis-à-vis* economic growth in presence of complex feedback mechanisms and interactions between supply (biased and directed labour-saving technical change and wage formation dynamics) and demand-side (aggregate consumption and investment patterns) factors.

4.1 'Biased' and 'Neutral' technical Change: a 'Counterfactual' scenario

In order to corroborate the hypothesis about the crucial role played by the emergent innovation bias on the decline of wage share and the overall model dynamics, a comparison between the baseline and a 'counterfactual' scenario has been performed.

We define 'counterfactual' scenario, an alternative model configuration wherein 'neutral' technical change (i.e. *Hicks-neutral*) is at work, that is where consumption-good firms compute a single random draw for both the growth rate of labour and capital productivity ($\hat{\varphi}_l = \hat{\varphi}_k$). Figure 4 shows the average trend component, across 100 MC runs, of artificial time series related to both baseline (black line) and 'counterfactual' (red line) scenario. As we expected, in the (baseline) 'innovation bias scenario' the direction of the choice of techniques towards 'excessive' labour-saving innovations overall negatively affects the macroeconomic configuration of our economy by weakening both real-GDP and real consumption growth. This is due to the persistent slowdown of wage dynamics with respect to labour productivity growth, also reflecting in contractions of the purchase power for workers, that is the class of households' agents with higher propensity to consume, leading to shrinking aggregate demand. On the contrary, within the 'neutral innovation scenario' firms almost indiscriminately choose improvement of both production input (labour and capital) without directing the innovation effort towards the input exerting higher pressure upon firms' cost structure (i.e. labour input). Hence, the neutral innovation hypothesis should not allows us to analyse the endogenous emergence of the decline in the labour share together with relatively higher levels of aggregate unemployment[28]. Therefore, we can look at the 'innovation bias' as one of the possible explanations for these new empirical evidences affecting advanced capitalist economies as a consequence of 'non-neutral' technical change trajectories. Furthermore, the artificial time series related to credit-to-GDP and public debt-to-GDP ratio, average number of consumption firms and average mark-up, under the baseline and 'counterfactual' scenario, additionally confirm a negative impact of the 'innovation bias' in terms of macroeconomic performances, competitive dynamics and market concentration. Indeed, under the baseline scenario, we have higher market concentration indicating

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[27]On this ground, Botta et al. (2019) recently proposed an AB-SFC model describing the role of 'rent-seeking' and credit dynamics on growth and financial instability.

[28]See Dosi et al. (2017) for a detailed discussion about the effect of 'competitive' and 'Fordist' regimes upon macroeconomic dynamics and unemployment persistence.

the presence of stronger competitive pressure exerted on consumption-good firms. As previously discussed, we ought to highlight that this model focuses on the effect of 'non-neutral' technical change upon long-run growth and *functional* income distribution, and that we are taking into account only *process* innovations. Thus, a more sophisticated model with the possibility of product innovations and a segmented labour market, with different skills and/or different income-classes, would allows us to deeper analyse the interplay between technical change, growth, distributive shares and employment as we can consider, for example, the effects of different wage regimes upon different classes of workers. This is the case in Caiani et al. (2018c) and Caiani et al. (2018b) wherein excessive labour-saving technical change is considered as not detrimental for growth and employment (or, *rectius*, wherein its effect is offset by a greater propensity to consume of lower-income workers) and where higher levels of unemployment have been explained as a consequence of growing income and wealth inequalities. However, a quite general dynamics has been presented for our artificial economy triggered by an excessive labour-saving technical change process which reproduces realistic patterns highlighted in theoretical and empirical contributions. Therefore, we can reliably ascribe the persistent decline of the wage share to the innovation bias towards increasingly labour-saving technical change, and we can conclude that the interplay between the latter and the magnitude of firms' capital accumulation, if not offset *via* strong 'wage-push' counter-forces, may lead to weaker macroeconomic performances as compared to those reached within the 'neutral innovation scenario'.

