A New Keynesian Model with Robots: Implications for Business Cycles and Monetary Policy
Online Supplemental Appendix

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Equilibrium Conditions

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Production

(1) Composite labor:

$$\ell_t = \left[\theta_a \left(\mu_t^a a_t\right)^{\phi} + (1-\theta_a) {n_t}^{\phi}\right]^{\frac{1}{\phi}}$$

(2) Capital demand:

$$r_t^k = mc_t \theta_k {z_t}^{\alpha} \left(\frac{y_t}{\mu_t^k k_t}\right)^{1-\alpha}$$

(3) Robot demand:

$$r_t^a = mc_t (1-\theta_k) {z_t}^{\alpha} \left(\frac{y_t}{\ell_t}\right)^{1-\alpha} \theta_a \left(\frac{\ell_t}{\mu_t^a a_t}\right)^{1-\phi}$$

(4) Human labor demand:

$$w_t = mc_t (1-\theta_k) {z_t}^{\alpha} \left(\frac{y_t}{\ell_t}\right)^{1-\alpha} (1-\theta_a) \left(\frac{\ell_t}{n_t}\right)^{1-\phi}$$

(5) Price optimality:

$$x_{1,t}^y = \varepsilon_y x_{2,t}^y$$

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(6) Auxiliary variable:

$$x_{1,t}^y = \tilde{p}_t \left[\Lambda_t y_t + \beta \lambda_y \mathbb{E}_t \frac{1}{\tilde{p}_{t+1}} \left(\frac{{\pi_t}^{\eta_y}}{\pi_{t+1}} \right)^{\frac{1}{1-\varepsilon_y}} x_{1,t+1}^y \right]$$

(7) Auxiliary variable:

$$x_{2,t}^y = \Lambda_t y_t mc_t + \beta \lambda_y \mathbb{E}_t \left(\frac{{\pi_t}^{\eta_y}}{\pi_{t+1}} \right)^{\frac{\varepsilon_y}{1-\varepsilon_y}} x_{2,t+1}^y$$

(8) Relative price:

$$\tilde{p}_t^{\frac{1}{1-\varepsilon_y}} = \frac{1 - \lambda_y \left(\frac{{\pi_{t-1}}^{\eta_y}}{\pi_t} \right)^{\frac{1}{1-\varepsilon_y}}}{1 - \lambda_y}$$

Household

(9) Capital law of motion:

$$k_{t+1} = (1 - \delta_k) k_t + \varepsilon_t^k \left[1 - \mathcal{S}^k \left(\frac{i_t^k}{i_{t-1}^k} \right) \right] i_t^k$$

(10) Robot law of motion:

$$a_{t+1} = (1 - \delta_a) a_t + \varepsilon_t^a \left[1 - \mathcal{S}^a \left(\frac{i_t^a}{i_{t-1}^a} \right) \right] i_t^a$$

(11) Consumption:

$$\Lambda_t = \varepsilon_t^b \left(c_t - h c_{t-1} \right)^{-\gamma} - h \beta \mathbb{E}_t \varepsilon_{t+1}^b \left(c_{t+1} - h c_t \right)^{-\gamma}$$

(12) Physical capital:

$$\Lambda_t q_t^k = \beta \mathbb{E}_t \Lambda_{t+1} \left[r_{t+1}^k \mu_{t+1}^k - \Psi^k \left(\mu_{t+1}^k \right) + q_{t+1}^k (1 - \delta_k) \right]$$

(13) Robots:

$$\Lambda_t q_t^a = \beta \mathbb{E}_t \Lambda_{t+1} \left[r_{t+1}^a \mu_{t+1}^a - \Psi^a \left(\mu_{t+1}^a \right) + q_{t+1}^a (1 - \delta_a) \right]$$

(14) Physical capital investment:

$$\Lambda_t = \Lambda_t q_t^k \varepsilon_t^k \left[1 - \mathcal{S}^k \left(\frac{i_t^k}{i_{t-1}^k} \right) - \mathcal{S}^{k\prime} \left(\frac{i_t^k}{i_{t-1}^k} \right) \frac{i_t^k}{i_{t-1}^k} \right] + \beta \mathbb{E}_t \Lambda_{t+1} q_{t+1}^k \varepsilon_{t+1}^k \mathcal{S}^{k\prime} \left(\frac{i_{t+1}^k}{i_t^k} \right) \left(\frac{i_{t+1}^k}{i_t^k} \right)^2$$

