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Wage Inequality, Labor Market Polarization and Skill-Biased Technological Change: An Evolutionary (Agent-Based) Approach

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Abstract

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Wage Inequality, Labor Market Polarization and Skill-Biased Technological Change: An Evolutionary (Agent-Based) Approach*

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November 6, 2018

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Keywords: innovation, agent-based modeling, Schumpeter, directed technological change

1 Introduction

Rising wage inequality is a widely discussed phenomenon, especially for the USA where it has been observed since the 1980s (see Autor, 2014). A number of possible explanations have been proposed and investigated, including globalization (see Helpman, 2016) and the diminished power of trade unions (Card, 2001; Pontusson, 2013). By the end of the last century, however, the hypothesis that new technologies are skill-biased to the benefit of higher-skilled workers (see Autor, Katz, & Krueger, 1998) became the "standard explanation" (Acemoglu, 2002). Acemoglu (1998, 2002) delivers a theoretical framework for this observation. He assumes that new technologies can

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be designed in a way that they fit the currently available skills (so-called directed technological change).[1]

In the beginning of the 2000s, however, this view was challenged. Autor, Levy, and Murnane (2003) argue that the effect of computing technologies is twofold: they complement non-routine tasks (which are typically performed by high-skilled, but also low-skilled labor) and substitute routine tasks (typically performed by medium-skilled workers). For example, computers support the work of scientists and (at this point) do not threaten the existence of their jobs, whereas travel agents were hit hard by the ability of customers to book their flights and hotels on the internet. Goos and Manning (2003) introduced the term "job polarization" to describe that medium-skilled workers are most affected by substitution as their jobs are automated and vanish. On the other hand, low-skilled as well as high-skilled jobs (or, as they put it, "lousy and lovely jobs") are on the rise. This result was confirmed repeatedly for the U.S. and Europe (Goldin & Katz, 2007; Goos, Manning, & Salomons, 2009; Autor & Dorn, 2013). Autor and Dorn (2013) and Autor (2015) speak, more broadly, of a polarization of the labor market and show that the polarization in employment was accompanied by a polarization of wages. Whether or not this trend will continue remains to be seen. Among others, Brynjolfsson and McAfee (2011), as well as Frey and Osborne (2017) suggest that new technologies become more and more sophisticated by the minute which might lead to a situation in which low- and high-skilled jobs are increasingly threatened as well. Meanwhile, the idea of directed technological change was developed further. Acemoglu and Restrepo (2018b) develop a framework in which directed technological change may lead to excessive automation that lead to wages which are relatively too high compared to the rental rate of capital (e.g. due to labor market rigidities). In the most sophisticated version of this model to date, a potential skill-mismatch between low and high-skilled labor is highlighted. To fully reap the benefits of new technologies, but also to decrease inequality, the skill-level of the population has to be increased (see Acemoglu & Restrepo, 2018a).

We want to contribute to the understanding of the relationship between wage inequality, polarization and skill-biased technological change by putting forward an approach that combines two aspects of technological change: technical and economic feasibility. Following Schumpeter ([1934] 2012), we distinguish between inventions and innovations. Inventions open up new possibilities to produce a certain (old or new) good. But they will only become economically relevant if somebody (an entrepreneur or estab-

[1]Acemoglu was not the first economist to implement the idea of directed (or induced) technological change in a neoclassical framework. His contribution, however, was able to reconcile two facts with neoclassical economics which it seemed to contradict before: the simultaneous increase of supply of high-skilled labor and the skill premium since the 1980s (see Brugger & Gehrke, 2017, for a literature survey).

lished firm) innovates by actually using this possibility, which is only possible if it is profitable to do so. The innovation process therefore crucially depends on prices: how much do the inputs cost and how much can a firm charge for the outputs? In other words, just because a technology becomes invented, i.e. technically feasible, it doesn't mean that it will lead to an innovation, as only economically feasible technologies will be used. For example, fast food restaurants increasingly rely on self-service kiosks instead of human cashiers. Those kiosks substitute for (unskilled) labor, as well as land (as kiosks take up much less space). While this technology is available worldwide, it is more likely to be used in countries and areas where (unskilled) labor and land are relatively expensive, as the investment only then pays off[2].

From this point of view, a potential skill-bias of technological change may arise both in the invention, as well as in the innovation process. It is much easier to invent a machine that replaces human cashiers than a technology that substitutes doctors. But doctors are very expensive, so there is a huge incentive to automate at least some of the tasks they perform. For a start, artificial intelligence is thought to play a big role in radiology in future (Chartrand et al., 2017).

Our approach thus combines both the perspectives of Autor et al. (2003), who emphasize the technical skill-bias of computing technology, as well as Acemoglu (1998, 2002) who assumes that the direction of technological change (and thus, a potential skill-bias) is determined (at least partly) by supply and demand.

We also assume that technological change adds up – the invention of self-service kiosks, for instance, depended on continuous improvements that made computers ever smaller and cheaper – and thus is path-dependent. If this is the case, the trajectory of technological change may not easily be reversed, even if the direction of future innovations is changed.

To model our approach, we rebuilt the core of the Keynes + Schumpeter agent based model family (Dosi, Fagiolo, & Roventini, 2006, 2008, 2010; Dosi, Fagiolo, Napoletano, & Roventini, 2013; Dosi, Fagiolo, Napoletano, Roventini, & Treibich, 2015; Dosi, Pereira, Roventini, & Virgillito, 2017) which seems to be perfectly suited as it features endogenous growth that is based on an invention and innovation process at the firm level. We tried to follow the reference model very closely and avoid major deviations. We then modified it by introducing heterogeneous labor in the form of three types of workers which assume different roles in the production process and are differently affected by technological change.

One may argue that technological change could be implemented using a much simpler model. But we assume that the technological development, the goods and the labor markets are interdependent and therefore require a general analysis. We chose agent based modeling, as it allows us to study

[2]The use of this technology obviously also depends on customer acceptance.

a) technological change and inequality, which are inherently heterogeneous processes and b) how technological change and the labor markets are shaped by equilibrating, but also by disequilibrating forces. Instead of creating a new model from scratch, we chose to follow an established one and only change it modestly to make our point. As we concede in section 4.3, we are not content with every single mechanism that we implemented. In the future, we plan to further improve on the model, but do so on a step-by-step basis to be able to grasp the effects of every small change.

By the time we set up our model, two major contributions to heterogeneous labor in a general agent-based model involving R&D were published that we are aware of. Dosi, Pereira, Roventini, and Virgillito (2018) do not distinguish between different types of workers but implement skill as a continuous variable. Caiani, Russo, and Gallegati (2016), on the other hand, feature a segmented labor market like ours, but do not focus their analysis on the trajectory of technological growth as we do.

On the one hand, our model reproduces important insights from the previously cited well-known general equilibrium models concerned with the impact of technological change on heterogeneous workers, as well as from agent based models (see subsection 4.1) On the other hand, it produces some distinct results which seem to be a promising starting point for further research (see subsections 4.2 and 4.3).

The rest of the paper is organized the following way: The next section gives an overview of the model, describes the sequence of events the invention/imitation process in more detail. For reasons of readability, we tried to stick to colloquial language in this chapter. We then introduce different labor market settings and policies that we are experimenting with. In the fourth section, we show how we validated our model and where its limitations are to then go on to present the results of our labor market experiments. In the final section, we review and discuss our findings. A detailed, more technical, account of the model is given in appendix A, whereas its initial parameters are displayed in appendix B.

2 The model

Dosi et al. (2017, p. 167) describe the Schumpeter + Keynes model as a „general disequilibrium agent-based model, populated by heterogeneous firms and workers, who behave according to boundedly rational behavioural rules“. Our version of it is, as described in figure 1, populated by:

- Three different types of workers who represent different skill levels. Engineers (high-skilled workers) are employed by capital good firms, workmen (low-skilled workers who of course also consist of women) by consumption good firms and administrators (medium-skilled workers) are needed in both types of firms. Employed workers receive a wage

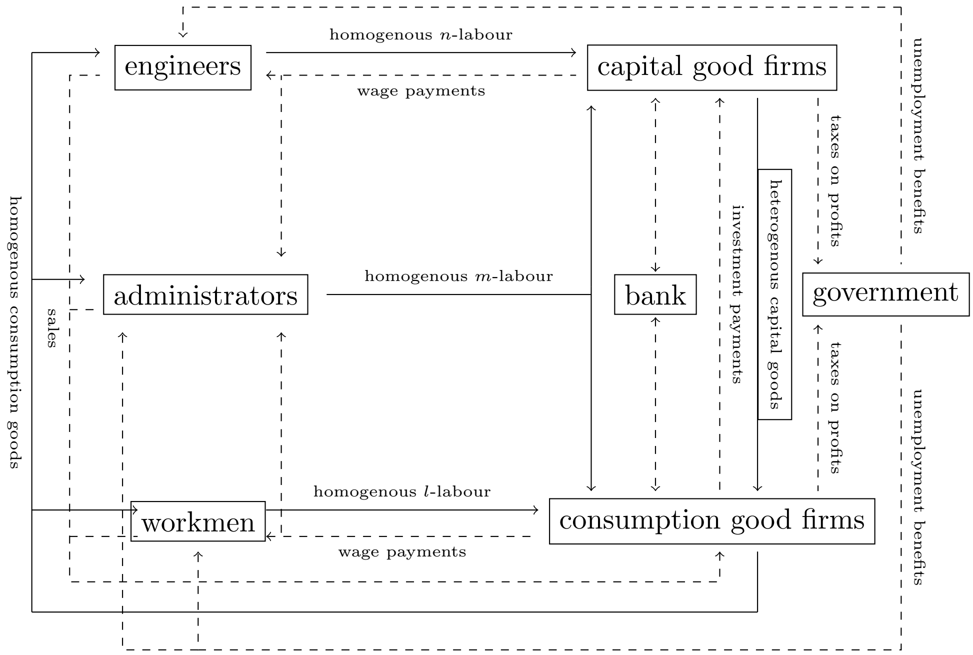

Figure 1: Flow diagram of the model. Dashed lines represent money flows

rate that depends on their occupation and the unemployed receive a fraction of their last wage as benefits from the government. Workers then use their funds to buy as many consumption goods as possible and save the rest of the money for the next period.