4.2 A sensitivity analysis: Innovation process and wage formation

The present section provides an attempt to stress the simulation results by means of a sensitivity analysis performed on two key parameters: i) the amplitude of the support from which the random draws for inputs productivity is computed (δ_{IN}); ii) the parameter tuning the strength of the relation between aggregate level of unemployment and the probability of upward or downward revising the requested or offered wage, i.e. the strength of workers' and firms' bargaining power (υ). For each scenario, that is for each parameters configuration, Fig. 5, 6, 7 and 8, display the artificial time series related to (trend) average values across 25 MC runs. The choice of these two parameters lies in the theoretical reasoning behind the description of the main results presented in the previous section. Therefore changes in the 'innovation parameter' δ_{IN} and in the 'wage parameter' υ reflect, respectively, the role of different intensities of the innovation process and of the direction of wage formation process in favour of workers' or firms' bargaining power. The first parameter sweep (on δ_{IN}) investigates the role and dynamics of the idiosyncratic learning process through which heterogeneous firms try to improve their production techniques[29]. This analysis allows us to integrate the results obtained through the comparison between the baseline 'innovation bias' scenario and the
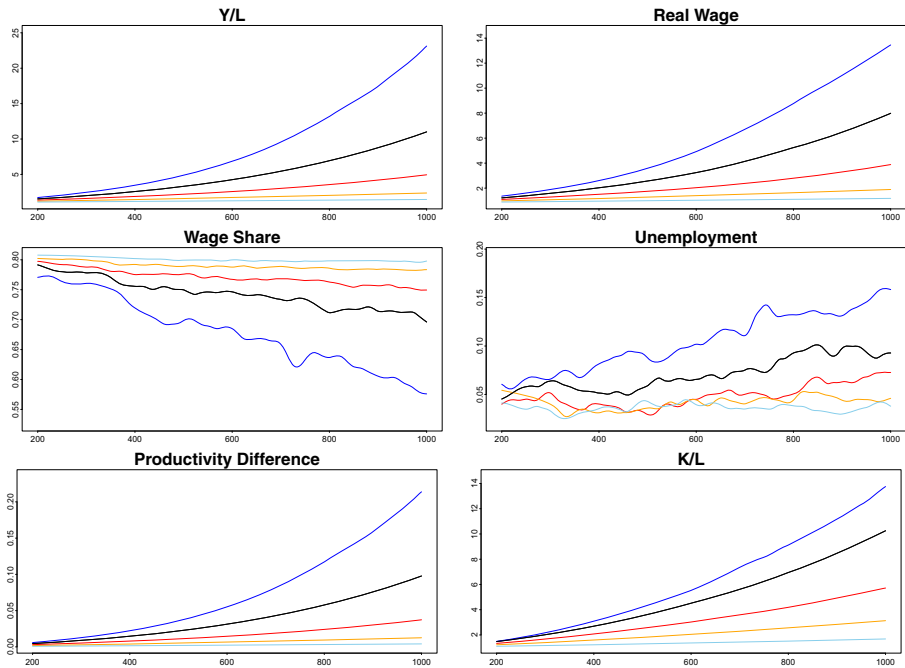
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[29]Dosi et al. (2016) recently propose a simulation model whereby the two crucial evolutionary mechanisms, that is idiosyncratic learning and market selection process, are deeply investigated in the light of micro and sectoral empirical evidences and statistical regularities about firms' heterogeneity.
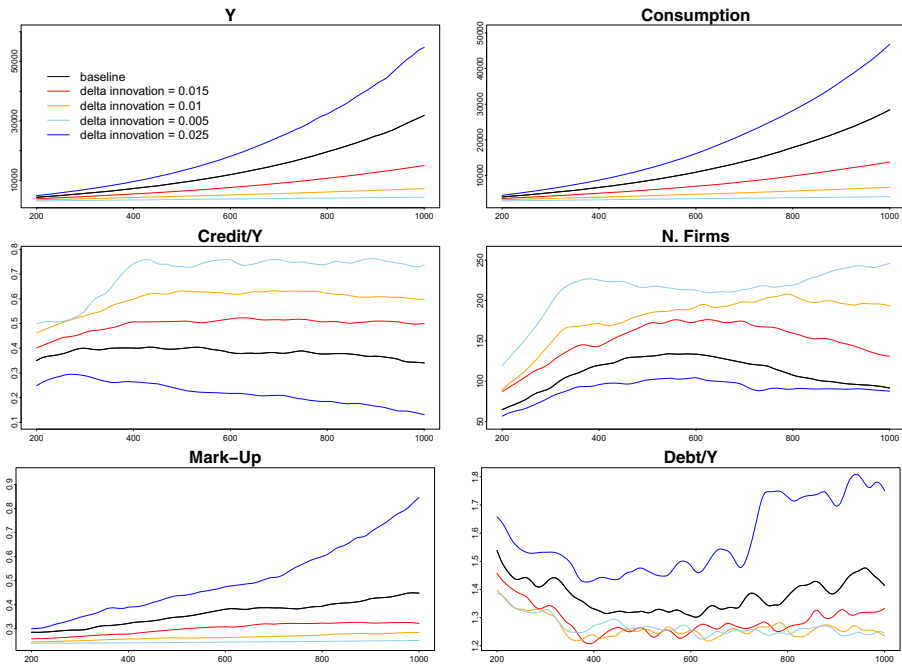
Fig. 5 Average trend (continuous lines) and standard deviations (dashed lines) across 25 MC runs for 800 time periods ($T = \{200:1000\}$) for different values of innovation parameter δ_{IN}. The artificial time series displays simulated data on real GDP, real consumption, credit-on-GDP ratio, the number of consumption firms, average mark-up and debt-on-GDP ratio. Different lines refer to different parameter configurations (different scenarios): i.e. the baseline scenario (black line) with $\delta_{IN} = 0.02$, and four alternative scenarios with $\delta_{IN} = 0.005$ (light blue), $\delta_{IN} = 0.01$ (yellow), $\delta_{IN} = 0.015$ (red) and $\delta_{IN} = 0.025$ (blue)

