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Robots in a Small Open Economy

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Abstract

In this paper, we build a small open-economy model *la* Ghironi & Melitz (2005) with endogenously produced and traded varieties and automation to analyze the effects of a slow-moving, permanent automation shock. Our results are threefold: *(i)* in the long run a permanent automation shock effectively produces a displacement effect that increases wage inequality between routine and non-routine workers, as well as a fall (increase) in the demand of firms for routine (non-routine) labor, *(ii)* the relative impact on routine and non-routine labor eventually depends on the relative size of labor supply elasticities, *(iii)* the external effects of an automation shock remain limited at best.

Keywords: Robots, Automation, Employment, Open-economy

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1 Introduction

Robots and automation are trending over the last 30 years around the world, as shown recently by Acemoglu & Restrepo (2017). Building on a task-model of automation, they also show theoretically and empirically that automation gives rises to a displacement effect, lowering demand for routine labor and increasing demand for non-routine labor, and to a positive productivity effect. As a major source of biased technical change, automation has been considered as an important factor of job polarization in advanced economies (see Goos, Manning & Salomons (2009)). As such, it has also been advocated to contribute to slow or jobless recoveries (Jaimovich & Siu (2012)).

In this paper, we lay out a small open-economy model *la* Ghironi & Melitz (2005) with endogenously produced and traded varieties and automation. The model borrows the robot sector and the production function from Guerreiro, Rebelo & Teles (2017). We use the model to analyze the effects of a slow-moving, permanent automation shock. Our goals are (*i*) to investigate whether the model is consistent with the above results, (*ii*) to determine the contribution of the extensive margins (new goods and new exported goods) to the long-run effects of automation on output, consumption and welfare, and (*ii*) to determine whether automation crucially affects external variables such as the trade balance or the real exchange rate.

We perform a business cycle exercise based on OECD data to calibrate our model carefully, and show that the model performs as good as any other open-economy model to match key aggregate variables. Looking at the long-run effects of a permanent automation shock calibrated to the available data, we show that it effectively produces a displacement effect that increases wage inequality between routine and non-routine workers, as well as a fall (increase) in the demand of firms for routine (non-routine) labor. We find that the relative impact on routine and non-routine labor eventually depends on the relative size of labor supply elasticities. If routine labor supply is relatively more elastic, as seems to be the case looking at business cycle frequency movements, then total labor income falls because routine labor falls more than non-routine labor rises in equilibrium. In this case, aggregate consumption and output fall along with total labor income, producing a rise in unemployment, and negative welfare effects once removed the benefits from higher home production.

Our second main result is that the long-run effects of a permanent automation shock are magnified by the introduction of an extensive margin of production and exports. In our model, aggregate consumption determines the size of the market firms can address, and is itself determined by total labor income. After an automation shock, if total labor income falls, aggregate consumption falls, which in turn raises the entry threshold and lowers the number of varieties in the economy. If total labor income rises, then aggregate consumption and the number of varieties rise as well. Hence, the extensive margin – the total number of varieties – magnifies the positive or negative effects of an automation shock. Whether those effects are positive or negative depend on the dynamics of total labor income, as explained above.

Finally, we find that the external effects of an automation shock remain limited at best. In our model, the domestic economy is small and experiences an automation shock while the rest of the world remains at a zero level of automation. We find that the automation shock produces very small effects on gross and net trade flows, on the number of exported goods, on the balance of trade or the real exchange rate. As such, it does not appear crucial in terms of the building of a competitive advantage in the long run.

The paper is structured as follows. Section 2 presents the model. Section 3 looks at the effects of transitory productivity shocks to calibrate the model. Section 4 investigates the effects of a permanent slow-moving automation shock, intended to mimic the upward trend in the number of robots observed over the last 30 years. It also investigates the robustness of our results to various changes in parameters or preferences. Section 5 concludes.

2 The model

We consider a small open economy model with endogenous entry and export participation *à la* Ghironi & Melitz (2005) with automation, building on Guerreiro et al. (2017).

2.1 Households

We consider a family composed of a unit continuum of individuals. This risk-sharing mechanism allows each family member to enjoy the same individual level of market consumption c_t. Among family members, a fraction h_t^r supplies routine labor, a fraction h_t^{nr} supplies non-routine labor and the remaining fraction $u_t = 1 - h_t^r - h_t^{nr}$ is unemployed. Unemployment is residual and unemployed households produce home goods in quantity η. In addition, unemployment generates a non-pecuniary utility cost as in McKay & Reis (2016). The family head maximizes lifetime welfare

$$\mathcal{W}_t = E_t \left\{ \sum_{s=t}^{\infty} \beta^{s-t} u \left(c_s + \eta u_s, h_s^r, h_s^{nr}, u_s \right) \right\} \tag{1}$$

The budget constraint of the family is

$$e_t b_t + p_t \left(c_t + ac_t \right) = e_t r^* b_{t-1} + w_t^r h_t^r + w_t^{nr} h_t^{nr} + \Pi_t \tag{2}$$

In this equation, e_t is the nominal exchange rate, b_t denotes the nominal value of foreign bonds returning a risk-free rate r^* between period t and $t+1$. The risk-free rate is constant due to the small open economy assumption. Further, p_t is the consumption price index (CPI), w_t^r and w_t^{nr} are respectively the routine and non-routine nominal wages, and ac_t represents an adjustment cost that depends on deviations of net foreign assets from their steady state value:

$$ac_t = (\phi_b/2)\left(e_t b_t/p_t - eb/p\right)^2 \tag{3}$$

Finally, Π_t denotes the nominal profits from final goods producers, net from entry costs. The head of the family maximizes the welfare function subject to the budget constraints with respect to consumption c_t, labor in routine h_t^r and non-routine jobs h_t^{nr} and foreign bonds b_t. First-order conditions imply

$$E_t\left(\beta_{t,t+1}\frac{q_{t+1}r^*}{q_t\left(1+\phi_b\left(b_t^r-b^r\right)\right)}\right) = 1 \tag{4}$$

$$-\frac{u_{h^r t}}{u_{ct}} = \frac{w_t^r}{p_t} \tag{5}$$

$$-\frac{u_{h^{nr} t}}{u_{ct}} = \frac{w_t^{nr}}{p_t} \tag{6}$$

where $q_t = e_t p^*/p_t$ is the consumption-based real exchange rate, $\beta_{t,t+1} = \beta u_{ct+1}/u_{ct}$ is the stochastic discount factor, u_{ct} being the marginal utility of market consumption, $b_t^r = e_t b_t/p_t$ is the real value of net foreign assets and $u_{h^r t}$ and $u_{h^{nr} t}$ denote the disutility from working in the routine and non-routine sectors. The last two equations are labor supply conditions and show that any difference in routine vs. non-routine labor supply results from differences in wage rates. The aggregate consumption basket is defined over a continuum of goods Ω, $c_t = \left(\int_{\omega\in\Omega} c_t\left(\omega\right)^{\frac{\theta-1}{\theta}} d\omega\right)^{\frac{\theta}{\theta-1}}$ where $\theta > 1$ is the elasticity of substitution between goods. At time t, only a subset $\Omega_t \subset \Omega$ of goods is produced and the CPI of the economy is $p_t = \left(\int_{\omega\in\Omega_t} p_t\left(\omega\right)^{1-\theta} d\omega\right)^{\frac{1}{1-\theta}}$, where $p_t\left(\omega\right)$ is the price of good ω. Accordingly, the demand for good ω is

$$c_t\left(\omega\right) = \left(\frac{p_t\left(\omega\right)}{p_t}\right)^{-\theta} c_t \tag{7}$$

2.2 Firms

Robot producers. Following Guerreiro et al. (2017), final goods producers combine non-routine labor and tasks to produce. Tasks can be performed by routine labor or robots. Let $i \in [0,1]$ denote a task, and define ϕ_t as the task-independent real unit cost of producing a robot. Robot producers operate on competitive markets and maximize their profit $\Pi_{it} = \max_{x_{it}} p_{it}x_{it} - \phi_t x_{it}$, which implies that the real relative price of a robot equates its real cost $p_{it} = \phi_t$, driving profits to zero in the sector of robot production ($\Pi_{it} = 0$).

