Should the Government Subsidize Innovation or Automation?

Chu, Angus C. and Cozzi, Guido and Furukawa, Yuichi and Liao, Chih-Hsing

Fudan University, University of St. Gallen, Chukyo University, Chinese Culture University

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Angus C. Chu Guido Cozzi Yuichi Furukawa Chih-Hsing Liao

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Abstract

This study introduces automation into a Schumpeterian model to explore the different effects of R&D and automation subsidies. R&D subsidy increases innovation and decreases the share of automated industries with an overall inverted-U effect on economic growth. Automation subsidy decreases innovation and increases the share of automated industries also with an inverted-U effect on growth. Calibrating the model to US data, we find that the current level of R&D (automation) subsidy is above (below) the growth-maximizing level. Simulating transition dynamics, we find that changing R&D (automation) subsidy to its growth-maximizing level causes a welfare gain of 3.8% increase in consumption.

JEL classification: O30, O40
Keywords: automation, innovation, economic growth

Chu: anguscсс@gmail.com. China Center for Economic Studies, School of Economics, Fudan University, Shanghai, China. Cozzi: guido.cozzi@unisg.ch. Department of Economics, University of St. Gallen, St. Gallen, Switzerland. Furukawa: you.furukawa@gmail.com. School of Economics, Chukyo University, Nagoya, Japan. Liao: chihhsingliao@gmail.com. Department of Economics, Chinese Culture University, Taipei, Taiwan. The authors are grateful to Lei Ning for his helpful advice. The usual disclaimer applies.

1 Introduction

Automation allows machines to perform tasks that are previously performed by workers. On the one hand, automation may be a threat to the employment of workers. For example, a recent study by Frey and Osborne (2017) examines 702 occupations and finds that almost half of them could be automated within the next two decades. On the other hand, automation reduces the cost of production and frees up resources for more productive activities. Given the rising importance of automation,[1] we develop a growth model with automation to explore its effects on the macroeconomy.

Specifically, we introduce automation in the form of capital-labor substitution into a Schumpeterian growth model. Then, we apply the model to explore the effects of R&D subsidy versus automation subsidy on innovation, economic growth and social welfare. In our model, an industry uses labor as the factor input before automation occurs. When the industry becomes automated, it then uses capital as the factor input. Innovation in the form of a quality improvement can arrive at an automated or unautomated industry. When an innovation arrives at an automated industry, the industry becomes unautomated and once again uses labor as the factor input.[2] Therefore, the share of automated industries, which is also the degree of capital intensity in the aggregate production function, is endogenously determined by automation and innovation.

In this growth-theoretic framework, we obtain the following results. An increase in R&D subsidy leads to a higher level of innovation as well as a higher rate of technological progress, which gives rise to a conventional positive effect of R&D subsidy on the growth rate of output. However, the increase in skilled labor for innovation crowds out skilled labor for automation and leads to a lower share of automated industries as well as a lower degree of capital intensity in the aggregate production function, which in turn causes a negative growth effect that is absent in previous studies with exogenous capital intensity in production. Therefore, an increase in R&D subsidy has an overall inverted-U effect on the growth rate of output due to endogenous capital intensity in production. Capital intensity affects growth because it determines the returns to scale of capital, which is a reproducible factor that can be accumulated.

An increase in automation subsidy has a negative effect on innovation and a positive effect on the share of automated industries but also an inverted-U effect on output growth. Calibrating the model to aggregate US data, we find that the current level of R&D subsidy is above the growth-maximizing level whereas the current level of automation subsidy is below the growth-maximizing level. Furthermore, decreasing R&D subsidy improves social welfare whereas increasing automation subsidy improves welfare. Simulating transition dynamics of the economy, we find that reducing the R&D subsidy rate (or raising the automation subsidy rate) to its growth-maximizing level would lead to a welfare gain that is equivalent to a permanent increase in consumption of 3.8%.

This study relates to the literature on innovation and economic growth. Romer (1990) develops the seminal R&D-based growth model in which innovation is driven by the inven-

[1] See for example Agrawal *et al.* (2018) for a comprehensive discussion on artificial intelligence, which is the latest form of automation.

[2] See Acemoglu and Restrepo (2018) for empirical evidence that "humans have a comparative advantage in new and more complex tasks."

tion of new products. Then, Segerstrom *et al.* (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992) develop the Schumpeterian quality-ladder model in which innovation is driven by the development of higher-quality products. Many subsequent studies in this literature use variants of the R&D-based growth model to explore the effects of R&D subsidies; see for example, Peretto (1998), Segerstrom (2000), Zeng and Zhang (2007), Impullitti (2010), Chu *et al.* (2016) and Chu and Cozzi (2018). These studies do not feature automation and hence tend to find a positive effect of R&D subsidies on innovation and growth. An exception is Segerstrom (2000), who finds a positive (negative) effect of R&D subsidy if it is applied to quality improvement (variety expansion). In his model, growth is driven by quality improvement, and there is a crowding-out effect between quality improvement and variety expansion. Our study finds a crowding-out effect between innovation and automation, which gives rise to an inverted-U growth effect of R&D subsidies because innovation and automation are both important to economic growth.

This study also relates to the literature on automation and innovation; see Aghion *et al.* (2017) for a comprehensive discussion of this literature. An early study by Zeira (1998) develops a growth model with capital-labor substitution, which forms the basis of automation in subsequent studies. Zeira (2006) contributes to the literature by introducing endogenous invention of technologies into Zeira (1998). Peretto and Seater (2013) propose a growth model with factor-eliminating technical change in which R&D serves to increase capital intensity in the production process. Our study relates to Peretto and Seater (2013) by considering both factor-eliminating technical change (i.e., automation) and factor-augmenting technical change (i.e., innovation) and exploring their relative importance on growth and welfare. Recent studies by Acemoglu and Restrepo (2018) and Hemous and Olson (2018) generalize the model in Zeira (1998) and introduce directed technological change between automation and variety expansion in order to explore the effects of automation on the labor market and income inequality.[3] Our study complements these interesting studies by embedding endogenous automation into the Schumpeterian quality-ladder model[4] and performing a comparative policy analysis to explore the different effects of R&D and automation subsidies.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 compares the effects of the two subsidies. The final section concludes.

2 A Schumpeterian growth model with automation

We introduce automation in the form of capital-labor substitution as in Zeira (1998) into a canonical Schumpeterian growth model. We consider a cycle of automation and innovation. An unautomated industry that currently uses labor as the factor input can become automated and then use capital as the factor input. Innovation in the form of a quality improvement can arrive at an automated or unautomated industry. When an innovation arrives at an automated industry, the industry becomes unautomated and once again uses labor as the factor input until the next automation arrives.[5] This cycle repeats indefinitely.