- Two different types of firms. Consumption good firms produce homogeneous consumption goods using labor from workmen and administrators, as well as (heterogeneous) capital goods. Capital good firms use labor from engineers and administrators to invent new prototypes of machines, which are offered to consumption good firms and produced on demand. Firms operate with a price markup on variable costs, both because they need to fund their investments and because they operate under imperfect competition.

- Capital goods which are characterized by the amount of engineer labor that is used in their production, the workmen labor necessary in their operation and the administrator labor used in both processes.

- A bank which provides credit to both types of firms.

- A government which charges taxes on profits of both types of firms and pays benefits to unemployed workers.

2.1 Sequence of events

The following sequence of events takes place in each period[3]:

1. *Price setting (1)*: Consumption good firms set their price markup (eq. 9). Capital good firms set their prices according to a fixed markup on variable costs (eq. 7).

2. *Advertisement*: Capital good firms advertise their most attractive prototype (eq. 8).

3. *Demand for capital goods*: Consumption good firms check how many new machines they expect to need in the upcoming period and order the most attractive [4] type they know of (eq. 16-19).

4. *Production planning*: Consumption good firms plan their production according to their expectations about future demand (eq. 13-15). Capital good firms plan according to the orders they received.

5. *Labor demand*: All firms calculate their labor demand and announce vacancies and dismissals (eq. 23-27).

6. *Labor market interaction*: All firms fire excess workers.

7. *Labor market interaction (2)*: All workers adapt their reservation wages (eq. 5 or 6). Unemployed workers apply to firms which offer vacancies matching their skills and wage expectations.

8. *Labor market interaction (3)*: Firms hire out of their queues of applicants.

9. *Production*: All firms produce according to their plans.

10. *Research and Development*: Capital good firms try to invent new prototypes and imitate their competitors (eq. 10-12).

11. *Wage payment*: All firms pay wages to employees. Unemployed workers receive benefits (eq. 30).

12. *Price setting (2)*: Consumption good firms set their prices (eq. 9).

13. *Consumption goods market*: Workers try to buy as many consumption goods as possible and save the rest of their funds for the next period. Sales are allocated to consumption good firms (eq. 20-22).

[3] We refer to the respective equations in parentheses. Most of them are located in the detailed account of the model in appendix A.

[4] The "attractiveness" of a certain type of machine depends on its costs in production and operation, see section A.1.1 for more details.

14. *Capital goods market*: New machines are delivered to and paid for by the consumption good firms.

15. *Depreciation*: Old capital stock depreciates and machines that reach the end of their life span are discarded.

16. *Profits*: All firms calculate their profits and pay taxes on them (eq. 28 & 29).

17. *Upskilling*: Unemployed workers may upskill.[5]

18. *Wages*: Workers decide whether they want to bargain. All firms adapt their wage offers and bargaining workers decide whether to accept the offer or quit (eq. 1 & 2 or 3 & 4).

19. *Insolvencies*: Insolvent firms are bailed out.[6]

2.2 Invention and imitation

We can find the Schumpeterian triad of invention, innovation and diffusion at the heart of the model. Capital good firms use a fixed percentage of past sales to employ engineers who invent new prototypes and imitate the competitors in every period. Successful inventions, as well as imitations, open up new technical possibilities to produce a machine (i.e. create a new prototype).

A prototype is characterized by the number of engineers used to produce this type of machine, the number of workmen needed to operate it and the number of administrators needed to administrate staff of engineers and workmen. The labor requirements of a certain machine are described by labor intensities[7].

A successful imitation simply copies the prototype of a competitor. Inventions are modifications of the prototype that the firm currently sells and change the labor intensities of administrators, workmen and/or engineers involved in the production processes. The change of workmen and engineer intensity depend on separate draws from a Beta distribution. The change of administrator intensity, however, depends on both draws and is therefore amplified to account for an assumption of a technical skill-bias against administrators.

[5] Not possible in the baseline scenario.

[6] We adopted the assumption of Dosi et al. (2010) that the number of firms is fixed. But to secure stock-flow consistency we wanted to avoid the creation of new firms with new capital stock or knowledge coming out of nowhere like *dei ex machina*.

[7] A workman intensity of two means that two workmen are needed to operate a machine. An engineer intensity of two means that two engineers are needed to produce a machine. An administrator intensity of two means that two administrators are needed for every workman and every engineer needed in the production processes.

But those modifications do not necessarily have to be labor-saving. For example, a newly invented (or imitated) prototype may need less engineers in its production but more workmen in its operation. Whether or not this prototype will actually be sold, depends on wages. Capital good firms want to sell the machine that seems most attractive to their customers (i.e. to the consumption good firms) and therefore only switch to a new prototype if it is more attractive than the currently used one. We assume that the "attractiveness" of a certain prototype is calculated using a formula that takes into account the price of the machine (which is given by a fixed markup on the wages of engineers and administrators used in its production), as well as the runtime costs (which is given by the wages of workmen and administrators used in its operation) within a certain time horizon (see eq. 8). This formula thus represents a boundedly rational approximation of whole-life costs.

This view of technological change, in which firms continuously adept to their environment dates back to Nelson and Winter (1982) and resembles Darwin's approach to selection, where "each slight variation, if useful, is preserved" Darwin (1859, p. 61) and may therefore be called evolutionary.

An invention that decreases both workmen and engineer intensities therefore always leads to an innovation. But a new prototype that increases workmen (engineer) intensity and decreases engineer (workmen) intensity, will only be sold if the decrease in runtime costs (price) is perceived to be more important than the increase in price (runtime costs). This decision depends a) on the magnitude of the changes (which are random) and b) on relative wages.

Technological change in our model is thus skill-biased against administrators in the invention process (accounting for the empirically observed decline of medium-skilled employment) and possibly against workmen or engineers in the innovation process (if their wages are perceived to be "too high" by the firms).

3 Labor market settings and policies

Unlike Dosi et al. (2017, p. 163), we do not study "archetypes of capitalism" but rather attempt to test the effects of different settings and policies starting from a benchmark scenario[8]. This approach has obvious drawbacks, as lots of different combinations of policies and settings consume a huge amount of simulation time. On the other hand, it allows us to single out the effects of each policy and setting, which due to the non-linear nature of our model

[8]A similar approach was chosen by Dosi et al. (2010), although we allow for multiple deviations from the benchmark scenario at once. While our "Fordist" and "Competitive" (reservation) wage setting mechanisms closely follow Dosi et al. (2017) in name and logic, they are not per se combined with other rules regarding e.g. labor market flexibility

may diverge in combinations with different other settings and policies.

3.1 Wage setting mechanisms

We experimented with three different initial wage settings: 1-1-1, 1-1.5-3, 1-2-4 (wages for workmen-administrators-engineers). We also explored two different wage setting mechanisms: In the "Fordist" setting, wages grow without regard to unemployment according to productivity. This setting could be imagined as a situation in which the trade unions are very powerful and want to make sure that the wage share remains constant. In this setting, firms raise their wage offers w_{t+1}^h according to the growth in individual and aggregate productivity (see eq. 1 and 2). By making the growth of wages dependent on the growth of individual productivity as well, we make sure that the more efficient firms also succeed on the labor market.

$$w_{j,t+1}^h = w_{j,t}^h \left(1 - \psi_1 \frac{\Delta\bar{\lambda}_t}{\bar{\lambda}_t} - \psi_2 \frac{\Delta\bar{\lambda}_{j,t}^l}{\bar{\lambda}_{j,t}^l}\right) |h = \{l, m\} \tag{1}$$

$$w_{i,t+1}^h = w_{i,t}^h \left(1 - \psi_1 \frac{\Delta\bar{\lambda}_t}{\bar{\lambda}_t} - \psi_2 \left(\frac{\tau_J}{1+\tau_J} \frac{\Delta\lambda_{i,t}^l}{\lambda_{i,t}^l} + \frac{1}{1+\tau_J} \frac{\Delta\lambda_{i,t}^n}{\lambda_{i,t}^n}\right)\right) |h = \{m, n\} \tag{2}$$

In the "Market" setting, it is assumed that wage offers also react to unemployment . To model it very simply, the increase of the "Fordist" setting is multiplied with the employment rate of the respective type of worker[9]. This means that firms which face full employment raise their wage offers according to the "Fordist" setting. If one type of workers faces high unemployment, however, their wage offers will only grow slowly as firms do not perceive a necessity to increase their wage offers rapidly if competition among workers is high (see eq. 3 and 4).

$$w_{j,t+1}^h = w_{j,t}^h \left(1 - (1 - \upsilon_{H,t})\psi_1 \frac{\Delta\bar{\lambda}_t}{\bar{\lambda}_t} - \psi_2 \frac{\Delta\bar{\lambda}_{j,t}^l}{\bar{\lambda}_{j,t}^l}\right) |h = \{l, m\} \tag{3}$$

$$w_{i,t+1}^h = w_{i,t}^h \left(1 - (1 - \upsilon_{H,t})\psi_1 \frac{\Delta\bar{\lambda}_t}{\bar{\lambda}_t} - \psi_2 \left(\frac{\tau_J}{1+\tau_J} \frac{\Delta\lambda_{i,t}^l}{\lambda_{i,t}^l} + \frac{1}{1+\tau_J} \frac{\Delta\lambda_{i,t}^n}{\lambda_{i,t}^n}\right)\right) |h = \{m, n\} \tag{4}$$

[9]If substitution is enabled, only the rate of employment at the lowest possible skill level is taken into account.