Intermediate goods. In the intermediate sector, a representative firm uses non-routine labor h_t^{nr} and a combination of routine labor h_{it}^r and robots x_{it} for each task i to produce γ_t units of intermediate goods. Within the continuum of task potentially performed by robots, only a fraction $m_t \in [0,1]$ is actually completed by robots, and the remaining fraction of tasks $1 - m_t$

is completed by routine workers. The corresponding production function is thus

$$\gamma_t = \left[\int_0^{m_t} x_{it}^{\mu} di + \int_{m_t}^{1} (a_t h_{it}^r)^{\mu}\, di\right]^{\frac{1-\alpha}{\mu}} (a_t h_t^{nr})^{\alpha} \tag{8}$$

where α is the elasticity of intermediate goods production to non-routine jobs. In addition $\mu < 1$ and a_t is a measure of aggregate labor-augmenting productivity.[1] Denoting φ_t as the relative price at which the intermediate good is sold to final goods producers, the representative intermediate firm maximizes its profits

$$\Pi_{\gamma t} = \varphi_t \gamma_t - \phi_t \int_0^{m_t} x_{it} di - \varpi_t^r \int_{m_t}^{1} h_{it}^r di - \varpi_t^{nr} h_t^{nr} \tag{9}$$

where $\varpi_t^r = w_t^r / p_t$ and $\varpi_t^{nr} = w_t^{nr}/p_t$ are the real wage of routine and non-routine labor, respectively. The first-order condition with respect to non-routine labor is independent from the type of task completed and yields

$$\alpha \frac{\gamma_t}{h_t^{nr}} = \frac{\varpi_t^{nr}}{\varphi_t} \tag{10}$$

The first-order conditions for routine labor and robots depend on whether task i is automated or not:

$$(1-\alpha) \left[\int_0^{m_t} x_{it}^{\mu} di + \int_{m_t}^{1} (a_t h_{it}^r)^{\mu}\, di\right]^{\frac{1-\alpha}{\mu}-1} (a_t h_t^{nr})^{\alpha} x_{it}^{\mu-1} = \frac{\phi_t}{\varphi_t}, \text{ for } i \in [0, m_t] \tag{11}$$

$$(1-\alpha)\, a_t \left[\int_0^{m_t} x_{it}^{\mu} di + \int_{m_t}^{1} (a_t h_{it}^r)^{\mu}\, di\right]^{\frac{1-\alpha}{\mu}-1} (a_t h_t^{nr})^{\alpha} (a_t h_{it}^r)^{\mu-1} = \frac{\varpi_t^r}{\varphi_t}, \text{ for } i \in (m_t, 1] \tag{12}$$

As discussed in Guerreiro et al. (2017), anything else than $\varpi_t^r = a_t \phi$ either yields full automation ($m_t = m = 1$) or null automation ($m_t = m = 0$). Since we want m_t to be determined in equilibrium, we assume $\varpi_t^r = a_t \phi$. Finally, since the production technology is constant returns to scale, $\Pi_{\gamma t} = 0$ and φ_t, the real price of the intermediate good, is also equal to the real marginal production cost.

Final goods. In the final goods sector, there is a continuum of heterogeneous firms that differentiate intermediate goods. The sector allows for endogenous entry and endogenous tradability. Over the entire space of potential varieties, only a subset will actually be created and commercialized. Firms have specific random productivity draws z, which remain fixed once firms have been created. Entry incurs a once and for all sunk costs f_e, paid in units of intermediate goods. At each period t, there are two types of firms: n_t firms that are already productive at the begin-

[1] Assuming a productivity measure that raises the productivity of all factors, including that of robots, would amount to make the implicit assumption of biased technical changes. Shocks to this measure would lead to labor reallocations that resemble automation shocks. The purpose of the labor-augmenting measure is to provide a source of non-biased changes in productivity to generate “usual” business cycles, as opposed to automation shocks (shocks to ϕ_t).

ning of the period and $n_{e,t}$ firms that are newly created – but non–productive yet – within the period. At the end of the period a fraction $\delta \in [0,1]$ of all existing firms is exogenously affected by an exit shock. The total number of varieties thus evolves according to:

$$n_t = (1-\delta)(n_{t-1} + n_{e,t-1}) \tag{13}$$

Among the firms created, only the most productive address the export market. Entry in the export market is subject to the repeated payment of a fixed cost f_x, also paid in units of intermediate goods, and incurs the payment of iceberg melting costs τ.[2] Firm-specific productivity z has a Pareto distribution with lower bound $z_{\min}$ and shape parameter $\varepsilon > \theta - 1$. The probability density function of z is $g(z) = \varepsilon z_{\min}^{\varepsilon} / z^{\varepsilon+1}$ and the cumulative density function is $G(z) = 1 - (z_{\min}/z)^{\varepsilon}$. Over the total number of potential firms, only a proportion n_t will actually be created

$$n_t = 1 - G(z_{d,t}) = (z_{\min}/z_{d,t})^{\varepsilon} \leq 1 \tag{14}$$

where $z_{d,t}$ will be determined by a free-entry condition. In addition, out of the total number of firms addressing the local market, the number of exporting firms $n_{x,t}$ will be those that are productive enough to cover the additional various export costs. Their number is:

$$n_{x,t} = (1 - G(z_{x,t}))\, n_t = (z_{\min}/z_{x,t})^{\varepsilon}\, n_t \tag{15}$$

where $z_{x,t}$ is the individual productivity of the cut-off exporting plant. Let $\kappa_t(z)$ denote the total current *real* profits of a firm with productivity z and $\varphi_t^r(z) = \varphi_t^r / z$ its specific production cost where $\varphi_t^r = \varphi_t / p_t$. Total current profits are composed of domestic and export profits, $\kappa_{d,t}(z)$ and $\kappa_{x,t}(z)$, respectively defined as

$$\kappa_{d,t}(z) = \left(\frac{p_{d,t}(z)}{p_t} - \frac{\varphi_t}{z}\right) y_{d,t}(z) \text{ and } \kappa_{x,t}(z) = \left(q_t \frac{p_{x,t}(z)}{p^*} - \frac{(1+\tau)\varphi_t}{z}\right) y_x(z) - f_x \varphi_t \tag{16}$$

where $p_{d,t}(z)$ is the domestic nominal price of good z, $p_{x,t}(z)$ is the foreign nominal price of good z expressed in terms of the foreign currency, and q_t is the consumption-based real exchange rate.[3] Optimal pricing conditions are derived subject to the goods demand functions and optimal prices imply

$$\rho_{d,t}(z) = \frac{p_{d,t}(z)}{p_t} = \frac{\theta}{\theta-1}\frac{\varphi_t}{z} \text{ and } \rho_{x,t}(z) = \frac{p_{x,t}(z)}{p^*} = (1+\tau)\frac{\theta}{\theta-1}\frac{\varphi_t}{q_t z} \tag{17}$$

Entry occurs one period before production starts and the productivity draw of the last entering firm remains fixed until the corresponding firm exits. The firm does not know its productivity

[2] Out of a quantity y produced and shipped, only $y/(1+\tau)$ actually arrives. Firms need to produce $(1+\tau)y$ to sell y.

[3] Due to the small open economy assumption, foreign variables are assumed to be constant. Hence the foreign CPI level is $p_t^* = p^*$ and the demand for variety z is $y_{xt}(z) = y_x(z)$.

draw prior entry. Hence, the entry condition equates the current entry cost, expressed in units of the intermediate good, to the total (domestic and export) discounted expected profits (starting in $t+1$) made by the average incumbent. The corresponding entry condition writes

$$\mathrm{E}_t \left\{ \sum_{s=t+1}^{\infty} \left(\beta_{t,s}\left(1-\delta\right)\right)^{s-t} \widetilde{\kappa}_s \right\} = f_e \varphi_t \tag{18}$$

where average profits $\widetilde{\kappa}_t$ will be defined later. After expressing the condition recursively, we get

$$\mathrm{E}_t \left\{ \beta_{t,t+1}\left(1-\delta\right)\left(\widetilde{\kappa}_{t+1} + f_e \varphi_{t+1}\right) \right\} = f_e \varphi_t \tag{19}$$

This equation is very similar to Ghironi & Melitz (2005), except that the entry sunk cost is paid in units of intermediate goods. It shows the determinants of firms' entry. Given the definition of profits, entry is high when current marginal costs are low, and when domestic and export markets are large. The entry condition also shows that entry is high when current entry costs are low or expected discounted entry costs higher than current costs. Among the firms that produce, only the most productive can profitably enter the export market given that exporting requires the repeated payment of iceberg and sunk export costs. Hence the export productivity cut-off is $\kappa_{x,t}\left(z_{x,t}\right) = 0$ or, after using the optimal pricing and demand conditions:

$$z_{x,t} = \frac{(1+\tau)}{(\theta-1)} \left(\frac{\theta \varphi_t}{q_t}\right)^{\frac{\theta}{\theta-1}} \left(\frac{f_x}{c^*}\right)^{\frac{1}{\theta-1}} \tag{20}$$

As in the case of firms' entry, the equation sheds light on the determinants of entry in the export market: low trade costs, low marginal costs, low fixed export costs and large foreign markets.

2.3 Aggregation and Data Consistency

Let us define the average productivity of firms addressing the domestic market as $\widetilde{z}_{d,t} = \nabla z_{d,t}$ where $\nabla = \left(\varepsilon / \left(\varepsilon - (\theta-1)\right)\right)^{\frac{1}{\theta-1}}$ and the average productivity of firms addressing both markets as $\widetilde{z}_{x,t} = \bigtriangledown z_{x,t}$.[4]

Average prices. Defining the average price of a domestic good as $\widetilde{\rho}_{d,t} = p_{d,t}\left(\widetilde{z}_{d,t}\right)/p_t$ and the average price of an exported good as $\widetilde{\rho}_{x,t} = p_{x,t}\left(\widetilde{z}_{x,t}\right)/p_t^*$, we obtain real average prices:

$$\widetilde{\rho}_{d,t} = \frac{\theta}{\theta-1}\frac{\varphi_t}{\bigtriangledown z_{d,t}} \text{ and } \widetilde{\rho}_{x,t} = (1+\tau)\frac{\theta}{\theta-1}\frac{\varphi_t}{q_t \bigtriangledown z_{x,t}}$$

[4] Average productivity levels are defined as $\widetilde{z}_{d,t} = \left[\frac{1}{1-G(z_{d,t})}\int_{z_{d,t}}^{\infty} z^{\theta-1} dG(z)\right]^{1/(\theta-1)}$ and $\widetilde{z}_{x,t} = \left[\frac{1}{1-G(z_{x,t})}\int_{z_{x,t}}^{\infty} z^{\theta-1} dG(z)\right]^{1/(\theta-1)}$. See Ghironi & Melitz (2005) for a discussion and Melitz (2003) for proofs.