'counterfactual' scenario with 'neutral' technical change (Subsection 4.1). To the purpose, Figs. 5 and 6, provide a complete landscape framing the role of different innovation bias intensities on the model dynamics, by comparing the baseline scenario ($\delta_{IN} = 0.02$) with four alternative scenarios describing, respectively, a restriction ($\delta_{IN} = \{0.005; 0.01; 0.015\}$) and an increase ($\delta_{IN} = 0.025$) of the parameter. Indeed, the higher the amplitude of the support for the random draws of inputs' productivity, the higher the intensity of the 'innovation bias'. This result is in tune with those discussed in Subsection 4.1, thereby validating the role of excessive adoption of labour-saving production techniques on the overall macroeconomic performance of our artificial economy. In particular, the main findings obtained by the present simulation model, that is the endogenous emergence of the 'innovation bias' and the persistent declining pattern of wage share, with increasing 'capital deepening' and persistently relatively higher level of unemployment, still hold.
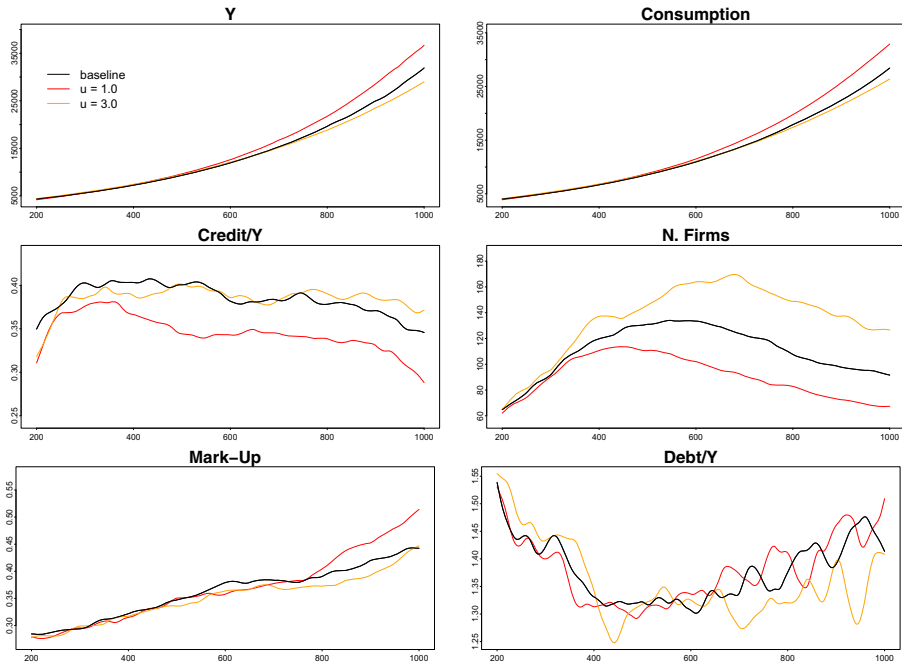
Moreover, Figs. 7 and 8 show a further investigation on the behaviour of our artificial economy under two different configurations of the model parameter reflecting the strength of workers' and firms' bargaining power (υ) as compared to the baseline scenario (with $\upsilon = 2.0$). As discussed in Section 3, the adaptive revision of wage demand and supply depends, respectively, on workers' occupational status in $t - 1$,