(15) Robot investment:

$$\Lambda_t = \Lambda_t q_t^a \varepsilon_t^a \left[1 - \mathcal{S}^a \left(\frac{i_t^a}{i_{t-1}^a} \right) - \mathcal{S}^{a\prime} \left(\frac{i_t^a}{i_{t-1}^a} \right) \frac{i_t^a}{i_{t-1}^a} \right] + \beta \mathbb{E}_t \Lambda_{t+1} q_{t+1}^a \varepsilon_{t+1}^a \mathcal{S}^{a\prime} \left(\frac{i_{t+1}^a}{i_t^a} \right) \left(\frac{i_{t+1}^a}{i_t^a} \right)^2$$

(16) Physical capital utilization:

$$r_t^k = \Psi^{k\prime}\left(\mu_t^k\right)$$

(17) Robot utilization:

$$r_t^a = \Psi^{a\prime}\left(\mu_t^a\right)$$

(18) Bonds:

$$\Lambda_t = \beta \mathbb{E}_t \Lambda_{t+1} \frac{R_t}{\pi_{t+1}}$$

Wage Setting

(19) Wage optimality:

$$x_{1,t}^w = \varepsilon_n \kappa_n x_{w,t}^2$$

(20) Auxiliary variable:

$$x_{1,t}^w = \tilde{w}_t^{\frac{1-\varepsilon_n(1+\sigma)}{1-\varepsilon_n}} \left[\Lambda_t n_t w_t^{\frac{-\varepsilon_n}{1-\varepsilon_n}} + \beta \lambda_n \mathbb{E}_t \tilde{w}_{t+1}^{\frac{-1+\varepsilon_n(1+\sigma)}{1-\varepsilon_n}} \left(\frac{\pi_t{}^{\eta_w}}{\pi_{t+1}} \right)^{\frac{1}{1-\varepsilon_n}} x_{1,t+1}^w \right]$$

(21) Auxiliary variable:

$$x_{2,t}^w = \varepsilon_t^b n_t{}^{1+\sigma} w_t{}^{\frac{-\varepsilon_n(1+\sigma)}{1-\varepsilon_n}} + \beta \lambda_n \mathbb{E}_t \left(\frac{\pi_t{}^{\eta_w}}{\pi_{t+1}} \right)^{\frac{\varepsilon_n(1+\sigma)}{1-\varepsilon_n}} x_{2,t+1}^w$$

(22) Wage index:

$$w_t{}^{\frac{1}{1-\varepsilon_n}} = (1-\lambda_n)\tilde{w}_t^{\frac{1}{1-\varepsilon_n}} + \lambda_n \left(w_{t-1} \frac{\pi_{t-1}{}^{\eta_w}}{\pi_t} \right)^{\frac{1}{1-\varepsilon_n}}$$

Stochastic Processes

(23) Productivity process:

$$\ln z_t = (1-\rho^z)\ln \mu_z + \rho^z \ln z_{t-1} + \varsigma^z \eta_t^z$$

(24) Robot investment disturbances:

$$\ln \varepsilon_t^a = (1-\rho^a)\ln \mu_{\varepsilon^a} + \rho^a \ln \varepsilon_{t-1}^a + \varsigma^a \eta_t^a$$

(25) Capital investment disturbances:

$$\ln \varepsilon_t^k = (1-\rho^k)\ln \mu_{\varepsilon^k} + \rho^k \ln \varepsilon_{t-1}^k + \varsigma^k \eta_t^k$$

(26) Demand disturbances:

$$\ln \varepsilon_t^b = (1-\rho^b)\ln \mu_{\varepsilon^b} + \rho^b \ln \varepsilon_{t-1}^b + \varsigma^b \eta_t^b$$

(27) Taylor rule disturbances:

$$\ln \varepsilon_t^{mp} = (1-\rho^{mp})\ln \mu_{\varepsilon^{mp}} + \rho^{mp} \ln \varepsilon_{t-1}^{mp} + \varsigma^{mp} \eta_t^{mp}$$

Monetary Authority

(29) Taylor rule:

$$\left(\frac{R_t}{R^*}\right) = \left(\frac{R_{t-1}}{R^*}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi^*}\right)^{\rho_\pi} \left(\frac{y_t}{y^*}\right)^{\rho_Y}\right]^{1-\rho_R} \varepsilon_t^{mp}$$