Average profits. Using the profit and pricing equations, we get

$$\widetilde{\kappa}_{d,t} = \frac{1}{\theta}\widetilde{\rho}_{d,t}^{1-\theta}c_t \text{ and } \widetilde{\kappa}_{x,t} = \frac{(\theta-1)}{\varepsilon-(\theta-1)}f_x\varphi_t \tag{21}$$

These equations can be used to obtain the dynamics of average total profits

$$\widetilde{\kappa}_t = \widetilde{\kappa}_{d,t} + (n_{x,t}/n_t)\widetilde{\kappa}_{x,t} \tag{22}$$

Variety effect. Based on the expression of the domestic CPI, we uncover the following variety effect:

$$n_t\widetilde{\rho}_{d,t}^{1-\theta} + n_x^*\widetilde{\rho}_x^{*1-\theta} = 1 \tag{23}$$

indicating a tight relation between the number of varieties produced and their domestic price.[5]

Market clearing. The routine labor market clearing is given by

$$\int_{m_t}^{1} h_{it}^r di = (1-m_t)\, h_{it}^r = h_t^r \tag{24}$$

An equilibrium with automation $0 < m_t < 1$ requires $\varpi_t^r = a_t\phi_t$ and thus implies $x_{it} = a_t h_{jt}^r$ for any $i \in [0, m_t]$ and for any $j \in (m_t, 1]$. As a consequence, $a_t h_t^r = (1-m_t)x_{it}$. Plugging the two previous conditions into the first-order condition for robots yields:

$$m_t = 1 - \left(\frac{\phi_t}{(1-\alpha)\,\varphi_t}\right)^{1/\alpha}\frac{h_t^r}{h_t^{nr}} \tag{25}$$

Further, the aggregate production function is then

$$\gamma_t = a_t\left(\frac{h_t^r}{1-m_t}\right)^{1-\alpha}(h_t^{nr})^{\alpha} \tag{26}$$

implying

$$(1-\alpha)\,(1-m_t)\,\frac{\gamma_t}{h_t^r} = \frac{\varpi_t^r}{\varphi_t} \tag{27}$$

which also pins down the real wage of non-routine labor when combined with the first-order condition on non-routine labor and the equilibrium level of automation m_t:

$$\varpi_t^{nr} = a_t\alpha\varphi_t^{1/\alpha}\left(\frac{1-\alpha}{\phi_t}\right)^{(1-\alpha)/\alpha} \tag{28}$$

Intermediate goods serve as inputs of final goods producers. When final goods producers are more efficient they need less intermediate input to address the demand from the final goods sector.

[5] Notice that the assumption of a small open economy implies that the number of foreign exporters as well as the price of foreign exports constant. In addition, there is no relevant foreign-based variety effect since the contribution of domestic exports to the foreign CPI is negligible under the assumption of a small open economy.

Further, the various entry costs and the robots are also paid in units of intermediate goods. The market clearing condition is thus

$$\gamma_t = \widetilde{\rho}_{d,t}^{-\theta} \frac{n_t}{\nabla z_{d,t}} (c_t + ac_t) + (1+\tau) \widetilde{\rho}_{x,t}^{-\theta} \frac{n_{x,t}}{\nabla z_{x,t}} c^* + n_{e,t} f_e + n_{x,t} f_x + (1-\alpha) m_t \gamma_t \tag{29}$$

The market clearing condition for the final goods sector is

$$y_t^c = n_t \widetilde{\rho}_{d,t}^{1-\theta} (c_t + ac_t) + n_{x,t} \widetilde{\rho}_{x,t}^{1-\theta} c^* \tag{30}$$

and shows that exports can only vary because of changes in the number of exported goods or in the real export price. Net foreign asset dynamics are obtained by aggregating all budget constraints and combining with market clearing conditions:

$$b_t^r - r^* (q_t/q_{t-1}) b_{t-1}^r = q_t n_{x,t} \widetilde{\rho}_{x,t}^{1-\theta} c^* - n_x^* \widetilde{\rho}_x^{*1-\theta} (c_t + ac_t) \tag{31}$$

Data consistency. As explained in Ghironi & Melitz (2005), our model variables have to be deflated by a price index capturing the aggregate variety effect. Indeed, in the presence of endogenous varieties and when household preferences exhibit love for variety, the welfare-based price index may vary, even though product prices remain fixed. In addition, the official statistics for price indices and real aggregates consider the number of varieties as fixed and update the range of good varieties on a rather infrequent basis, while the number of varieties changes every period in our model. Hence, we define macroeconomic aggregates and prices in a way that is consistent with the data. Defining $\widetilde{p}_t = (n_t + n_x^*)^{\frac{1}{\theta-1}} p_t$, as a deflator that takes into account the total number of varieties that enter the consumption bundle, any real data-consistent aggregate x_t writes $x_t^r = p_t x_t / \widetilde{p}_t$. Along the same lines, the data-consistent real exchange rate is $\widetilde{q}_t = e_t \widetilde{p}_t^* / \widetilde{p}_t$, where $\widetilde{p}_t^*$ is the foreign equivalent of $\widetilde{p}_t$. Finally, data-consistent trade flows (exports and imports) are computed using deflators that take into account the relevant number of traded varieties. The data-consistent trade balance is defined as data-consistent exports minus data-consistent imports. It is reported as a percentage of data-consistent GDP. The data-consistent measure of GDP is defined adding data-consistent consumption, investment and the trade balance.

3 Calibration

We use various data sources to calibrate our model. Some of our targets will pertain to the steady-state and other targets to business cycle moments. We consider an average OECD country. For business cycle moments, our dataset comprises 12 OECD countries, and considers GDP, private expenditure in consumption goods, gross fixed capital formation, total employment, the unemployment rate and net exports.[6]

The steady state is symmetric in the sense that $c = c^*$, implying $q = 1$ and $b^r = 0$. In addition, our initial steady state is one without automation, *i.e.* $m = 0$, which implies adjusting ϕ, the unit cost of robots accordingly. As such, we consider the baseline calibration as capturing the dynamics of OECD economies during the early 1990's. We also impose $a = 1$, without loss of generality. The model is quarterly, and the discount factor is $\beta = 0.99$. The utility function is:

$$u\left(c_t + \eta u_t, h_t^r, h_t^{nr}\right) = \log\left(c_t + \eta u_t\right) - \chi^r \frac{\left(h_t^r\right)^{1+\psi^r}}{1+\psi^r} - \chi^{nr} \frac{\left(h_t^{nr}\right)^{1+\psi^{nr}}}{1+\psi^{nr}} - \xi u_t \tag{32}$$

We consider an initial unemployment rate of $u = 0.07$, and assume that the labor force is divided in two equal subgroups respectively occupying routine and non-routine jobs, *i.e.* $h^r = h^{nr} = (1-u)/2$.[7] The values of χ^r and χ^{nr} are adjusted to obtain these initial steady-state values. The Frisch elasticities of labor supply are adjusted to match (i) the relative standard deviation of aggregate total employment and (ii) the fact that, at least in the U.S., the volatility of routine employment was 1.4345 the volatility of non-routine employment in 1991Q1.[8] We get $\psi^{nr} = 0.6028$ and $\psi^{nr} = 0.4030$. The home production parameter η is equal to 0.44, which makes home production roughly 90% of the steady-state real wage of workers.[9] Finally, we follow McKay & Reis (2016) and calibrate the non-pecuniary cost of unemployment so that the marginal leisure benefits of being unemployed are compensated by the marginal non-pecuniary cost.[10]

In the intermediate goods sector, we follow the baseline calibration of Guerreiro et al. (2017), and impose $\alpha = 0.5$. In the production sector, the values of f_e and f_x are determined endogenously to match respectively a given steady-state number of varieties n and a given number of traded varieties n_x. We impose $n = 0.5$, which yield a value of f_e that makes investment over observed GDP $(n_e f_e \varphi / \tilde{y}_t)$ equal to 13.25%. Further, based on European data from the SDBS Database, firms' death rate is consistent with $\delta = 0.0375$. In addition, we follow Cacciatore, Fiori & Ghironi (2016) and calibrate the elasticity of substitution between varieties at $\theta = 3.8$.[11]

[6] We consider Australia, Canada, Denmark, Germany, France, Italy, Japan, New Zealand, Spain, Sweden, the UK and the U.S. The sample ranges from 1991Q1 to 2016Q4. GDP, consumption, investment, exports and imports are all expressed in constant units of local currency. Total employment is expressed in thousands of persons. We obtain net exports by subtracting imports from exports and divide by GDP to obtain a rate, in percents. The unemployment rate is expressed in percents. For each country, we take the log of all variables (except net exports, taken in level), extract the cyclical component using an HP-filter with $\lambda = 1600$, and compute business cycle moments, before taking the average of business cycle moments across sample countries.