[3] See also Prettner and Strulik (2017) for a variety-expanding model with automation and education.

[4] See also Aghion *et al.* (2017) who develop a Schumpeterian model with *exogenous* automation.

[5] Acemoglu and Restrepo (2018) make a similar assumption that all new inventions are first produced by labor until they are automated.

2.1 Household

The representative household has the following utility function:

$$U = \int_0^{\infty} e^{-\rho t} \ln c_t dt, \tag{1}$$

where the parameter $\rho > 0$ is the subjective discount rate and c_t is the level of consumption. The household supplies l units of low-skill labor and one unit of high-skill labor to earn wages and makes consumption-saving decision to maximize utility subject to the following asset-accumulation equation:

$$\dot{a}_t + \dot{k}_t = r_t a_t + (R_t - \delta) k_t + w_{l,t} l + w_{h,t} - \tau_t - c_t. \tag{2}$$

a_t is the real value of assets (i.e., the share of monopolistic firms), and r_t is the real interest rate. k_t is physical capital, and $R_t - \delta$ is the real rental price net of capital depreciation. $w_{l,t}$ and $w_{h,t}$ are respectively the real wage rates of low-skill labor and high-skill labor. τ_t is a lump-sum tax (or transfer). From standard dynamic optimization, the Euler equation is

$$\frac{\dot{c}_t}{c_t} = r_t - \rho. \tag{3}$$

Also, the no-arbitrage condition $r_t = R_t - \delta$ holds.

2.2 Final good

Competitive firms produce final good y_t using the following Cobb-Douglas aggregator over a unit continuum of differentiated intermediate goods:

$$y_t = \exp\left(\int_0^1 \ln x_t(i) di\right), \tag{4}$$

where $x_t(i)$ denotes intermediate good $i \in [0, 1]$.[6] The conditional demand function for $x_t(i)$ is given by

$$x_t(i) = \frac{y_t}{p_t(i)}, \tag{5}$$

where $p_t(i)$ is the price of $x_t(i)$.

2.3 Intermediate goods

There is a unit continuum of industries, which are also indexed by $i \in [0, 1]$, producing differentiated intermediate goods. If an industry is not automated, then the production process uses labor and the production function is

$$x_t(i) = z^{n_t(i)} l_t(i), \tag{6}$$

[6] We follow Zeira (1998) to interpret $x_t(i)$ as intermediate goods. Alternatively, one could follow Acemoglu and Restrepo (2018) to interpret $x_t(i)$ as tasks.

where the parameter $z > 1$ is the step size of each quality improvement, $n_t(i)$ is the number of quality improvements that have occurred in industry i as of time t, and $l_t(i)$ is the amount of low-skill labor employed in industry i. Given the productivity level $z^{n_t(i)}$, the marginal cost function of the leader in an unautomated industry i is $w_{l,t}/z^{n_t(i)}$. The monopolistic price is a constant markup over the marginal cost such that

$$p_t(i) = \mu \frac{w_{l,t}}{z^{n_t(i)}}, \tag{7}$$

where the markup $\mu > 1$ is a policy parameter determined by the government.[7] Therefore, the wage payment in an unautomated industry is

$$w_{l,t} l_t(i) = \frac{1}{\mu} p_t(i) x_t(i) = \frac{1}{\mu} y_t, \tag{8}$$

and the amount of monopolistic profit in an unautomated industry is

$$\pi_t^l(i) = p_t(i) x_t(i) - w_{l,t} l_t(i) = \frac{\mu - 1}{\mu} y_t. \tag{9}$$

If an industry is automated, then we follow Zeira (1998) to assume that the production process uses capital and the production function is

$$x_t(i) = z^{n_t(i)} k_t(i). \tag{10}$$

Given the productivity level $z^{n_t(i)}$, the marginal cost function of the leader in an automated industry i is $R_t/z^{n_t(i)}$.[8] The monopolistic price is also a constant markup over the marginal cost such that

$$p_t(i) = \mu \frac{R_t}{z^{n_t(i)}}. \tag{11}$$

The capital rental payment in an automated industry is

$$R_t k_t(i) = \frac{1}{\mu} p_t(i) x_t(i) = \frac{1}{\mu} y_t, \tag{12}$$

and the amount of monopolistic profit in an automated industry is

$$\pi_t^k(i) = p_t(i) x_t(i) - R_t k_t(i) = \frac{\mu - 1}{\mu} y_t. \tag{13}$$

[7] Grossman and Helpman (1991) and Aghion and Howitt (1992) assume that the markup is equal to the quality step size z, due to limit pricing between current and previous quality leaders. Here we follow Howitt (1999) and Dinopoulos and Segerstrom (2010) to consider an alternative scenario in which new quality leaders do not engage in limit pricing with previous quality leaders because after the implementation of the newest innovations, previous quality leaders exit the market and need to pay a cost before reentering. Given the Cobb-Douglas aggregator in (4), the unconstrained monopolistic price would be infinite. We follow Evans *et al.* (2003) to consider price regulation under which the regulated markup ratio cannot be greater than $\mu > 1$. This additional markup parameter enables us to perform a more realistic quantitative analysis.

[8] The marginal cost of production using capital is $R_t/z^{n_t(i)}$ whereas the marginal cost of production using labor is $w_{l,t}/z^{n_t(i)}$. Given that R_t remains constant and $w_{l,t}$ grows on the balanced growth path, $w_{l,t} > R_t$ will eventually hold.

2.4 R&D and automation

Equations (9) and (13) show that $\pi_t^l(i) = \pi_t^l$ and $\pi_t^k(i) = \pi_t^k$ for each type of industries. Therefore, the value of inventions is also the same within each type of industries such that $v_t^l(i) = v_t^l$ and $v_t^k(i) = v_t^k$.[9] The no-arbitrage condition that determines the value v_t^l of an unautomated invention is

$$r_t = \frac{\pi_t^l + \dot{v}_t^l - (\alpha_t + \lambda_t) v_t^l}{v_t^l}, \tag{14}$$

which states that the rate of return on v_t^l is equal to the interest rate. The return on v_t^l is the sum of monopolistic profit π_t^l, capital gain $\dot{v}_t^l$ and expected capital loss $(\alpha_t + \lambda_t)v_t^l$, where α_t is the arrival rate of automation and λ_t is the arrival rate of innovation.[10] Similarly, the no-arbitrage condition that determines the value v_t^k of an automation is

$$r_t = \frac{\pi_t^k + \dot{v}_t^k - \lambda_t v_t^k}{v_t^k}, \tag{15}$$

which states that the rate of return on v_t^k is also equal to the interest rate. The return on v_t^k is the sum of monopolistic profit π_t^k, capital gain $\dot{v}_t^k$ and expected capital loss $\lambda_t v_t^k$, where λ_t is the arrival rate of innovation.[11]

