Technology, Inequality, and Aggregate Demand*

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Abstract

What is the macroeconomic implications of inequality caused by technological progress? Using a standard over-lapping-generations model with skill heterogeneity and the Roy-type occupational choice, this paper examines how routine-biased technological change impacts income distribution and aggregate demand. It finds that the relatively rapid labor productivity increase in the manufacturing sector compared to the service sector can explain job and wage polarization and about two-thirds of the decline in the real interest rate in the US from the 1980's to 2010's. It also documents the potential contribution of that biased technological change to the stagnation of aggregate output.

Keywords: Routine-Biased Technological Change, Income Inequality, Aggregate Demand, Secular Stagnation

JEL Codes: E21, E24, J24, J62, O33

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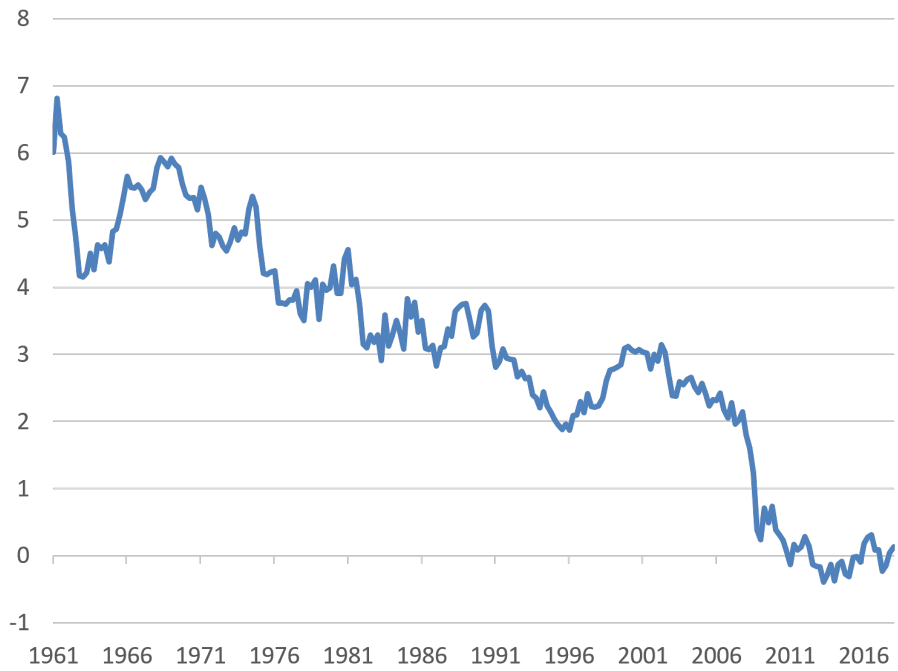
1 Introduction

1.1 Secular Stagnation

The US economy has experienced a dramatic decline in interest rate and stagnating output so does Summers (2014) calls "Secular Stagnation". According to Laubach and Williams (2003), which estimates natural rate of interest from 1960 to present, the US economy has experienced about 6% point decline during this 50 years.[1]

Figure 1: Natural Rate of Interest in the US



Note. Percentage, estimates by Laubach and Williams (2003)

Summers (2014) and Summers (2015) discuss several factors to account for the low equilibrium interest rate on a sustained basis. Several factors are reducing investment demand. They include (i) slowdown in Population Growth, (ii) decline in the relative price of capital, reducing the amount of savings needed for a given real investment, and (iii) excess cash holdings by some tech companies. At the same time, several factors are increasing the supply of savings. They include (i) increasingly large reserves that developing economies accumulating, (ii) larger demand for safe asset by more stringent capital or collateral requirement, (iii) increase in aggregate propensity of saving from rising inequality, and so on. Based on these discussion, Eggertsson et al. (2017) quantitatively assesses which factors are important and proposes that demographic factors- such as the decline in fertility and mortality rate- and technological factors- the decline in TFP growth- play major roles.

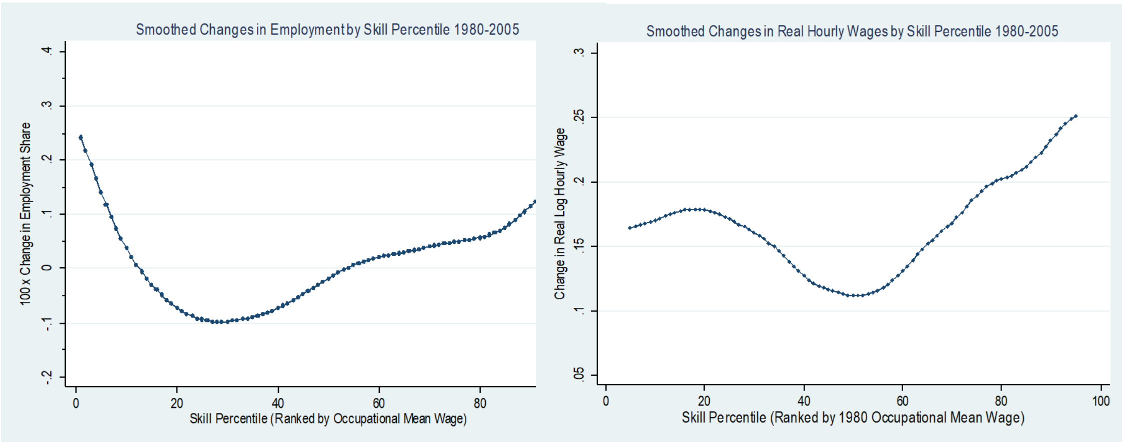
However, a closer examination of technological factors reveals that the US economy has experienced a steady or even increasing growth rate of labor productivity and that in really biased manner, so called Routine-Biased Technological Progress (hereafter RBTC).