[7] U.S. data (see Appendix A) suggest 53% in 1991Q1, close enough to the 50% calibration we choose to impose.

[8] We use the data kindly provided by Albertini, Hairault, Langot & Sopraseuth (2017), reported in Appendix A both in level and in log-deviation from an HP-filter trend with $\lambda = 1600$.

[9] Routine and non-routine workers receive the same wage for the calibration considered under null automation.

[10] This implies $\xi = \chi^r \left(h^r\right)^{1+\psi^r} / \left(1+\psi^r\right) + \chi^{nr} \left(h^{nr}\right)^{1+\psi^{nr}} / \left(1+\psi^{nr}\right)$.

[11] Incidentally, a value of $\theta = 3.8$ implies rather high steady state markups over marginal costs. However, given the presence of fixed costs, markups over average costs are in line with values found in the literature. See Bilbiie, Ghironi & Melitz (2008) for an extensive discussion.

In the trade sector, we impose the share of exporting firms in the steady state at $n_x/n = 0.2$, in line with French data (see Berman, Martin & Mayer (2012)), and adjust the export cost f_x accordingly. Eaton, Kortum & Kramarz (2011) estimate Pareto parameters governing the distribution of French firms and their best estimate is $\varepsilon = 4.87$. We impose this precise value, and choose the value of the iceberg cost parameter $\tau = 0.1$ to obtain a degree of (data-consistent) trade openness of 65.69%, in line with the average of OECD countries. Our calibration implies that exporters are 20.7% more productive than non-exporters, and that domestic prices are 9.73% higher than export prices (trade costs included). Finally, we follow Schmitt-Grohé & Uribe (2003) and set the international bond adjustment cost parameter to $\phi_b = 0.0007$.

Business cycles are driven by transitory shocks to labor productivity. From our dataset, for each country, we compute labor productivity as GDP per worker, take the log and remove a linear trend before estimating an AR(1) process. The average resulting persistence parameter is $\hat{\rho}_a = 0.9440$. We adjust the standard deviation of innovations to match the observed absolute standard deviation of GDP, and get $\sigma_a = 0.4566\%$. Parameter values in the baseline calibration are reported in Table 1 below.

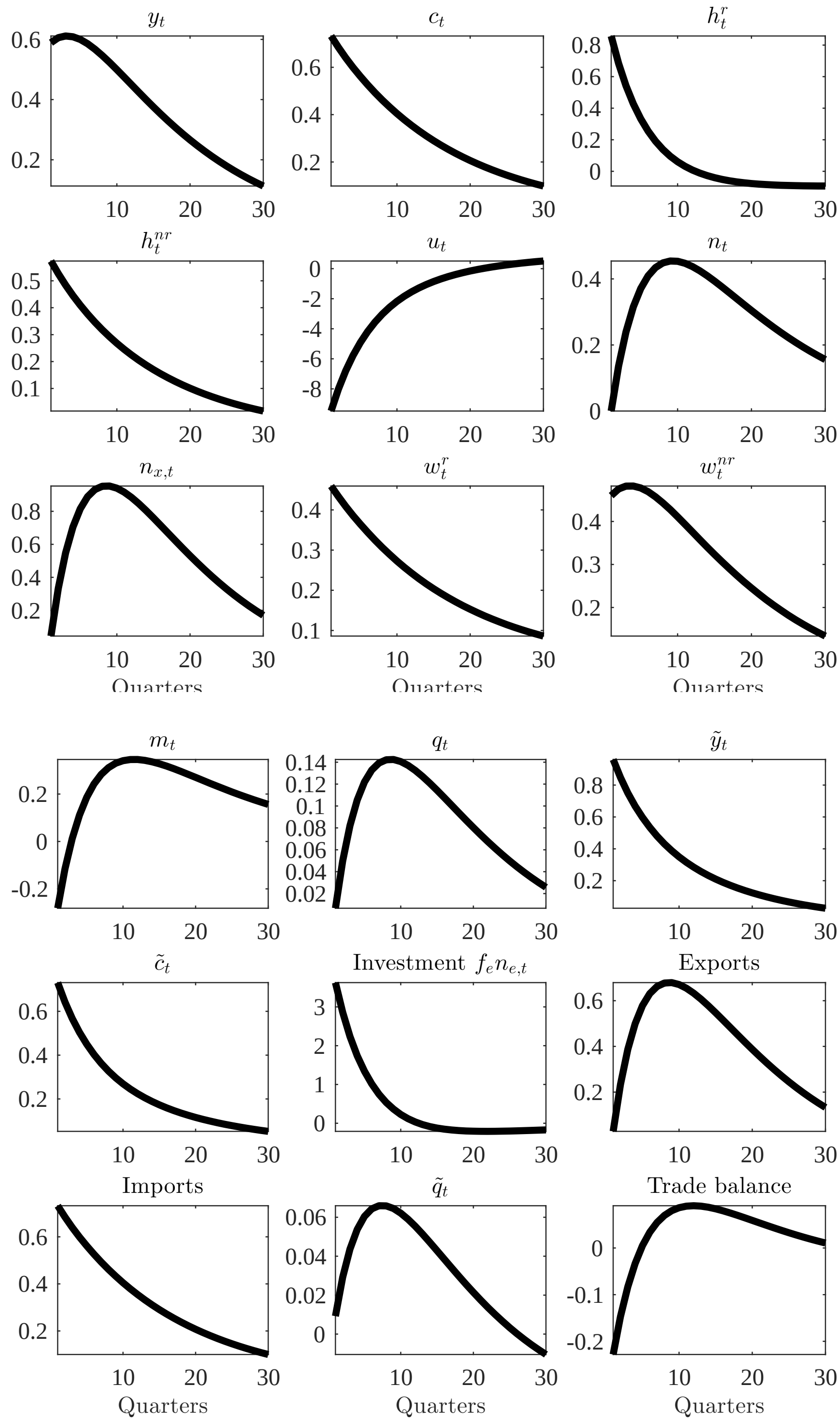
Table 1: Parameter values.

Discount factor	$\beta = 0.99$
Inverse of Frisch elast., routine	$\psi^r = 0.3954$
Inverse of Frisch elast., non-routine	$\psi^{nr} = 0.6187$
Home production parameter	$\eta = 0.44$
Non-pecuniary cost of unemployment	$\xi = 0.5945$
Steady-state unemployment rate	$u = 0.07$
Consumption / leisure weights	χ^r and χ^{nr} adjusted to get $h^r = h^{nr} = (1-u)/2$
Steady-state unit cost of robots	ϕ adjusted to get $m = 0$
Elasticity of production to non-routine labor	$\alpha = 0.5$
Entry cost	f_e adjusted to get $n = 0.5$
Export cost	f_x adjusted to get $n_x/n = 0.2$
Exogenous death rate	$\delta = 0.0375$
Elasticity of subs. between varieties of final goods	$\theta = 3.8$
Pareto curvature parameter	$\varepsilon = 4.87$
Steady-state trade costs	$\tau = 0.1$
Portfolio adjustment costs on bonds	$\phi^b = 0.0007$
Persistence of labor productivity shocks	$\rho_a = 0.9440$
Standard deviation of labor productivity innovations	$\sigma_a = 0.4567\%$

Figure 1 displays the response of the economy to a one standard deviation positive labor productivity shock. The equilibrium conditions of the model are approximated at a second-order around the steady state using perturbation methods.

A positive labor productivity shock raises output and consumption both at the intensive and extensive margins. labor demand increases for both types of labor, inducing an increase in the corresponding real wages and a fall in the unemployment rate. The rise in aggregate consumption

Figure 1: IRFs to a 1 sd positive labor productivity shock.



<u>Note</u>: Percent deviations from the steady state, except for automation (m_t, pp. deviations) and the trade balance (as a percentage of data-consistent GDP).

enlarges the size of the domestic market, which provides incentives for new firms to enter the market. As a consequence, the entry threshold falls, and the number of entries (investment) jumps, progressively boosting the total number of varieties produced. Looking at the open-economy dimension, the labor productivity shock makes local goods cheaper compared to the unchanged price of foreign goods, and the real exchange rate depreciates. This in turn lowers the export entry threshold, and further boost the number of exported varieties. The response of imports follows closely that of aggregate consumption. This set of IRFs is qualitatively consistent with the empirical patterns of comovements among the corresponding macroeconomic aggregates. Table 2 confirms the qualitative and quantitative success of the model.

