



**Master Program in
Macroeconomic Policy and Financial Markets**

“Automation and Polarization in the Labor Market”

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We combine the basic Diamond (1982), Mortensen (1982), and Pissarides (1985) (DMP) labor market matching model with the one proposed by Autor et al. (2006) to analyze the labor market equilibria in a framework with frictions, where automation is introduced as an increase in the labor-replacing capital. Identical productivities of routine and manual workers, do generate significant increases in unemployment in routine tasks and a subsequent fall in the labor income share of this sector. Complementarity of labor-replacing capital on university graduates is not detected because of a no profitability mechanism but evidence of substitutability of lower-skilled workers is captured, after controlling for changes in labor force bases. By construction, the model fails to detect wage polarization, but it provides evidence of skilled-biased wage premia.

ABSTRACT IN CATALAN (100 words)

Combinem el model corresponent de mercat ocupacional basic de Diamond (1982), Mortensen (1982), i Pissarides (1985) (DMP) amb el que proposen Autor et al. (2006) per analitzar l'equilibri del mercat ocupacional en un context amb friccions, on l'automació és presentada com un increment en el capital substitutiu de l'ocupació. Rendiments idèntics de treballadors amb tasques rutinàries o manuals generen augments significatius en desocupació en tasques rutinàries i la subseqüent caiguda de la part de la renta ocupacional del sector. La complementarietat del capital substitutiu del treball en graduats universitaris no és identificada degut al mecanisme de no-rendibilitat, però sí es recull evidència de la capacitat de substituir treballadors menys qualificats, després de controlar les variacions en les bases de la força laboral. Estructuralment, el model no detecta la polarització salarial, però mostra evidència de bonificacions salarials basades en l'experiència.

KEYWORDS IN ENGLISH (3):

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Automation and Polarization in the Labor Market

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Abstract

We combine the basic Diamond (1982), Mortensen (1982), and Pissarides (1985) (DMP) labor market matching model with the one proposed by Autor et al. (2006) to analyze the labor market equilibria in a framework with frictions, where automation is introduced as an increase in the labor-replacing capital. Identical productivities of routine and manual workers, do generate significant increases in unemployment in routine tasks and a subsequent fall in the labor income share of this sector. Complementarity of labor-replacing capital on university graduates is not detected because of a no profitability mechanism but evidence of substitutability of lower-skilled workers is captured, after controlling for changes in labor force bases. By construction, the model fails to detect wage polarization, but it provides evidence of skilled-biased wage premia.

1 Introduction

Technological changes are among the most prevailing theories, that have concentrated much academic attention, in explaining the wage inequality observed in the U.S. and the majority of developed countries since late 1970s. Labor market restructuring in terms of relative supply of skilled workers triggered the discussion of wage inequality around skill-premia differentials. Indeed, within group wage inequality has rapidly risen during the last almost 50 years, with a sharp increase in the returns of education and wage stagnation for the average of the income and labor earnings distribution. Extensive access to college, which is an undeniable reality though, cannot coincide with this divergence in wage differentials. Acceleration in skill-bias hypothesis seems to be a no-

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table and valid argument, suggesting that advances in technological innovations crucially affect the demand for skills, in an endogenous way, and thus the compelling wage dispersion is detected.

However, technological progress, hereafter addressed as automation of tasks, does not change the demand of different types of skills in a similar way. Hence, a multiple-skill index model appears to be the appropriate approach for the wage inequality and polarization studying purposes. For this reason, we will combine the Diamond (1982), Mortensen (1982), and Pissarides (1985) (DMP) labor market matching model with Autor et al. (2006) one explaining this job polarization in the U.S. labor market with a goal of studying the effects that an increase in automation might have on wage inequality and workers' turnover when there are frictions in the labor market. We abstract from the basic Autor et al. (2006) model and introduce frictions in labor markets through the DMP framework, since market clearing equilibria are at odds with the empirical evidence. Specifically, information, search and other barriers resulting from bargaining, endogenous and exogenous job destruction, costs and labor market legislation create a wedge between wages and marginal products. Furthermore, an additional departure from the standard DMP model accounts for including more than one, and specifically, three, labor markets. In particular, in order to allow for task-specific technical change, the DMP Nash-bargaining game is now played in distinct labor markets, perfectly independent from each other in terms of their functioning, defined by the level of skills of the workers, namely high-skilled college graduates and low-skilled high-school degree holders. Transition from one market to the other is then granted such that employment and wage adjustments are in line with the empirical results regarding skill-differentials and labor market polarization.

The three labor markets in this economic setup refer to abstract tasks, routine-intensive tasks and non-routine or manual ones. Connecting those occupations with reality, abstract tasks regard for cognitive, requiring higher education tasks that are highly paid. Routine tasks are described by occupations with little interpersonal interaction, requiring no higher-college education and being middle paid, while manual tasks demand low educational and soft qualifications. Automation is modeled as the possibility of routine tasks being implemented by capital instead of labor. Thus, routine tasks are such that they can be perfectly summarized as a set of specific activities accomplished by following well-defined instructions and procedures that a machine can individually

perform, whereas this is not the case for the abstract and manual tasks. Therefore, technological innovations, formed as increases in the amount of capital used, are not uniformly transformative. That is, routine tasks that are perfect substitutes of automating capital, are in general mostly affected, but DMP bargaining games and the switching possibilities of some agents to other labor markets allows for employment in abstract and manual tasks to get affected from automation, too.

Unlike the adverse effect of automation or the so-called "creative destruction" of the process of technological changes on routine task-based jobs, in our model, unemployment is determined endogenously by decisions of both firms and workers and no job turnover is allowed. It is indeed assumed that the decision of substituting labor with capital is made by the firm-side of the economy. Given the features mentioned beforehand, indeed, the model, further analyzed and discussed in Section 2, provides the right dynamics to explain changes in employment structure, that is a change in labor force within the bottom education distribution accompanied by a cease or even fall in the employment rates of that group, observed since the 1990s.

In order to prove the soundness of our assumptions about the nature of processes related to automation and labor market characteristics, we perform the following experiment. First, we calibrate our benchmark model to match empirical facts of the U.S. labor market of 1992. Then, we introduce changes in the amount of the labor-replacing capital used in the economy, expecting these changes to cause responses of the main economic variables that will lead to the new state of the economy, similar to the one observed in U.S. in 2017. While our model cannot perfectly capture the empirical facts and dynamics of the real U.S. economy, there are several interesting insights that can be derived from our experiment.