Fig. 6 Average trend (continuous lines) and standard deviations (dashed lines) across 25 MC runs for 800 time periods ($T = \{200:1000\}$) for different values of innovation parameter δ_{IN}. The artificial time series displays simulated data on average output-labour ratio (i.e. aggregate labour productivity), real wages, the wage share, aggregate unemployment rate, the 'innovation bias' (i.e. the (percentage) difference between average labour and capital productivity) and the capital-labour ratio (i.e. the 'capital deepening'). Different lines refer to different parameter configurations (different scenarios): i.e. the baseline scenario (black line) with $\delta_{IN} = 0.02$, and four alternative scenarios with $\delta_{IN} = 0.005$ (light blue), $\delta_{IN} = 0.01$ (yellow), $\delta_{IN} = 0.015$ (red) and $\delta_{IN} = 0.025$ (blue)
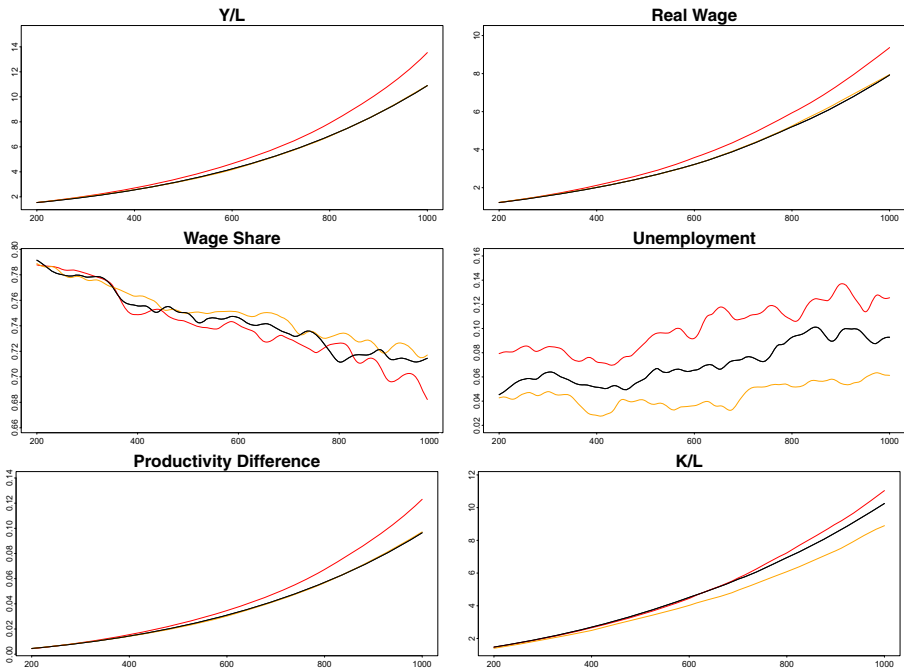
and on firms' gap between the amount of workers needed and effectively hired in $t-1$ (see Eq. 12 and 28). The probability of upward (downward) revising the requested (offered) wage for workers (firms) depends, in turn, on the aggregate level of unemployment in $t - 1$, so to reflect the 'tightness' of the labour market. The strength of this relation is tuned by parameter υ[30]. Figs. 7 and 8 compare the baseline scenario with two alternative scenarios whereby the probability for workers to upward revising the wage claim is, respectively, higher ($\upsilon = 1.0$) and lower ($\upsilon = 3.0$). This analysis allows us to investigate how the negative feedback mechanism exerted by the innovation bias on relatively higher levels of aggregate unemployment affects workers' bargaining power thereby weakening the dynamics of aggregate consumption with detrimental effects on firms demand expectations and market performances.