3.2 Reservation wage setting mechanisms

Whether or not an unemployed worker applies for a job or an employed worker wants to bargain for a higher wage depends on their reservation wage $\underline{w}_{h,t}$. We tested two different mechanisms: In the “Competitive” setting, employed workers expect a certain wage growth ω_2. Unemployed workers, on the other hand, accept every job that offers a wage above their unemployment benefits. This setting makes sure that labor market frictions are low - employed workers basically try to bargain in every period and unemployed workers are very likely to take up jobs.

$$\underline{w}_{h,t} = \begin{cases} (1+\omega_2)\underline{w}_{h,t-1} & \text{if employed} \\ w^g_{h,t} & \text{if unemployed} \end{cases} \tag{5}$$

In the “Market” setting, workers react to the situation they perceive at the labor market. They think of the labor market as a lottery with two possible outcomes: With a probability given by the rate of employment they expect to find a job that pays not only the last wage, but also a raise amounting to the average gain in productivity. With the complementary probability (the rate of unemployment), however, they estimate to end up unemployed and collect unemployment benefits. The reservation wage is then given by the expected payoff of the lottery.

$$\underline{w}_{h,t} = (1-\tilde{\upsilon}_{H,t})\frac{w^g_{h,t}}{\omega_1}\left(1-\frac{\Delta\bar{\lambda}_{t-1}}{\bar{\lambda}_{t-1}}\right) + \tilde{\upsilon}_{H,t} w^g_{h,t} \mid h = \{l, m, n\} \tag{6}$$

3.3 Substitution and upskilling

We experimented with (limited) substitution, allowing workers to work in a job that is one level below their skill level (i.e. administrators may work as workmen and engineers may work as administrators). We finally allowed for upskilling: A certain percentage (0%, 0.5%, 1% or 1.5%) of unemployed workers of a certain type raises their skill level at the end of the period (i.e. unemployed workmen may become administrators and unemployed administrators may become engineers).

4 Results

We also follow the tradition of Dosi et al. (2010) in the analysis of our model. Due to the fact that it depends on stochastic processes and non-linear interactions between heterogeneous agents, we are not able to fully analyze its properties analytically. Instead, we ran Monte Carlo simulations starting from a base line model in order to test the results of various different labor market settings and policies with the help of averages and regressions. This approach may be considered to be problematic, as an important feature of our model is its path-dependency. By testing different labor market settings and initial values, however, we can get a grip on what determines the direction of this path apart from pure chance[10].

4.1 Validation

Following Dosi et al. (2010), we propose a validation of the model based on its ability to replicate stylized facts (SF) that can be observed empirically in the real world. As all models of the K+S family, our model produces endogenous real growth of GDP, consumption and investment (**SF1**) with persistent fluctuations and business cycles (**SF2**, see fig. 2).

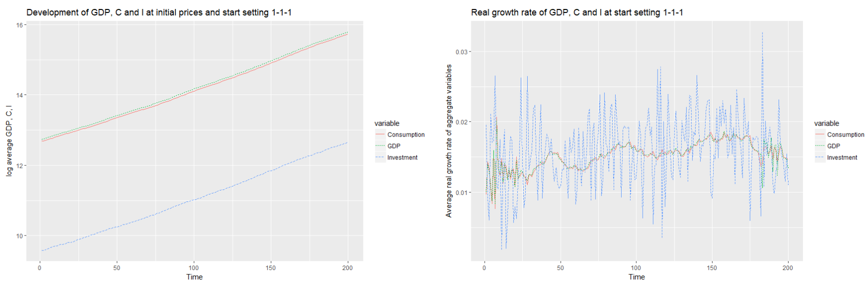

Figure 2: Development of log aggregate levels (left) and growth rates (right) at initial wages of 1-1-1

Our model also replicates the Phillips curve (see Phillips, 1958) (**SF 3**) and Beveridge curve (**SF 4**) (see Dow & Dicks-Mireaux, 1958, p. 592) (see fig. 3) and the corresponding shifts of the curves in the face of a change in structural unemployment. The model also meets three of Kaldor's initial stylized facts: the capital/output ratio remains constant, but the output/worker ratio rises, as the capital intensity (i.e. the capital/worker ratio) increases steadily over time (**SF 5**) (see Kaldor, 1957, p. 592).

More importantly, our model reproduces the empirical tendencies towards wage inequality (**SF 6**) (e.g. Autor, 2014), job polarization (**SF 7**, (Goos & Manning, 2003; Goos et al., 2009) and wage polarization (**SF 8**, (Autor & Dorn, 2013; Autor, 2015) (see fig. 4).

Those tendencies can be attributed to skill-biased technological change (**SF 9**) (e.g. Autor et al., 1998). The relative labor intensities of administrators (for technical reasons, see Autor et al. (2003)) and workmen (for

[10] We ran 50 simulation for each configuration up to period 250 and then cut out the first 50 periods. We also simulated the baseline setup up to period 1050 and confirmed the validation results. Looking at such ultra-long periods, however, would not only draw the attention away from the medium-term reaction of the model to different initial parameter settings, but also require an ultra-long term view of the economy involving the creation of new industries and skills and thus seems inappropriate for this model.

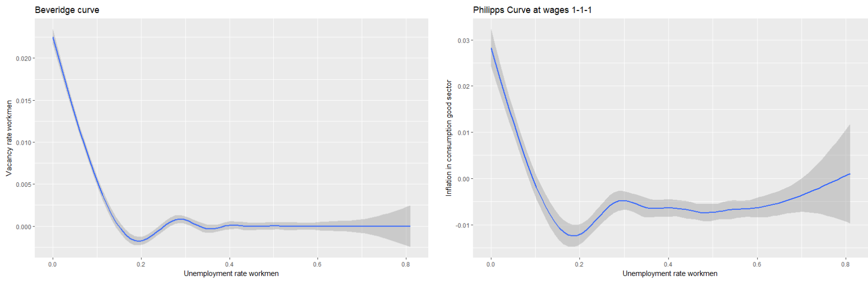

Figure 3: Beveridge curve (left) over all initial wages and Philipps curve (right) for workmen at initial wages of 1-1-1

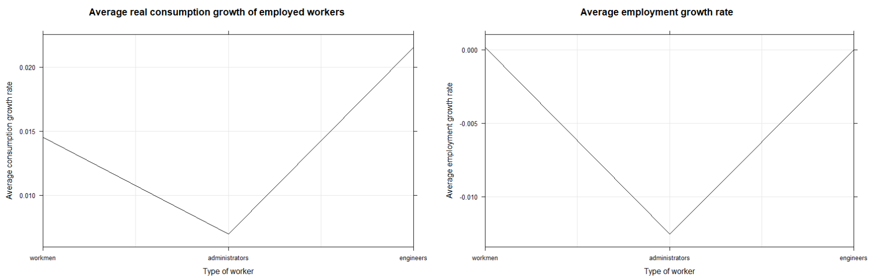

Figure 4: Average growth rate of real consumption of employed workers (left) and average growth rate of employment (right) at initial wages 1-1-1

economic reasons) experience a decline. As the employment of workmen is constrained by the number of machines available (and their labor intensities) and the employment of administrators by the number of employed workmen and engineers, both types of workers are affected by technological unemployment (**SF 10**) (see Frey & Osborne, 2017). The changes in employment then translate to changes in relative wages (see Autor & Dorn, 2013; Autor, 2015) (see fig. 5).

4.2 Policy experiments

Once we established the fact that our model actually replicates the tendencies that we are interested in, we can now proceed to test different labor market settings and policies. The goal of this exercise is to get aware of how wage inequality and polarization develop in different settings, whether they are harmful or beneficial and what could be done against them – at least within the limitations of our model.