Our model generates substantial increase in unemployment for workers established in both routine and manual sectors. Subsequent falls in the Nash-bargained wages and the marginal productivities because of changes in the amount of capital employed, substituting for routine labor, lead to considerable falls in the income share possessed by routine labor, as opposed to the constant of abstract and manual labor one. Skill-biased wage premia hypothesis and wage inequality measured by income shares is being captured. In contrast with the usual labor market polarization, that is employment rate increases for abstract tasks due to complementarity effects and relative gains in manual unemployment, our model fails to deliver the same outcomes. Specifically,

allowing for identical productivities between routine and manual labor, together with labor market frictions yield to increases in steady state unemployment in general, driven by both forces. Capital complementarity on abstract wages is found, not on employment rates though. Furthermore, wage polarization is by construction not identified, since identical productivities yield to same marginal products and Nashed-bargained wages between routine and manual sectors.

The rest of the paper is organized as follows. The rest of Section 1 briefly reviews the already existing literature on the effects of automation on the labor market outcomes. Section 2 focuses on describing the model and its main features. Specifically, subsection 1 describes the model's environment and in subsection 2, market equilibrium is defined. Section 3 reviews the methodology to calibrate for the parameters according to data for the US or previous works in order to obtain the simulated results. Section 4 is divided in two subsections. The first one presents the steady state results from the model simulation, where we try to find similarities with the inequality and distributional changes observed in the U.S. labor market from 1990 on wards. In the second one we study the dynamics of the variables from the steady state of our benchmark model to the one given by a situation where there is a positive shock in labor replacing capital, in other words, an increase in automation. Section 5 shortly summarizes the main results and findings of the paper.

1.1 Literature Review

The effects of automation on labor market outcomes were studied in multiple academic papers. Important contributions to our understanding of the relation between automation and income inequality patterns was made by David Autor. While Autor et al. (1998) only examines the effects of computerization seen as a skill-biased technological change that leads to greater differentiation of wages among different educational groups, in Autor et al. (2006) a richer model is introduced.

Assuming that machines are able to replace humans in performing routine tasks, the authors model the effect of automation on labor market as a decrease in the price of capital. The approach proposed in Autor et al. (2006) has had a significant influence on more recent papers, the number of which grew substantially in line with the contemporary advancements in technological development, namely with rapid evolution of artificial intelligence. Following the same terminology and skills categorization, developed by Autor et al. (2006), Goos et al. (2009) explain job polarization

in fourteen European countries. Starting by using the canonical model of constant elasticity of substitution between high and low skilled labor, initially introduced by Acemoglu (2002), they later extend their approach to analyze technological changes in task-based framework instead, and allow for abstract, routine and manual-intensive labor tasks to explain unemployment dynamics in Europe since the early 1980s.

Some modern academic articles concentrate on more narrow analysis which consists in artificial intelligence impact studies. For example, Aghion et al. (2017), analyze the potential impact of artificial intelligence on economic growth. Introducing the concept of tasks from Acemoglu and Autor (2011) into the model of automation proposed by Zeira (1998), the authors manage to derive sufficient conditions for overall balanced growth with a constant capital share associated with nearly complete automation. Nordhaus (2015) studies the nature of AI and evaluates its ability to cause the state referred to as technological singularity, which may supposedly result in a sharp rise in economic growth.

Automation might realize itself in different ways, for example, as an "invasion" of capital into production that substitutes middle-skilled labor, as technological deepening that increases productivity and demand for labor, etc. Nevertheless, in any case, technological changes should, in general, better be studied in a task-based framework for the purposes of explaining job polarization and distributional changes in unemployment. Acemoglu and Restrepo (2018) as well as some empirical evidence, such as, a decrease in the labor share of output, suggest that modeling automation as substitution of machines for labor tasks has many appealing implications in comparison to modeling this phenomenon as a factor augmenting technological change since factor augmenting approaches do not allow researchers to consider both displacement effects we observe in actual economies and the effects that may cause augmentation of labor demand. In the mentioned paper automation is modeled as an increase in the proportion of tasks that could be performed by machines in the whole mass of tasks, whereas a non-arbitrage condition between labor and capital due to perfect substitutability is ensured by comparative productivity advantage of labor over machines in higher-indexed tasks.

However, many authors still use either capital- or labor-augmenting technological change approaches to explain wage inequality and changes in income distribution. For example, Graetz

and Michaels (2015), treat the increase in the use of robots as a capital-augmenting technological change, which leads to the possibility of more productive and cheaper capital to substitute for labor in a process governed by the elasticity of substitution. The results of their research suggest that robots did not significantly reduce the total employment, however, reducing the low-skilled workers employment share. Bessen (2017), on the other hand, treats automation processes as labor-augmenting technological changes. He explores existing relations between technological advancements and unemployment and finds that computer use leads to lowering of employment in manufacturing industries, but not in other sectors. Acemoglu (2000) also examines the wage inequality and the labor market distributional changes due to technical advancements over the 19th and 20th centuries and develops further discussion on steady-state demand versus acceleration in skill-bias hypotheses using the canonical model instead of the task-based approach.

Several other contributions of D. Acemoglu and P. Restrepo on how automation influences labor markets are also worth mentioning in the context of our work. One of them is Acemoglu and Restrepo (2018), in which different types of technological changes are defined and different oppositely directed effects of automation on labor market are described. The core idea of the work is that automation first of all causes the displacement effect replacing workers in the tasks they previously performed. Nevertheless, the authors admit the existence of the countervailing forces that might lessen the displacement effect or even lead to a situation in which automation increases the labor demand. Among these forces the authors name productivity effect, capital accumulation, deepening of automation and reinstatement effect (creation of new tasks).

Acemoglu and Restrepo (2017), estimate negative effects of the increase in industrial robot usage on the main characteristics of the U.S. local labor markets, using the data from International Federation of Robotics. Specifically, they find that one more robot per thousand workers leads to reduction of the employment to population ratio by about 0.18-0.34 percentage points and wages by 0.25-0.5 percent. Interestingly enough, they find that the impact of robots exploitation is distinct from the influence of other variables that are generally seen as affecting situation on the labor markets, namely, imports from Mexico and China, offshoring, etc.