[1] They provide their estimates after 2003 as well. The data and programs used for estimating the model are available at http://www.frbsf.org/economic-research/economists/LW_replication.zip

1.2 Routine-Biased Technological Change

In a seminal study, Autor and Dorn (2013) documents that this type of technological transformation since the 1980s has greatly impacted on employment and wages in the US[2]. Specifically, they find that the automation of jobs in manufacturing sector brought about to "Job and wage polarization", in which workers in the manufacturing sector were replaced by machines and forced to move to either lower- or higher-skilled occupations. Figure 2 and 2 show the non-monotonic growth in both employment share and wage in the US from 1980.[3] In both statistics, high-skill and low-skill occupations have experienced higher growth than middle-skill occupations, which is consistent with "skill-biased technological change" hypothesis.

Figure 2: Changes in Employment and Hourly Wages by Skill Percentile, 1980-2015



Note. Figure from Autor and Dorn (2013)

As this empirical evidence emerges, there are increasing numbers of theoretical papers to construct models to explain it. Firstly developed by Zeira (1998), the attempts are being revived its attention recently because of these empirical evidences. Some of the most relevant examples from automation literature are Acemoglu and Restrepo (2016), Acemoglu and Restrepo (2017), Acemoglu and Restrepo (2018) or Korinek and Stiglitz (2017). These papers try to capture how advancements in technology, including automation, artificial intelligence, or machine learning, would affect labor markets. Also, there are other papers, which study the effect of technology on labor market from structural change literature, including Ngai and Pissarides (2007), Buera and Kaboski (2012), Bárány and Siegel (2018), and Aum et al. (2018). This paper is more relevant to the latter studies because of their quantitative features as well as their tractability.

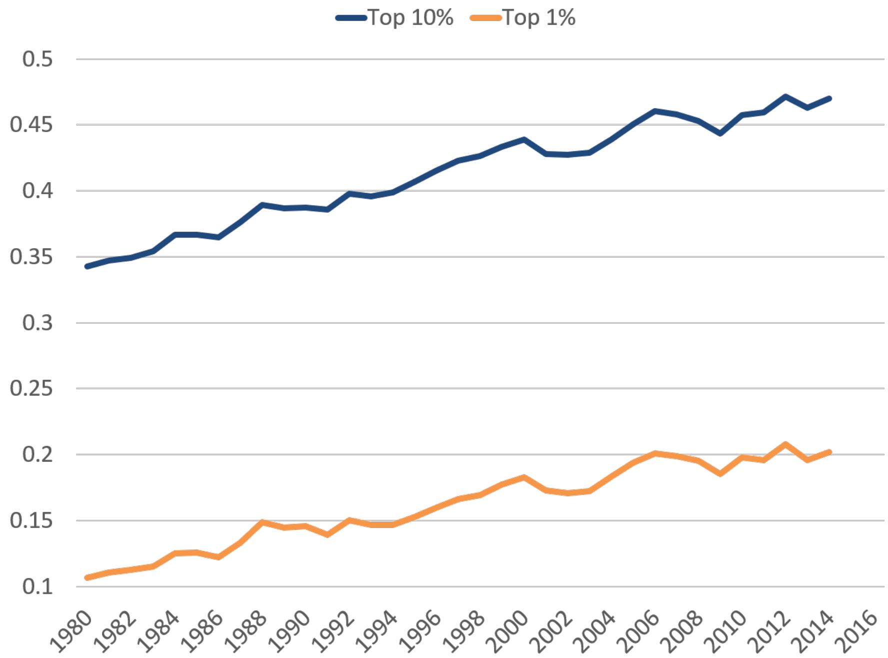
1.3 Inequality and Aggregate Demand

Rising income inequality is one of the most prominent global issues. Figure 3 plots the time-path of income share of top 10% and top 1% in the US from 1980 to present. It shows the increase by 12 percentage points and 10 percentage points, respectively, in 35 years.

[2]See Goos et al. (2014) for the episodes in European countries.

[3]See Autor and Dorn (2013) for details.

Figure 3: Income share of top 10% and top 1% in the US



Note. Data from World Inequality Database

This rising income inequality should have an important implication for aggregate consumption and saving behavior.[4] Dynan et al. (2004) and Saez and Zucman (2014) document that the rich save more fraction of their income, that is, saving rate is increasing function of income or wealth level, respectively.

Fisher (1930) argues that if one's income is a scaled version of another, "the smaller the income, the higher the preference for present over future" consumption. However, in most of the standard macroeconomic models, the property of homothetic preference leads economists to the Permanent Income Hypothesis (PIH) and does not allow the rich to save dis-proportionally more in the long run. Therefore, income distribution does not matter for Aggregate Demand in canonical models in macroeconomics. Yet, there is emerging empirical evidence, which rejects PIH.

[4]In the context of technological progress, there are two major perspectives for impacts of inequality by biased technological progress on macro economy- efficiency versus inequality. On the one hand, one may argue that technological progress is always good for aggregates even if it brings inequality as a result. For instance[5], as documented in Acemoglu and Restrepo (2017), automation can increase aggregate output through greater productivity, further capital accumulation, and the emergence of newly labor-intensive jobs. Resources become concentrated in more productive sectors, and this leads to an increase in aggregate output. Other factors include the incentive to work harder, which derives from income inequality, and to invest and undertake risks to take advantage of high rates of return. On the other hand, however, such distributional consequences also create negative effects on aggregate output. On the demand side, displacement and volatility in income processes depress aggregate demand through precautionary motives. As discussed in Auclert and Rognlie (2018), this decreases aggregate output. On the supply side, inequality results in less human capital accumulation for the poor, or resources being mis-allocated. Moreover, the declining aggregate demand for consumption depresses incentives for firms to invest and in turn decreases output.

The paper which has the closest motivation to this paper is Straub (2018).[6] He investigates elasticity of consumption to permanent income and consistently estimate that it is around 0.7. This can be best interpreted as follows: "if household A earns twice as much as household B, A will NOT spend 100% more than B, but 70% more". He also provides an OLG version of Aiyagari model with a bequest motive, which is a source of non-homothetic preferences. He shows that the non-homothetic preference model performs better than the homothetic model in terms of replicating aggregate economic implications of expanding income inequality. This paper is different from his paper because it incorporates heterogeneous skills across households, who choose their occupation, based on Straub (2018), and see how RBTC affects aggregate variables- the equilibrium interest rate.

