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Robots at Work in Developing Countries: How Bad Could It Be?

By Carlos J. García, Wildo D. Gonzalez, and Tiare T. Rivera*

We address the impact that robots will have on developing economies. Although the stock of these machines is scarce, substantial reductions in their price will produce an accelerated replacement of medium and low-skill workers, so that these economies can continue to compete in international markets. The expected impact in the first decades is negative and substantial at the aggregate level, which is then reversed by productivity gains. Despite the latter reversal, this group of workers loses permanently in the absence of technological retraining. Even with moderate retraining that improves the complementarity of labor and robots, the gap with the developed world rises. Only through the direct production of robots, which produces a virtuous circle with other sectors via the magnitude of the resources involved, can a developed economy begin to close the development gap.
JEL: E20, F60, J20, O11, O30, O40, O57.
Keywords: Robots, productivity, technological change, developing countries, trade.

I. Introduction

An important recent literature reports the effects of robots on productivity, hours worked, and employment in developed countries. Evidence indicates that robots will have an aggregate negative impact on jobs (Acemoğlu and Restrepo (2020)), inequality (Prettner and Strulik (2020); Berg, Buffie, and Zanna (2018)), unemployment (Cords and Prettner (2018)), and wages (Leduc and Liu (2020)) and a marginal effect on hours worked (Graetz and Michaels (2018)). This occurs through the direct replacement of mainly medium-skilled and some low-skilled workers (Frey and Osborne (2017)), a process that some researchers predict will be dramatic (Grace et al. (2018)). This will exacerbate the polarization of the labor market that has already begun with information and communication technologies (Michaels Natraj, and Van Reenen (2014)). These negative results are obtained even considering the positive effects on productivity that robots have in the specific industries in which they are used to replace human beings.

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In this paper, we expand the analysis to understand and measure both the impact and long-term dynamics that robots will have in developing countries at the aggregate and sectoral levels. The dynamics in these countries will be different from those in developed countries, so the ultimate impact may go well beyond the labor market. In developed countries, there are several benefits that reduce impact of the replacement of workers by robots, basically because they can produce their own robots. In other words, in addition to the productivity increases derived from the adoption of robots in specific industries, there are additional positive effects related to the scientific and technical capacity to produce these complex machines and the magnitude of resources that will be allocated to their production, which will have virtuous effects throughout the economy.

In contrast, developing countries will adopt robots through direct imports of machines for use in less automated sectors such as industry and agriculture. These economies are therefore expected to experience more severe effects on employment because the new technologies are characterized by saving jobs rather than creating them (Frey and Rahbari (2017); Autor, Dorn, and Hanson (2015)). This increase in imports depends crucially on robot prices being competitive for these lower-income countries and on the economies having the available resources to acquire them. Otherwise—as Artuc, Bastos, and Rijkers (2018) argue—robotization would occur only in the countries of the North, while those of the South would benefit from the increased demand for inputs. However, a continuation of the negative trend in robot prices recorded over the last 30 years could make the purchase of robots feasible even for developing countries.

From a human-capital standpoint, investment in re-educating the workforce to complement or produce robots will take time in developing countries, as did the technological changes that the introduction of Chinese imports caused in developed countries in Europe (Bloom, Draca, and Van Reenen (2016)). However, developing countries will face worse conditions than developed countries. First, there are extremely limited options for workers to change decisions about their human capital, because of the poor development of robotics-related subjects in the educational system in these countries. Second, the more skilled labor force in these countries is much smaller and less prepared to complement these machines, and they are probably not able to produce these machines in the short or medium term. This implies that in the medium term, the most likely scenario is one in which robots are imported and workers are replaced without substantial improvements in human capital of the most skilled workers, as could be expected in more developed countries (Bloom et al. (2013)).