(Reservation) wage setting mechanisms We begin our policy experiments by testing the different (reservation) wage setting mechanisms. The highest expectations are held, of course, for the "Fordist" wage setting mechanism as one could expect that if we start with equal wages and wages grow

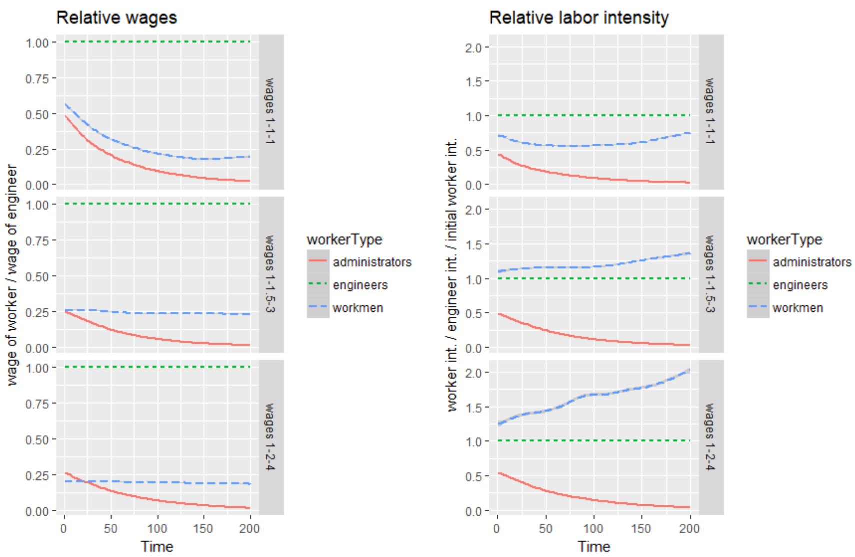

Figure 5: Relative wage (left) and relative labor intensity (right) at different initial wage settings. A value of one in the left graph indicates that the wage is equal to the average engineer. A value of one in the right graph indicates that the initial number of engineers is enough to create jobs for all workers of the corresponding type in the long run.

with productivity, inequality would be low. But if we look at the average worker of a certain skill, the “Market” wage settings lead to the only Pareto efficient outcomes (i.e. it would be possible to make the average workman and administrator better off by switching from the “Fordist” to te “Market” wage setting mechanism, without making the average engineer worse off). While the “Competitive” reservation wage setting mechanism provides the best outcome for workmen, the “Market” reservation wage setting mechanism is best for administrators and engineers. As we can see from the total average consumption, this effect can not only be traced back to redistribution, but also to an increase in GDP. The average workman is by far worst off in the combination “Fordist” wage setting and “Market” reservation wage (see fig. 6).

This is result is contrary to the Dosi et al. models, where the “Fordist” wage setting mechanism typically ensures a “twofold virtuous cycle” (Dosi, Pereira, Roventini, & Virgillito, 2018, p. 11) in which increases in productivity translate to wage increases, which then increase aggregate demand, which feeds back to investment and employment creating more aggregate demand and so on. If we dig a little deeper into the data, we can see what drives those results:

At initial wages 1-1-1, workmen labor is perceived to be relatively expensive, thus those inventions which save more workmen labor are favored in

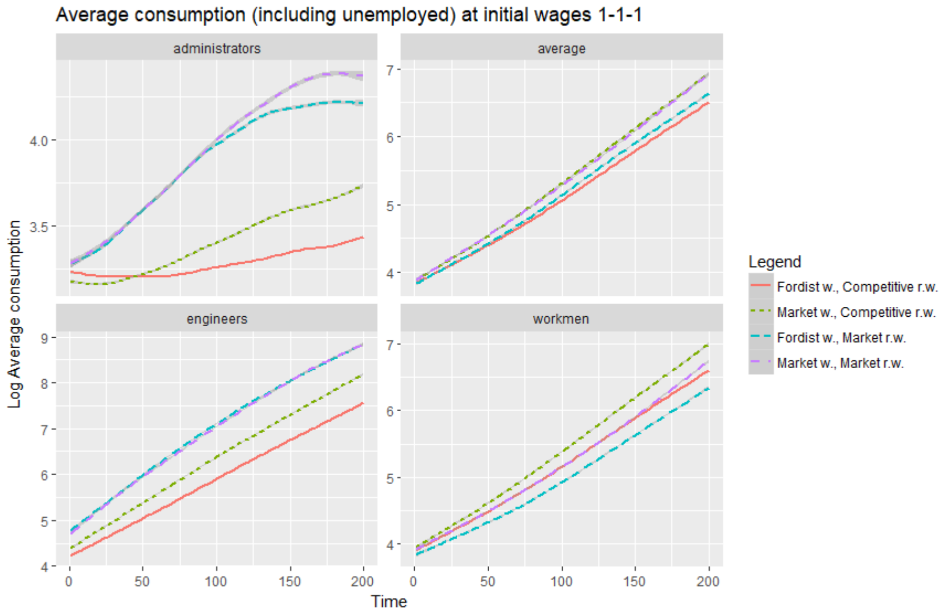

Figure 6: The development of average consumption of different types of workers over time at initial wage setting 1-1-1

comparison to those which save more engineer labor. This tendency can be observed in fig. 7, which shows the development of relative labor intensities of different types of workers to engineer intensity. While relative engineer intensity is by definition 1, relative workmen and administrator intensities are far below their initial settings. The latter can be attributed to the technological bias, but we are more interested in the economic bias concerning the former.

The main difference between the “Fordist” and the “Market” wage setting is now that the relative workman intensity starts to rise again at a certain point in the “Market” setting, but stays at a low level in the “Fordist” setting. This aspect can be attributed to unemployment and how wage setting is influenced by it: Both wage setting mechanisms lead to high rates of workmen unemployment (see fig. 8). In contrast to the “Fordist” setting, the “Market” wage setting allows firms to adapt to the oversupply. Thus, wage offers will be relatively lower, which feeds back to the technological development which makes a turn around. In the end, workmen unemployment will go down again.

As we can see in fig. 9, the development in offered wages is only partly reflected in the development of actual wages. In the “Market” reservation wage setting, workers who are confronted with a high unemployment rate in their respective skill level are rather timid and only seldom bargain. Therefore, the high offered wages can only be translated to actual

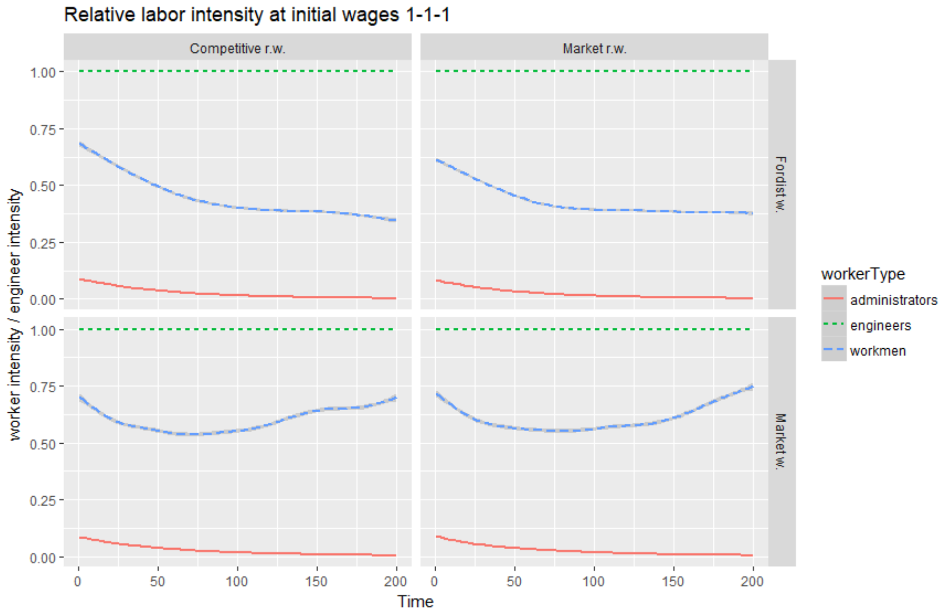

Figure 7: The development of relative labor intensities of different types of workers over time at initial wage setting 1-1-1

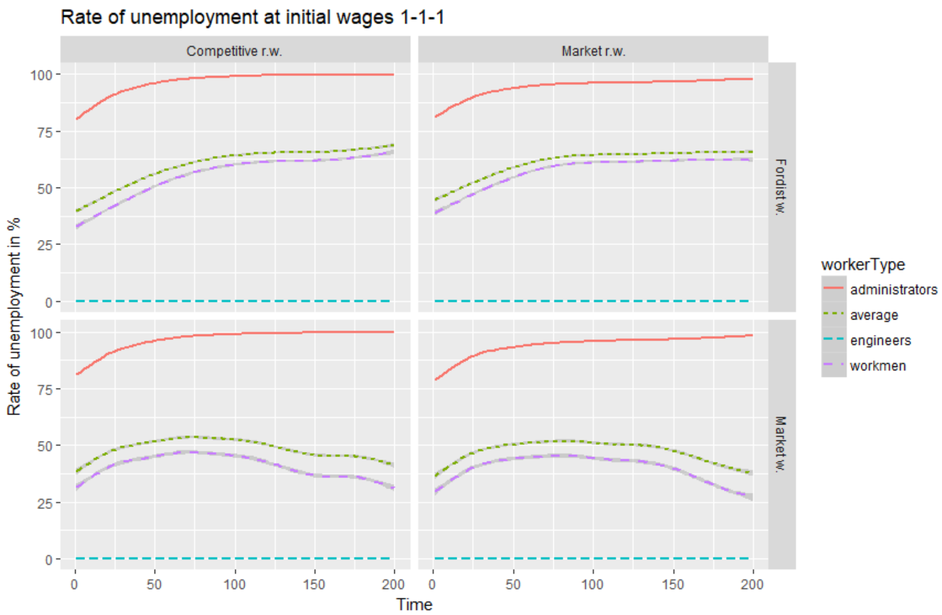

Figure 8: The development of relative labor intensities of different types of workers over time at initial wage setting 1-1-1

wages in the "Competitive" reservation wage mechanism. Workmen in the

"Fordist"/"Market" setting are worst off, as unemployment is high and actual wages are low (which explains the result seen in fig. 6). As we can now differentiate between employed and unemployed workers, we can now see that the "Fordist" / "Competitive" combination is also Pareto efficient, as those workmen who have a job are very well off, leading to a high horizontal (within-group) inequality.