2 The Model

In order to study the effects of automation in the labor market, we will introduce frictions in Autor et al. (2006) model explaining job and wage polarization in the US labor market by adding to it the well known Diamond (1982), Mortensen (1982), and Pissarides (1985) (DMP) labor market matching model.

2.1 Environment

The economy contains a unique final good Y_t produced by the only producing firm that behaves perfectly competitively. This big firm aims at profit maximization, defined as the difference between total revenue and total costs. Total revenue is given by Y_t , since we normalize the price of the final good, and total costs are given by the amount of production factors times their prices.

$$\max_{\{A_t, R_t, M_t\}} Y_t - w_{A,t}A_t - w_{R,t}R_t - w_{M,t}M_t \quad (1)$$

The production process of the firm is characterized by the following equation:

$$Y_t = z_t A_t^\zeta (R_t + K)^\delta M_t^\gamma \quad (2)$$

where $\zeta + \delta + \gamma = 1$.

As in Autor (2006), the firm needs three types of tasks in order to produce: abstract A_t , routine R_t and manual M_t . The production function is depicted in a Cobb-Douglas to represent the relation between factors of production and it admits constant returns to scale. We assume that manual and abstract tasks can be performed only by workers, however, routine tasks can either be performed by workers or by machinery and equipment capital, K . Capital and labor in routine tasks are perfect substitutes. Moreover, capital is supplied exogenously and perfectly elastically to the big firm at a price r_K . Z_t , represents total factor productivity and it is assumed to follow a first order auto regressive and stationary process such that:

$$\ln z_t = \phi \ln z_{t-1} + \epsilon_t \quad (3)$$

where $|\phi| < 1$ and $\epsilon_t \sim \mathcal{N}(0, 1)$

Labor inputs in the three different types of tasks are supplied by intermediate firms that connect workers with the big firm. To visualize independency in the supply of tasks to the big firm, we assume that specific-task labor supply is determined in frictional environments that function as in autarky. Therefore, a matching technology function that generates matches between intermediate firms and workers is engineered. The function is also assumed to be increasing and concave in order to represent the fact that when there are more job seekers or vacancies in the economy the number of matches increases.

$$\mathcal{M}_{i,t} = \mathcal{M}(u_{i,t}, v_{i,t}) = \frac{u_{i,t}v_{i,t}}{(v_{i,t}^\gamma + u_{i,t}^\gamma)^{1/\gamma}} \quad (4)$$

for $i = \{A, R, M\}$. The matching function uses as inputs unemployed workers, $u_{i,t}$ and job vacancies, $v_{i,t}$ and gives as output the number of hirings, $\mathcal{M}_{i,t}$. It is important to notice that $\mathcal{M}(0, v_{i,t}) = \mathcal{M}(u_{i,t}, 0) = 0$, that is, we need a positive number of job seekers and vacancies in order to have a match. Moreover, the function is bounded from above by either $u_{i,t}$ or $v_{i,t}$, whichever is lower.

Independence of these frictional labor markets is modelled as the existence of three markets, one for abstract tasks, where only college graduate workers can participate, another for routine tasks and a final one for manual tasks. These two last markets are accessible to high-school workers who will need to choose in which one to participate. In contrast, initial establishment and switches from routine to manual-specific labor markets and vice-versa is only allowed for high-school graduates, whereas participation of college graduates to these markets is restricted.

On one hand, we assume the existence of a large number of infinitely lived intermediate firms and free entry in each of the labor markets in order to endogenize job creation. Therefore, as long as positive profits are expected, firms are going to allocate in each market and create jobs at a cost κ . The value of creating a vacancy in each market, $i = \{A, R, M\}$, for the intermediate firms is given by:

$$V_{i,t} = -\kappa + \beta [q_t(\theta_i)J_{i,t+1} + (1 - q_t(\theta_i))V_{i,t+1}] \quad (5)$$

As we can observe, this value is given by the present cost of creating a vacancy, κ and the future discounted payoffs given by the fact that the vacancy might not be filled. $q(\theta_i)$ represents

the probability of filling a vacancy in each market and it is given by:

$$q_t(\theta_i) = \frac{\mathcal{M}(u_{i,t}, v_{i,t})}{v_{i,t}} = \mathcal{M}\left(\frac{u_{i,t}}{v_{i,t}}, 1\right) = \mathcal{M}(\theta_i, 1) \quad (6)$$

Since $q_t(\theta_i) \in (0, 1)$, we need to divide the number of matches and the number of vacancies by the amount of people in each market in order to obtain rates. θ_i represents the market tightness for each type of task. It is defined as the ratio between unemployment rate and vacancy rates and serves as indicator to see the easiness of filling a job. J_i represents the value of having a vacancy filled and it is given by:

$$J_{i,t} = w_{i,t} - \tilde{w}_{i,t} + \beta [(1 - \lambda)J_{i,t+1} + \lambda V_{i,t+1}] \quad (7)$$

where λ is the exogenous probability of separation, that is, the match ceasing between intermediate firm and worker. $w_{i,t}$ is the marginal product paid by the big firm and $\tilde{w}_{i,t}$ the Nash-bargained wage that will be paid to the worker in each market $i \in \{A, R, M\}$. Therefore, the value of filling a vacancy is given by the profits of the intermediate firm in each market, given by the difference in the payoff it gets for selling labor to the big firm and the wage it will have to pay to each worker, and the future discounted payoff given by the fact that the pairing could get dissolved.