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[30] As in Caiani et al. (2018a) the parameter has been set to the same value for both workers' and firms' wage revision. Recently, Caiani et al. (2019) propose an extension of their multi-country AB-SFC model (which is the ancestor of the present model), wherein the wage rule has been refined so to perform a detailed analysis on how different wage regimes may affect the economic performance of member countries belonging to an artificial monetary union.

Fig. 7 Average trend (continuous lines) and standard deviations (dashed lines) across 25 MC runs for 800 time periods ($T = \{200:1000\}$) for different values of 'wage parameter' υ. The artificial time series displays simulated data on average output-labour ratio (i.e. aggregate labour productivity), real wages, the wage share, aggregate unemployment rate, the 'innovation bias' (i.e. the (percentage) difference between average labour and capital productivity) and the capital-labour ratio (i.e. the 'capital deepening'). Different lines refer to different parameter configurations (different scenarios): i.e. the baseline scenario (black line) with $\upsilon = 2.0$, two alternative scenarios, one reflecting a strengthening of workers' bargaining power $\upsilon = 1.0$ (red line) and the other one in the opposite direction $\upsilon = 3.0$ (yellow line)

On the one hand, the higher probability for workers to upward revising their wage, given a certain level of aggregate unemployment, leads to relatively higher output and consumption growth (Fig. 7), as well as to better aggregate productivity performances (Fig. 8). This result is well in tune with the empirical evolutionary and Schumpeterian literature about the long-run detrimental effect of wage and labour flexibility on the innovation process (Kleinknecht et al. 1988; Cetrulo et al. 2019) as well as with the simulation findings provided by Caiani et al. (2019) about the effect of different wage regimes in an artificial monetary union. However, from an individual firm-level perspective, in absence of any coordination strategy, the stronger wage dynamics also affects firms' cost structure thereby encouraging them to intensify the innovation effort towards the adoption labour-saving production techniques in order to preserve their profit margins and market positions. Indeed, in this scenario ($\upsilon = 1.0$), we have a more concentrated market structure characterised by fewer firms with relatively higher dimensions and market power (Fig. 7), but also boosting the innovation process, with faster growth of the 'innovation bias' and higher 'capital deepening' (Fig. 8). As discussed in Section 4 and Subsection 4.1,

Fig. 8 Average trend (continuous lines) and standard deviations (dashed lines) across 25 MC runs for 800 time periods (T ={200:1000}) for different values of 'wage parameter' υ. The artificial time series displays simulated data on average output-labour ratio (i.e. aggregate labour productivity), real wages, the wage share, aggregate unemployment rate, the 'innovation bias' (i.e. the (percentage) difference between average labour and capital productivity) and the capital-labour ratio (i.e. the 'capital deepening'). Different lines refer to different parameter configurations (different scenarios): i.e. the baseline scenario (black line) with $\upsilon = 2.0$, two alternative scenarios, one reflecting a strengthening of workers' bargaining power $\upsilon = 1.0$ (red line) and the other one in the opposite direction $\upsilon = 3.0$ (yellow line)