Resource Constraint

(30) Resource constraint:

$$y_t = c_t + i_t^k + i_t^a + \Psi^k\left(\mu_t^k\right) k_t + \Psi^a\left(\mu_t^a\right) a_t$$

(31) Aggregate demand:

$$y_t = p_t^* y_t^*$$

(32) Aggregate labor demand:

$$n_t = w_t^* n_t^*$$

(33) Aggregate supply:

$$y_t^* = z_t \left[\theta_k \left(\frac{\tilde{k}_t}{\ell_t}\right)^\alpha + (1-\theta_k)\right]^{\frac{1}{\alpha}} \left[\theta_a \left(\frac{\tilde{a}_t}{n_t}\right)^\phi + (1-\theta_a)\right]^{\frac{1}{\phi}} n_t$$

(34) Price distortion:

$$p_t^{*-1} = (1-\lambda_y)\tilde{p}_t^{\frac{\varepsilon_y}{1-\varepsilon_y}} + \lambda_y {p_{t-1}^*}^{-1} \left(\frac{{\pi_{t-1}}^{\eta_y}}{\pi_t}\right)^{\frac{\varepsilon_y}{1-\varepsilon_y}}$$

(35) Wage distortion:

$$w_t^{*-1} = (1-\lambda_n)\left(\frac{\tilde{w}_t}{w_t}\right)^{\frac{\varepsilon_n}{1-\varepsilon_n}} + \lambda_n {w_{t-1}^*}^{-1} \left(\frac{w_{t-1}}{w_t}\frac{{\pi_{t-1}}^{\eta_w}}{\pi_t}\right)^{\frac{\varepsilon_n}{1-\varepsilon_n}}$$

Miscellaneous Functions

Investment adjustment cost function:

$$\mathcal{S}(x) = \frac{\kappa_x}{2}(x-1)^2.$$

Its first order derivative:

$$\mathcal{S}'(x) = \kappa_x(x-1).$$

Utilization cost functions:

$$\Psi_k(\mu^k) = r^k \left\{\frac{\exp\left[\nu_k(\mu^k-1)\right]-1}{\nu_k}\right\};$$

$$\Psi_a(\mu^a) = r^a \left\{\frac{\exp\left[\nu_a(\mu^a-1)\right]-1}{\nu_a}\right\},$$

where r^k and r^a are the steady state rental rates. Their first order derivatives:

$$\Psi_k'(\mu^k) = r^k \left\{\exp\left[\nu_k(\mu^k - 1)\right]\right\};$$
$$\Psi_a'(\mu^a) = r^a \left\{\exp\left[\nu_a(\mu^a - 1)\right]\right\}.$$

Calibration

Capital and Robot Shares in the CES Production Function

According to data from the Bureau of Economic Analysis (BEA), in 2015 the private, non-residential current-cost net stock of fixed assets was \$21.9 billion, while gross domestic product (GDP) was \$17.8 billion for a capital-to-output ratio of 1.2, or 4.8 at a quarterly rate. The stock of "robots" is of course not measured by the BEA. An upper bound for the stock of robots would be fixed assets in the form of equipment, which in 2015 was \$6.4 billion or 29 percent of fixed assets. A lower bound would be the stock of information and communications technologies (ICT) capital which according to data from the Conference Board's EU KLEMS database (http://www.euklems.net/) constituted 16 percent of fixed capital in the United States in 2007 (the most recent survey year). We set the ratio of robot capital to total capital at 20 percent, implying a steady state capital-to-robot ratio of 4, a steady state traditional capital-to-output ratio of 3.8, and a steady state robot capital-to-output ratio of 1.0. This implies $\theta_k = 0.5459$ and $\theta_a = 0.1251$.

Stochastic Processes

We construct a time series for total factor productivity by log-linearizing our constant elasticity of substitution (CES) production, abstracting from capacity utilization. Total factor productivity (TFP) is given by the expression:

$$\hat{z}_t = \hat{y}_t - \theta_k \left(\frac{k}{y}\right)^{\alpha} \hat{k}_t - (1-\theta_k)\theta_a \left(\frac{\ell}{y}\right)^{\alpha} \left(\frac{a}{\ell}\right)^{\phi} \hat{a}_t - (1-\theta_k)(1-\theta_a) \left(\frac{\ell}{y}\right)^{\alpha} \left(\frac{n}{\ell}\right)^{\phi} \hat{n}_t,$$

where the "hat" variables indicate log-deviation from steady state. Parameter values are calibrated in the main text, and the steady state ratios are computed using the parameters. Our data for output, traditional capital stock, robot capital stock, and hours are from the Conference Board's EU-KLEMS database (http://www.euklems.net/). Data for capital inputs is from the November 2009 release of the United States North American Industry Classification System (USA-NAICS) database. Data for output and hours is from the March 2013 USA Basic Tables database. We use data for the period 1977–2007. All data is annual. The data series with EU-KLEMS mnemonics in parentheses are:

- Gross output, volume indices, total industries, 2005 = 100 (`GO_QI`);
- Hours worked, volume indices, 2005 = 100 (`H_EMP_QI`);
- Real fixed capital stock, 1995 prices, non-ICT assets, total industries (`K_NonICT`);
- Real fixed capital stock, 1995 prices, ICT assets, total industries (`K_ICT`).

Each series is logged and de-trended using the Hodrick-Prescott filter.

The resulting annual series for $\hat{z}_t$ is then converted to quarterly frequency using the cubic spline method in Eviews. We estimate an AR(1) process for this series over the period between the first quarter of 1978 to the fourth quarter of 2007. The estimated persistence parameter is $\rho^z = 0.9854$ and the standard deviation of the innovations is $\varsigma^z = 0.0023$.

We use the price of non-ICT capital and ICT capital from the EU-KLEMS database to proxy for the price of traditional and robot capital in our model. The precise series are:

- Gross fixed capital formation price index, 1995 = 1.0, total industries, non-ICT capital (`Ip_NonICT`);
- Gross fixed capital formation price index, 1995 = 1.0, total industries, ICT capital (`Ip_ICT`).

Each series is deflated by the PCE deflator from the Bureau of Economic Analysis. We then log and de-trend each series using the Hodrick-Prescott filter. As with TFP, we convert the price series to the quarterly frequency using the cubic spline method and then estimate AR(1) process for each series. For the price of ICT capital the persistence parameter is $\rho^a = 0.9652$ and the standard deviation of the innovations is $\varsigma^z = 0.0079$. For the price of non-ICT capital the persistence parameter is $\rho^k = 0.9662$ and the standard deviation of the innovations is $\varsigma^k = 0.0035$.

To estimate the monetary policy shock process we estimate a monetary policy rule for the United States from the first quarter of 1990 to the fourth quarter of 2007:

$$R_t = R^* + \beta_1 R_{t-1} + \beta_2 \hat{\pi}_t + \beta_3 \hat{y}_t + \eta_t^R.$$

The data is quarterly from the St. Louis Federal Reserve Economic Database (FRED), https://fred.stlouisfed.org/. The interest rate R_t is the effective federal funds rate (`FEDFUNDS`). The inflation rate π_t is the 4-quarter percentage change in the PCE price index (`PCECTPI`). The output gap y_t is the percentage difference between real GDP (`GDPC1`) and potential real GDP as measured by the Congressional Budget Office (`GDPPOT`). We then estimate an AR(1) process for the estimated monetary policy residual η_t. We arrive at a persistence parameter $\rho^{mp} = 0.7063$ and a standard deviation for the innovates $\varsigma^{mp} = 0.0007$.

Permanent Robot Price Change

The debate on the economic effect of robots has focused on the impact on employment and wages in the long run. Before addressing business cycle issues in the next section, this paper examines the long run effects of robots in the model.

Byrne and Corrado (2017) show that the relative price of ICT investment (a broad proxy for investment in robot capital) declined at annual rates near ten percent since the late 1970's before stabilizing somewhat in the last decade. The decline in the price of ICT investment is represented in the model as a secular increase in the productivity of robot investment $\bar{\varepsilon}^a$.

One can understand the effects of a permanent increase in ε^a by examining the steady state expressions for the real wage and labor's share:

$$w = \frac{(1-\theta_k)(1-\theta_a)}{\varepsilon^y}\left(\frac{\ell}{y}\right)^{\alpha-1}\left(\frac{\ell}{n}\right)^{1-\phi};$$
$$LS \equiv \frac{wn}{y} = \frac{(1-\theta_k)(1-\theta_a)}{\varepsilon^y}\left(\frac{\ell}{y}\right)^{\alpha}\left(\frac{\ell}{n}\right)^{-\phi}.$$

Tracing its effect through the steady state equations, one can see that an increase in ε^a induces the household to invest more heavily in robots, thus substituting robots for human labor. This increases the robot to human labor ratio, and equivalently, increases the composite labor to human labor ratio $\frac{\ell}{n}$. The total supply of composite labor increases because robots are not perfect substitutes for human labor. Since composite labor and traditional capital are complements, the capital stock rises as well; in fact, the capital stock rises proportionately to the increase in composite labor leaving the ratio of traditional capital to composite labor, hence the ratio of composite labor to output $\frac{\ell}{y}$, unchanged.