Table 2: Business cycle properties

	Data			Model		
$\downarrow x$	$\sigma(x)$	$\rho(x)$	$\rho(x,\widetilde{y})$	$\sigma(x)$	$\rho(x)$	$\rho(x,\widetilde{y})$
Output ($\widetilde{y}_t$)	1.20	0.82	–	1.20	0.68	–
Consumption ($\widetilde{c}_t$)	0.87	0.74	0.68	0.76	0.67	1.00
Investment ($n_{e,t} f_e \varphi_t$)	3.16	0.82	0.79	3.68	0.64	0.96
Total employment ($h_t^r + h_t^{nr}$)	0.74	0.86	0.57	0.74	0.66	0.99
Unemployment rate (u_t)	6.68	0.88	−0.67	9.84	0.66	−0.99
Net exports	0.67	0.63	−0.08	0.31	0.65	−0.77

Note: $\sigma(x)$ denotes the standard deviation (for output and net exports) or the standard deviation normalized by the standard deviation of output. $\rho(x)$ represents the autocorrelation at one lag and $\rho(x, \tilde{y})$ stands for the contemporaneous correlation of each variable with output.

Despite the simplicity of the model and the fact that it is driven by a single shock, it performs relatively well in matching the relative volatility of consumption and investment. The relative volatility of the unemployment rate is a bit too large and its persistence is not well reproduced, which is not surprising given that we consider Walrasian labor markets and abstract from any kind of frictions. Finally the cyclical pattern with respect to GDP is qualitatively well reproduced: consumption, investment and employment are all procyclical, while the unemployment rate and net exports are counter-cyclical, as in the data.

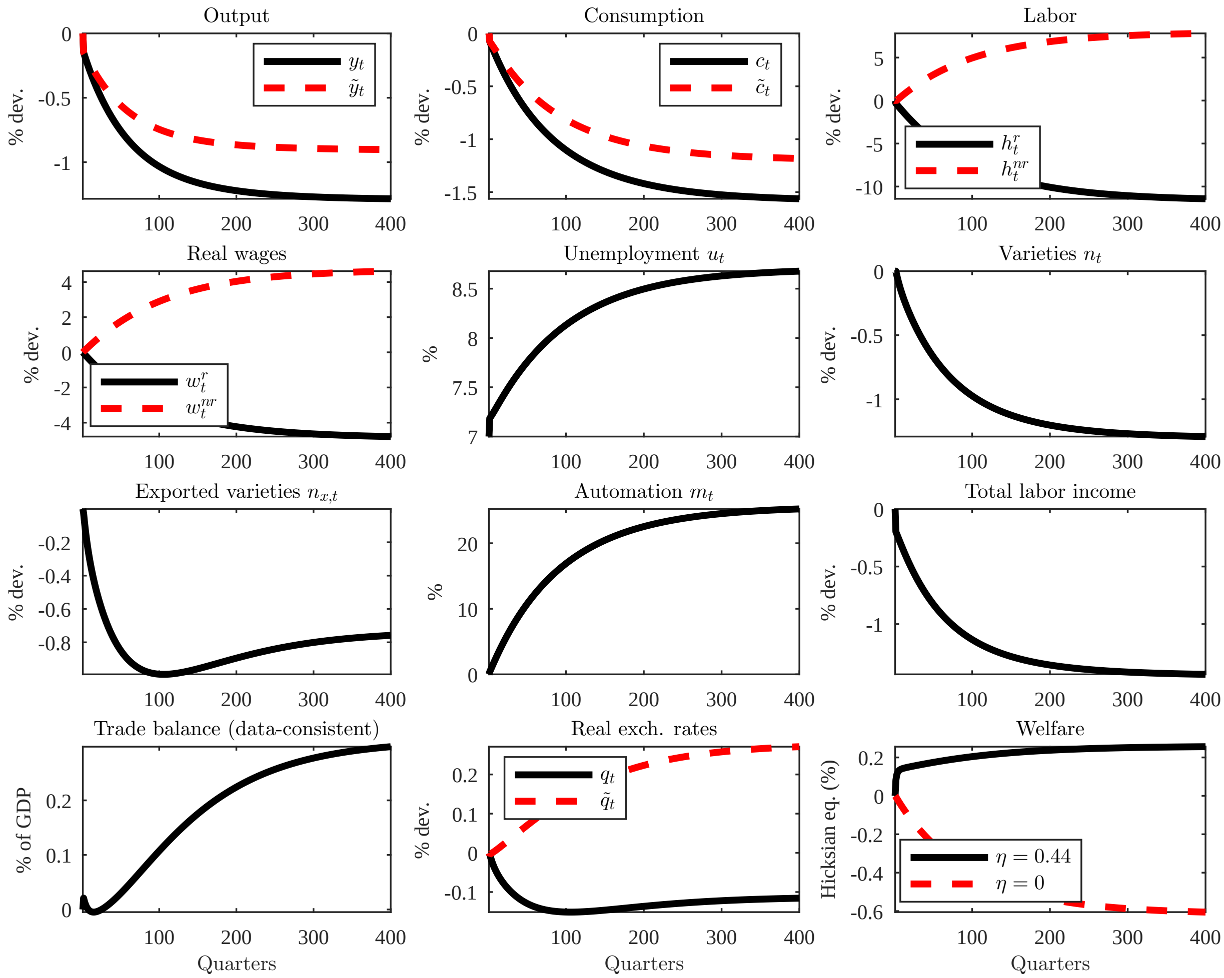
The model performs at least as well as other IRBC models with productivity shocks only, even though the above business cycle exercise is conducted to calibrate the model, and more especially the Frisch elasticities of labor supply. These parameters are indeed crucial to gauge the long-run effects of a permanent automation shock, an experiment that we conduct in the next Section.

4 A permanent automation shock

4.1 Baseline experiment

The data reported by Acemoglu and Restrepo (2018) suggest that Germany was almost not automated in the early 1990's and is now highly automated, actually much more than other countries. Considering a path for automation that replicates German data would thus serve as an upper bound of the potential effects of automation. A quick back of the envelop calculation suggests that automation in Germany was basically zero in the early 1990's ($m_t = 0$) and increased slowly to roughly 12% ($m_t = 0.12$) recently. Assuming that the transition is very slow (a 0.99 persistence) and a 5% fall in the unit cost of robots ϕ_t yields a similar transition path (from $m_t = 0$ to $m_t = 0.12$ over a 80 quarters period). Of course, such a shock will put automation to a level higher than $m_t = 0.12$ in the final steady state, around 26%. The resulting transition path reported in Figure 2 will be considered as the benchmark against which alternative experiments will be conducted.[12]

Figure 2: The effects of a permanent automation shock.



Note: Periods are quarters. The shock brings automation from $m_t = 0$ to $m_t = 0.12$ in 80 quarters, as suggested by the data on robots per worker in Germany.

[12]The shock is permanent and implies a change in steady states. As such, the form of portfolio adjustment costs is changed to $ac_t = \phi_b \left(b_t^r - b_{t-1}^r\right)^2/2$ to allow the shock to have permanent endogenous effects on net foreign assets.

Focusing first on the labor-market effects of the shock, Figure 2 shows that an automation shock produces a displacement effect: the demand for routine jobs falls along with the fall in robots price, and the demand for non-routine labor increases. While the effects on real wages – through labor demand – on the equilibrium real wages of routine and non-routine labor are symmetric, the effects on routine and non-routine labor also depend on labor supply, driven by the Frisch elasticities. As explained in details in the calibration Section, business cycle data suggest that routine employment is more volatile than non-routine employment, and this fact is accounted for by assuming that the supply of routine labor is more elastic than the supply of non-routine labor. Hence, for a given labor demand driven fall (resp. rise) in the real wage of routine (resp. non-routine) labor, labor supply falls (resp. rises) more (resp. less) for routine (resp. non-routine) jobs.

This asymmetry in the displacement effect is crucial, as it determines the overall dynamics of households labor income. Since changes in real wages are symmetric but the fall in routine labor is deeper than the rise in non-routine labor, total labor income falls, making households overall poorer. In addition, unemployment increases substantially. The total demand for final goods falls, the size of the goods market shrinks, which has effect both at the intensive and the extensive margin. Indeed, entry and export thresholds rise, raising the average productivity of surviving producers but reducing the total number of varieties produced and exported. Both margins are determined by the same variable: households total labor income and the associated total demand for final goods.

The external effects of the automation shock are understood through the dynamics of aggregate consumption and that of the real exchange rate. Both are clearly related by the Euler equation: the fact that current consumption is larger than future consumption is consistent with a reduced subjective real interest rate. To achieve this fall in returns, the real exchange rate must appreciate. The effect on trade flows is thus the following. The fall in aggregate consumption reduces imports while the real exchange rate appreciation limits this fall through the expenditure switching effect. Exports fall because the real exchange rate appreciation both raises the export threshold and the domestic currency price of exports. However, in this small open economy set-up, foreign consumption remains constant. As a consequence, in spite of an appreciating welfare-based real exchange rate, exports fall less than imports, resulting in a trade surplus.

The welfare effects of the automation shock are somehow mixed. On the one hand the fall in consumption produces a large welfare loss. On the other hand, the rise in unemployment raises leisure, home production but also raises the non-pecuniary cost of unemployment. Overall, considering the exact form the utility function and our baseline calibration, the permanent automation yields overall moderate welfare gains, slightly more than 0.2% of (Hicksian) consumption equivalent. However, neutralizing the contribution of home production to the utility function by setting $\eta = 0$ (instead of $\eta = 0.44$) in the computation of the Hicksian equivalent suggests that the welfare losses from the fall in consumption and the rise in unemployment are substantial, and overturn the welfare gains from higher home production. Abstracting from the impact of home production turns the 0.2% welfare gain into a 0.6% welfare losses.