1.4 This Paper

Given these sets of empirical evidence and theoretical prediction above, RBTC cannot be assumed to occur without implications for the demand side, in which a higher level of inequality increases aggregate propensity of saving and contributes to decline in interest rate. This mechanism is not formally examined before, including Eggertsson et al. (2017).[7]

In this paper, using a standard over-lapping-generations model with skill heterogeneity and occupational choice, I examine how routine-biased technological change impacts income distribution and aggregate demand. It finds that the relatively rapid labor productivity increase in the manufacturing sector compared to the service sector can explain job and wage polarization and about tow-thirds of the decline in the real interest rate in the US from the 1980s to 2010s. It also documents the potential contribution of that biased technological change to the stagnation of aggregate output.

The rest of this paper is organized as follows. Section 2 lays out the baseline model and formulate theoretical prediction. Next, Section 3 and 4 provide the theoretical and quantitative results, respectively. Moreover, Section 5 investigates the implications for aggregate output. Finally, Section 6 concludes with potential directions for future research.

2 Basic Model

2.1 Production

Production sectors are based on Bárány and Siegel (2018) (Hereafter, BS), and I add capital as an additional production factor in the final good producer's production function. There are three intermediary sectors providing different labor services to the final good producer. The final good producer uses these labor services and capital to produce consumption goods.

2.1.1 Intermediary Sectors

There are three intermediary sectors using each type of labor to provide labor services to the final good producer. The three labor types are $j = h, m, l$, each of which corresponds to High-skill service, Manufacturing, Low-skill service, respectively. Production function in sector j is given by

$$y_j = A_j N_j \tag{1}$$

[6] For others, see De Nardi (2004), Dynan et al. (2004), Kaplan et al. (2014), and Kaplan et al. (2018)

[7] They briefly discuss in footnote and appendix and say that they leave a fuller analysis for further research

where y_j denotes labor services, A_j denotes labor productivity, and N_j denotes labor supply in efficiency unit.

2.1.2 Final Good Producer

The final good producer uses capital and the labor services from three sectors as production factors and produces consumption goods. Its technology is given by

$$Y = K^{\alpha} X^{1-\alpha} \tag{2}$$

where variable Y denotes output, K denotes capital, X denotes combined labor services provided by the three sectors, and α denotes capital share. Capital depreciates at rate of $0 < \delta < 1$.

The final good producer combines the labor services from three sectors using the following technology;

$$X = \left(y_h^{\frac{\varepsilon-1}{\varepsilon}} + y_m^{\frac{\varepsilon-1}{\varepsilon}} + y_l^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} \tag{3}$$

where ε denotes elasticity of substitution for the three types of labor services. Then, the first order conditions become

$$\frac{Y_l}{Y_m} = \left(\frac{p_l}{p_m} \right)^{-\varepsilon} \tag{4}$$

$$\frac{Y_h}{Y_m} = \left(\frac{p_h}{p_m} \right)^{-\varepsilon} \tag{5}$$

Combining this with the production function, we have

$$\frac{A_l N_l}{s_m N_m} = \left(\frac{p_l}{p_m} \right)^{-\varepsilon} \tag{6}$$

$$\frac{A_h N_h}{s_m N_m} = \left(\frac{p_h}{p_m} \right)^{-\varepsilon} \tag{7}$$

All the factor markets are competitive. Therefore, we can reduce the production side to the following problem

$$\max_{K, N_h, N_m, N_l} Y - r^d K - w_h N_h - w_m N_m - w_l N_l \tag{8}$$

subject to

$$Y = K^{\alpha} \left\{ \left((A_h N_h)^{\frac{\varepsilon-1}{\varepsilon}} + (A_m N_m)^{\frac{\varepsilon-1}{\varepsilon}} + (A_l N_l)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} \right\}^{1-\alpha} \tag{9}$$

where r^d is rental rate of capital from households, which are described in the next subsection.

2.2 Household

2.2.1 Demographics

Household side is a deterministic over-lapping-generation model with skill heterogeneity, which generates permanent income inequality. For the OLG part I follow Benhabib et al.

(2018). Each agent lives finite and deterministic T years. Since I consider only stationary environments[8], the variables are indexed only by age t, and index for time is left implicit.

2.2.2 Preferences

Every period t, consumers choose consumption c_t and accumulate savings a_t, subject to a no-borrowing constraint. They leave wealth a_T as a bequest at the end of their lives. They get utility from consumption $u(c_t)$ at period $t = 1, ..., T$ and warm-glow utility from bequest $e(a_T)$ at $t = T$. Their functional forms display Constant Relative Risk Aversion:

$$u(c_t) = \frac{(c_t/z)^{1-\sigma}}{1-\sigma} \qquad e(a_T) = \phi \frac{(a_T/z)^{1-\Sigma}}{1-\Sigma} \tag{10}$$

where z is a normalization parameter.[9] The case when $\sigma = \Sigma$ leads to homothetic preferences while $\sigma \neq \Sigma$ exhibits non-homothetic preferences. In particular, if $\sigma > \Sigma$, seen in De Nardi (2004), De Nardi and Fella (2017), Straub (2018), or Benhabib et al. (2018), this preference leads the rich save more- saving rate of the richer is higher than that of the poorer.

2.2.3 Occupational Choice

In addition to the standard OLG model, within each cohort, households are heterogeneous in skill for each occupation ($\mathbf{s} \in \mathbb{R}^3$) and each household can choose an occupation (=sector) based on its skill set, following Bárány and Siegel (2018). This allows households within each cohort differ only in permanent income.