Competitive entrepreneurs recruit high-skill labor to perform innovation. The arrival rate of innovation in industry i is given by

$$\lambda_t(i) = \varphi_t h_{r,t}(i), \tag{16}$$

where $\varphi_t \equiv \varphi h_{r,t}^{\epsilon-1}$. The aggregate arrival rate of innovation is $\lambda_t = \varphi h_{r,t}^{\epsilon}$, where $h_{r,t}$ denotes aggregate R&D labor. Here the parameter $\epsilon \in (0,1)$ captures an intratemporal duplication externality as in Jones and Williams (2000) and determines the degree of decreasing returns to scale in R&D at the aggregate level. In a symmetric equilibrium, the free-entry condition of R&D becomes

$$\lambda_t v_t^l = (1-s) w_{h,t} h_{r,t} \Leftrightarrow \varphi v_t^l = (1-s) w_{h,t} h_{r,t}^{1-\epsilon}, \tag{17}$$

where $s < 1$ is the R&D subsidy rate.[12]

There are also competitive entrepreneurs who recruit high-skill labor to perform automation. The arrival rate of automation in industry i is given by

$$\alpha_t(i) = \phi_t h_{a,t}(i), \tag{18}$$

where $\phi_t \equiv \phi(1-\theta_t) h_{a,t}^{\epsilon-1}$. The endogenous variable $\theta_t \in (0,1)$ is the fraction of industries that are automated at time t. In other words, $1-\theta_t$ captures the following effect: a larger

[9] We follow the standard approach in the literature to focus on the symmetric equilibrium. See Cozzi *et al.* (2007) for a theoretical justification for the symmetric equilibrium to be the unique rational-expectation equilibrium in the Schumpeterian model.

[10] When the next innovation occurs, the previous technology becomes obsolete. This is known as the Arrow replacement effect; see Cozzi (2007) for a discussion.

[11] Here we assume the Arrow replacement effect applies such that the previous automation becomes obsolete when the next innovation arrives. Acemoglu and Restrepo (2018) also make a similar assumption that when a new unautomated variety arrives, a previous automated variety becomes obsolete.

[12] If $s < 0$, then it acts as a tax on R&D.

mass of currently unautomated industries that can be automated makes automation easier to complete. The aggregate arrival rate of automation is $\alpha_t = \phi h_{a,t}^{\epsilon}$, where $h_{a,t}$ denotes aggregate automation labor and we have used the condition that $h_{a,t}(i) = h_{a,t}/(1-\theta_t)$.[13] In a symmetric equilibrium, the free-entry condition of automation becomes

$$\alpha_t v_t^k = (1-\sigma)w_{h,t}h_{a,t}/(1-\theta_t) \Leftrightarrow \phi(1-\theta_t)v_t^k = (1-\sigma)w_{h,t}h_{a,t}^{1-\epsilon}, \tag{19}$$

where $\sigma < 1$ is the automation subsidy rate.[14]

2.5 Government

The government collects tax revenue to finance the subsidies on R&D and automation. The balanced-budget condition is

$$\tau_t = s w_{h,t}h_{r,t} + \sigma w_{h,t}h_{a,t}. \tag{20}$$

2.6 Aggregate economy

Aggregate technology Z_t is defined as[15]

$$Z_t \equiv \exp\left(\int_0^1 n_t(i)di \ln z\right) = \exp\left(\int_0^t \lambda_\omega d\omega \ln z\right), \tag{21}$$

where the last equality uses the law of large numbers. Differentiating the log of Z_t in (21) with respect to time yields the growth rate of technology given by

$$g_{z,t} \equiv \frac{\dot{Z}_t}{Z_t} = \lambda_t \ln z. \tag{22}$$

Substituting (6) and (10) into (4) yields

$$y_t = \exp\left(\int_0^1 n_t(i)di \ln z + \int_0^{\theta_t} \ln k_t(i)di + \int_{\theta_t}^1 \ln l_t(i)di\right) = Z_t\left(\frac{k_t}{\theta_t}\right)^{\theta_t}\left(\frac{l}{1-\theta_t}\right)^{1-\theta_t}, \tag{23}$$

where the share θ_t of automated industries also determines the degree of capital intensity in the aggregate production function. The evolution of θ_t is determined by

$$\dot{\theta}_t = \alpha_t(1-\theta_t) - \lambda_t\theta_t, \tag{24}$$

where $\alpha_t = \phi h_{a,t}^{\epsilon}$ and $\lambda_t = \varphi h_{r,t}^{\epsilon}$ are respectively the arrival rates of automation and innovation. Using (2), one can derive the familiar law of motion for capital as follows:[16]

$$\dot{k}_t = y_t - c_t - \delta k_t. \tag{25}$$

[13] Recall that automation is only directed to currently unautomated industries, which have a mass of $1-\theta_t$.
[14] If $\sigma < 0$, then it acts as a tax on automation.
[15] Recall that automation does not improve quality but only allows for capital-labor substitution.
[16] Derivations are available upon request.

From (8) and (12), the capital and labor shares of income are respectively

$$R_t k_t = \frac{\theta_t}{\mu} y_t, \tag{26}$$

$$w_{l,t} l = \frac{1-\theta_t}{\mu} y_t. \tag{27}$$

2.7 Decentralized equilibrium

The equilibrium is a time path of allocations $\{a_t, k_t, c_t, y_t, x_t(i), l_t(i), k_t(i), h_{r,t}(i), h_{a,t}(i)\}$ and prices $\{r_t, R_t, w_{l,t}, w_{h,t}, p_t(i), v_t^l(i), v_t^k(i)\}$ such that the followings hold in each instance:

- the household maximizes utility taking $\{r_t, R_t, w_{l,t}, w_{h,t}\}$ as given;
- competitive final-good firms produce $\{y_t\}$ to maximize profit taking $\{p_t(i)\}$ as given;
- each monopolistic intermediate-good firm i produces $\{x_t(i)\}$ and chooses $\{l_t(i), k_t(i), p_t(i)\}$ to maximize profit taking $\{w_{l,t}, R_t\}$ as given;
- competitive entrepreneurs choose $\{h_{r,t}(i), h_{a,t}(i)\}$ to maximize expected profit taking $\{w_{h,t}, v_t^l(i), v_t^k(i)\}$ as given;
- the market-clearing condition for capital holds such that $\int_0^{\theta_t} k_t(i)di = k_t$;
- the market-clearing condition for low-skill labor holds such that $\int_{\theta_t}^1 l_t(i)di = l$;
- the market-clearing condition for high-skill labor holds such that $\int_0^1 h_{r,t}(i)di + \int_{\theta_t}^1 h_{a,t}(i)di = 1$;
- the market-clearing condition for final good holds such that $y_t = c_t + \dot{k}_t + \delta k_t$;
- the value of inventions is equal to the value of the household's assets such that $\int_0^{\theta_t} v_t^k(i)di + \int_{\theta_t}^1 v_t^l(i)di = a_t$; and
- the government balances the fiscal budget.