The effect of a change in the price of robots on real wage and labor's share, then, is driven by its effect on the composition of composite labor. An increase in ε^a always increases the real wage since $\phi < 1$. Its effect on labor's share depends on the value of ϕ: in the Cobb-Douglas case where $\phi = 0$, labor's share is unaffected. When robots and human labor are complements as in the no robot scenario, labor's share rises, but when they are substitutes labor's share falls.

Table 1 shows the quantitative effect of a 10 percent decrease in the price of robots in the model. The ratio of composite labor to human labor rises with a fall in the price of robot investment, more so the greater the elasticity of substitution between robots and human capital. This drives the real wage up and labor's share down, the effects being greater the greater the elasticity of substitution. Output rises because of the increase in composite labor and the induced investment in traditional capital, while employment falls somewhat due to the income effect on labor supply. These results echo those in Acemoglu and Restrepo (2018) who find that wages rise, but labor's share fall with an increase in automation.

Table 1: Percentage change in the steady state value of select endogenous variables after a 10-percent permanent increase to the robot investment scale parameter $\bar{\varepsilon}^a$

	No robot $\phi = -1$	Weak robot $\phi = 0.25$	Strong robot $\phi = 0.5$
Output	0.27%	2.39%	11.50%
Employment	-0.07%	-0.57%	-3.00%
Robot to human labor ratio	5.11%	15.67%	33.56%
Capital to composite labor ratio	0.00%	0.00%	0.00%
Real wage	0.69%	2.22%	7.25%
Labor's share	0.35%	-0.74%	-7.25%

Source: Own calculations based on calibrated parameters.

Robots in a Frictionless Model

This paper now takes a brief detour to examine the effect of shocks on wages, employment, labor's share, and other key variables at business cycle frequencies using a real business cycle model modified to include robot capital alongside traditional capital. This model removes the frictions from the New Keynesian model by setting the parameters h, κ_k, κ_a, ν_k, and ν_a to zero, removing the monopolistic competitive intermediate good firms, and removing the labor union. In addition, there is no monetary policy component in the frictionless model. The frictionless model isolates the effect of robots as the shocks operate through the production technology and highlights the extent to which nominal rigidities interact with the presence of robot capital.

As in the previous section, the wage rate is given by the firm's first order condition for human labor. This is identical to the New Keynesian model except that there is no marginal cost term in this model. The real wage is an increasing function of TFP, the output to composite labor ratio, and the composite labor to human labor ratio:

$$w_t = (1-\theta_k)(1-\theta_a){z_t}^{\alpha}\left(\frac{y_t}{\ell_t}\right)^{1-\alpha}\left(\frac{\ell_t}{n_t}\right)^{1-\phi}. \tag{1}$$

Labor's share, $LS_t \equiv \frac{w_t n_t}{y_t}$, is:

$$LS_t = (1-\theta_k)(1-\theta_a){z_t}^{\alpha}\left(\frac{y_t}{\ell_t}\right)^{-\alpha}\left(\frac{\ell_t}{n_t}\right)^{-\phi}. \tag{2}$$

Given the similarities between this model and the one examined before, this paper continues to focus on the role of the capital to composite labor ratio $\frac{k_t}{\ell_t}$ and the robot to human labor ratio $\frac{a_t}{n_t}$ in determining the real wage and labor's share of income.

The unique qualities of robot capital are once again apparent from a comparison of shocks to the price of traditional capital shown in Figure 1 with shocks to the price of robot capital shown in Figure 2. A reduction in the price of traditional capital causes the household to increase investment in traditional capital and substitute away from robot capital. The household's desire to produce more capital increases employment, output, and the real wage. The robot to human labor ratio falls and the capital to composite labor ratio rises, leading to an increase in labor's share. The increase in labor's share is greater the more substitutable are robots and human labor.