On the other hand, we assume a large number of infinitely lived agents and firms. The mass of college workers is normalized to one, same as the mass of high school workers. As stated before, while college graduates will go to abstract market, high school graduates have to decide whether to go to the routine or the manual market. When unemployed, workers derive utility from home production, b , also defined as unemployment benefits. Moreover, they search for a job in the chosen market, becoming employed, i.e., finding a job with probability $p_t(\theta_i)$ defined as:

$$p_t(\theta_i) = \frac{\mathcal{M}(u_{i,t}, v_{i,t})}{u_{i,t}} = \mathcal{M}\left(1, \frac{v_{i,t}}{u_{i,t}}\right) = \mathcal{M}\left(1, \frac{1}{\theta_i}\right) \quad (8)$$

for $i \in \{A, R, M\}$. Again, since $p_t(\theta_i) \in (0, 1)$, we need to divide the number of matches and the number of unemployed in each market by the market's population in order to obtain rates. The value function of being unemployed is then given by:

$$U_{i,t} = b + \beta [E_{i,t+1} p_t(\theta_i) + U_{a,t+1} (1 - p_t(\theta_a))] \quad (9)$$

We allow for intermediate labor market transition for high-school graduates only. That is, low-skilled workers unemployed in the routine sector are allowed to switch to manual sector and vice-versa. Labor employed or unemployed in abstract tasks is not assumed to transfer to different labor markets. The probability of a high school worker changing from manual market to routine market is given by ¹:

$$\pi_t^{M,R} = \frac{1}{1 + \exp(U_{m,t} - U_{r,t})} \quad (10)$$

Since there are no cost for changing markets, this probability is equal to staying in manual market, i.e. $\pi_t^{M,M}$. Thus, the probability of changing from routine market to manual market is given by:

$$\pi_t^{R,M} = 1 - \pi_t^{M,R} \quad (11)$$

As before, due to the non existence of transition costs, this probability is equal to the probability of staying in the routine market, $\pi_t^{M,M}$.

Once the decision of staying unemployed in the market of previous establishment or switching sectors by the high-school graduates is made, the evolution of unemployment in each sector is defined as:

$$u_{r,t} = (1 - p_t(\theta_r)) \pi_{t-1}^r u_{r,t-1} + (1 - p_t(\theta_r)) \pi_{t-1}^r u_{m,t-1} + \lambda R_{t-1} \quad (12)$$

$$u_{m,t} = u_{m,t-1} (1 - p_t(\theta_m)) \pi_{t-1}^m + u_{r,t-1} (1 - p_t(\theta_m)) \pi_{t-1}^m + \lambda M_{t-1} \quad (13)$$

Additionally, intermediary firms are not allowed to switch sectors, since, once matched with some employer, the net surplus of the match is positive and they have no profit incentives to re-establish in another sector.

When employed, they consume the wage the intermediate firm will pay to them, \tilde{w}_t and with a probability of separation that, as stated before, we denote by λ , they lose their job. The value function for being employed in each market is given by:

¹According to Pilossoph (2012), this probability can be calculated with Logit probabilities from Discrete Choice Theory.

$$E_{i,t} = \tilde{w}_{i,t} + \beta [(1 - \lambda) E_{i,t+1} + \lambda U_{i,t+1}] \quad (14)$$

As we can observe, the value of being employed is given by the Nash bargained wage that the intermediate firm will pay to the worker and the discounted future payoffs taking into account that the match between the firm and the worker can be terminated.

Intermediate firms will allocate in each market depending on their expectations for wages paid by the big firm, $w_{i,t}$, wages they will pay to workers, $\tilde{w}_{i,t}$ and market tightness, $\theta_{i,t}$. College workers will allocate in the abstract market and high school workers will allocate either in routine or manual markets according also to the market tightness, $\theta_{i,t}$ and the wages they will receive, $\tilde{w}_{i,t}$. Once, workers and intermediate firms are allocated in each market, they Nash-bargain the wages according to the following problem:

$$\max_{\{\tilde{w}_{i,t}\}} (E_{i,t} - U_{i,t})^{1-\alpha} (J_{i,t} - V_{i,t})^\alpha \quad (15)$$

for $i \in \{A, R, M\}$ and with α being the bargaining power of workers.

2.2 The equilibrium

Definition 1. An equilibrium consists on a sequence $\{\theta_{i,t}, \tilde{w}_{i,t}\}_{t=0}^{\infty}$, a sequence $\{A_t, R_t, M_t, K_t\}_{t=0}^{\infty}$ for $i \in \{A, R, M\}$ and a price for capital r_K such that:

- (i) The free entry condition for intermediate firms is satisfied.
- (ii) The wage condition is satisfied.
- (iii) The big firm chooses capital and labor optimally.
- (iv) The value of being unemployed in routine and manual market is the same.
- (v) Wage of routine workers is the same as the price of capital.

Due to the free entry condition, firms will create vacancies in a market just until the cost of creating a vacancy equal the profit obtained for creating it. This implies that equation (5) has to be equal to 0 and therefore:

$$\kappa_i = \beta q_t(\theta_{i,t}) \frac{w_{i,t} - \tilde{w}_{i,t}}{(1 - \beta(1\lambda))} \quad (16)$$

From the Nash-bargaining problem we obtain the following first order condition:

$$\alpha [J_{i,t} - V_{i,t}] = (1 - \alpha) [E_{i,t} - U_{i,t}] \quad (17)$$

As we can observe, intermediate firms and workers split the surplus of the match² in each market according to the bargaining power α . In equilibrium we know that $V_{i,t} = 0$ and substituting equations (7), (9) and (14), we get the wage condition:

$$\tilde{w}_{i,t} = (1 - \alpha)b + \alpha(w_{i,t} + \theta_{i,t}\kappa) \quad (18)$$

Solving the big firm's profit maximization problem we obtain the the market clearing prices for each type of labor, i.e. the factor income:

$$\tilde{w}_{a,t} = \zeta \frac{Y_t}{A_t} \quad (19)$$

$$\tilde{w}_{r,t} = \delta \frac{Y_t}{(R_t + K)} \quad (20)$$

$$\tilde{w}_{m,t} = \nu \frac{Y_t}{M_t} \quad (21)$$

As we can see, labor income for abstract is a proportion ζ of total output, for routine it is a proportion δ and for manual a proportion ν .

As stated before, in the steady state the value of being unemployed in routine and in manual is implied to be the same due to indifference of unemployed high-school graduates between routine and manual sectors, which requires that equation (9) for $i \in \{R, M\}$ has to be equal and therefore, assuming the same bargaining power for each market, we get:

$$\kappa_R \theta_R = \kappa_M \theta_M \quad (22)$$

²Surplus, S is defined as the difference between what worker and firm will obtain when together and what they will obtain when separate, $S = E_{i,t} - U_{i,t} + J_{i,t} - V_{i,t}$

3 Calibration

Our benchmark model is calibrated such that it replicates some empirical facts about labor market conditions that were observed in the U.S. economy in 1992. Initially, since we are interested in the analysis of employment conditions for labor markets corresponding to different tasks, we calibrate the model to correctly match the unemployment rate for workers with different educational levels, namely, for those who carry university degree and for high school graduates. In 1992 the unemployment rate observed for university degree holders was close to 3%, whereas for high school graduates it constituted around 6%.