3 Growth and welfare effects of R&D and automation

From (9) and (13), the amount of monopolistic profits in both automated and unautomated industries is

$$\pi_t^l = \pi_t^k = \frac{\mu - 1}{\mu} y_t. \tag{28}$$

The balanced-growth values of an innovation and an automation are respectively

$$v_t^l = \frac{\pi_t^l}{\rho + \alpha + \lambda} = \frac{\pi_t^l}{\rho + \phi h_a^\epsilon + \varphi h_r^\epsilon}, \tag{29}$$

$$v_t^k = \frac{\pi_t^k}{\rho + \lambda} = \frac{\pi_t^k}{\rho + \varphi h_r^\epsilon}. \tag{30}$$

Substituting (29) and (30) into the free-entry conditions in (17) and (19) yields

$$\frac{\varphi(1-\sigma)h_a^{1-\epsilon}}{\phi(1-\theta)(1-s)h_r^{1-\epsilon}} = \frac{\rho + \phi h_a^\epsilon + \varphi h_r^\epsilon}{\rho + \varphi h_r^\epsilon},$$

which can be reexpressed as

$$\frac{1-\sigma}{1-s}\left[\frac{\varphi}{\phi} + \left(\frac{1-h_r}{h_r}\right)^\epsilon\right] = \left(\frac{h_r}{1-h_r}\right)^{1-\epsilon} + \left(\frac{h_r}{1-h_r}\right)^{1-2\epsilon}\frac{\phi}{\varphi + \rho/h_r^\epsilon}. \tag{31}$$

If we assume $\epsilon \leq 1/2$,[17] then the right-hand side of (31) is increasing in h_r, whereas the left-hand side is always decreasing in h_r. Therefore, there exists a unique steady-state equilibrium value of R&D labor h_r and automation labor h_a. R&D labor $h_r(s,\sigma)$ is increasing in R&D subsidy s but decreasing in automation subsidy σ, whereas automation labor $h_a(s,\sigma)$ is increasing in automation subsidy σ but decreasing in R&D subsidy s.

From (24), the steady-state share of automated industries is

$$\theta(s,\sigma) = \frac{\alpha}{\alpha + \lambda} = \frac{\phi h_a^\epsilon}{\phi h_a^\epsilon + \varphi h_r^\epsilon}, \tag{32}$$

which is increasing in automation subsidy σ but decreasing in R&D subsidy s. The steady-state equilibrium growth rate of technology is

$$g_z(s,\sigma) = \lambda \ln z = \varphi h_r^\epsilon \ln z, \tag{33}$$

which is increasing in R&D subsidy s but decreasing in automation subsidy σ.

Given that y_t and k_t grow at the same rate on the balanced growth path, the production function in (23) implies that the steady-state equilibrium growth rate of output y_t is

$$g_y(s,\sigma) = \frac{g_z}{1-\theta} = \frac{\lambda \ln z}{1-\theta} = (\phi h_a^\epsilon + \varphi h_r^\epsilon)\ln z, \tag{34}$$

where $g_y = g_z/(1-\theta)$ is increasing in capital intensity θ for a given g_z because a larger θ increases the returns to scale of capital, which is a reproducible factor that can be accumulated. In (34), $g_y(s,\sigma)$ can be increasing or decreasing in automation subsidy σ and R&D subsidy s. Intuitively, although automation subsidy σ decreases the technology growth rate g_z, it may increase the output growth rate g_y by expanding the share of automated industries and increasing the degree of capital intensity in production. In contrast, although R&D subsidy s increases the technology growth rate g_z, it may decrease the output growth rate g_y

[17] In the appendix, we derive a weaker parameter condition.

by reducing the share of automated industries and decreasing the degree of capital intensity in production.

Differentiating g_y in (34) with respect to h_a subject to $h_a + h_r = 1$ yields the growth-maximizing level of automation as

$$h_a^* = \frac{\phi^{1/(1-\epsilon)}}{\varphi^{1/(1-\epsilon)} + \phi^{1/(1-\epsilon)}} \in (0, 1). \tag{35}$$

Therefore, for a given R&D subsidy rate s, there exists an automation subsidy rate $\sigma^* < 1$ that maximizes g_y by equating the steady-state equilibrium h_a to h_a^*. Similarly, for a given automation subsidy rate σ, there also exists an R&D subsidy rate $s^* < 1$ that maximizes g_y. Proposition 1 summarizes these results

Proposition 1 *An increase in the R&D subsidy rate s has a positive effect on the technology growth rate g_z, a negative effect on the share θ of automated industries and an inverted-U effect on the output growth rate g_y. An increase in the automation subsidy rate σ has a negative effect on the technology growth rate g_z, a positive effect on the share θ of automated industries and an inverted-U effect on the output growth rate g_y.*

Proof. See Appendix A. ■

We now explore how automation affects social welfare. The steady-state level of social welfare U can be expressed as

$$\rho U = \ln c_0 + \frac{g_c}{\rho} = \underbrace{\ln\left[1 - (g_y + \delta)\frac{k}{y}\right]}_{=\ln(c/y)} + \underbrace{\theta \ln\left(\frac{k}{\theta}\right) + (1-\theta)\ln\left(\frac{l}{1-\theta}\right)}_{=\ln y_0} + \frac{g_y}{\rho}, \tag{36}$$

where Z_0 is normalized to unity. The steady-state capital-output ratio is given by

$$\frac{k}{y} = \frac{\theta}{\mu R} = \frac{\theta}{\mu(r+\delta)} = \frac{\theta}{\mu(g_y + \rho + \delta)}, \tag{37}$$

where θ is given by (32) and g_y is given by (34). If we shut down the automation process by setting h_a and θ to zero, then the welfare function simplifies to $\rho U = \ln l + (\varphi \ln z)/\rho$, which together with (36) shows the following welfare effects of introducing automation. First, it reduces the consumption-output ratio by requiring the household to devote some output to invest in physical capital. Second, the presence of physical capital contributes to the production of output. Third, a lower labor intensity reduces the contribution of labor to the production of output. Finally, introducing automation initially increases the growth rate of output because the growth-maximizing level of automation h_a^* in (35) is positive.