A decrease in the price of robot capital has competing effects on the demand for factors of production. The household substitutes away from human labor towards robot capital, pushing employment and wages down. At the same time, the need for labor to build robots pushes employment and wages up. The net effect is an increase in employment and a decrease in wages in the short run, with wages rising and employment falling in the longer run as the number of robots increases. Employment is also pushed down in the longer run as a result of an income effect accompanying the rise in output. The robot to human labor ratio rises while the capital to composite labor ratio falls, causing labor's share to fall. Again, the decline in labor's share is considerably larger in the high substitutability case.

The presence of robots has an effect on the economy's response to TFP shocks as well. In Figure 3, the increase in TFP raises demand for all three factors of production. At the same time, however, the rise in current and expected future income reduces labor supply. When robots and human labor are substitutes the household responds by increasing investment in robots to compensate for the failure of employment to rise sufficiently while purchasing less traditional capital than they otherwise would. The result is an increase in the robot to human labor ratio and a decrease in the capital to composite labor ratio when robots are substitutes for human labor. Labor's share of income rises slightly in the no robots case, stays roughly constant when robots are weak substitutes for human labor, and falls substantially in the strong substitutes case.

The key results from the New Keynesian model are repeated in the frictionless model, but there are some differences as well. In the frictionless model as in the New Keynesian model a negative shock to the price of traditional capital causes labor's share to rise while a shock to the price of robot capital causes labor's share to fall. In each case the effect is stronger the greater the elasticity of substitution between robots and human labor. On the other hand, whereas real wages rise in both cases in the New Keynesian model, a decrease in the price of robot capital reduces the real wage in the periods immediately following the shock. This is because adjustment of the real wage is slowed down in the New Keynesian model by nominal rigidities and adjustment costs to investment.

Labor's share falls much less dramatically following a shock to total factor productivity in the frictionless model. Comparing the New Keynesian model to the frictionless model suggests the main reason for the deterioration in labor's share in the New Keynesian model is rigidities that prevent real wages from immediately capturing the increase in the marginal product of labor. This manifests itself as a sharp decrease in marginal cost in the New Keynesian model that causes a one-for-one decrease in labor's share. Without these rigidities, labor's share declines markedly only in the strong robot case.

This exercise suggests that much of the response of labor's share to shocks in the New Keynesian model can be explained by the introduction of robots per se rather than the various rigidities included in the model. In the case of shocks to TFP, however, rigidities greatly magnify the response of labor's share.