Each agent i is heterogeneous in skill endowment, which is a pair of efficiency units of labor to each three sector (s_h, s_m, s_l) drawn from a time invariant distribution $f(\mathbf{s})$. Given relative wage per efficiency unit $(\frac{w_l}{w_m}, \frac{w_h}{w_m})$, each worker chooses

- sector L if and only if $s_l w_l \geq s_m w_m$ and $s_l w_l \geq s_h w_h$
- sector M if and only if $s_m w_m \geq s_l w_l$ and $s_m w_m \geq s_h w_h$
- sector H if and only if $s_h w_h \geq s_l w_l$ and $s_h w_h \geq s_m w_m$

Then, given relative wage $(\frac{w_l}{w_m}, \frac{w_h}{w_m})$ and $f(s_l, s_m, s_h)$, labor allocation can be derived

$$N_l(\frac{w_l}{w_m}, \frac{w_h}{w_m}) = \int_0^\infty \int_0^{\frac{w_l}{w_m} s_l} \int_0^{\frac{\frac{w_l}{w_m}}{\frac{w_h}{w_m}} s_l} s_l f(s_l, s_m, s_h) ds_h ds_m ds_l \tag{11}$$

$$N_m(\frac{w_l}{w_m}, \frac{w_h}{w_m}) = \int_0^\infty \int_0^{\frac{1}{\frac{w_l}{w_m}} s_m} \int_0^{\frac{1}{\frac{w_h}{w_m}} s_m} s_m f(s_l, s_m, s_h) ds_h ds_l ds_m \tag{12}$$

$$N_h(\frac{w_l}{w_m}, \frac{w_h}{w_m}) = \int_0^\infty \int_0^{\frac{\frac{w_h}{w_m}}{\frac{w_l}{w_m}} s_h} \int_0^{\frac{w_h}{w_m} s_h} s_h f(s_l, s_m, s_h) ds_m ds_l ds_h \tag{13}$$

[8]In non-homothetic case- the case when $\sigma > \Sigma$-, stationary equilibrium might not exist or be unique, and that is hard to verify (Benhabib et al. (2018)). In the later quantitative part, I will plot aggregate supply and demand of asset as functions of the interest rate on fine grids, which expand reasonably large range of values of interest rate to check the slope of each.

[9]Assume z grows at the same speed as the economy. This captures the idea that for savings behavior it is not the absolute level of one's income that matters, but the income relative to the aggregate economy.

In raw labor, the following holds.

$$L_l(\frac{w_l}{w_m},\frac{w_h}{w_m}) = \int_0^\infty \int_0^{\frac{w_l}{w_m}s_l} \int_0^{\frac{\frac{w_l}{w_m}}{\frac{w_h}{w_m}}s_l} f(s_l,s_m,s_h)ds_h ds_m ds_l \tag{14}$$

$$L_m(\frac{w_l}{w_m},\frac{w_h}{w_m}) = \int_0^\infty \int_0^{\frac{1}{\frac{w_l}{w_m}}s_m} \int_0^{\frac{1}{\frac{w_h}{w_m}}s_m} f(s_l,s_m,s_h)ds_h ds_l ds_m \tag{15}$$

$$L_h(\frac{w_l}{w_m},\frac{w_h}{w_m}) = \int_0^\infty \int_0^{\frac{\frac{w_h}{w_m}}{\frac{w_l}{w_m}}s_h} \int_0^{\frac{w_h}{w_m}s_h} f(s_l,s_m,s_h)ds_m ds_l ds_h \tag{16}$$

2.2.4 Household Recursive Problem

Following Benhabib et al. (2018), let $\beta < 1$ be the discount rate and $V_t(a_t)$ be the present discounted utility of a household with asset a_t at the beginning of period t.

$$\begin{aligned} V_t(a) = &\quad \max_{c,a'} u(c) + \beta V_{t+1}(a') \\ s.t. &\quad a' = (1+r)a - c + \max_{j=h,m,l}\{w_j \cdot s_{i,j}\} \\ &\quad 0 \le c \le a,\ t = 1,...T-1 \\ V_T(a) = &\quad \max_{c,a'} u(c) + e(a') \end{aligned}$$

where $\max_{h,m,l} w_j \cdot s_{i,j}$ is individual labor income, which is different across i due to occupational choice based on their skill endowment and market wage in efficiency unit. It is a product of efficiency unit wage times skill endowment in occupation j, which each individual chooses to work at.

Assume that when agents die, their children with left bequest enter the economy. There is no inter-generational link of skill endowment. Each agent randomly draws its skill endowment, which is a pair of efficiency units of labor to each three sector (s_h, s_m, s_l), from a time invariant distribution $f(\mathbf{s})$.

2.3 Stationary Equilibrium

Definition 2.1 *A Stationary equilibrium is a vector of aggregates* $\{Y, \{y_j\}_{j=h,m,l}\}$*, labor allocation* $\{N_j\}_{j=h,m,l}, \{L_j\}_{j=h,m,l}$ *a set of policy functions* $\{c_i, a_i'\}_i$*, interest rate* $\{r\}$*, and wage* $\{w_h, w_m, w_l\}$ *such that*

1. *the firms maximize their profit*
2. *the policy functions solve agents' problem*
3. *the good market clears*
4. *the bond market clears*
5. *the labor market clears*

3 Theoretical Analysis

3.1 Non-homothetic Utility and Saving Rate

First, implications of non-homothetic utility on saving/consumption behavior can be derived as follows.

Assumption 1 *Non-homothetic utility*

$$\Sigma/\sigma < 1$$

This assumption is common in the literature as such Straub (2018) estimates this key parameter for concavity Σ/σ and concludes that $\widehat{\Sigma/\sigma} \approx 0.7$ using micro-data.