The analysis should not be limited to a fall in the robot import price for production in important sectors in developing economies, but should also be extended to exports, since a significant percentage of that same production will be exported. Many of these countries are small open economies that export a handful of goods—although important as a percentage of gross domestic product (GDP)—especially to developed economies. Bastos, Silva, and Verhoogen (2018) explain that exporting to these markets compels companies to increase the average quality of the goods they produce, because of the markets' willingness to pay more for higher-quality goods, which in turn leads them to acquire higher quality inputs, because of the complementarity between these inputs and higher quality. Exporting to these markets also requires other services that can be replaced by robots, such as distribution, transport, and advertising, activities that are intensive in skilled labor (Matsuyama (2007); Brambilla, Lederman, and Porto (2012)). Thus, the adoption of robots by individual countries is likely to result in lower prices for their exports to these markets, because of reduced costs without sacrificing product quality. As a result, developing-country industries in the commercial sector will be forced to use robots; otherwise, they will lose market share in developed-country markets.

Thus, the strong dependence of these economies on international markets implies that the effects of robotics will not be limited to the direct impact on the employment of different types of workers and the distributive effects mentioned in the literature. On the contrary, the trade effects can be significant and will include key relative prices such as the interest rate, the real exchange rate, and of course the real wages of different types of workers. This will result in general equilibrium effects on welfare, growth, income distribution, consumption of different types of families, investment in traditional and robotic capital, and so on.

In this article, we propose a model for a small open developing economy to measure the relative importance of both direct labor market effects and general equilibrium effects following the incorporation of robots in the production system, assuming that robot prices fall substantially to become affordable for these countries. The simulations start with a baseline scenario in which robots are imported directly over a horizon of up to 40 years. We then compare the baseline with two counterfactual cases: (i) the developing economy can directly produce robots; and (ii) more skilled workers are trained to complement the imported robots.

The comparison with the first alternative scenario serves to measure the gap in the different macroeconomic indicators and in the income distribution that will occur between developing and developed countries due to robotization. The strategy is as follows: we compare developing economies with a prototype of a small open but developed economy that can rapidly produce robots. In this simulation, we do not consider the externalities of producing robots, but only the impact of the allocation of resources toward the robotic sector and the resulting virtuous effects on the rest of the economy. This comparison is fair because the small economies we are studying—both developed and developing—are not comparable to the United States, Europe, Japan, or China.

In contrast, the second counterfactual scenario allows us to measure the costs of this technological revolution if developing countries do not adequately prepare at least their most skilled workers to take advantage of the positive externalities of handling robots. We explore two questions, given the assumption that the robotics revolution occurs at prices low enough to be adopted by developing economies. What would be the benefit if the workforce could be gradually re-educated in a fairly short time horizon? More importantly, is this a valid alternative to the domestic production of robots for achieving development?

Our results confirm that there are negative effects on the labor market and income distribution for medium and low-skilled workers, as has been found in the literature for developed countries. However, the general equilibrium effects on the aggregate economy—in terms of welfare, GDP, consumption, and private investment—are negative for the first fifteen years in a scenario in which robots are exclusively imported, causing these developing countries to lose the equivalent of several years of potential growth. After that initial period, the results are partially reversed by the increase in productivity generated by the robots, but in the absence of retraining, it is not possible to improve the situation of medium and low- skilled workers in developing countries, and the effects on income distribution are permanent. Even when countries are able to implement some worker retraining to take advantage of the positive externalities of robot manipulation, the inability to produce robots substantially limits the virtuous circle that is produced between the robotics sector and the rest of the economy, producing in a few decades an abysmal gap with small developed countries on all kinds of measures of macroeconomic performance, living standards, welfare, and income distribution. Given this last result, a strategy of only partial retraining to achieve complementarity with imported robots would not be sufficient to reach the development levels of the developed world, despite the positive effects on trade from the developed to the underdeveloped world.

The paper is organized as follows: the details of the model are presented in section II, the results of different simulations are analyzed in section III, and we conclude in section IV.