Thus, elasticities of production function are calibrated in order to match the empirical evidence, that is the different unemployment rates for workers with different levels of education. In order to replicate the unemployment levels observed in the U.S. economy in 1992 for different educational groups, we need to set elasticity of production function with respect to abstract tasks much higher than the elasticities that correspond to manual and routine tasks. Empirical evidence for this asserts that university degree holders contribute more to the economic prosperity of a country than high-school graduates. Indeed, in the Brookings Institution report (2015), it was estimated that the average bachelor's degree holder contributes \$278,000 more to local economies than the average high school graduate through direct spending over the course of his lifetime.

Table 1 presents an explicit list of all parameter values used in our model and their description. Parameters used in our model are mostly calibrated to match those widely used in the academic literature focused on the U.S. labor market analysis. Period of the model is one month. The bargaining power of workers α is set to be 0,72 and monthly separation rate λ is calibrated to be 0,034 following Shimer (2005). Shimer constructs monthly separation rate from seasonally adjusted employment, unemployment, and mean unemployment duration, using Current Population Survey data from the U.S. Bureau of Labor Statistics. In addition, we follow Shimer (2005) for the value of b , which can be interpreted as home production, unemployment benefits or value of leisure. Parameter b is set to be around 40% of the mean labor income in the model output, therefore, the value of b is 0,16. This lies at the upper end of the range of income replacement rates in the United States if interpreted entirely as an unemployment benefit. For the discount factor β we use a value equal to 0,995, which we take from Krusell et al (2010). The elasticity of the matching function γ

Table 1: Calibrated Model Parameters

Name	Definition	Value	Source
b	Home production/ unemployment benefits	0,16	Shimer (2005)
α	Workers' bargaining power	0,72	Shimer (2005)
β	Discount factor	0,995	Krusell et al (2010)
γ	Elasticity of matching function	2,2	Hagedorn and Manovskii (2008)
δ	Income share of output for routine tasks	0,15	Matches unemployment rate
ν	Income share of output for manual tasks	0,1	Matches unemployment rate
ζ	Income share of output for abstract tasks	0,75	Matches unemployment rate
λ	Exogenous separation rate	0,034	Shimer (2005)
κ_A	Vacancy cost in abstract market	0,067	Consistent with steady state
κ_R	Vacancy cost in routine market	0,013	Consistent with steady state
κ_M	Vacancy cost in manual market	0,013	Consistent with steady state
K	Labour-replacing capital	0,23	Consistent with steady state

equals to 2,2 from Hagedorn and Manovskii (2008), using the same functional specification of the matching function.

In our benchmark model we assume that people with the same level of education receive identical wages due to same marginal productivity and thus be subject to a similar level of unemployment, as the probability of finding a job is identical. We calibrate the initial value of K , corresponding to the amount of labor-replacing capital used, κ_M , κ_R and κ_A , corresponding to costs of posting a vacancy in each particular sector, in a way, that guarantees that the model is consistent with the aforementioned assumptions. Since K is assumed to be exogenously given in this economy, it enters the model as a parameter. The steady state equilibrium calibrated value for machinery and equipment capital is found to be 0,23, as displayed in **Table 1**. Steady state output for our benchmark model, for which unemployment in routine and manual sectors is identical, following the initial assumptions, is 0,85.³ This corresponds to a capital-output ratio of 27,05%. Given general

³Further discussion and reference in **Table 2**.

consensus of capital-output ratio being 300%, which accounts for capital stock being 3 times higher than output, whereas in our model, capital is 0,27 times higher than output, when output is normalized to 1. While in our case, capital represents only machinery and equipment capital, we conclude to a proportion of 9% for labor-replacing capital out of total capital stock at steady state. In fact, this is the case for the U.S economy in 1992, using information from the Fixed Assets Tables ⁴ of the Bureau of Economic Analysis. Accounting for Private fixed assets, only for Nonresidential equipment and Software, since we do not account for neither Structures nor Residential equipment being classified as labor-replacing capital. From Nonresidential equipment and Software, categories such as transportation equipment, Industrial equipment and Other equipment are excluded. The corresponding labor-replacing capital over total capital stock computed accounts for 8.09%, which gives a good approximation of our steady state machinery and equipment capital in our benchmark model.

4 Results

In this section, we introduce an exogenous shock in the level of capital that will cause changes in the distribution of high-school workers between routine and manual tasks. Since the production function specification, used by Autor et al.(2006) implies not only substitutability of routine tasks by capital but also complementary effects of capital employed in production process in abstract and manual tasks as well, an increase in the level of capital used in the production of the unique good is expected to change steady state equilibrium outcomes with particular interest in, namely, labor force, unemployment, bargained wages and marginal productivities in different tasks to capture job and wage polarization due to the introduction of machinery and equipment capital.

As mentioned in Section 2, we allow for intermediate labor market transition for high-school graduates. Thus, as soon as a shock in the rented machinery and equipment capital is introduced, unemployed high-school graduates choose whether to reallocate between sectors by solving the following maximization problem:

$$\max\{U_{R,t}, U_{M,t}\} \tag{23}$$

⁴Table 2.3: Historical-Cost Net Stock of Private Fixed Assets; Equipment, Software, and Structures; by Type

Once the shift of workers between routine and manual sectors has taken place, market tightness and expected profitability would be affected that might lead to a different steady state equilibrium in which again intermediary firms enter sectors up to the point where their expected profits equal to zero and wages are Nash-bargained, partly determining employment-unemployment equilibrium values together with filled positions and vacancies.

4.1 Comparison of steady states

This section discusses the simulated steady state equilibrium results, obtained in Dynare, after imposing percentage increases in the benchmark steady state machinery and equipment capital. First, the benchmark model equilibrium outcomes are reported. Since high-school graduates are assumed to be identical in terms of productivity and vacancy-posting costs are the same, labor replacing capital is calibrated such that employment levels in routine and manual tasks are identical, as explained in Section 3. Implied by this result, it follows that job-finding and filling probabilities in the two sectors as well as marginal products, Nash-bargained wages and unemployment levels are equal. On the other hand, once capital shocks are imposed, that is, an increase in the level of automation of routine tasks, equilibrium objects in the routine and manual sectors exhibit differences due to unemployed agents' re-optimizing in terms of re-establishing themselves in between the two tasks, not accounting for the changes in the labor force in each sector.