4.2 The role of labor supply elasticities

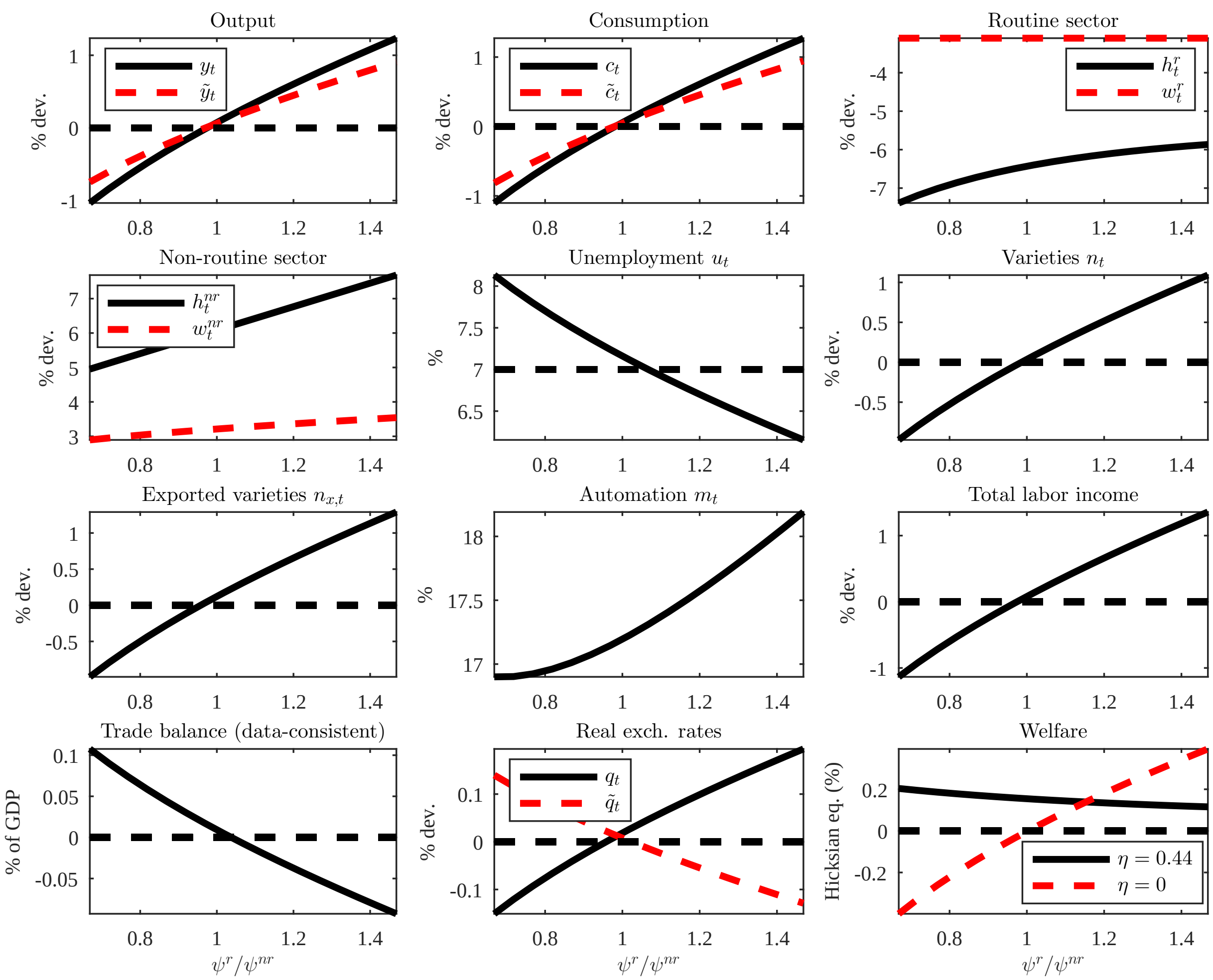
Crucial to the above results seems to be the relative elasticity of labor supply. In particular, the latter determines whether an automation shock raises or lowers output and aggregate consumption. In any case, the extensive margin of output and exports both amplify the movements. To see this more clearly, let us keep the average value of $\psi = (\psi^r + \psi^{nr})/2$ constant, and vary the value of ψ^r/ψ^{nr}. Total labor remains similarly elastic but the larger the ratio, the more elastic non-routine labor supply relative to routine labor supply. Figure 3 reports the values 100 quarters after the transition resulting from the permanent automation shock described in the previous Section.

Let us start by looking at the effects on routine labor and wages. First, the model presentation made it clear that the real wage of routine workers was solely determined by the price of robots. Therefore labor supply does not play any role, the effect remains flat. However, as routine labor supply becomes relatively less elastic compared to non-routine labor supply, the negative effect of the automation shock on routine labor is reduced, although not substantially. When non-routine labor supply becomes relatively more elastic, the rise in both the real wage and the quantity of labor is magnified.

As a consequence, the effects of the very same shock on total labor income, aggregate consumption, output, varieties and exported varieties (that all depend on aggregate consumption), is negative when routine labor is relatively more elastic. When both types of labor supply are roughly similarly elastic, the shock has almost no effects on these above mentioned quantities. When non-routine labor supply is more elastic than routine labor supply, the effects of the shock start becoming positive on consumption, output, varieties, exported varieties. Notably, the extensive margin of output and trade only makes the above effects larger, both when they are positive and negative. The relative elasticity of labor supply also matters for the external effects: the trade surplus observed in the baseline case tends to fall along the relative volatility of non-routine labor supply. As a consequence of the dynamics of consumption, the effects on welfare-based and data-consistent measures of the real exchange rate are also sensitive to the relative elasticity of labor supplies. Finally, the welfare effects also critically depend on the relative elasticity of labor supplies, especially when neutralizing the effects of home production on utility.

In terms of economic interpretation, the relative elasticity of non-routine labor should not be considered as an elasticity at the individual level but as capturing the speed of labor reallocations

Figure 3: Sensitivity of the effects after 100 quarters to the relative elasticity of non-routine



Note: The shock brings automation from $m_t = 0$ to $m_t = 0.12$ in 80 quarters, as suggested by the data on robots per worker in Germany. The dashed black lines represent the initial steady-state values.

from routine to non-routine tasks. As such, elasticities at the business-cycle frequency are only imperfect proxies for the long-run elasticities, that not only depend on the sensitivity of labor supply to the real wage but also on structural labor-market characteristics such as geographic and skill mobility, labor-market rigidities, institutions or professional training programs. Our model thus suggests that any mechanism that favors the mobility from routine to non-routine occupations/task should contribute to magnify the positive aggregate effects of automation shocks.

4.3 The role of the output elasticity to non-routine labor

The exposition of the model also makes clear that the initial non-routine labor share α deeply affects the dynamics of non-routine labor wage (see Equation 28). In the data the non-routine labor share was roughly 50% in the early 1990's in the U.S., which justifies our benchmark calibration. However the skill content of production in other countries may lead to consider slightly higher value of α. Figure 3 thus reports the values 100 quarters after the transition resulting from the permanent automation shock described in the previous Section, for value of α between 0.5 and 0.7.