Proposition 1 *Under the assumption above, marginal propensity to consume is decreasing in relative income level to the economy. In short, consumption function is concave in income level.* ***Proof.*** *c* **is concave** *in a' when $\Sigma/\sigma < 1$ as follows, and so is in income;*

$$\frac{c}{z} = (\phi(1+r))^{-1/\sigma} \left(\frac{a'}{z}\right)^{\Sigma/\sigma} \tag{17}$$

■

This feature captures the idea that if the preference is non-homothetic as bequest is luxury good, saving rate in permanent income is higher for the rich. This result is consistent with the higher saving rate of the richer in terms of bequest documented by various papers[10]

3.2 Technology and Labor Market Polarization

Second, using the optimal sorting of individuals and the production function, relationships between technology and labor market can be summarized in the following two equations. This proposition is basically the same as the one in Bárány and Siegel (2018).

$$\frac{N_l\left(\frac{w_l}{w_m}, \frac{w_h}{w_m}\right)}{N_m\left(\frac{w_l}{w_m}, \frac{w_h}{w_m}\right)} \left(\frac{w_l}{w_m}\right)^{\varepsilon} = \left(\frac{s_m}{s_l}\right)^{1-\varepsilon} \qquad \frac{N_h\left(\frac{w_l}{w_m}, \frac{w_h}{w_m}\right)}{N_m\left(\frac{w_l}{w_m}, \frac{w_h}{w_m}\right)} \left(\frac{w_h}{w_m}\right)^{\varepsilon} = \left(\frac{s_h}{s_l}\right)^{1-\varepsilon} \tag{18}$$

Proposition 2 *The relatively faster labor productivity increase in manufacturing sector leads to Wage/Job polarization, if manufacturing goods and two types of services are complement ($\varepsilon < 1$). In particular, when s_m/s_h and s_m/s_l increase, w_h/w_m and w_l/w_m increase, and N_h/N_m and N_l/N_m increase.*

Proof. By total differentiation of equations (18). ■

The intuition of this job/wage polarization due to the biased technological changes is explained as follows; Focus on the two sectors (M&S). Increase in labor productivity in manufacturing ($\uparrow s_m$), on the one hand, reduces relative supply of service sector ($\downarrow y_S$), and on the other hand, reduces relative demand for S through an increase in the relative price of S ($\uparrow \frac{p_S}{p_M}$) If M and S are complements, relative Supply of S has to increase, and share of labor in S ($\uparrow L_S$) increases, which requires increase in relative wage in S ($\uparrow \frac{w_S}{w_M}$).

[10] For example, see De Nardi and Fella (2017) or Straub (2018)

4 Quantitative Analysis

In the previous section, the theoretical prediction which is consistent with the previous literature is derived. In this section, I quantitatively assess these mechanisms to answer to the original question- "How does routine-biased technological change affect income distribution and aggregate demand?". I use a time-variant exogenous path of labor productivity in three sectors for routine-biased technological progress, which is the same path of Bárány and Siegel (2018)[11] Then, I see how labor market and consumption-saving behavior changes in a response to that technological change.

4.1 Parameter Calibration

For parameter values, I report the values I use in Table 2. For production side, I follow Bárány and Siegel (2018) and use standard values for the rest ones. For skill distribution $f(\mathbf{s})$, the same log-normal distribution with Bárány and Siegel (2018) is used. The 1st moment of marginal distribution of $f(\mathbf{s})$ is re-calibrated to match $L_{j,1980}$, while the 2nd is the same. Elasticity of substitution between three sectors is 0.002, following Bárány and Siegel (2018). Capital share and depreciation rate are standard values in annual settings for the US economy. I use 0.36 for capital share and 0.06 for depreciation rate, following De Nardi (2004).

For the parameters which represent households' preference, I follow Benhabib et al. (2018) for discount rate and elasticity of utility function for consumption and bequest. I use 0.97 for discount factor (annually), 2.0 for elasticity of substitution in standard CES utility over consumption, and 0.6 for that over bequest. The only parameter I calibrate here is the weight on bequest in the utility function, targeting real interest rate in the initial period of this experiment, 1980.

Table 1: Calibration for time-invariant parameters

Parameter	Description	Value	Source/Target
Production			
$f(a)$	Skill endowment distribution	log-normal	Bárány and Siegel (2018)
ε	CES between L, M, and H	0.002	Bárány and Siegel (2018)
α	Capital share	0.36	Standard. De Nardi (2004)
δ	Depreciation rate	0.06	Standard. De Nardi (2004)
Preference			
β	Discount rate	0.97	Benhabib et al. (2018)
σ	EIS for u	2	Benhabib et al. (2018)
Σ	EIS for e	0.6	Benhabib et al. (2018)
ϕ	Weight on Bequest Motive	0.006	Target $r_{1980} = 0.043$

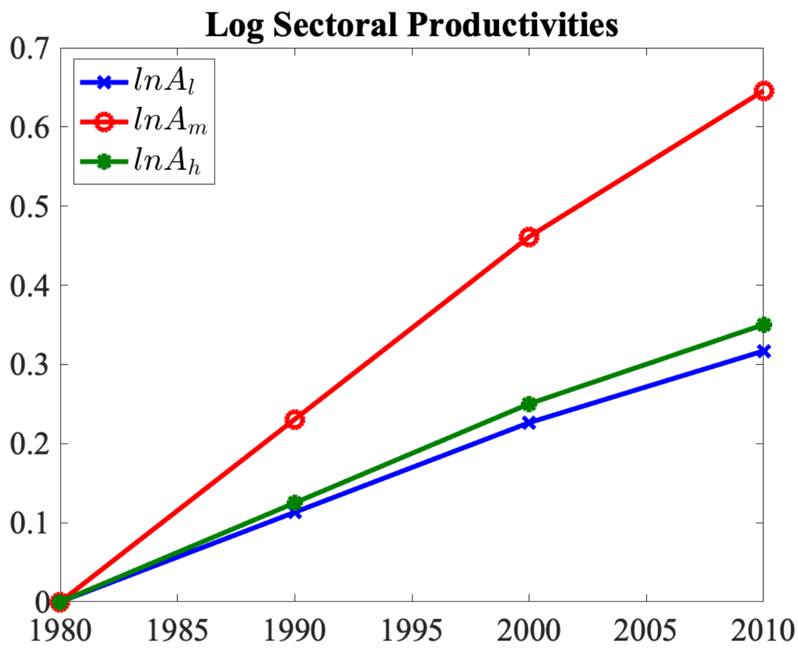
4.2 Biased Technological Change

From 1980 to 2010, the US economy has experienced biased technological change (Bárány and Siegel (2018)). Figure 4 shows labor productivity in log for three sectors- High-skill service, Manufacturing, and Low-skill service. Data is from Bárány and Siegel (2018). They

[11] Sectoral definition is same as Bárány and Siegel (2018).

measure labor productivity growth by dividing growth rate of industry-level output by hours worked data and aggregate them up to the three sectors. For details, see Bárány and Siegel (2018). It shows the changes in sectoral productivity in log, normalized each initial value in 1980 to 0. It implies that productivity in the manufacturing sector has grown about three times faster than the others.