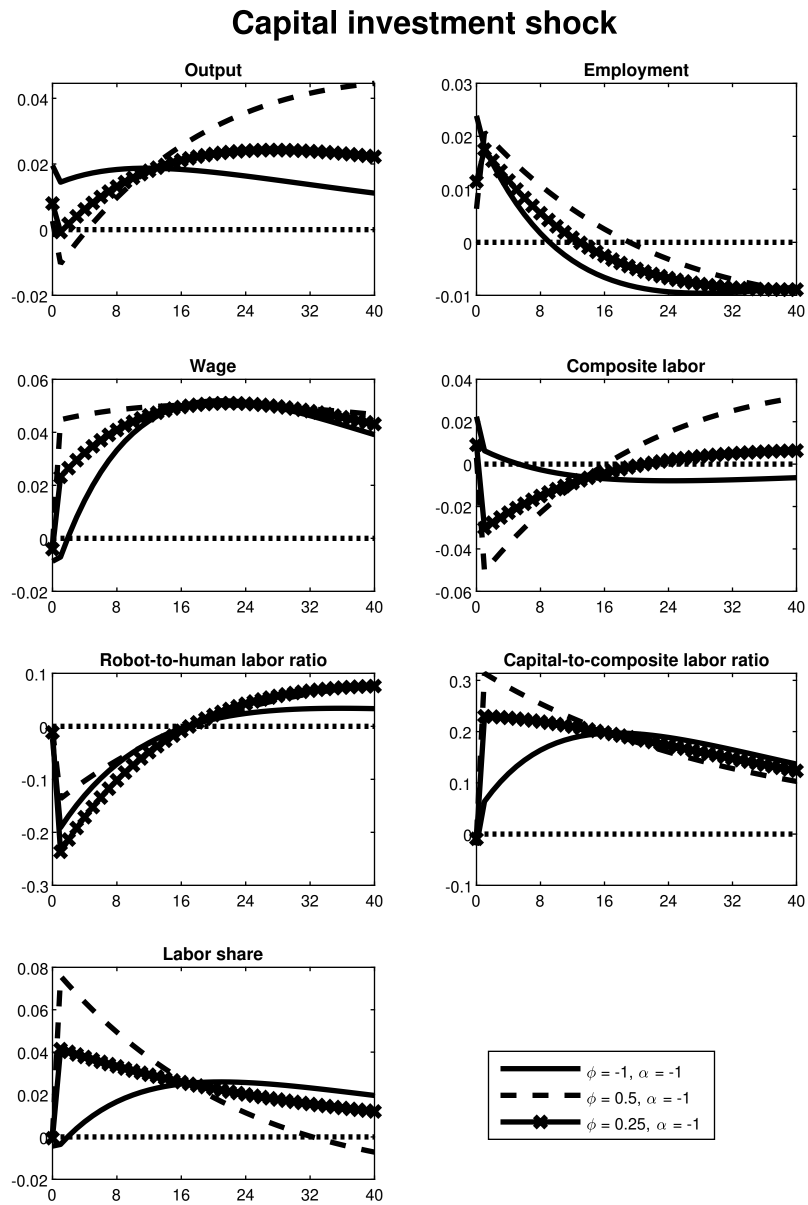

Figure 1: Frictionless model, capital investment-specific shock. The plain solid line represents the specification in which $\alpha = \phi = -1$; the solid line with $\times$ represents the specification in which $\alpha = -1$ and $\phi = 0.25$; the dashed line represents the specification in which $\alpha = -1$ and $\phi = 0.5$. Source: Own calculations based on the calibrated parameters.