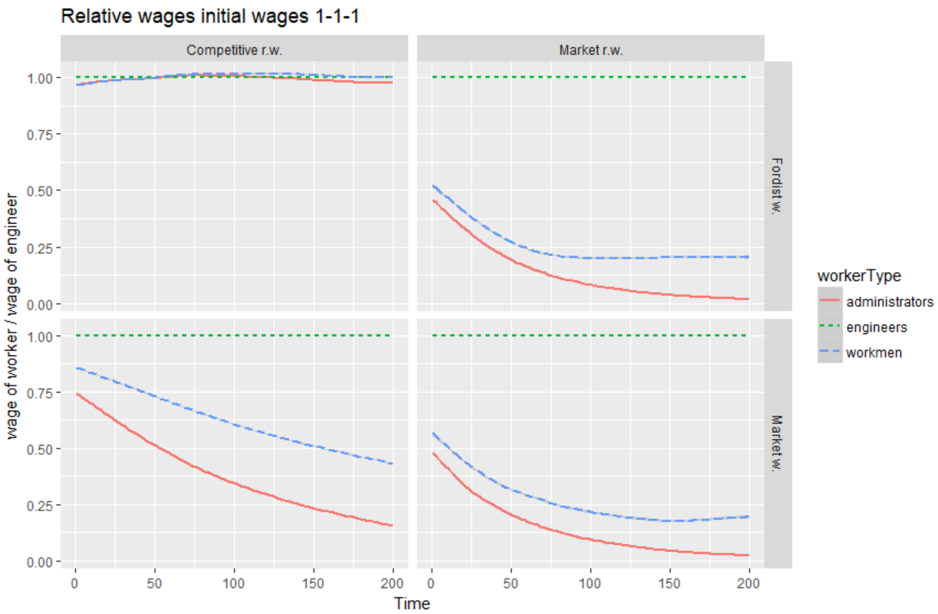

Figure 9: The development of relative wages actually paid to different types of workers over time at initial wage setting 1-1-1

The main finding of this comparison is that the firms cannot be "tricked" into relative prices they believe are wrong in the long term, as they have the power to influence relative labor demand via the channel of technological change. If they perceive the wages of workmen as too high, the innovation process will be skill-biased. This, in turn, leads to technological unemployment for workmen. In the "Market" wage setting mechanism, however, wages react to unemployment, which feeds back to the direction of technological change after some time. This effect makes the "Market" wage setting in the end more efficient.

Initial wage settings This main finding does not change if we vary the initial wages. The performance of the "Fordist" setting drastically improves if we start with a skill premium, and it even seems to slightly outperform the "Market" wage setting in the 1-2-4 case. But all that the "Fordist" setting does is to cement a high level of inequality that already existed in the beginning (i.e. relative prices that firms think are correct). Workmen and the average population are best off at initial wages of 1-1.5-3, whereas engineers and administrators would on average achieve their highest level of consumption with the “Market” wage setting mechanism at initial wages of 1-1-1 (see fig. 10).

Figure 10: The development of average consumption at “Market” reservation wage and different initial wage settings

This result seems peculiar, but it comes from the virtual elimination of workmen unemployment at 1-1.5-3 (see fig. 11) which hints to a more even technological development in this setting (thus enabling a quasi-balanced growth path).

Substitution and upskilling So far, unemployed workers have very limited options to react to the situation at the labor market: They can only apply to jobs matching exactly their skill level. This is especially bad for administrators, as their jobs vanish. We now introduce substitution and upskilling. Those measures are very important, as they equip workers with the ability (within a certain limit) to adapt to the needs articulated at the market. This, in turn, changes the labor supply at the macro-level and thus has a leveling impact on the balance of power between firms and workers, but also between workers of different skills. Although they are both targeting labor supply, fig. 12 suggests that those measures have different effects for different types of workers: Enabling substitution mainly serves to eliminate the difference between administrators and workmen, as administrators start to pick up workmen jobs, which in turn leads to slightly lower consumption

Figure 11: The development of the rates of unemployment at "Market" reservation wage and different initial wage settings

for workmen and slightly higher consumption for engineers. Upskilling, on the other hand, serves to raise the level of consumption of workmen. If substitution is enabled and upskilling set to 1.5% per period, we end up with only very low inequality. But upskilling is not a Pareto improvement (i.e. those who were engineers before will be worse off), as welfare gains resulting from a higher GDP are coupled with redistribution. The pie, so to speak, does not only get larger but each engineer receives a smaller share of it once they are more numerous.

The picture changes, however, if we analyze other initial wage settings than 1-1-1 (see fig. 13). Upskilling is only able to combat some wage inequality in 1-1.5-3, but almost none in 1-2-4. This result is, of course, crucially influenced by our assumption that only unemployed workers may upskill. Low levels of unemployment therefore translate into low levels of upskilling which perpetuates the inequality that persists from the beginning.

Educative measures on its own are thus not enough to combat inequality, but must be combined with equalizing labor market policies. Together, they not only make sure that there are many "lovely jobs" (to use the terminology of Goos and Manning (2003)) and many people out there who are skilled enough to do them, but guarantee a decent standard of living for the rest of the population too.

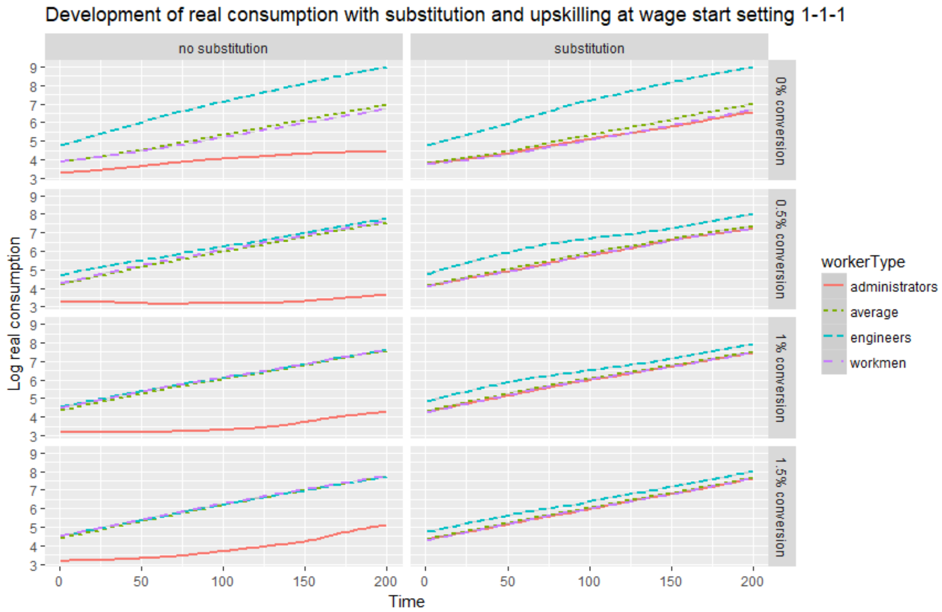

Figure 12: The development of average consumption at "Market" wage and reservation wage settings, with initial wages 1-1-1 and different substitution/upskilling settings

4.3 Discussion and limitations of the model

Our policy experiment results are partly in contradiction with the most advanced version of the general equilibrium directed technological change model to date as presented by Acemoglu and Restrepo (2018a). They, too, find that labor market rigidities (i.e. high relative workmen wages) lead to an excessive level of automation (i.e. a low relative workmen intensity). They also emphasize the role of raising the supply of highly skilled workers (i.e. upskilling). But they do not draw a connection between these topics. It is obvious that workers need time to upskill and those who work full-time (and maybe have some childcare obligations, too) will find it very difficult to raise their skill (e.g. get a college education) in the evening or night. Our assumption that only unemployed workers are able to upskill is obviously simplified. One could also argue that a high wage premium also provides a high incentive to upskill (which would, of course, mitigate our results). But a certain trade-off between taking a low-skilled job and upskilling cannot be ignored. It is self-evident for young people on an individual level: Do I spend the next couple of years to get a college degree and benefit from a higher wage (or more fulfilling job) afterwards or do I take a job now? A scarcity of low-skilled jobs would have a huge impact on this decision. We think that it is worth studying this question in more detail in the future.

While our model replicates a number of prominent stylized facts, es-

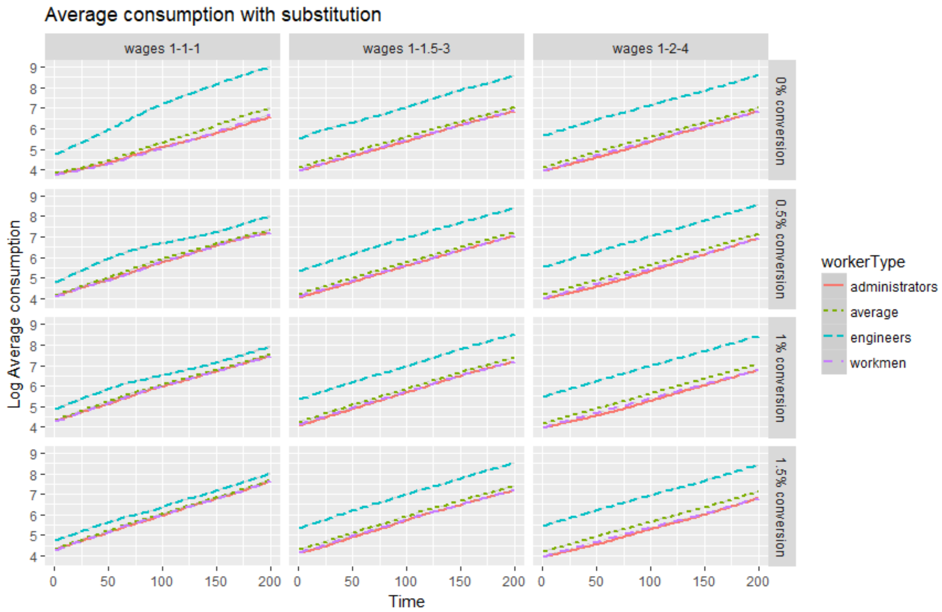

Figure 13: The development of average consumption at "Market" wage and reservation wage settings, with substitution and different initial wage settings

pecially regarding the labor market, some other results do not reflect real world data. This mainly concerns the pricing mechanism (and subsequently the levels of inflation, the distribution between capital and labor and the occurrence of crises) as well as industry evolution. We plan to overcome these problems in future versions of our model.