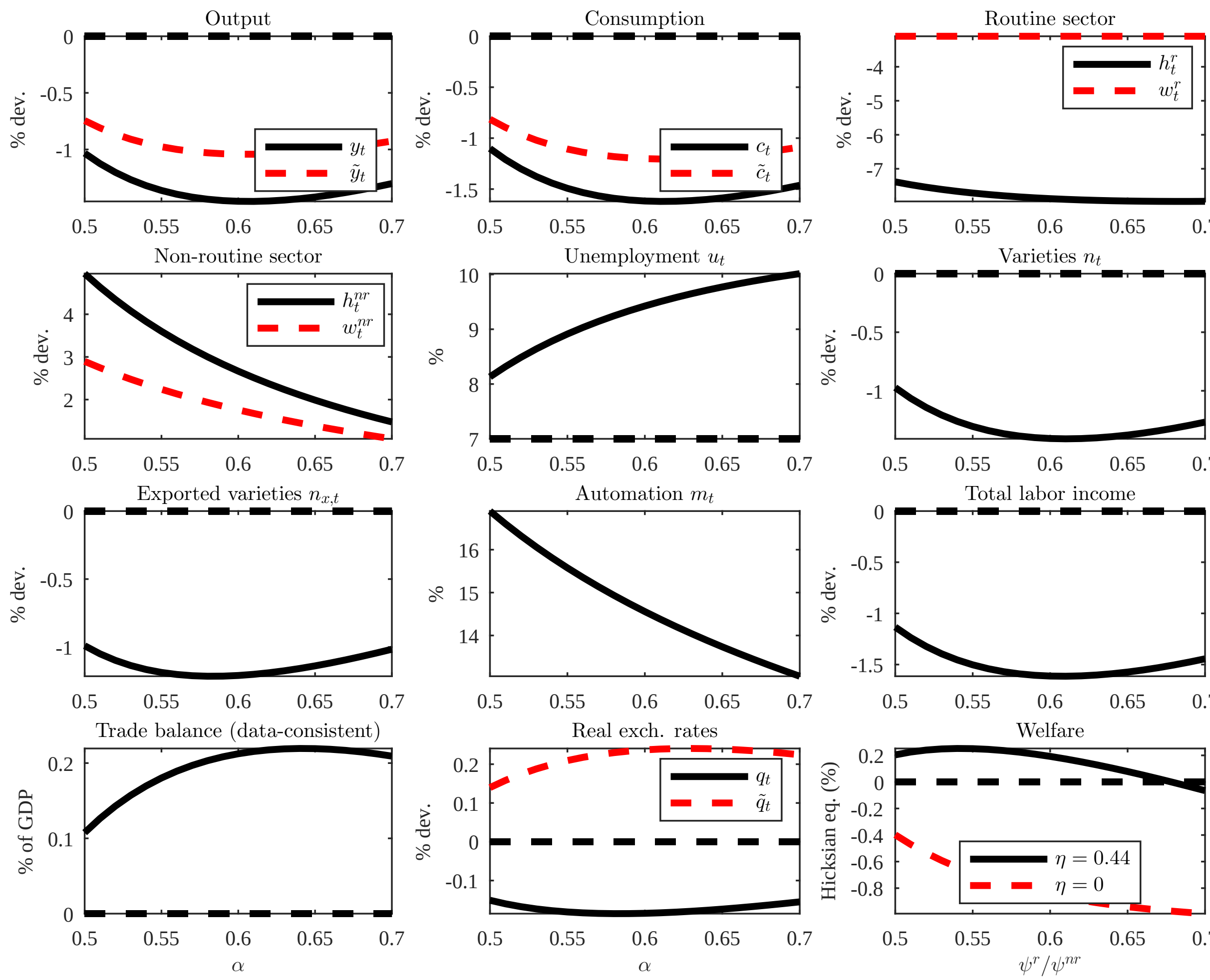
On the one hand, a larger initial elasticity lowers the positive impact of an automation shock on non-routine real wages and labor. This attenuated impact thus reduces the positive impact on total labor income. On the other hand, the larger elasticity lowers the negative impact of decreasing routine labor on total labor income through a composition effect, as non-routine labor receives a larger share of labor income. Overall, changes in output elasticity to non-routine labor – which is also the initial non-routine labor share – have little impact on total labor income, aggregate consumption and therefore on the aggregate output effects of an automation shock. Similarly, since the effects on aggregate consumption are relatively small, the external effects – on the trade balance and the real exchange rate – are mostly unaffected. However, the labor reallocation induced by the automation shock with a larger α is overall much more negative, since non-routine labor increases less and routine labor falls more. In sum, the initial non-routine labor share matters for the size of labor reallocations, but not so much for the aggregate output and consumption effects of an automation shock.

4.4 GHH preferences

The above analysis shows that labor supply elasticities are crucial in shaping the size of labor reallocations resulting from automation shocks, as well as in determining the dynamics of total labor income. Let us now consider an alternative form of preferences, and assume preferences *à la* Greenwood, Hercowitz & Huffman (1988):

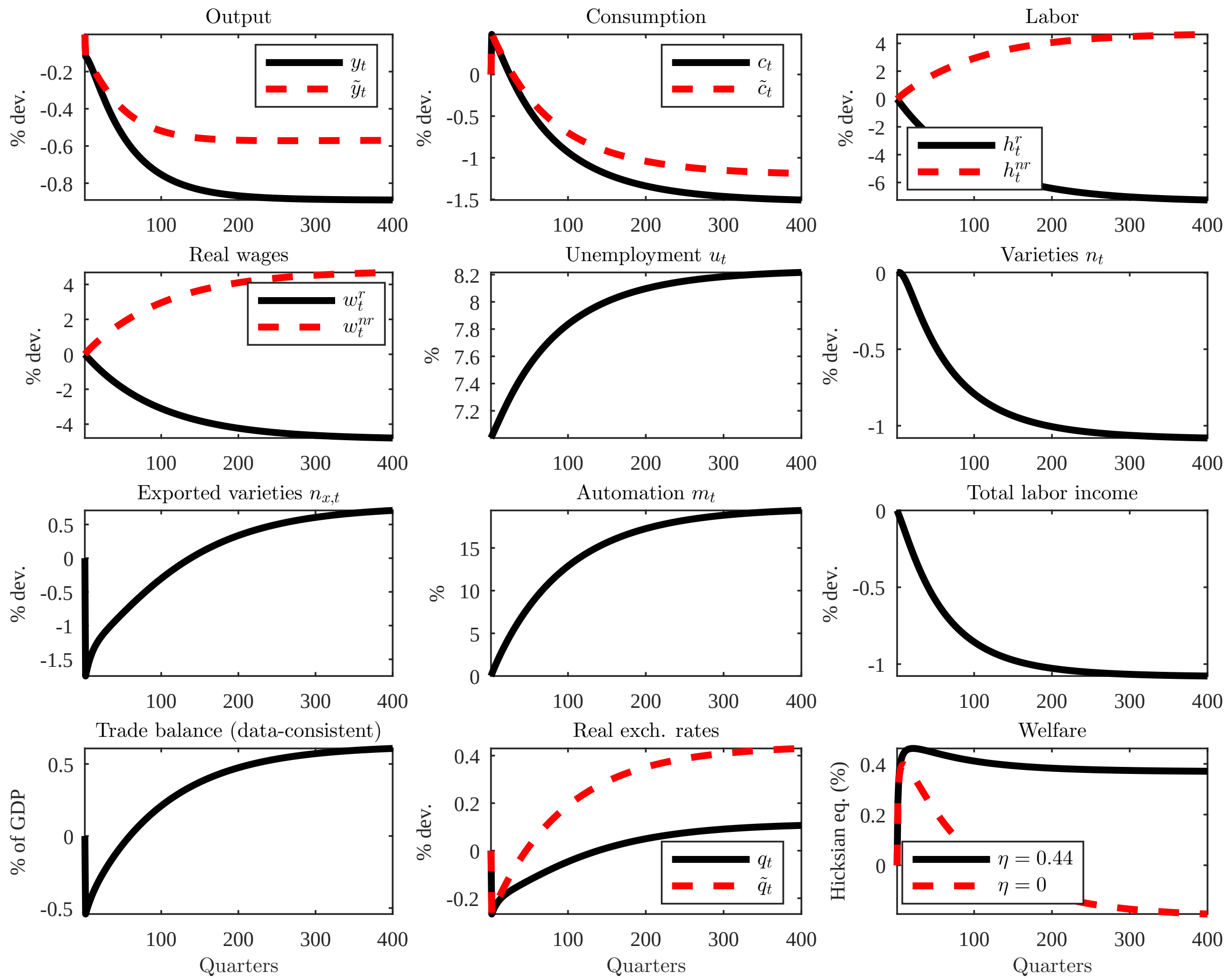
$$u\left(c_t + \eta u_t, h_t^r, h_t^{nr}\right) = \log\left(c_t + \eta u_t - \chi^r \frac{\left(h_t^r\right)^{1+\psi^r}}{1+\psi^r} - \chi^{nr} \frac{\left(h_t^{nr}\right)^{1+\psi^{nr}}}{1+\psi^{nr}}\right) - \xi u_t \tag{33}$$

Figure 4: Sensitivity of the effects after 100 quarters to the output elasticity to non-routine



Note: The shock brings automation from $m_t = 0$ to $m_t = 0.12$ in 80 quarters, as suggested by the data on robots per worker in Germany. The dashed black lines represent the initial steady-state values.

Our calibration strategy remains the same: find the values of labor supply elasticities that match the overall volatility of employment and the higher relative volatility of routine labor compared to non-routine labor. With GHH preferences, we get $\psi^r = 0.6516$ and $\psi^{nr} = 1.0093$. This calibration also implies a new value for the non-pecuniary cost of unemployment $\xi = 0.6770$.[13] Figure 5 replicates Figure 2 with GHH preferences and the associated calibration for labor supply elasticities.



Note: Periods are quarters. The shock brings automation from $m_t = 0$ to $m_t = 0.12$ in 80 quarters, as suggested by the data on robots per worker in Germany.

Figure 5 shows that most results uncovered in the baseline case remain qualitatively unchanged. In particular, the dynamics of output, consumption and total labor income remain overall negative. The labor displacement effect is also fully preserved: the routine real wage and employment fall while the non-routine real wage and employment rise. Movements in non-routine labor are

[13] The non-pecuniary cost of unemployment is now computed as $\xi = log(c+\eta u) - log(c+\eta u - \chi^r (h^r)^{1+\psi^r}/(1+\psi^r) - \chi^{nr} (h^{nr})^{1+\psi^{nr}}/(1+\psi^{nr}))$.

more important that movements in non-routine labor due to the larger labor supply elasticity in the routine sector, which produces a rise in unemployment. Finally, in line with the fall in consumption, the entry threshold increases and the total number of varieties falls, as in the baseline case. Quantitatively speaking, labor reallocation is reduced compared to the baseline case, which marginally lowers the size of the resulting rise in unemployment and fall in labor income, output, consumption and varieties.