Figure 4: Biased technological change in the US



Note. The blue line with Cross is the path of Low-skill service, the red with Circle is that of Manufacturing, and the green with Asterisk is that of High-skill service.

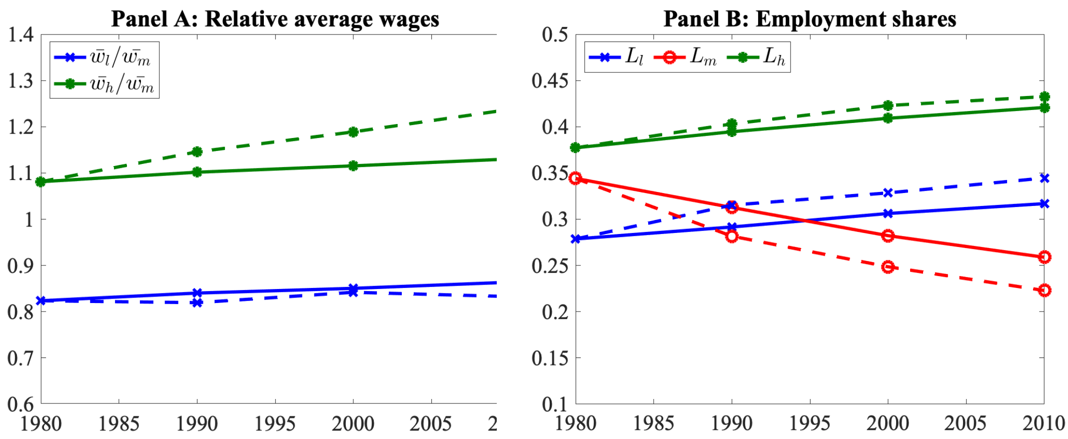
4.3 Results

Using the exogenous path of sectoral productivity changes from 1980 to 2010, I compute the response of the rest of the economy, including changes in relative average wage, employment share, and real interest rate. Then, I compare these model-implied response to the actual path by Bárány and Siegel (2018).[12]

Figure 5 shows the results in labor market. Panel A shows the change in relative wages, and Panel B shows the changes in the employment share in three sectors. Even though the model underestimates the increase in relative wage in high-skill service, together with employment share, the model provides a fairly good fit for labor market despite its simpleness. The findings for the labor market is consistent with the previous studies, which document Job and Wage polarization. These findings are consistent with vast literature including Autor and Dorn (2013) and Goos et al. (2014).

[12]They use data from IPUMS US census data. Note since census data was available up to 2000, they used ACS data in 2007 for the last period, and I follow them. In future research when census data in 2010 is available, I will use data of 2010 and recalculate the path.

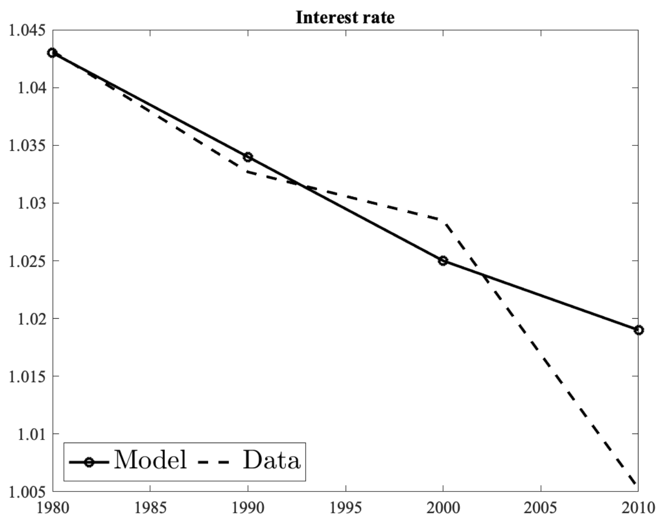
Figure 5: Wage and Job Polarization as a Result of Biased Technological Change



Note. Solid lines are the model-implied path, while dotted lines are data or estimates.

What about the implications for changes in real interest rate? Figure 6 shows the model-impled path of interest rate and estimates of natural rate of interest by Laubach and Williams (2003). The model predicts about 1.9% percent point decline, which is 63% of the estimates.

Figure 6: Decline in Interest Rate



Note. Solid lines are the model-implied path, while dotted lines are data or estimates.

The mechanism behind this decline is the changes in income distribution, in particular, income inequality. The intuition behind this decline is as follows. From asset supply (investment demand) side, technological progress increases marginal product of capital given the same level of aggregate capital. However, from asset demand side, income inequality among households expands, and this increases aggregate propensity to saving. Note that the scale parameter z, which corresponds the growth rate of output, ensures that there is no level effect in MPC of each household. Thus, dispersion in income distribution can be the only cause for this change in interest rate due to heterogeneous MPC across relative income level.