To explore the relative magnitude of these different effects, we first use the aggregate production function in (23) to derive the balanced-growth level of capital as

$$k = \frac{\theta l}{1-\theta}\left(\frac{k}{\theta y} Z\right)^{1/(1-\theta)}, \tag{38}$$

where the steady-state capital-output ratio is given by (37). Normalizing Z_0 in (38) to unity and substituting (38) into (36) yield

$$\rho U = \ln\left[1-(g_y+\delta)\frac{k}{y}\right] + \frac{\theta}{1-\theta}\ln\left(\frac{k}{\theta y}\right) + \ln\left(\frac{l}{1-\theta}\right) + \frac{g_y}{\rho}. \tag{39}$$

Equation (39) implies that the optimal allocation is $\{h_r^{**}, h_a^{**}\} \to \{0,1\}$, in which case our growth model approaches an AK model in which economic growth can be sustained by capital accumulation without technological progress. As $\{h_r, h_a\}$ approaches $\{0,1\}$, the growth rate of output becomes $g_y \to \phi \ln z$, whereas the share of automated industries becomes $\theta \to 1$. In this case, the capital-output ratio in (37) becomes $k/y \to 1/[\mu(\phi \ln z + \rho + \delta)]$, which in turn implies that the consumption-output ratio is positive even as $\theta \to 1$. To see this,

$$\frac{c}{y} = 1-(g_y+\delta)\frac{k}{y} \to \frac{\mu\rho + (\mu-1)(\phi\ln z+\delta)}{\mu(\phi\ln z+\rho+\delta)} > 0,$$

where $\rho > 0$ and $\mu > 1$. Then, as the share of automated industries approaches unity, the returns to scale of capital in production approaches constant, which amplifies the effect of investment on the accumulation of capital and the level of output. This effect is captured by $\frac{\theta}{1-\theta}\ln\left(\frac{k}{\theta y}\right)+\ln\left(\frac{l}{1-\theta}\right)$ in (39), which approaches infinity as $\theta \to 1$. Therefore, setting automation subsidy $\sigma \to 1$ to devote all research resources to approach a fully automated production process is socially optimal. This finding suggests that the case with only factor-eliminating technical change analyzed in Peretto and Seater (2013) is not a restrictive limitation.

3.1 Quantitative analysis

In this section, we calibrate the model to aggregate US data in order to perform a quantitative analysis on the growth and welfare effects of the two subsidies. The model features the following set of parameters $\{\rho, \delta, \mu, z, \varphi, \phi, \epsilon, s, \sigma\}$.[18] We choose a conventional value of 0.05 for the discount rate ρ. As for the capital depreciation rate δ, we calibrate its value using an investment-capital ratio of 0.0765 in the US. We use the estimate in Laitner and Stolyarov (2004) to consider a value of 1.10 for the markup ratio μ. We calibrate the quality-step size z using a long-run technology growth rate of 0.0125 in the US. We calibrate the R&D productivity parameter φ using an innovation arrival rate of one-third as in Acemoglu and Akcigit (2012). We calibrate the automation productivity parameter ϕ using a labor-income share of 0.60 in the US. As for the intratemporal externality parameter ϵ, we follow Jones and Williams (2000) to set ϵ to 0.5. Given that the US currently does not apply different rates of subsidies to innovation and automation, we consider a natural benchmark of symmetric subsidies $s = \sigma$.[19] Then, we follow Impullitti (2010) to set the rate of subsidies in the US to 0.188. Table 1 summarizes the calibrated parameter values.

[18] Our calibration does not require us to assign a value to low-skill production labor l. Although the welfare function in (39) features low-skill production labor l, it only affects the level of social welfare but not the change in welfare.

[19] In our simulation, we will change the individual values of s and σ separately.

Table 1: Calibration								
ρ	δ	μ	z	φ	ϕ	ϵ	s	σ
0.050	0.058	1.100	1.039	0.403	0.296	0.500	0.188	0.188

In the rest of this section, we simulate the separate effects of R&D subsidy s and automation subsidy σ on the technology growth rate g_z, the share θ of automated industries, the output growth rate g_y and the steady-state level of social welfare U.[20] Figure 1 simulates the effects of R&D subsidy s. Figure 1a shows that R&D subsidy s has a positive effect on the technology growth rate. Figure 1b shows that R&D subsidy s has a negative effect on the share of automated industries. Figure 1c shows that R&D subsidy s has an inverted-U effect on the growth rate of output. Starting from the current level of $s = 0.188$, any further increase in the rate of R&D subsidy reduces economic growth, and the growth-maximizing R&D subsidy rate is $s^* = 0.148$. Figure 1d shows that decreasing R&D subsidy improves social welfare; for example, reducing the R&D subsidy rate from the current level of 0.188 to the growth-maximizing level of $s^* = 0.148$ would lead to a steady-state welfare gain that is equivalent to a permanent increase in consumption of about 5.8%.

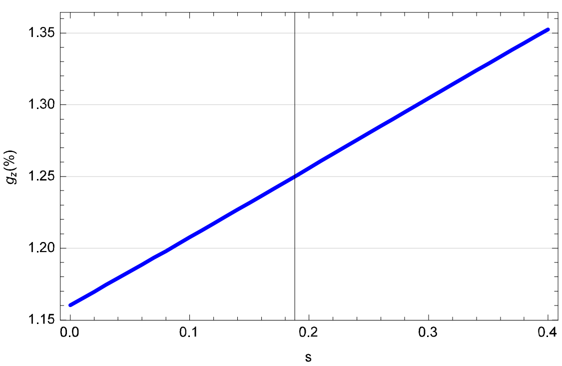

Figure 1a: Effect s on g_z

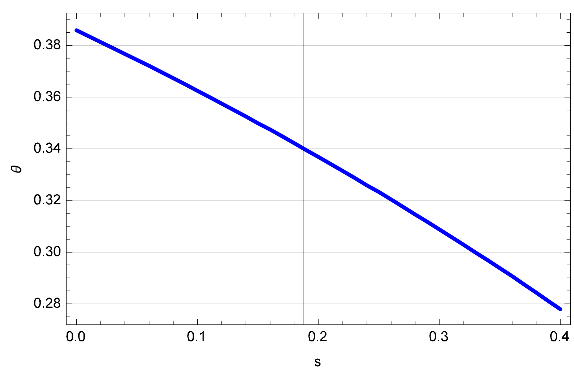

Figure 1b: Effect s on θ

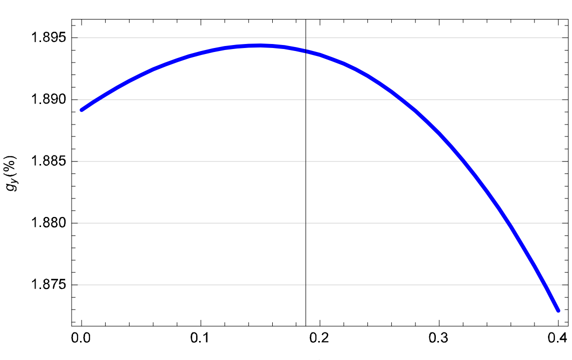

Figure 1c: Effect s on g_y

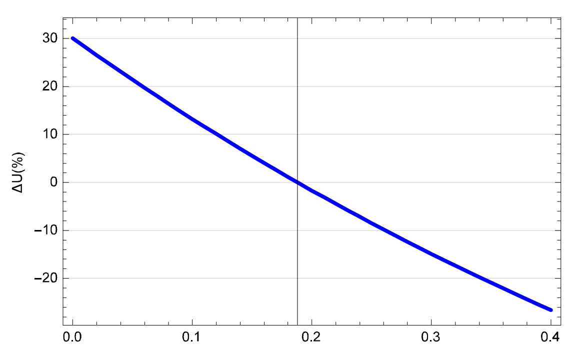

Figure 1d: Effect s on ΔU

[20]We focus on the steady state in this section and consider transition dynamics in the next section.