Table 2 presents the equilibrium objects of unemployment, employment, output and sector-switching probabilities. The corresponding steady state equilibrium values of marginal products and Nash-bargained wages in each of the three sectors for the benchmark model, previously mentioned as initial steady state, and the corresponding values once shocks of 5%, 10%, 20% and 30% increases in the amount of machinery and equipment capital employed are presented in **Table 3**.

Indeed, for the benchmark model, unemployment in abstract tasks or equivalently college graduates is 3%, whereas for high-school diploma holders it accounts for 6% unemployment, matching the U.S. labor features displayed in 1992.

As already stressed, equilibrium Nash-bargained wages, and marginal products are almost identical, as implied by the steady state amount of capital calibrated for these purposes. Another important detail regards to the the switching-market probabilities π_R and π_M . For the benchmark

Table 2: Steady State Comparison

	Benchmark Model	5% increase	10% increase	20% increase	30% increase
	K=0,23439	K=0,246195	K=0,257829	K=0,281268	K=0,304707
A					
<i>Labor force in A</i>	100,00%	100,00%	100,00%	100,00%	100,00%
<i>Employment rates</i>	96,56%	96,56%	96,56%	96,56%	96,56%
<i>unemp_A</i>	3,44%	3,44%	3,44%	3,44%	3,44%
R					
<i>Labor force in R</i>	50,02%	49,51%	48,99%	47,97%	46,92%
<i>Employment rates</i>	93,96%	93,72%	93,47%	92,85%	92,14%
<i>unemp_R</i>	6,04%	6,28%	6,53%	7,15%	7,86%
M					
<i>Labor force in M</i>	49,97%	50,48%	50,98%	52,01%	53,06%
<i>Employment rates</i>	93,98%	93,74%	93,51%	92,96%	92,35%
<i>unemp_M</i>	6,02%	6,26%	6,49%	7,04%	7,65%
Y					
π_R	0,857	0,859	0,860	0,864	0,866
π_M	50,02%	49,59%	49,17%	48,36%	47,59%
π_M	49,98%	50,41%	50,83%	51,64%	52,41%

economy, probabilities of switching from the manual sector to the routine one, or remaining in the routine, is equal to the respecting complementary one, as expected.

As the amount of labor replacing capital increases, unemployment in abstract tasks remains constant, which comes in contrast to the expected result that employment levels increase due to capital complementarity to abstract tasks. However, since we do not allow for re-establishment of the college graduates, the changes in the amount of capital are not sufficient enough to change the labor market structure of abstract tasks. As one can observe in **Table 3**, the percentage changes of marginal productivities of college degree holders are identical to the increases of the Nash-bargained wages, not allowing for relative profitability gains that would lead to decreases of unemployment due to higher vacancy rates in this market. On the other hand, unemployment in routine tasks is significantly adversely affected due to substitutability effects. The same pattern is observed in the case of manual tasks. However, since the shift of high-school graduates is allowed between routine and manual tasks, labor force basis does change after the materialization of the positive shock in the amount of capital. This result arises from the increase in the switching-task

probabilities π_M . Specifically, although the mass of high-school degree holders is always 1, there is a significant increase in the total labor force - employed and unemployed workers - established in the manual tasks as opposed to the reduction of the labor force in the routine sector. In particular, in the benchmark economy, 50.02% of the high-school graduates are established in the routine sector, whereas 49.98% are established as manual workers. On the other hand, after a 10% increase in the amount of machinery and equipment capital in the production process, labor force concentrated in the routine sector falls to 49.51%. The aforementioned results are more pronounced in the case of a 30% increase in the amount of capital employed. Notably, 53.06% of high-school graduates are established in manual sector in this steady state equilibrium.

However, new labor market conditions under this reallocation of the high-school labor force between the two tasks, do not allow for a fall in the unemployment rate of manual tasks since labor basis is not taken into account in the results presented. In particular, unemployment rates when labor force basis changes are considered, increase in both routine and manual tasks. Nevertheless, unemployment in routine task does increase more than the manual equivalent. **Table 5** provides further information on this issue. U_R represents the mass of unemployed high-school graduates in the routine sector. The corresponding unemployment rate in this sector for the steady state equilibrium after a 30% increase in labor replacing capital is 7.86%, whereas for the benchmark model, the equivalent unemployment rate is 6.04%. For the manual tasks sector, the rates are 7.65% and 6.03% respectively. A possible explanation of this unexpected result compared to Autor et al. (2006) unemployment outcomes, lies again in the frictional environment imposed in this model. As discussed in Section 2, intermediate profitability arises from differences in marginal productivity and Nash-bargained wages. **Table 3** reports identical percentage changes in the marginal productivities and Nash-bargained wages in both routine and manual tasks. This implication suggests that restricted profitability of the intermediate firms do not grant better employment conditions in neither of the two markets. Labor force shifts are not accompanied by vacancy rate increases, which, in turn leads to increases in unemployment. Labor market tightness does play a role in re-establishment choices of the agents.

Another implication of this equilibrium outcome after the shocks occurs, is that Nash-bargained wages fall for both manual and routine sectors in absolute terms, which is in line with skill-

Table 3: Steady State Comparison-Wages

	Benchmark Model	5% increase	10% increase	20% increase	30% increase
	0,23439	0,246195	0,257829	0,281268	0,304707
\bar{w}_A	0,6580	0,6593	0,6606	0,6630	0,6653
<i>% Change wrt Benchmark</i>		0,20%	0,39%	0,76%	1,11%
<i>% Change wrt Previous</i>		0,20%	0,19%	0,37%	0,34%
\bar{w}_A	0,1819	0,1808	0,1797	0,1777	0,1758
<i>% Change wrt Benchmark</i>		-0,62%	-1,20%	-2,32%	-3,36%
<i>% Change wrt Previous</i>		-0,62%	-0,59%	-1,13%	-1,06%
\bar{w}_A	0,1819	0,1809	0,1799	0,1780	0,1763
<i>% Change wrt Benchmark</i>		-0,57%	-1,11%	-2,14%	-3,09%
<i>% Change wrt Previous</i>		-0,57%	-0,54%	-1,04%	-0,97%
w_A	0,6656	0,6669	0,6682	0,6707	0,6730
<i>% Change wrt Benchmark</i>		0,20%	0,39%	0,76%	1,11%
<i>% Change wrt Previous</i>		0,20%	0,19%	0,37%	0,34%
w_A	0,1825	0,1814	0,1803	0,1782	0,1763
<i>% Change wrt Benchmark</i>		-0,62%	-1,21%	-2,33%	-3,37%
<i>% Change wrt Previous</i>		-0,62%	-0,59%	-1,14%	-1,06%
w_A	0,1825	0,1814	0,1805	0,1786	0,1768
<i>% Change wrt Benchmark</i>		-0,57%	-1,11%	-2,14%	-3,10%
<i>% Change wrt Previous</i>		-0,57%	-0,55%	-1,04%	-0,97%