The pricing mechanisms on the goods and labor markets partly react to excess supply, but not to excess demand. We experience excessive demand at the labor market for engineers, the consumption goods market and the capital goods market. The shortage of engineers leads to a situation in which capital good firms do not only compete on the goods market, but (even more importantly) on the labor market. Both wage setting mechanisms we explored favor more productive firms, thus our capital good sector monopolizes very quickly (it is a so-called winner-take-all market). The assumption that all capital good firms charge the same markup aggravates the situation, as less productive firms cannot decrease their markup to make their product more competitive (or vice versa, more productive firms do not raise their markup to reap surplus profits). On the other hand, this assumption makes it likely that full monopolization is in fact one of the (or even the) most efficient possible outcomes, as all capital goods are produced by the monopolist who offers the cheapest one and does not exploit the situation.

We experienced similar issues regarding the pricing mechanism in the consumption good sector: here, as well, firms do not explicitly react to market-wide excess demand which may persist over long periods of time and therefore reduces the "Keynesian" properties of the model. The fact that investment is constrained by supply of engineers contributes to that dynamic as the levels of investment can be expected to be smoothed.[11] At the same time, however, the restriction of labor supply of highly skilled workers and their low levels of unemployment are important empirical facts. We plan to rework the pricing mechanism, as this will give us the opportunity to extend our analysis, as well as to further validate our results.

Whether and how our results will be influenced by a change of the pricing mechanism depends to a large degree on which type of firms is able to benefit more from this situation. An increase in the markup of capital goods firms would make inventions that save engineer labor more attractive, thus possibly mitigating a skill-bias against administrators. On the other hand, if consumption good firms increase their markup, this will have an impact on the demand for new capital goods (which would be decreased). This could then feed back on the employment of engineers, their wages and at a later stage on the direction of technological change. After all, we would also have to analyze how workers react to this inflationary tendencies. An alternative (or complementary) approach to mitigate this problem could be to assume that workers do not use up all of their funds for consumption but save some (like e.g. Caiani, Godin, et al. (2016) do).

The government and the banking sector are obviously only crudely implemented and there are many ways to improve the model's depth in this area. Dosi et al. (2013) already implemented an interesting approach to the banking sector. It would also be interesting to try to model a government that is acting in a more dynamic way (e.g. reacts to particular challenges).

For these reasons, we do not propose to analyze industry evolution, inequality between capital and labor, the financial or government sector with our current model. We are also cautious about the implications of an increased "Keynesian" element on the magnitudes of the levels of income or unemployment. The "Keynesian" element could potentially also alleviate inequality, if it affects engineers more than workmen and it could make a case for the "Fordist" wage setting mechanism. It is, however, unlikely that it would change the direction or fundamental dynamics we are describing. We also corrected our findings for eventual excess demand by looking at real consumption and not only real wage data.

The fundamental dynamics of our model depend on the hierarchical structure of our model: the employment of engineers is only constrained by the demand for machines, while workmen employment is restricted by not only the demand for consumption goods, but also by the supply of machines

[11] Although, as we saw in fig. 2, investment is still much more volatile than consumption and GDP.

(which need to be created by engineers first). The model is also an important exercise in the evaluation of long-run dynamics. In the long run and without technological change, our initial setting of 1-1-1 would lead to a full employment equilibrium with equal wages. But technological change needs time to diffuse: While engineers immediately start to produce newly developed machines, workmen will due to the long lifespan of machines always also use outdated equipment. Finally, our results crucially depend on the mechanism that firms employ to determine whether an invention/imitation leads to an innovation, as well as on the supply of the different types of workers and their initial productivities (which we, as already mentioned, calibrated to a long-run equilibrium). Engineers are a small minority and their skill premium can therefore (influenced by the other properties of our model mentioned) evolve to be very high, even if they start with none at all.

We also experienced a high sensitivity to our initial rate of unemployment – an unusually high rate is needed to get the system going, which in turn (as described above) has an impact on the magnitude of wage inequality, but builds on a pre-existing tendency. In order to alleviate the problem, we cut the first 50 periods of our simulations out, as unemployment could be eliminated after only 20 periods. The downside of this approach is that the processes we are interested in react towards policies as soon as they are implemented (and we implicitly assumed that this happens in period zero).

5 Conclusion

The driving forces of our model are wages, unemployment and technological change, which feed back to each other in multiple ways. Simply taking control of wages (either through initial setting or through the "Fordist" wage setting mechanism) is not enough to combat inequality, as firms will counter those policies by directing their innovation effort in a way that will re-establish vertical inequality (i.e. inequality between workmen and engineers) but also create horizontal inequality (i.e. between employed and unemployed workmen).

The main finding is that the market cannot simply be "tricked" into prices in the long term if powerful agents (in our case firms) are able to influence supply and demand and their power is left unchecked. In our case, firms react to high wages for workmen by limiting the demand for them via the channel of technological change (thus making their high wage acceptable at a certain point). In the real world, this might be complemented by other sources of power, e.g. firms may decide that domestic workers are too expensive and engage in offshoring activities. This behavior usually creates welfare losses – we saw that the GDP growth was lower when the technological development was directed towards "wrong" relative prices and not towards the real conditions at the labor market.

The picture changes, however, if we move on from partial government intervention to a more holistic approach aimed at leveling the playing field. In our case, the introduction of upskilling enabled the workers to react to the changing requirements of labor market, thus countering the shift of demand with a shift of supply. In this state, the share of high skilled workers is much larger, but low skilled workers are pretty well off, too. At the same time, however, a minority (the initial population of engineers) would experience a smaller growth of their consumption and therefore may resist to those changes.

The reality is obviously a little bit more complex than our model. Training and education does not come for free and some people may not be able to learn new skills, even if resources are spent towards that goal. But since the dawn of capitalism, the education sector, as well as the overall skill level grew dramatically (albeit with some backlashes). On the one hand, this was necessary as many industries needed those skills. On the other hand, this was possible because we did not have to work on the fields all day anymore. The digital revolution provides a major challenge for today's societies. Where partial government intervention fails and creates perverse effects, holistic government intervention involving training and education may be able to distribute the skills necessary to meet this challenge and be successful in combating inequality at the same time. But that doesn't mean everybody would be happy about it.

6 Acknowledgements

We are grateful to Andrea Roventini for answering our questions about the K+S model and to Christian Gehrke, Theresa Hager, Marlies Schütz, Laura Zillian and Stella Zillian, who commented on a previous version of this paper. We also thank the participants of the Graz Schumpeter Summer School 2018, the PhD colloquium of the Social Simulation Conference 2018 and the Doctoral School Economics of the University of Graz for their valuable feedback. All remaining errors are ours. We implemented our model using NetLogo (Wilensky, 1999). We analyzed our results and visualized our data using the programming language R (R Core Team, 2013) with the packages ggplot2 (Wickham, 2009) and lattice (Sarkar, 2008).

Appendix A Agent behaviors

A.1 Firms

A.1.1 Pricing and advertisement

At the beginning of each period, capital good firms recalculate the price p^k and subsequently the cost factor ρ of each prototype they are able to produce. The calculations depend on the wage rates of workmen w^l, administrators w^m and engineers w^n as well as on the labor intensities of production (λ^l, λ^m, λ^n). Capital good firms set their prices p^k by adding a fixed markup μ_I on unit production costs.

$$p^k_{k,t} = (1 + \mu_I)(w^n_{i,t} + w^m_{i,t}\lambda^m_{k,t})\lambda^n_{k,t} \tag{7}$$

It is assumed that consumption good firms do not base their investment decision solely on the price of machines, but try to approximate the total costs of the investment based on a cost factor ρ, which also takes into account the runtime costs within a fixed payback period τ. Capital good firms do not know the exact wage rates of their potential customers and thus calculate the cost factor using average wage rates $\bar{w}^l_{J,t}$ and $\bar{w}^m_{J,t}$.

$$\rho_{k,t} = p^k_{k,t} + \tau_J(\bar{w}^l_{J,t} + \bar{w}^m_{J,t}\lambda^m_{k,t})\lambda^l_{k,t} \tag{8}$$

Once the capital good firms calculated ρ for all prototypes at their disposal, they select the prototype with the lowest ρ and advertise it to all consumption good firms that once ordered machines from the firm as well as to a set of new firms.