Figure 2 simulates the effects of automation subsidy σ. Figure 2a shows that automation subsidy σ has a negative effect on the technology growth rate. Figure 2b shows that automation subsidy σ has a positive effect on the share of automated industries. Figure 2c shows that automation subsidy σ has an inverted-U effect on the growth rate of output. Starting from the current level of $\sigma = 0.188$, a marginal increase in the rate of automation subsidy stimulates economic growth, and the growth-maximizing automation subsidy rate is $\sigma^* = 0.226$. Figure 2d shows that increasing automation subsidy improves social welfare. For example, raising the automation subsidy rate from the current level of 0.188 to the growth-maximizing level of $\sigma^* = 0.226$ would also lead to a steady-state welfare gain that is equivalent to a permanent increase in consumption of about 5.8%.

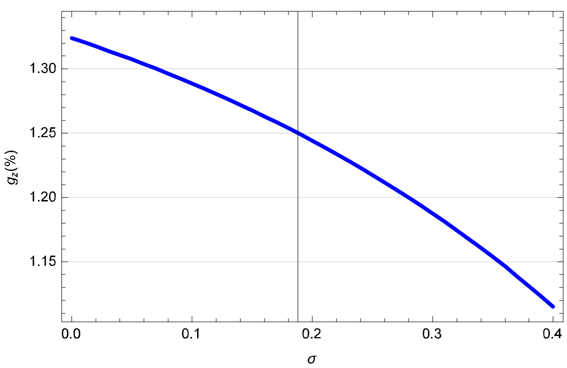

Figure 2a: Effect of σ on g_z

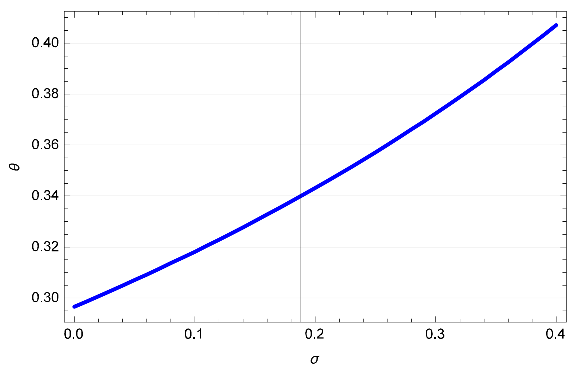

Figure 2b: Effect of σ on θ

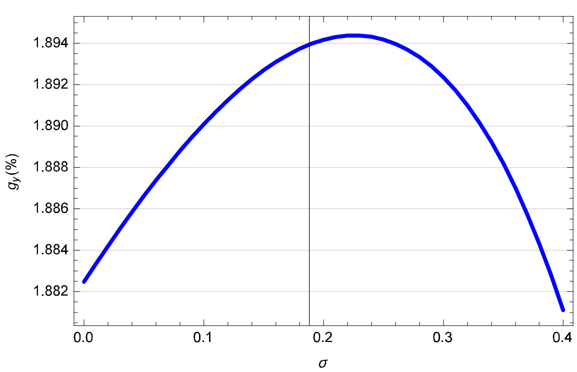

Figure 2c: Effect of σ on g_y

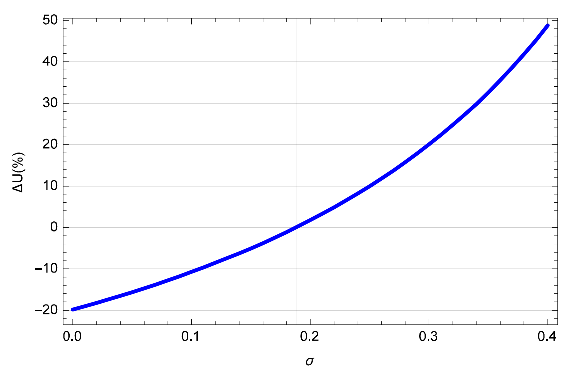

Figure 2d: Effect of σ on ΔU

3.2 Transition dynamics

We use the relaxation algorithm in Trimborn *et al.* (2008) to simulate the transitional dynamic effects of reducing R&D subsidy s to the growth-maximizing level of $s^* = 0.148$.[21]

[21] The effects of raising automation subsidy σ to its growth-maximizing level $\sigma^* = 0.226$ are the same.

Figure 3a shows that a decrease in R&D subsidy leads to a lower technology growth rate $g_{z,t}$. The initial drop in $g_{z,t}$ is larger than the decrease in the long run. As shown in Figure 3b, capital intensity θ_t increases towards a higher level that requires a large amount of automation labor $h_{a,t}$, which crowds out R&D labor $h_{r,t}$. Figure 3c shows that despite the fall in technology growth $g_{z,t}$, the output growth rate $g_{y,t}$ increases initially before gradually falling towards the new steady state, which is above the initial steady state. The drastic initial increase in output growth $g_{y,t}$ is due to the high initial growth in capital intensity θ_t. Figure 3d shows that the (log) level of consumption decreases initially because the increase in capital intensity leads to a higher level of capital investment, which crowds out consumption. Then, the high output growth $g_{y,t}$ leads to a high consumption growth $g_{c,t}$. Gradually, consumption converges to a new balanced growth path (BGP), which has a higher growth rate than the initial BGP. Comparing the new transitional path of consumption and its initial BGP, we compute a welfare gain equivalent to a permanent increase in consumption of 3.8%. Finally, Figure 4a shows that the transitional welfare effects of R&D subsidy s are about two-thirds of the steady-state welfare effects of s in Figure 1d, whereas Figure 4b shows that the transitional welfare effects of automation subsidy σ are also about two-thirds of the steady-state welfare effects of σ in Figure 2d.