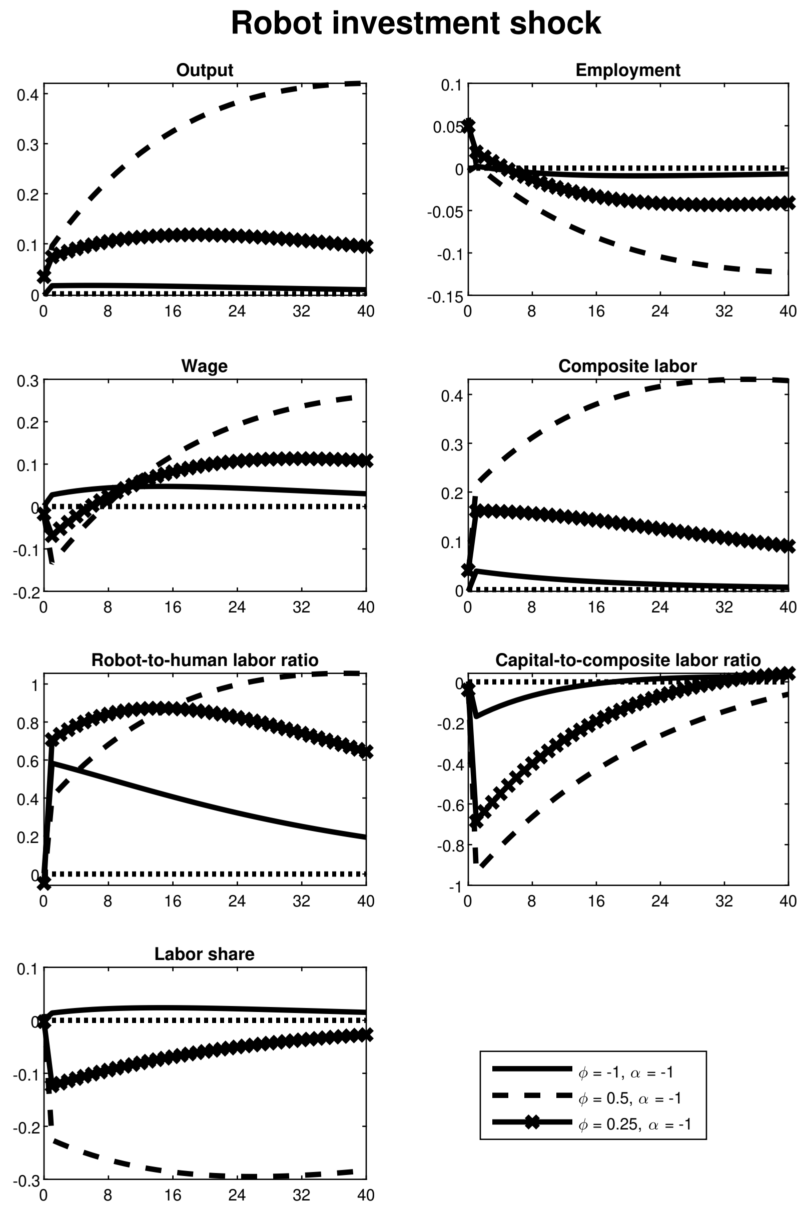

Figure 2: Frictionless model, robot investment-specific shock. The plain solid line represents the specification in which $\alpha = \phi = -1$; the solid line with $\times$ represents the specification in which $\alpha = -1$ and $\phi = 0.25$; the dashed line represents the specification in which $\alpha = -1$ and $\phi = 0.5$. Source: Own calculations based on the calibrated parameters.

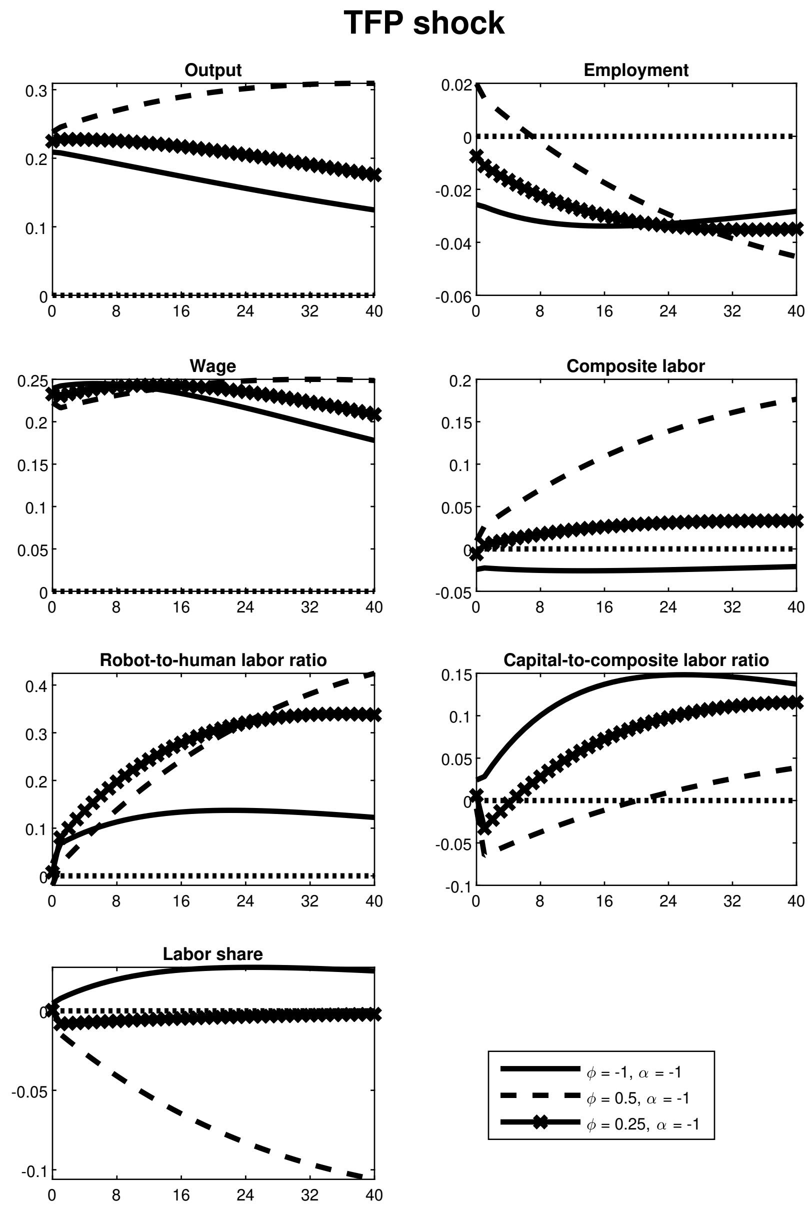

Figure 3: Frictionless model, TFP shock. The plain solid line represents the specification in which $\alpha = \phi = -1$; the solid line with $\times$ represents the specification in which $\alpha = -1$ and $\phi = 0.25$; the dashed line represents the specification in which $\alpha = -1$ and $\phi = 0.5$. Source: Own calculations based on the calibrated parameters.

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