Consumption good firms try to adaptively increase their market share and profits by setting their price markup based on the development of their assigned market share $\tilde{z}$ (see eq. 20). If the market share increased in the last period, markup is raised and vice versa. The price is calculated by adding the markup to variable costs of production. We also introduced a minimum markup, which is given by the interest rate charged on debt ω_4, which serves to keep the markup positive.

$$\begin{aligned} p^x_{j,t} &= (1 + \mu_{j,t})\frac{\sum_{h^\star} w_{h,t}}{q_{j,t}} | h^\star = \{l, m : \text{employed by } j\} \\ \mu_{j,t+1} &= \max\left(\omega_4, \mu_{j,t}(1 + \overline{\mu}_J)\frac{\tilde{z}_{j,t} - \tilde{z}_{j,t-1}}{\tilde{z}_{j,t-1}}\right) \end{aligned} \tag{9}$$

A.1.2 Research and development

Capital good firms try to invent new prototypes and imitate the competitors in every period using the staff assigned to R&D $N^{RD}_{i,t}$. They split their staff into engineers who are assigned to invention $N^{IN}_{i,t}$ and those who imitate $N^{IM}_{i,t}$, except for the firm that is technologically most advanced and thus does not want to waste resources on imitation. If a firm was not able to fill all of its vacancies, priority is given to R&D activities instead of production in order to stay competitive.

$$
\begin{aligned}
N_{i,t}^{IN} &= \begin{cases} \nu \min\left\{N^{RD}, N_{i,t}\right\} & \text{for followers} \\ \min\left\{N^{RD}, N_{i,t}\right\} & \text{for leaders} \end{cases} \\
N_{i,t}^{IM} &= \begin{cases} (1-\nu)\min\left\{N^{RD}, N_{i,t}\right\} & \text{for followers} \\ 0 & \text{for leaders} \end{cases}
\end{aligned} \tag{10}
$$

Whether or not the attempts to invent and imitate are successful, is determined by a Bernoulli experiment. The probability θ for a successful invention/imitation depends on the number of engineers assigned to the corresponding activity and a fixed parameter ζ.

$$
\begin{aligned}
\theta_{i,t}^{IN} &= 1 - e^{-\zeta^{IN} N_{i,t}^{IN}} \\
\theta_{i,t}^{IM} &= 1 - e^{-\zeta^{IM} N_{i,t}^{IM}}
\end{aligned} \tag{11}
$$

Inventions are modeled as new prototypes which are modifications of the prototype that the firm currently sells. New prototypes change the labor intensities of administrators, workmen and/or engineers involved in the production processes[12]. The changes of workmen intensity γ^l and engineer intensity γ^n depends on two separate draws from a Beta distribution, which is defined by its parameters and the interval determined by its supporters $(\alpha, \beta, \underline{\gamma}, \overline{\gamma})$. The change of administrator intensity, however, depends on both draws and is therefore amplified, as we assume a technical skill-bias against administrators.

$$
\begin{aligned}
\lambda_{k,t}^{l^{IN}} &= \lambda_{i,t-1}^{l}(1 - \gamma_{i,t}^{l^{IN}}) \\
\lambda_{k,t}^{n^{IN}} &= \lambda_{i,t-1}^{n}(1 - \gamma_{i,t}^{n^{IN}}) \\
\lambda_{k,t}^{m^{IN}} &= \lambda_{i,t-1}^{m}(1 - \gamma_{i,t}^{l^{IN}})(1 - \gamma_{i,t}^{n^{IN}})
\end{aligned} \tag{12}
$$

Successful imitations, on the other hand, simply copy the labor intensities of the prototype used by one competitor. In line with Dosi et al. (2013, p. 1621) we assume that imitations are more likely to occur within the technological neighborhood. In our model, we rank advertised prototypes according to their average intensity and allow every company to imitate only the prototype which is ranked just above its own.

If one of the newly discovered prototypes is deemed superior (i.e. its cost factor is the lowest), the capital good firm innovates and starts to sell the new machine in the next period. This view of technological change resembles

[12] A workman intensity of two means that two workmen are needed to operate a machine. An engineer intensity of two means that two engineers are needed to produce a machine. An administrator intensity of two means that two administrators are needed for every workman and every engineer needed in the production processes.

Darwin's approach to selection, where "each slight variation, if useful, is preserved" Darwin (1859, p. 61) and may therefore be called evolutionary.

A.1.3 Consumption good production and investment

Sales and their development over time determine future expectations of consumption good firms. More specifically, firms look at the nominal demand they faced in the last period $\max(z^d_{j,t}, z_{j,t})$ and its growth rate.

$$d^e_{j,t+1} = \left(1 + \varepsilon \frac{z^d_{j,t} - z^d_{j,t-1}}{z^d_{j,t-1}}\right) \frac{\max(z^d_{j,t}, z_{j,t})}{p^x_{j,t}} \tag{13}$$

Expected demand then influences how much output a firm desires q^d. But firms add certain proportion of extra inventories ι_2 in case they are confronted with an unusually high demand and dispose of current inventories $x_{j,t}$ left over from the past period.

$$x_{j,t} = s_{j,t-1} - \frac{z_{j,t-1}}{p^x_{j,t-1}} q^d_{j,t} = \max((1 + \iota_2) d^e_{j,t} - x_{j,t}, 0) \tag{14}$$

Machines have a constant production capacity ς, that determines the amount of machines the firm wants to operate in the current period $K^d_{j,t}$.

$$K^d_{j,t} = \min(K_{j,t}, \frac{q^d_{j,t}}{\varsigma}) \tag{15}$$

This calculation is subsequently used to determine labor demand (see eq. 23 & 24)

The expectations for the current period $q^d_{j,t}$ are also used to determine how many machines K^{d^2} a firm desires to have in the next period. The investment decision K^{inv} then depends on the difference between the desired K^d and actual capital stock K as well as on discarded machines K^{ex} and desired substitutions K^{sub}. Machines have to be discarded when their age ϕ reaches its maximum. Machines are listed for substitution if they are considered to be technologically obsolescent, which is decided upon comparison of the machine with the current prototype offered by the chosen supplier $i^\star$. Finally, the firm sends their orders K^{inv} to $i^\star$.

$$k^{ex}_j : \phi_{k,t} = \phi^{max} \tag{16}$$

$$k^{sub}_j : \frac{p_{i^\star,t}}{(p^l_{j,t} + p^m_{j,t}\lambda^m_{k,t})\lambda^l_{k,t} - (p^l_{j,t} + p^m_{j,t}\lambda^m_{i^\star,t})\lambda^l_{i^\star,t}} \leq \tau_J \tag{17}$$

$$K^{d^2}_{j,t} = \frac{q^d_{j,t}}{\varsigma} \tag{18}$$

$$K^{inv}_{j,i^\star,t} = \max(K^d_{j,t} - K_{j,t} + K^{ex}_{j,t} + K^{sub}_{j,t}, 0) \tag{19}$$

A.1.4 Consumption goods market interaction

Although consumption goods are homogeneous, firms have to decide on their price p^x because the consumption goods market is characterized by imperfect information. Consumers want to avoid firms that charge a relatively high price, but also firms where they encountered empty shelves in the past. Therefore, p^x and unfilled nominal demand z^u determine a value indicating the competitiveness / attractiveness π of the firm. Individual π and average competitiveness $\bar{\pi}$ then determine the evolution of the market share that is assigned to the firm $\tilde{z}^d$ according to a replicator dynamic.[13]. There is a lower bound $\underline{\tilde{z}}^d_J$ to the assigned market share that once reached triggers an insolvency.

$$\begin{gathered}\pi_{j,t} = -\psi_3 p^x_{j,t} - \psi_4 z^u_{j,t-1} \ , \ \bar{\pi}_{J,t} = \sum_j \pi_{j,t} \tilde{z}^d_{j,t-1} \\ \tilde{z}^d_{j,t} = \max\left(\tilde{z}^d_{j,t-1}\left(1 + \chi \frac{\bar{\pi}_{J,t} - \pi_{j,t}}{\bar{\pi}_{J,t}}\right), \underline{\tilde{z}}^d_J\right)\end{gathered} \tag{20}$$

Afterwards, the nominal demand is divided divided among the firms in a two-step procedure. In the first step, the assigned market shares are normalized so that every firm encounters a share $z^d_{j,t}$ of total nominal demand.

$$z^d_{j,t} = \tilde{z}^d_{j,t} \tilde{z}^d_{J,t} \tag{21}$$

Firms then try to satisfy all of the demand which is allocated to them in the first round. Their ability to do so (measured by z^r) depends on their supply and price. If they are not meet the demand, the remaining demand is allocated to those firms who still have supplies left. This accounts for consumers who encounter empty shelves and go to shops where they hope to find consumption goods left.

$$\begin{gathered}z_{j,t} = \begin{cases} z^d_{j',t} & \text{for} j^\star : z^u_{j,t} = z^d_{j',t} - s_{j',t} p^x_{j',t} = 0 \\ s_{j,t} p^x_{j,t} & \text{for} j' : z^u_{j,t} = z^d_{j',t} - s_{j',t} p^x_{j',t} > 0 \\ z^d_{j,t} + \frac{z^r_{j,t}}{z^r_{J,t}} \min(z^r_{J,t}, z^u_{J,t}) & \text{for} j^\circ : z^r_{j,t} = s_{j,t} p^x_{j,t} - z^d_{j,t} > 0 \end{cases} \\ z^r_{J,t} = \sum_{j^\circ} z^r_{j,t} \ , \ z^u_{J,t} = \sum_{j'} z^u_{j,t} \ , \ z_{J,t} = \sum_j z_{j,t} \ , \ z^d_{J,t} = \sum_h b_{h,t} | h = \{l, m, n\}\end{gathered} \tag{22}$$

[13]Notice that the formula slightly differs from Dosi et al. (2006, p. 17) and the subsequent models. When we tested the original formula, we realized that it had the opposite effect, i.e. more expensive firms and firms that cannot meet their demand gained a higher market share. This seems not to be the case in Dosi, Roventini, and Russo (2018), where the original formula is also employed, but the competitiveness factor is calculated in a different way to be strictly positive.