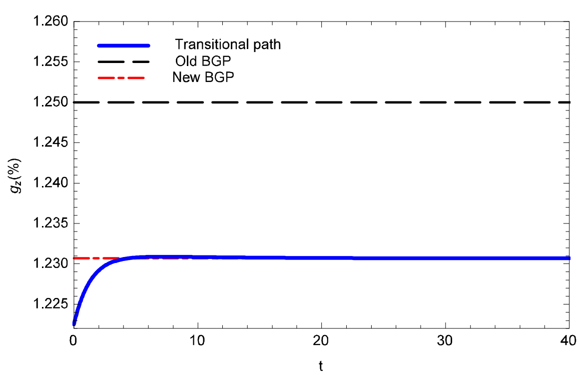

Figure 3a: Dynamic effect of a lower s on g_z

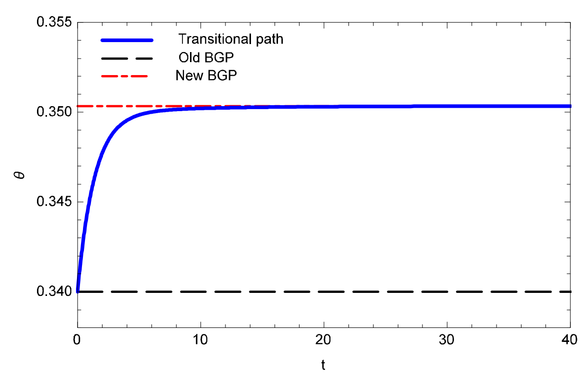

Figure 3b: Dynamic effect of a lower s on θ

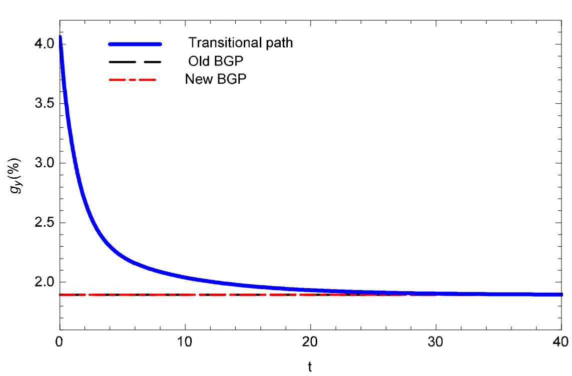

Figure 3c: Dynamic effect of a lower s on g_y

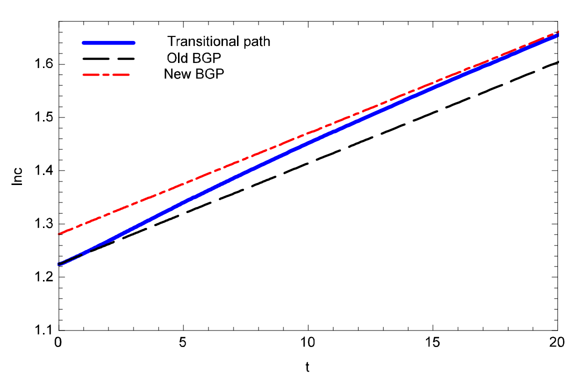

Figure 3d: Dynamic effect of a lower s on c

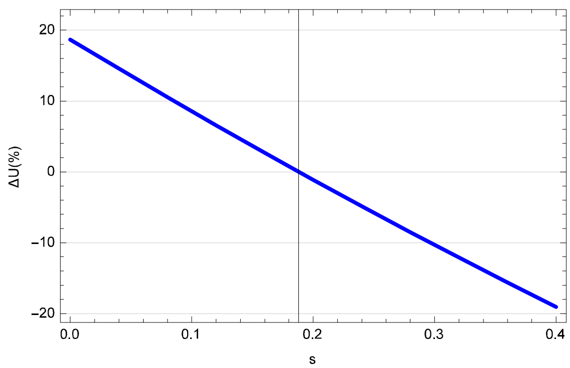

Figure 4a: Effect of s on ΔU

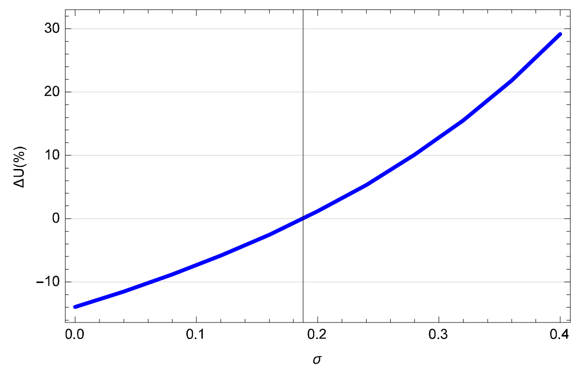

Figure 4b: Effect of σ on ΔU

4 Conclusion

In this study, we have developed a Schumpeterian growth model with automation. Our model features innovation in the form of quality improvement and also automation in the form of capital-labor substitution. Innovation gives rise to technological progress whereas automation increases the returns to scale of capital in production. Therefore, innovation and automation both affect economic growth measured by the growth rate of output. R&D subsidy increases innovation but crowds out automation, whereas automation subsidy increases automation but crowds out innovation. As a result, each of the two subsidies has an inverted-U effect on economic growth. In contrast, the welfare effects of the two subsidies are monotonic. Specifically, increasing R&D subsidy reduces welfare despite its positive effect on technological progress whereas increasing automation subsidy improves welfare despite its negative effect on the growth rate of technologies. Therefore, one cannot infer the welfare implication of a policy change from its effect on technologies alone. Finally, we have also found that devoting resources to approach a fully automated production process is optimal.

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Appendix A

Proof of Proposition 1. We first establish the following sufficient parameter condition for the uniqueness of the equilibrium:

$$\epsilon < \frac{\phi + \rho}{2\phi + \rho} \in (1/2, 1). \tag{A1}$$

The left-hand side (LHS) of (31) is decreasing in h_r, whereas the derivative of the right-hand side (RHS) of (31) is given by

$$\frac{d}{dh_r} RHS = \frac{1}{(1-h_r)^2} \left(\frac{1-h_r}{h_r} \right)^{\epsilon} \underbrace{\left[\frac{\epsilon \rho \phi (1-h_r)^{1+\epsilon}}{(\varphi h_r^{\epsilon} + \rho)^2} + (1-\epsilon) - (2\epsilon - 1) \frac{\phi (1-h_r)^{\epsilon}}{\varphi h_r^{\epsilon} + \rho} \right]}_{\equiv \Phi}. \tag{A2}$$

Equation (A2) shows that when $\epsilon < 1/2$, RHS of (31) is monotonically increasing in h_r. As for $\epsilon > 1/2$, we consider the following lower bound of Φ:

$$\Phi > (1-\epsilon) - (2\epsilon - 1) \frac{\phi (1-h_r)^{\epsilon}}{\varphi h_r^{\epsilon} + \rho} > (1-\epsilon) - \frac{\phi (2\epsilon - 1)}{\rho}. \tag{A3}$$

Equation (A3) shows that $\epsilon < (\phi + \rho) / (2\phi + \rho)$ in (A1) is a sufficient condition for $\Phi > 0$; in this case, RHS of (31) is monotonically increasing in h_r. Therefore, we have established that the equilibrium h_r is uniquely determined by (31) as shown in Figure 5.