biased premia hypothesis. However, comparing the labor shares of each of the tasks to the total output produces insightful results concerning wage polarization in this theoretical environment. In particular, in the case of the benchmark model, labor force employed in routine tasks possesses almost 10% of total output, whereas, after a 30% increase in capital, the corresponding percentage falls to 8.8% and the rest of 15% income share is owned by the labor replacing capital employed. In the case of the manual tasks though, the steady state equilibrium under the benchmark model generates a 10% specific-labor share and once the shock is imposed, the proportion remains the same, as well as for abstract tasks, as it can be observed in **Table 4**. On the other hand, marginal

productivity of abstract-task workers does present a rise, as opposed to the marginal productivities of high-school graduates employed in routine and manual tasks. From the perspective of the Nash-bargained wages devoured by the employed agents though, one can observe that movements of the wages paid by the intermediary firms replicate the percentage changes of the marginal products, discussed above and displayed in **Table 3**.

Table 4: Income Shares

	Benchmark Model	5% increase	10% increase	20% increase	30% increase
	K=0,23439	K=0,246195	K=0,257829	K=0,281268	K=0,304707
A	75,00%	75,00%	75,00%	75,00%	75,00%
K	4,99%	5,20%	5,40%	5,81%	6,20%
R	9,98%	9,80%	9,60%	9,19%	8,80%
M	10,00%	10,00%	10,00%	10,00%	10,00%

Concerning the outcomes of each variable in the five steady state equilibriums, presented in **Table 5** in the Appendix, we can observe that unemployment levels in abstract tasks remains constant, whereas, employment gains in manual tasks outweigh unemployment increases in the routine tasks, leading to an increase of unemployment levels in total, driven by increases in the routine and manual sectors. This is a result of high-school graduates possessing exactly the same productivity, which does not allow for relative gains of the intermediary firms between the two markets, such that different labor market conditions allow for differences in the direction of unemployment within the two sectors. Furthermore, increases in the amount of machinery and equipment capital also yields to increases in the production of the unique final good, as expected.

4.2 Steady state dynamics

Hereafter, we show the evolution of our main variables from one steady state to another. For that, we perform a simulation of 40 periods in Dynare. We will study how our variables move from the benchmark situation to a scenario where there is an increase of 30% in the level of labor-replacing capital, i.e., an increase in automation and how long they take to reach the new steady state. The red line represents the steady state level of the benchmark model, whereas the one after the increase

in K is given by the blue line. The first thing to notice from **Figure 1** is that, except from output, Y , levels of employment, A , and unemployment, $unemp_a$, in abstract market and Nash-bargained wages, \tilde{w}_a , and marginal productivity for abstract workers, w_a , variables reach the new steady state around period 15, that is, 15 months after the permanent shock is introduced.

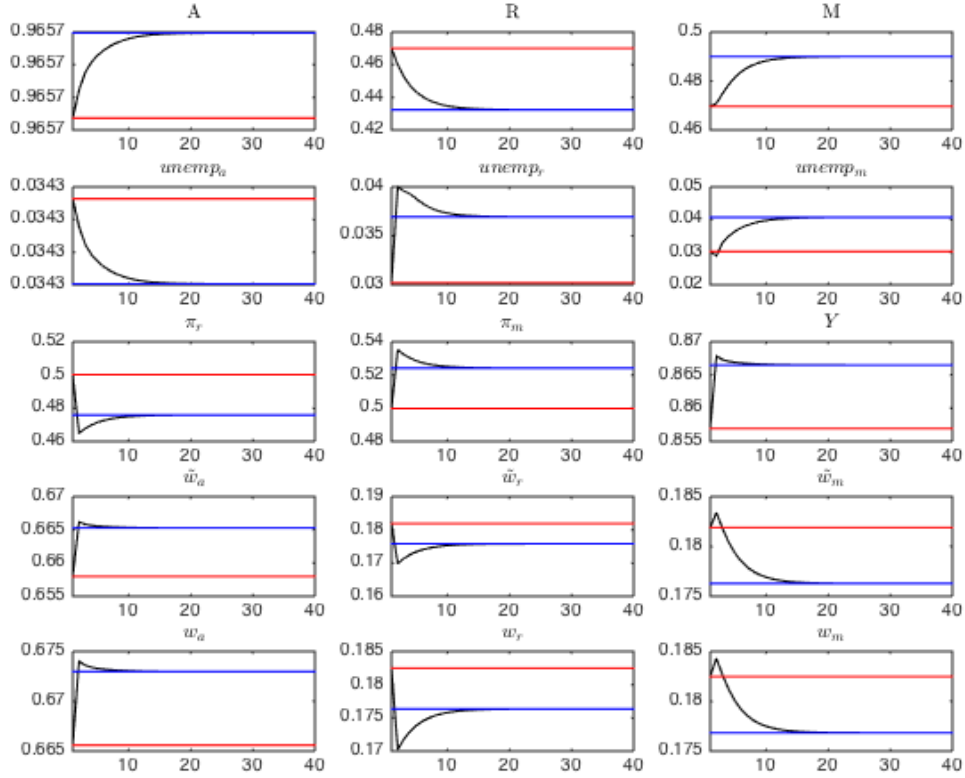


Figure 1: Steady state dynamics

As we discussed in the previous subsection, the levels of employment and unemployment in abstract market are not affected by an increase in automation since, as we can observe in **Figure 1**, the differences come after the fourth decimal, therefore, even if it seems there is an increase in the employment rate and a decrease in the unemployment rate in sector A, it is not the case. With respect to the level of output, Y , we can observe that after the shock is introduced, it suffers an initial increase due to the increase in capital, however, since labor in abstract stays constant and labor in routine decreases, it starts to adjust downwards to the new steady state, higher than the previous one due to the increase in manual labor and capital.