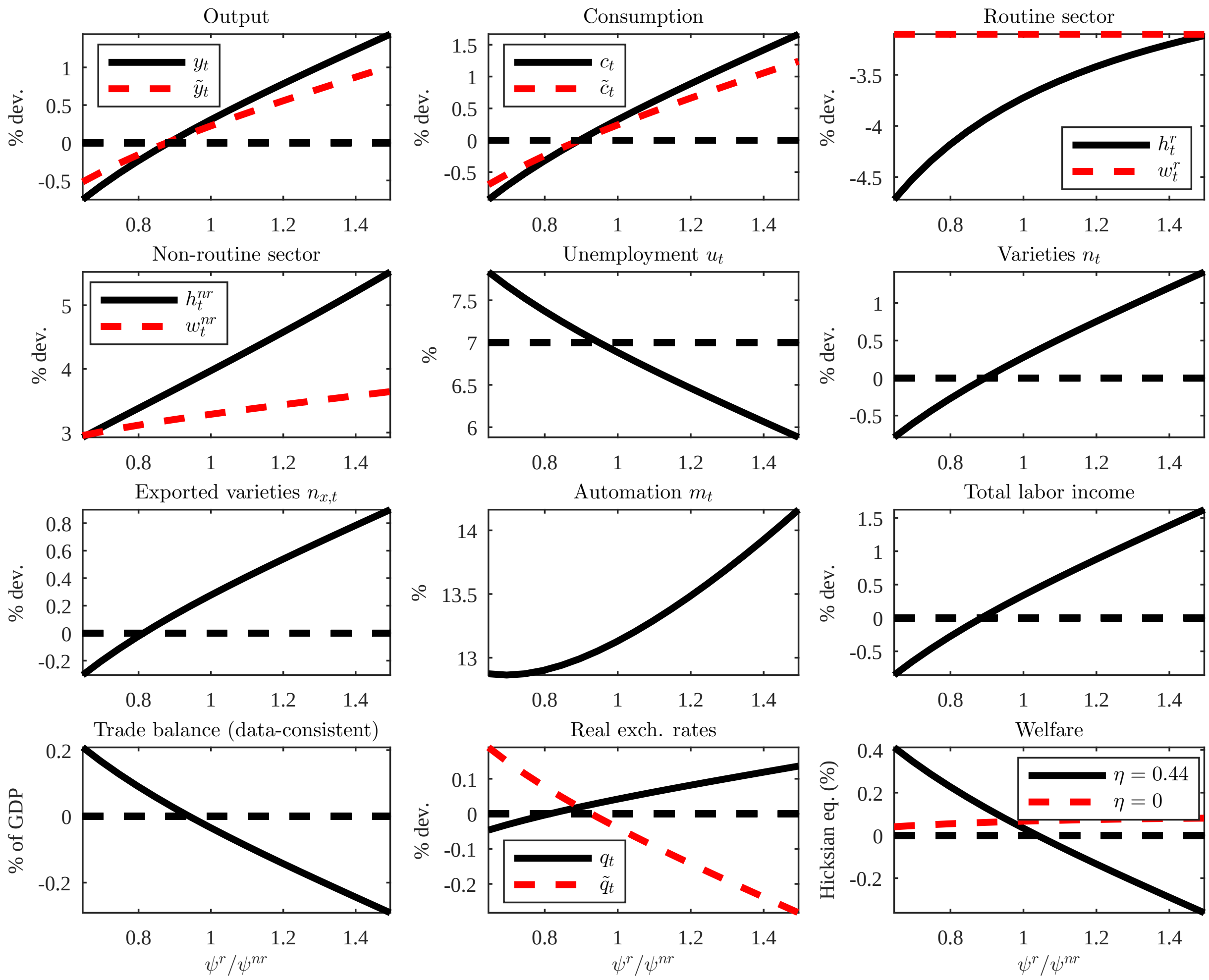
The only variables that display different dynamics are consumption (but only in the very short run), the real exchange rate and the number of exported varieties. This all results from the presence of employment variables in the marginal utility of consumption. In the baseline model, the negative dynamics of aggregate consumption implies a positive dynamics of the marginal utility of consumption, which is then the only driver of the real exchange rate appreciation. This appreciation in turn lowers the total number of exported varieties. With GHH preferences, the marginal utility of consumption also depends on the dynamics of routine and non-routine employment. As a consequence, the short-run dynamics of the marginal utility of consumption is consistent with an appreciation which then reverses to produce a long-run real exchange rate depreciation, that in turns raises the total number of exported varieties. In addition, the sharp short-run real exchange rate appreciation – as opposed to the slow appreciation in the baseline case – produced a short-lived rise in aggregate consumption, that also impacts positively the short-run welfare effects.

Overall, introducing GHH preferences does not overturn our main results. If anything, GHH preferences slightly attenuate the negative effects of an automation shock on output, consumption and welfare. Figure 6 further confirms that the overall sensitivity of our results to the relative labor supply elasticities is qualitatively unchanged with GHH preferences.

5 Conclusion

In this paper, we investigated the effects of an automation shock in a small open economy with an extensive margin of production and exports. We showed that the aggregate effects on output and consumption ultimately depended on the dynamics of total labor income. In the general equilibrium, the latter is mostly affected by the relative elasticity of substitution of routine vs. non-routine labor supply. When routine labor supply was more (resp. less) elastic than non-routine labor supply, the negative effects of lower wages and lower employment in the routine sector dominated (resp. were dominated by) the positive effects of higher wages and employment in the non-routine sector: the effects of a permanent automation shock on aggregate output consumption and welfare were negative (resp. positive). The presence of an endogenously determined number of produced and traded varieties acted as amplifiers of the shock, and the effects of the shock on external variables like the real exchange rate and the trade balance were relatively minor.

Figure 6: Sensitivity of the effects after 100 quarters to the relative elasticity of non-routine



Note: The shock brings automation from $m_t = 0$ to $m_t = 0.12$ in 80 quarters, as suggested by the data on robots per worker in Germany. The dashed black lines represent the initial steady-state values.

In our model, the key determinant of the aggregate effects of automation was the process of labor reallocation. The present paper assumed walrasian labor markets, and did not fully account for potential frictions in the adjustment of employment between sectors. The introduction of frictional labor markets to describe in details the transition from routine to non-routine jobs remains beyond the scope of this paper, and is therefore left for potential future research.

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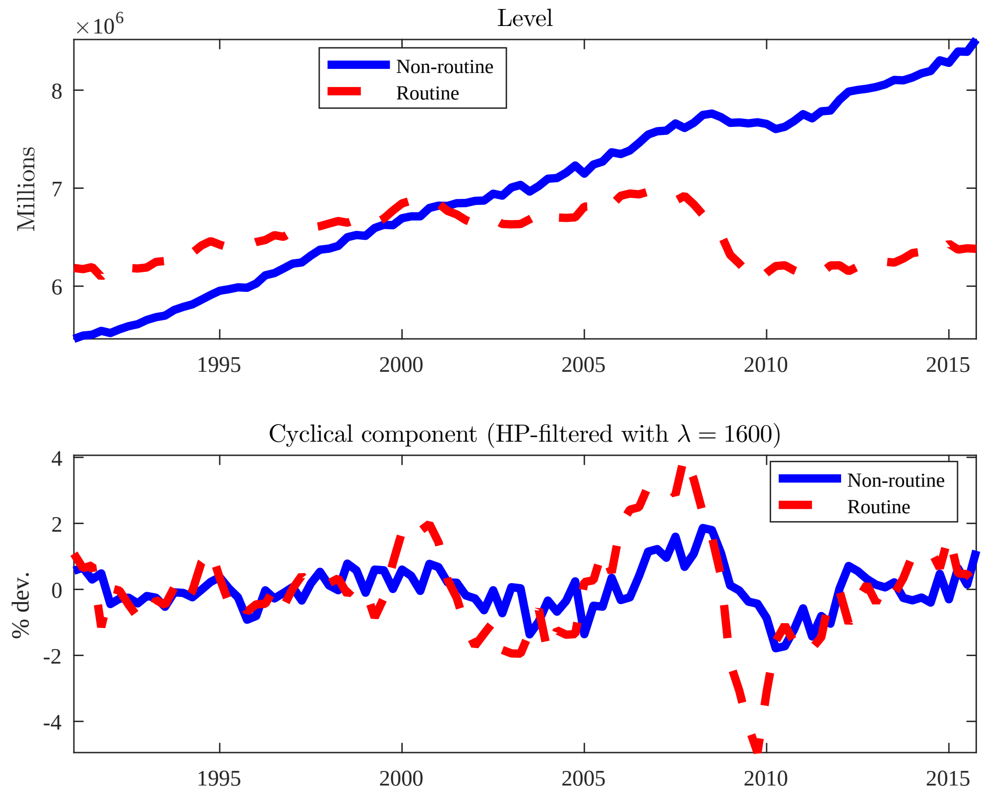
A Routine vs. non-routine employment in the U.S.

Based on the data computed by Albertini et al. (2017), routine and non-routine total employment in the U.S. evolve as reported in Figure 7 below.

Figure 7: Routine vs. non-routine employment in the U.S.



Source: Albertini et al. (2017).