Eggertsson et al. (2017) discusses a demographic factor- decrease in mortality- is also an important determinant to contribute this decline in interest rate. The logic is simple: people live longer and save more. While this should account for some parts of the decline in interest rate, that might be valid only for this decade. UN[13] reports that Old-age dependency ratio (ratio of population aged 65+ per 100 population 15-64)- one measure for aging population- had been stable around 18 19% from 1980 to 2000. Only after 2005, the speed has become faster: 18.4%, 19.4%, 22.1%, 25.7% in 2005, 2010, 2015, 2020(projected), respectively.

5 Aggregate Demand and Output

In this section, I examine quantitative assessment on how much aggregate labor shrinks and how much of growth rate Aggregate Demand Effect suppresses. In order to allow demand to matter for output, some additional features *à* la Auclert and Rognlie (2018) are introduced. In particular, aggregate labor is introduced in the production functions and labor income determination. Also, downward nominal wage rigidity and inflexibility of monetary policy operation are considered.

5.1 Additional Features of Model

5.1.1 Production

Production function involves an additional input, aggregate labor L. Production function of each sector j is given by

$$Y_j = A_j n_j L^{\alpha} \tag{19}$$

Then the final goods firm chooses the aggregate labor level and produces the final goods using the following technology;

$$Y \equiv \left[Y_l^{\frac{\varepsilon-1}{\varepsilon}} + Y_m^{\frac{\varepsilon-1}{\varepsilon}} + Y_h^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{20}$$

Note that the demand for Aggregate Labor is independent with allocation.

$$F_L = \alpha L^{\alpha-1} \cdot \left(\left[(A_l n_l)^{\frac{\varepsilon-1}{\varepsilon}} + (A_m n_m)^{\frac{\varepsilon-1}{\varepsilon}} + (A_h n_h)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \right) = \frac{W}{P} \tag{21}$$

This decides aggregate labor demand equation $L = L^d(\frac{W}{P})$. With a flexible monetary policy to achieve full-employment equilibrium, the nominal interest rate will be chosen to ensure $L = 1$, and thus, W/P is given by $(L^d)^{-1}(1)$.

5.1.2 Household

There are two main differences to the previous setting. One is that the household labor income depends on the equilibrium level of the aggregate labor. Labor income of household

[13] https://population.un.org/wpp/

i with occupation j is given by

$$x_{i,t} = \max_{h,m,l} \{w_h s_{i,h}, w_m s_{i,m}, w_l s_{i,l}\} \left(\frac{W}{P} \cdot L \right) \tag{22}$$

where W_t is the Aggregate Reference Wage (nominal), and P_t is aggregate price level.

Also, since production function is not constant return to scale, firms will receive profit. I assume that all households equally hold equity share of firms and can not trade it. Thus, all the households can receive π profit each period, and their problems become as follows;

$$\begin{aligned} V_t(a) = & \quad \max_{c,a'} u(c) + \beta V_{t+1}(a') \\ s.t. & \quad a' = (1+r)a - c + x + \pi \\ & \quad 0 \le c \le a, \; t = 1, ...T-1 \\ V_T(a) = & \quad \max_{c,a'} u(c) + e(a') \end{aligned}$$

5.1.3 Downward Nominal Wage Rigidity and ZLB

Similar to Auclert and Rognlie (2018), Downward Nominal Wage Rigidity is introduced as such Aggregate Reference Wage does not fall too much;

$$W_t \ge \kappa W_{t-1} \tag{23}$$

Also, monetary policy is not fully flexible. The central bank sets the nominal interest rate according to a Taylor rule subject to the zero lower bound ($\underline{i} = 0$).

$$i_t = \max\{\underline{i}, R^*(1+\pi^*) \left(\frac{P_t/P_{t-1}}{1+\pi^*} \right)^{\phi} - 1\} \tag{24}$$

where π^* is inflation target and $\phi > 1$ Therefore, under ZLB, $L = 1$ may not be attained.

5.1.4 Equilibrium under ZLB

Definition 5.1 *Given nominal wage W_{-1}, an initial joint distribution of skill endowment and bequest $\Psi_{-1}(\mathbf{s}, b)$, and sectoral productivity $\{\{A_j\}_{j=h,m,l}\}$, an equilibrium is a vector of aggregates $\{Y, C, L\}$, sectoral aggregates $\{\{Y_j, N_j, L_j\}_{j=h,m,l}\}$, price $\{R, P, W\}$, relative unit wage $\{w_l/w_m, w_h/w_m\}$, a set of individual policy functions $\{\{c_i\}, b'_i\}_i$, government/CB policy rules $\{\zeta, i\}$, and joint distribution $\Psi(\mathbf{s}, b)$ such that*

1. *the representative firm maximizes its profit,*
2. *the policy functions solve agents' problem,*
3. *each worker choose the best occupation for each, CB set the nominal interest rate by (24),*
4. *the Fisher equation holds,*
5. *the good market clears,*
6. *the asset market clears*

5.2 Calibration

Assume the economy is at ZLB in 2010 and embrace the exogenous path of the biased technological change as same as actually observed from 2000 to 2010, which are $\Delta s_m \simeq 20\%$ (annually 1.8%) and $\Delta s_h \& \Delta s_l :\simeq 10\%$ (annually 1.0%).

I compare the aggregate output at the steady state for the full-employment equilibrium ($L = 1$, R adjusts) and the ZLB equilibrium ($i = 0, R = 1$, L adjusts). Parameters are chosen as follows; Labor share in production function α is set to be 0.66 from standard calibrations, and wage deflation rate κ is chosen to be 1, following Auclert and Rognlie (2018).

5.3 Results

The key factor to constitute interesting implications for economic responses under ZLB is asset market clearing. In general, aggregate R and L jointly clear the Asset/Bequest market. Asset demand from households (value of total asset, R^{-1}) is given by

$$B^d = R^{-1} \int g(L, R, b_i, \mathbf{s}_i) di \tag{25}$$

$$= R^{-1} \int h(x_i, R) di \tag{26}$$

where $x_i = \frac{W}{P} \cdot w_{i,j} \cdot L \cdot a_{i,j}$ is individual labor income. Asset supply is given by

$$B^s = \zeta L^\alpha \underbrace{\left[(A_l n_l)^{\frac{\varepsilon-1}{\varepsilon}} + (A_m n_m)^{\frac{\varepsilon-1}{\varepsilon}} + (A_h n_h)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}}}_{independent\ from\ Aggregate\ variables\ L\ and\ R} \tag{27}$$

When the economy is away from ZLB, real interest rate R clears the market as usual. However, under ZLB, R cannot adjust, and thus, L adjusts to clear the market.