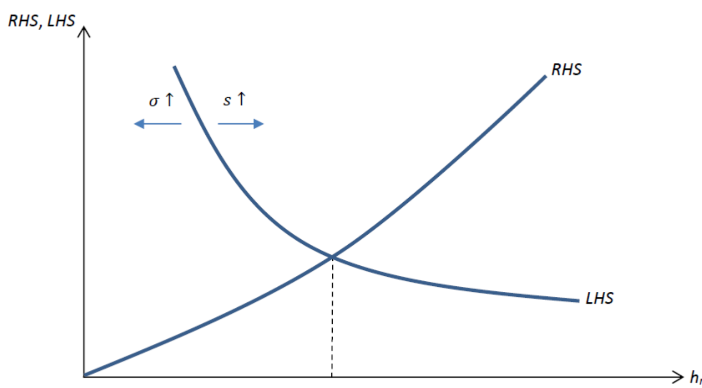

Figure 5: Equilibrium uniqueness

LHS of (31) being increasing in s (decreasing in σ) implies that h_r is monotonically increasing from 0 to 1 as $s < 1$ increases on its domain (decreasing from 1 to 0 as $\sigma < 1$ increases on its domain).[22] For the effects of $\{s, \sigma\}$ on $\{\theta, g_z\}$, we use (32) and (33). As for the inverted-U effects of $\{s, \sigma\}$ on g_y, we use (34) and (35) to establish that g_y is an inverted-U function of h_r reaching a maximum at some interior point $h_r^* \in (0, 1)$, which in turn implies that g_y is also an inverted-U function of s and σ. ■

[22] Recall that s and σ can be negative, in which case they act as taxes.

Appendix B (not for publication)

This appendix describes the dynamics of the economy. Using (23) and (26), we obtain

$$r_t = R_t - \delta = \frac{\theta_t y_t}{\mu k_t} - \delta = \frac{Z_t}{\mu}\left(\frac{\theta_t}{1-\theta_t}\frac{l}{k_t}\right)^{1-\theta_t} - \delta. \tag{B1}$$

Substituting (B1) into (3) yields the growth rate of consumption as

$$\frac{\dot{c}_t}{c_t} = \frac{Z_t}{\mu}\left(\frac{\theta_t}{1-\theta_t}\frac{l}{k_t}\right)^{1-\theta_t} - \delta - \rho. \tag{B2}$$

Using (9), (13), (23), (B1), $\lambda_t = \varphi h_{r,t}^{\epsilon}$ and $\alpha_t = \phi h_{a,t}^{\epsilon}$, we reexpress (14) and (15) as

$$\frac{\dot{v}_t^l}{v_t^l} = \frac{Z_t}{\mu}\left(\frac{\theta_t}{1-\theta_t}\frac{l}{k_t}\right)^{1-\theta_t} - \delta + \phi h_{a,t}^{\epsilon} + \varphi h_{r,t}^{\epsilon} - \frac{(\mu-1)/\mu}{(\theta_t)^{\theta_t}(1-\theta_t)^{1-\theta_t}}\frac{\left[k_t/(lZ_t^{1/(1-\theta_t)})\right]^{\theta_t}}{v_t^l/(lZ_t^{1/(1-\theta_t)})}, \tag{B3}$$

$$\frac{\dot{v}_t^k}{v_t^k} = \frac{Z_t}{\mu}\left(\frac{\theta_t}{1-\theta_t}\frac{l}{k_t}\right)^{1-\theta_t} - \delta + \varphi h_{r,t}^{\epsilon} - \frac{(\mu-1)/\mu}{(\theta_t)^{\theta_t}(1-\theta_t)^{1-\theta_t}}\frac{\left[k_t/(lZ_t^{1/(1-\theta_t)})\right]^{\theta_t}}{v_t^k/(lZ_t^{1/(1-\theta_t)})}. \tag{B4}$$

From (23) and (25), we derive the growth rate of capital k_t as

$$\frac{\dot{k}_t}{k_t} = \frac{Z_t}{(\theta_t)^{\theta_t}(1-\theta_t)^{1-\theta_t}}\left(\frac{l}{k_t}\right)^{1-\theta_t} - \frac{c_t}{k_t} - \delta. \tag{B5}$$

The dynamics of θ_t and Z_t are given by

$$\dot{\theta}_t = \left(\phi h_{a,t}^{\epsilon}\right)(1-\theta_t) - \left(\varphi h_{r,t}^{\epsilon}\right)\theta_t, \tag{B6}$$

$$\frac{\dot{Z}_t}{Z_t} = \varphi h_{r,t}^{\epsilon} \ln z. \tag{B7}$$

Differential equations in (B2)-(B7) describe the autonomous dynamics of $\{c_t, v_t^l, v_t^k, k_t, \theta_t, Z_t\}$ along with the following two static conditions:

$$h_{r,t} = \frac{\left[\varphi(1-\sigma)v_t^l\right]^{1/(1-\epsilon)}}{\left[\phi(1-s)(1-\theta_t)v_t^k\right]^{1/(1-\epsilon)} + \left[\varphi(1-\sigma)v_t^l\right]^{1/(1-\epsilon)}}, \tag{B8a}$$

$$h_{a,t} = \frac{\left[\phi(1-s)(1-\theta_t)v_t^k\right]^{1/(1-\epsilon)}}{\left[\phi(1-s)(1-\theta_t)v_t^k\right]^{1/(1-\epsilon)} + \left[\varphi(1-\sigma)v_t^l\right]^{1/(1-\epsilon)}}, \tag{B8b}$$

which are obtained by eliminating $w_{h,t}$ from (17) and (19) to derive

$$\frac{h_{r,t}}{h_{a,t}} = \left[\frac{\varphi(1-\sigma)}{\phi(1-s)(1-\theta_t)}\frac{v_t^l}{v_t^k}\right]^{1/(1-\epsilon)} \tag{B9}$$

and by substituting (B9) into $h_{a,t}+h_{r,t}=1$. Finally, one can divide $\{c_t, v_t^l, v_t^k, k_t\}$ by $lZ_t^{1/(1-\theta_t)}$ to define stationarized variables and also eliminate l from the dynamic system.