these mechanisms also negatively affect macroeconomic dynamics of credit and debt-on-GDP ratios (Fig. 7). Moreover, looking at the pattern of wage share and aggregate unemployment (Fig. 8), the reasoning about the interplay between more intensive labour-saving technical change patterns, leading to higher levels of aggregate unemployment (as the stronger workers' bargaining power may allow them to conquer relatively more stable position on the labour market), and the shrinking of wage share, due to slower wage growth *vis-à-vis* productivity dynamics, still holds. Nevertheless, this is just an attempt to analyse the role of biased and directed technical change on growth and distribution within a Schumpeterian innovation model explicitly interacting with Keynesian demand effects. Indeed, further refinements of the present model should crucially take into account: i) the role of product innovations on potential 'labour-friendly' counterbalancing effects and the role of sectoral differentiation among heterogeneous consumption firms; ii) the possibility for workers to have different skills endowments and their interaction with firms internal knowledge-base and organizational capabilities; iii) the role of labour market policies aimed at guarantee labour-friendly innovation patterns and the effect of coordination bargaining strategies on wage and occupational dynamics.

5 Conclusions

The main strength of the present contribution relates to the integration of a *classical-fashioned* induced and directed innovation process within a *Keynesian* demand-led and *evolutionary* endogenous growth model. The AB-SFC macro modelling approach allows us to analyse the '*innovation bias*' as an *emergent property* of the technical change process engaged by heterogeneous consumption-good firms choosing both the *intensity* and the *direction* of the innovation towards a labour- or capital-saving choice of technique. Therefore, as discussed in Section 2, from a theoretical standpoint the present model propose an attempt to overcome one of the main critiques opposed to the IPF *á-la-Kennedy*, that is its independence on the bias along the pattern of technical change, by explicitly taking into account the *path-dependent* nature of technical change process.

In the long-run the model also reproduces the so-called 'Kaldor Stylised Facts' (i.e. we have a purely labour-saving technical change), however during the transitional phases the model shows a labour-saving/capital using innovation pattern as the aggregate output-capital ratio decreases until it stabilises in the long-run. Moreover, the model endogenously reproduces the persistent decline of the wage share observed during the last decades in many advanced (and developing) economies. We can ascribe this evidence to the complex interplay between the directed and biased technical change process, leading to increasing adoption of labour-saving production techniques, its negative effect on aggregate unemployment and the dynamics of wages and aggregate demand. Indeed, the comparison between the baseline scenario and the 'counterfactual' scenario, wherein a 'neutral' technical progress is at work, confirms our hypothesis by displaying weaker growth of real-GDP, wages and consumption within the 'innovation bias' scenario as well as persistent downswings in labour share and relatively higher unemployment rate *vis-à-vis* the 'neutral innovation' scenario. These results have been further confirmed through the innovation and wage formation parameters investigation proposed as a sensitivity analysis.

The endogenous emergence of the '*innovation bias*' within an evolutionary and Keynesian environment, together with a persistent declining pattern of wage share explicitly driven by both demand- and supply-side phenomena represent the main novelty of the present model as compared to traditional *supply-side* ITC models, both Neoclassical and Classical-evolutionary. On this ground, as discussed in Section 2, the present model also represents an attempt to bridge the *induced/directed* and the *localized/evolutionary* approaches to the source of technical change. Therefore, the present model allows us to analyse the effect of explicit feedback mechanisms arising from the interplay between ITC, capital accumulation, wage formation and aggregate demand.

Of course, this is just a first step towards the analysis of the interplay between biased technological change, employment, growth and income distribution. Indeed, there are many aspects that should be further investigated starting from this model. For instance, the present model exclusively considers process innovation in a closed-economy model, whereas further investigations could also concern the role of product innovations and the effect of labour-saving technical change upon both sectoral and aggregate distributive shares, within a two-sector framework, and upon growth and

competitiveness gaps between two (or even more) countries, within a multi-country modelling framework. Other important refinements should concern the possibility for workers to have different skills endowments thereby allowing to analyse their interaction with firms internal knowledge-base and organizational capabilities. Finally, some policy investigation should be proposed by analysing either the role of labour market policies, aimed at guarantee labour-friendly innovation trajectories, and the effect of coordination bargaining strategies on wage and occupational dynamics.