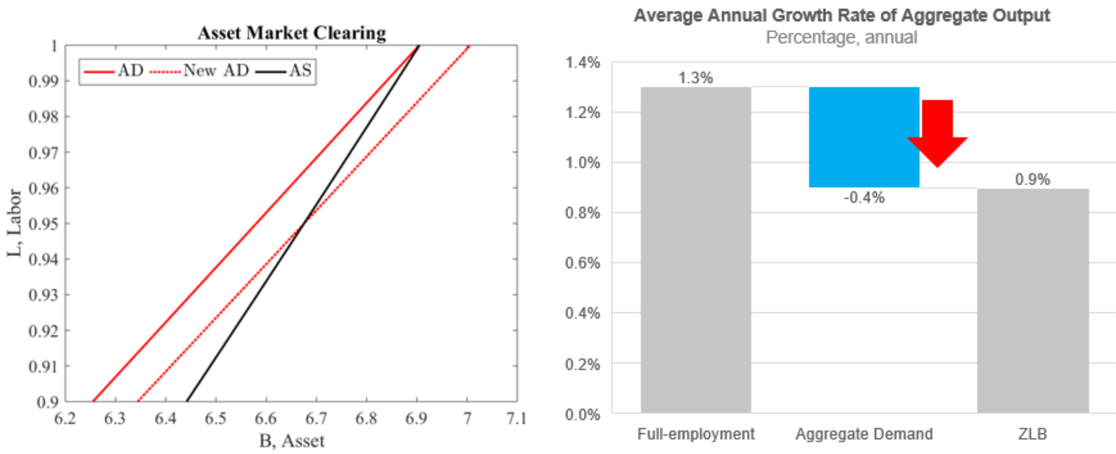
Accordingly, there are two main implications here. First, since the economy is under the ZLB, the nominal interest rate cannot decline as opposed to the full-employment equilibrium. When the aggregate asset demand increases due to expanding income inequality, aggregate labor declines to clear the asset market. Thus, as the left panel of Figure 7 shows, the aggregate labor shrinks by 5%.

Second, due to the decline in aggregate labor, the growth of the aggregate output is suppressed. Although this negative effect does not overturn the effect of the increase in productivity, as the right panel shows, one-third of the growth is lost. Compared to the case of full-employment equilibrium, where the economy grows by 1.3% annually, the growth rate becomes 0.9% under the ZLB.

6 Conclusion

Using a standard over-lapping-generations model with skill heterogeneity and the Roy-type occupational choice, this paper examines how routine-biased technological change impacts income distribution and aggregate demand. It finds that the relatively rapid labor productivity increase in the manufacturing sector compared to the service sector can explain job and wage polarization and about two-thirds of the decline in the real interest rate in the US from the 1980s to 2010s. It also documents the potential contribution of that biased technological change to the stagnation of aggregate output.

Figure 7: Labor Decline and Aggregate Demand



Note. The left panel shows changes in aggregate demand curve for asset on B-L plane given r. The right panel shows the aggregate demand impact on the output

There are several important direction for future research. First of all, I only model technological change as a source of life-time inequality to keep the model as simple as possible to examine the effect of technological progress on aggregate demand via permanent income inequality. Kaymak and Poschke (2016) finds that more than half of the dispersion in inequality is due to technology. Be that as it may, there are several other important factors- return heterogeneity (Benhabib et al. (2018)) or human capital investment (Kiyotaki and Zhang (2018)), which might have interesting implications for the equilibrium interest rate. By including these factors into the model, one may be able to match the moment of income and wealth distribution and assess relative importance of RBTC to secure stagnation.

Second, I keep life-cycle structure very simple: I assume that workers receive the same amount of labor income throughout their lives, they perfectly inherit bequest and skill endowment of those of their parents, and elasticity of inter-temporal substitution is constant over the life-cycle. These elements can be elaborated more to make the model closer to the reality.[14]

Thirdly, I use very simple model to examine the effect of inequality on output in Section 5. One could use more elaborated two-asset general equilibrium model with heterogeneous agents to allow that increase in saving rate of households does not necessarily lead to increase in supply of productive capital as documented in Auclert and Rognlie (2018).

Finally, one can consider the optimal monetary policy to RBTC in this framework. In a standard New Keynesian model, the optimal monetary policy toward TFP shock is to accommodate. However, if the technology shock is biased and does not increase so much- or even dampens- aggregate consumption, central banks should consider more active responses.

[14] See De Nardi (2004), Benhabib et al. (2018), Straub (2018) for these complications

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Computational Appendix

The computational procedures for the the baseline model are as follows;

1. Set exogenous sectoral productivity path $\{s_l, s_m, s_h\}$
2. Solve for sectoral relative wage $\{w_l/w_m, w_h/w_m\}$ and employment share $\{l_l, l_m, l_h\}$ from the followings;
   (a) Given the skill endowment distribution $f()$, derive labor supply function
   (b) Given the optimal labor allocation equations, derive labor demand function
3. Simulate to get relative labor income ($w_m = 1$) path for ten million individuals for each age $j = 1, \ldots 40$, in total, 10 mil$\times$ 40=400 million.
4. Solve for steady state interest rate r from the iteration;
   (a) Guess aggregate capital demand
   (b) Given the aggregate capital path, derive interest rate and wage
   (c) Solve households' problems for 400 million agents, and aggregate saving demand to derive capital supply.
   (d) Check whether aggregate capital demand (guess) and supply are close enough
      - If close, end loop
      - If not close, update guess of aggregate capital demand and iterate