As a consequence of the increase in capital, marginal productivity of routine falls and, as it can

be seen, right after the capital shock, it falls way below the new steady state level. This decrease helps explain the decline in Nash-bargained wages and the initial increase of unemployment rate in routine, an increase higher than the new steady state level. Therefore, people in routine sector decide to move to the manual one, which is captured by the initial increase of π_m , representing the proportion of people moving from routine to manual, explaining why unemployment in routine market starts adjusting downwards. Once π_m reaches its state level, unemployment in routine ceases to decrease reaching a new steady state level, higher than the one given by the benchmark model.

By a similar argument, we can explain the increase in unemployment in the manual sector. As explained in the previous subsection, capital complements manual and abstract tasks, therefore, the result of an increase in the level of capital is the increase in the marginal productivity of these two tasks, as reflected in **Figure 1**, indeed, marginal productivity of abstract increases and reaches a higher steady state due to the fact that labor in abstract stays constant. However, since the amount of people employed in manual sector increases, marginal productivity of manual workers starts to decrease two periods after the positive shock to capital occurs, reaching a new steady state level, lower than the previous one. On the other hand, given the increase in the number of employed we would expect a decline in unemployment in manual sector. However, this is not the case, since the number of people going to manual sector is higher than those moving to the routine sector, as reflected by the decline in π_r . The labor force in manual sector after the increase in the amount of capital is larger than that in routine, indicating that people prefer to stay unemployed in manual than in routine sector.

5 Conclusions

We combine the basic Diamond (1982), Mortensen (1982), and Pissarides (1985) (DMP) labor market matching model with the one proposed by Autor et al. (2006) to analyze the labor market equilibria in a framework with frictions, where automation is introduced as an increase in the labor-replacing capital, in order to explain the job polarization phenomena generated during the recent past decades. We introduce three differentiated labor markets, functioning as in pure autarky, under a frictional environment, with high-skilled and low-skilled workers establishing in

either abstract-intensive and routine or manual tasks, respectively. Our analysis depends on the introduction of a positive capital shock, measured by percentage increases in the amount of capital employed in the production of the final good, that would approximate the implications of an increase in automation might have on labor market outcomes.

Based on the simplifying assumptions, our model fails to replicate labor market unemployment dynamics since 1992 and thus job polarization observed since 1990's, in general. Automation is though a plausible explanation, together with labor outsourcing providing evidence on increases in the upper-tail inequality, proxied by income gap between abstract and routine tasks, and compression in the lower-tail inequality, that is between routine and manual tasks. Even under the assumption of manual and routine having identical efficiency production units and the consecutive implication in labor market outcomes, skill-biased technological change does generate some evidence of income share polarization, which supports evidence against episodic reasons behind the rise in inequality since 1980s, such as institutional forces. Specifically, machinery and equipment capital introduction staggers routine-labor income share from almost 10% in our benchmark model, to 8,8% and unemployment rate for the lower-skilled workers does increase by more than 1.5 percentage points. Identical productivities, though, create, even under frictional labor market environment, Nash-bargained wage changes equal to marginal productivities changes, not allowing for market tightness adjustments due to vacancy rate. That is, unemployment increases for the manual sector are a result of labor force shifts from routine sector, which are not accompanied by any change in the vacancy postings in the former sector. Complementarity of labor-replacing capital on university graduates is not detected because of the same mechanism but evidence of substitutability of lower-skilled workers is captured by decreases in employment rates, after controlling for changes in labor force bases. Acceleration in skill-bias hypothesis is corroborated whereas wage polarization is, by construction, not identified.

The way our variables evolve from one steady state to another show reasonable dynamics and confirm the fact that our results are mainly a consequence of the simplifying assumptions used. Therefore, a more sophisticated version of our model, including differences in efficiency units of production among high-school graduates, such that there exists a productivity threshold that does not freely allow lower-skilled workers to shift among routine and manual sectors, could be

a theoretically improvement of our model, producing the desired effects on employment growth polarization. Also, allowing for the possibility to move to abstract market, incurring in a cost, could allow for some differences in the outcome obtained after an increase in capital. Specifically, we would expect rapid increases in the high-skill jobs, slowest growth in the middle-skilled jobs and a modest one for the low-skilled or manual tasks. Furthermore, frictional environment is added not only because market clearing equilibria are in dispute of empirical evidence, but also as an additional force replicating the magnitude of unemployment outcomes after labor-replacing shocks in the economy. However, no endogenous separation is considered in our simplistic model and no changes in the labor market structure, due to educational or demographic changes, over time are studied.

Adding the possibility to switch from one "sector" of the labor market to another not only for unemployed workers but also for the employed ones, one might possibly improve the ability of the model analyzed in this work to replicate the real world processes. Furthermore, the current version of the model assumes that in the total amount of workers in the economy the share of university degree holders remains constant, whereas in real economies it is obviously not the case. The model can be extended by adding other educational groups, for example, currently we are abstracting from workers that received less than high school workers. All these changes can possibly be introduced in the framework we introduced in our paper and represent possible ideas for further studies in the field.

Appendix

Table 5: Steady State Comparison

	Benchmark Model	5% increase	10% increase	20% increase	30% increase
	K = 0.23439	K=0.246195	K=0.257829	K=0.281268	K=0.304707
A	0.965	0.965	0.965	0.965	0.965
R	0.470	0.464	0.457	0.445	0.432
M	0.469	0.473	0.476	0.483	0.490
u_A	0.034	0.034	0.034	0.034	0.034
u_R	0.030	0.031	0.032	0.034	0.036
u_M	0.030	0.031	0.033	0.036	0.040
\tilde{w}_A	0.657	0.659	0.660	0.662	0.665
\tilde{w}_R	0.181	0.180	0.179	0.177	0.175
\tilde{w}_M	0.181	0.180	0.179	0.178	0.176
w_A	0.665	0.666	0.668	0.670	0.672
w_R	0.182	0.181	0.180	0.178	0.176
w_M	0.182	0.181	0.180	0.178	0.176
Y	0.856	0.858	0.860	0.863	0.866
π_R	0.500	0.495	0.491	0.483	0.475
π_M	0.499	0.504	0.508	0.516	0.524

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