Appendix

Table 4 Baseline calibration

Symbol	Description	Value
W	Number of workers	3000
M	Number of capitalists	200
Ψ	Matching Parameter	10
A_0	Firms' initial net worth	10
υ	Wage revision probability parameter	2.0
φ_{l0}	Initial labour productivity (consumption firms)	1.0
φ_{k0}	Initial capital productivity (consumption firms)	1.0
$a_{K,0}$	Initial labour productivity (capital sector)	1.0
w_0	Initial wage	1.0
p_0	Initial consumption-good price	1.0
δ	Adaptive parameter	0.03
ρ	Share of dividends distributed	0.95
γ	Share of R&D expenditure	0.03

Table 4 (continued)

Symbol	Description	Value
ν	R&D success probability parameter	0.8
δ_{IN}	Innovation random draws parameter	0.02
$\mu_{c,0}$	Consumption firms' initial mark-up	0.2
$\mu_{k,0}$	Capital firms' initial mark-up	0.01
θ	Inventories share parameter	0.2
κ	Capital goods duration	20
λ_1	Investment function profit rate weight	0.05
λ_2	Investment function capacity utilization weight	0.05
$\bar{r}$	'Normal' profit rate	0.045
$\bar{u}$	'Normal' rate of capacity utilization	0.9
α_{1w}	Workers' propensity to consume out of income	0.95
α_{2w}	Workers' propensity to consume out of wealth	0.35
α_{1m}	Capitalists' propensity to consume out of income	0.75
α_{2m}	Capitalists' propensity to consume out of wealth	0.15
η	Banks-firms minimum proportion	0.03
σ	Banks' minimum dimension relative to firms	4.0
μ_1	Total credit supply parameter	20.0
μ_2	Minimal reserve requirement parameter	0.1
χ	Loan interest parameter	0.003
ι_l	Loans' probability parameter	0.2
ι_b	Bonds' probability parameter	0.1
τ_0	Initial tax rate	0.4
G_0	Initial public expenditure	0.4
i_{res}	Interest paid on banks' reserves	0.001
i_0^b	Initial interest rate on bonds	0.001
ζ	Deposit interest-discount rate ratio	0.1

Table 5 Results Summary

Variable	Baseline MC Average	Counterfactual MC Average
Real GDP	12.702,18	28.813,78
(s.e.)	(0.009)	(0.006)
Real consumption	11.475,32	21.710,22
(s.e.)	(0.007)	(0.005)
Real investment	220	113
(s.e.)	(0.01)	(0.008)
Unemployment	0.07	0.04
(s.e.)	(0.005)	(0.003)

Table 5 (continued)

Variable	Baseline MC Average	Counterfactual MC Average
Labour productivity growth	0.003	0.004
(s.e.)	(0.0002)	(0.0001)
Real wage growth	0.002	0.003
(s.e.)	(0.0001)	(0.0002)
Credit/GDP	0.39	0.51
(s.e.)	(0.003)	(0.003)
Mark-up	0.36	0.31
(s.e.)	(0.002)	(0.001)
Number of cons. firms	98	119
(s.e.)	(0.0005)	(0.0002)
Number of capital firms	40	29
(s.e.)	(0.0001)	(0.0001)
Number of banks	7	9
(s.e.)	(0.05)	(0.03)
Debt/GDP	1.32	1.26
(s.e.)	(0.003)	(0.005)
R&D/GDP	0.031	0.035
(s.e.)	(0.0001)	(0.0001)
Wage Share	0.74	0.77
(s.e.)	(0.002)	(0.001)

Average trend components across 100 MC runs of the artificial time series (for the time-span 200:1000) related to some macroeconomic variable, obtained through the HP filter with a smoothing parameter $\lambda = 1600$. Standard errors in parenthesis.

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