A.1.5 Labor market interaction

Consumption good firms calculate their labor demand based on the capital stock they want to use in the current period and its associated labor intensities.

$$L^d_{j,t} = K^d_{j,t} * \bar{\lambda}^{ld}_{j,t} \tag{23}$$

$$M^d_{j,t} = L^d_{j,t} * \bar{\lambda}^{md}_{j,t} \tag{24}$$

The demand of capital good firms for engineers $N^d_{i,t}$ depends on the total machine orders $q^d_{i,t}$ they receive from the consumption good firms and the engineer intensity $\lambda^n_{i,t}$. Additionally, they try to hire as many engineers for R&D $N^{RD}_{i,t}$ as they can afford with a fraction (ι_1) of past sales (z_{t-1}) and enough administrators to administrate the workforce.

$$N^{RD}_{i,t} = \frac{\iota_1 * z_{t-1}}{w^n} \tag{25}$$

$$N^d_{i,t} = q^d_{i,t} * \lambda^n_{i,t} + N^{RD}_{i,t} \tag{26}$$

$$M^d_{i,t} = N^d_{i,t} * \lambda^m_{i,t} \tag{27}$$

Any positive difference between labor demand and the current labour force is announced as the number of vacancies. We assume that there are no labor market rigidities that prevent redundancies, so any negative difference leads to a corresponding amount of dismissals. All dismissals are executed first and workers who were fired can directly apply for a new job. At the end of the period, firms adapt their wage offers according to a logic described in section 3. Wages of the current staff are not updated automatically. Instead, only workers who bargain and unemployed workers looking for a job receive the new wage offer.

A.1.6 Profits and taxes

Profits are sales minus costs. For capital good firms, cost consist of wage payments and interest paid on debt a (see eq. 28). Consumption good firms also have to take the depreciation of their capital stock into account (see eq. 29).

$$\Pi_{i,t} = p^k_{i,t} \sum_j K^{del}_{i,j,t} - \omega_4 a_{i,t} - \sum_{h^\star} w_{h,t} | h^\star = \{m, n : \text{employed by } i\} \tag{28}$$

$$\Pi_{j,t} = z_{j,t} - \omega_4 a_{j,t} - \frac{\sum_{k_j} p_k}{\phi^{max}} - \sum_{h^\star} w_{h,t} | h^\star = \{l, m : \text{employed by } j\} \tag{29}$$

After they calculated their profits, firms pay a flat tax rate of ω_3 on them.

A.1.7 Loans and insolvencies

For simplicity, we assume that a firm takes a loan whenever its deposits turn negative. Once its net debts exceed the maximum debt to sales ratio za^{max}, the firm is listed for insolvency. The same happens to firms who only operate at the minimum market share $\underline{\tilde{z}}^d$. We adopted the assumption of Dosi et al. (2010) that the number of firms is fixed, but to account for stock-flow consistency, an insolvent firm is bailed out to avoid a situation in which we would need a *deus ex machina*. Firms that are bailed out are endowed with a new stock of debt and deposits in the inflation-adjusted initial amount. They adapt their offered wage rate to the one average workers of a certain type get paid and plan their business expecting the market share that was assigned to them in the last period (at least $\underline{\tilde{z}}^d$).

A.2 Workers

Workers behave according to a very simple set of rules, which largely depend on the reservation wage that is set according to a rule specified in section 3.2. Unemployed workmen/administrators/engineers apply to every job that matches their skill profile and offers a wage rate that is at least as high as the worker's reservation wage. Employed workers who are discontent with their pay as their reservation wage is above their actual wage rate, bargain with their employer and quit their jobs if they get an offer which is below their reservation wage. Workers use their funds, which are replenished by wages and unemployment benefits, to buy as many consumption goods as possible.

A.3 Bank

The banking sector is modeled as a bank who behaves as a rather passive agent: It provides firms with loans (see section A.1.7) and charges an interest rate on debts ω_4. The debts of insolvent firms are listed as non-performing assets. The bank also stores any savings of workers, but does not pay any interests.

A.4 Government

The government is another passive agent that collects a flat tax rate ω_3 on profits and pays unemployment benefits w^u to workers, which depend on their last wage.

$$w^u_{h,t} = \begin{cases} \omega_1 w_{h,t-1} & \text{if h} \in \text{ \{l,m, n\} employed in t-1} \\ w^u_{h,t-1} & \text{if h} \in \text{ \{l,m, n\} unemployed in t-1} \end{cases} \tag{30}$$

Appendix B Parameters

Symbol	**Description**	**Initial value**
I	Number of capital good firms	25 [4]
J	Number of consumption good firms	100 [4]
K	Number of machines	800 * J [3]
L	Number of workmen	124000
M	Number of administrators	26090
N	Number of engineers	6448
$\overline{\phi}_K$	maximum life span of machines	20 [2]
$\underline{\tilde{z}}^d_J$	minimum market share assigned to consumption good firms	0.00001 [3]
$\overline{\mu}_J$	markup coefficient of consumption good firms	0.04 [3]
μ_I	fixed markup of capital good firms	0.05 [3]
τ_J	payback period for investments	3 [2]
ι_1	propensity to invest in R&D	0.04 [2]
ι_2	proportion of inventories desired by consumption good firms	0.1 [2]
ν	propensity to invest in invention	0.5 [2]
ζ	capability parameter for inventions and imitations	0.3, 0.3 [2]
α, β	parameters of beta distribution for inventions	3, 3 [2]
$\underline{\gamma}, \overline{\gamma}$	supporters of beta distribution for inventions	-0.15, 0.15 [2]
ς	production capacity of a machine	40 [3]
ψ_1	Wage setting parameter for aggregate productivity	0.5 [3]
ψ_2	Wage setting parameter for individual productivity	0.5 [3]
ψ_3, ψ_4	Competitiveness parameters	1, 1 [3]
ω_1	unemployment benefit rate	0.4 [3]
ω_2	expected wage growth rate	0.02 [3]
ω_3	tax rate on profits	0.1 [3]
ω_4	interest rate on debt	0.01 [2]
χ	replicator dynamics	1 [3]

Variables

Symbol	Description	Initial value
p_k^k	price of a specific capital good	acc. eq. 7
p^l	wage rate offered to a workman	1 / 1 / 1 [3]
p^m	wage rate offered to an administrator	1 [3] / 1.5 / 3
p^n	wage rate offered to an engineer	1 [3] / 3 / 4
$p_{l/m/n}$	actual wage rate of a specific worker	$p_{i/j}^{l/m/n}$ or 0
$p_{l/m/n}^g$	unemployment benefit of a specific worker	$\omega_1 p_{i/j}^l$
$\bar{\lambda}_j^l$	average workman intensity of the capital stock designated for use	-
$\bar{\lambda}_j^m$	average administrator intensity of the capital stock designated for use	-
λ_k^l	workman intensity of a specific capital good	1
λ_k^m	administrator intensity of a specific capital good	0.2
λ_k^n	engineer intensity of a specific capital good	1
ρ_k	cost factor of a capital good k	acc. eq. 8
$theta_i$	probability of a successful invention or imitation for a specific capital good firm i	-
γ_i^l, γ_i^n	variation of labor intensities achieved by a successful invention	-
x_j	inventories remaining at consumption good firm j	$\iota_2 d_j^e$
d_j^e	demand expected by consumption good firm j	q_j^d
q_j^d	output desired by consumption good firm j	q_j
q_j	output achieved by consumption good firm j	ςK_j
K_j	number of machines owned by consumption good firm j	800 [3]
K_j^d	number of machines desired by consumption good firm j	K_j
$k^e x_j$, $K^e x_j$	machines to be discarded by consumption good firm j and their number	$\frac{K_j}{\bar{\phi}_K}$

$K^e x_j$	number of machines to be discarded by consumption good firm j	$\frac{\lvert K_j \rvert}{\overline{\phi}_K}$
k_j^{sub}, K_j^{sub}	machines to be substituted by a specific consumption good firm and their number	acc. eq. 18
s_j	supply of consumption good firm j	$q_j + x_j$
s_i	supply of capital good firm i	q_i
q_i	output of a capital good firm i	$\frac{\lvert K \rvert}{\lvert I \rvert \overline{\phi}_K}$
q_i^d	output desired by capital good firm i	-
N_i^d	engineer demand of capital good firm i	-
$M_{i/j}^d$	administrator demand of a specific firm	-
L_j^d	workmen demand of consumption good firm j	-
$K^d el_{i,j}$	amount of capital goods delivered from firm i to j	-
$\Pi_{i/j}$	profits of a specific firm	-
π_j	competitiveness of consumption good firm j	-
$\overline{\pi}_J$	average competitiveness of consumption good firms	-
z_j	sales of consumption good firm j	$q_j p_j^x$
z_j^u	sales demand unsatisfied	0
p_j^x	price of a consumption good offered by firm j	...
μ_j	markup of consumption good firm j	0.3 [3]
$\tilde{z}_j^d$	market share assigned to consumption good firm j	$\frac{1}{J}$
z_j^d	sales assigned to consumption good firm j	z_j
z_j^r	sales that firm j can absorb additionally	-

Table 2: Parameters, variables and their calibration

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