II. Model

To analyze the aggregate, sectoral, and distributive effects of the impact of the robotics revolution in developing countries, we develop a general equilibrium model that integrates relevant aspects of these economies beyond the labor market, incorporating fundamental elements such as the trade in different types of goods and the endogenization of key relative prices such as the real interest rate, wages, and the real exchange rate, and measures the effects on macroeconomic performance and the distributional outcome not only in absolute terms but also relative to developed countries.

One of the main assumptions of the model is that there is no uncertainty, in the sense that companies and families know in advance that a technological change that introduces robots into production will materialize through a permanent drop in the price of these inputs in the near future.

A. *Firms*

The model considers a continuum of firms, indexed by $i \in [0,1]$, where the production function depends on traditional capital, $\widetilde{K}(i)$; non-robotic imports, $M(i)$; a composite product, $\widetilde{Y}(i)$; and high-skilled labor, $N_2(i)$:

$$Y_t(i) = A_{1,t}(i)\widetilde{K}_{t-1}(i)^{\alpha_1} M_t(i)^{\alpha_2} \widetilde{Y}_t(i)^{\alpha_3} N_{2,t}(i)^{\alpha_4}. \tag{1}$$

The capital stock includes assembly lines, non-robotic machinery (which is defined more precisely below), industrial buildings, and so forth. The non-robotic imports are raw materials such as oil or other products to be sold in the domestic market using other inputs. High-skilled workers include engineers, scientists, lawyers, managers, and specialized technicians. Finally, the composite output is the result of the use of robots and medium and low-skilled workers, and it is equal to:

$$\widetilde{Y}_t(i) = A_{2,t}(i)\left(\widetilde{R}_{t-1}(i)^{\frac{\epsilon}{\epsilon-1}} + N_{1,t}(i)^{\frac{\epsilon}{\epsilon-1}}\right)^{\frac{\epsilon}{\epsilon-1}}, \tag{2}$$

where $N_1(i)$ is medium and low-skilled labor and $\widetilde{R}(i)$ is the stock of fully autonomous, multipurpose, reprogrammable machines that replace workers. The level of substitution between the two inputs is measured by the elasticity, ϵ, in equation (2). In the case of medium and low-skilled labor, we assume that it is possible to differentiate between male and female workers:

$$N_{1,t}(i) = \left(\alpha N_{11,t}(i)^{\frac{\epsilon_1}{\epsilon_1-1}} + (1-\alpha)\, N_{12,t}(i)^{\frac{\epsilon_1}{\epsilon_1-1}}\right)^{\frac{\epsilon_1}{\epsilon_1-1}}, \tag{3}$$

where α is male participation in medium and low-skilled work, $(1-\alpha)$ is female participation, and ϵ_1 is the elasticity of substitution between males and females.

We disaggregate men and women basically because we suppose different propensities to work. In some countries, women have a systematically lower labor participation rate than men, which coincides with a higher wage elasticity. This is the case in Chile, the developing country we use to calibrate our model. The relevant point is that there are different types of workers competing with robots, and they have varying responses to changes in wages. In other developing countries, the differences might be between types of jobs with different skill levels, so there would be no need to differentiate by gender in the modeling strategy. In the case of Chile or similar countries, the possible negative effect of falling robot prices on wages will be greater for women, reinforcing their low labor participation rate.

The first-order conditions that determine the demand for each input are:

$$\alpha_1 \frac{Y_t(i)}{\widetilde{K}_{t-1}(i)} = \widetilde{Z}_t, \tag{4}$$

$$\alpha_2 \frac{Y_t(i)}{M_t(i)} = E_t, \tag{5}$$

$$\alpha_3 \frac{Y_t(i)}{\widetilde{Y}_t(i)} = \widetilde{P}^y_t, \text{ and} \tag{6}$$

$$\alpha_4 \frac{Y_t(i)}{N_{2,t}(i)} = W_{2,t}, \tag{7}$$

where $\widetilde{Z}_t$ is the rental price of non-robotic capital; E_t is the real exchange rate, defined by $\left(S_t P^*_t\right)/P_t$, where S_t is the nominal exchange rate, P^*_t the external price level, and P_t the price level; and $W_{2,t}$ is the real wage of high-skilled workers. To obtain $\widetilde{P}^y_t$, the price of $\widetilde{Y}_t$, we solve the usual cost-minimization problem:

$$\frac{R_{t-1}(i)}{N_{1,t}(i)} = \left(\frac{\widetilde{P}^R_t}{W_{1,t}}\right)^{-\epsilon}, \text{ and} \tag{8}$$

$$\frac{N_{11,t}(i)}{N_{12,t}(i)} = \frac{\alpha^{\epsilon_1}}{(1-\alpha)^{\epsilon_1}} \left(\frac{W_{11,t}}{W_{12,t}}\right)^{-\epsilon_1}, \tag{9}$$

where $\widetilde{P}^R_t$ is the rental price of robots and $W_{11,t}$ and $W_{12,t}$ are the wage rate for medium and low-skilled women and men, respectively. Thus, the respective price indexes are:

$$\widetilde{P}_t^y = \left(\widetilde{\alpha}^{\epsilon} W_{1,t}^{1-\epsilon} + (1-\widetilde{\alpha})^{\epsilon} \left(\widetilde{P}_t^R \right)^{1-\epsilon} \right)^{\frac{1}{1-\epsilon}}, \text{ and} \tag{10}$$

$$W_{1,t} = \left(\alpha^{\epsilon_1} W_{11,t}^{1-\epsilon_1} + (1-\alpha)^{\epsilon_1} W_{12,t}^{1-\epsilon_1} \right)^{\frac{1}{1-\epsilon_1}}. \tag{11}$$

B. Households

The model considers a continuum of households, indexed by $j \in [0,1]$. Household preferences are given by Greenwood-Hercowitz-Huffman (GHH) preferences to capture the higher volatility of open developing economies, where $C(j)$ is consumption and $N(j)$ is the labor supply for different types of worker. We assume that each type of worker has their own utility function. For high-skilled workers:

$$\max_{\left\{C_{1i,t}(j), N_{2i,t}(j), B_{t+1}(j), B_{t+1}^*(j)\right\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t U_{2,t}(j) = \sum_{t=0}^{\infty} \beta^t \frac{\left(C_{2,t}(j) - \theta_2 \frac{N_{2,t}(j)^{1+\nu_2}}{1+\nu_2} \right)^{1-\sigma} - 1}{1-\sigma}, \tag{12}$$

where σ is the relative risk aversion parameter, ν_2 is the inverse of the elasticity of labor supply to wages, and θ_2 is a parameter calibrated to obtain a realistic version of hours worked in steady state. The budget constraint for this type of workers is given by:

$$C_{2,t}(j) \leq W_{2,t} N_{2,t}(j) + B_t(j) - B_t^*(j) + D_t - T_t - \frac{B_{t+1}(j)}{\widetilde{R}_t} + \frac{E_t}{E_{t+1}} \frac{B_{t+1}^*(j)}{\Phi_t R_t^*}, \tag{13}$$

where B_t and B_t^* are the domestic and external debt of households; D_t corresponds to dividends; Φ_t is the country risk premium function, and R_t^* ,$\widetilde{R}_t$, and T_t are the gross foreign real interest rate, the gross domestic real interest rate, and lump-sum taxes.

For medium and low-skilled workers, we assume that the utility function is similar, but their consumption is restricted to their labor income and they do not pay taxes.

(14)
$$\max_{\{C_{1i,t}(j),N_{1i,t}(j)\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t U_{1i,t}(j) = \sum_{t=0}^{\infty} \beta^t \frac{\left(C_{1i,t}(j) - \theta_{1i}\frac{N_{1i,t}(j)^{1+\nu_{1i}}}{1+\nu_{1i}}\right)^{1-\sigma} - 1}{1-\sigma},\ i = 1, 2,$$

subject to:

$$C_{1i,t}(j) = W_{1i,t}N_{1i,t}(j),\ i = 1, 2. \tag{15}$$

The continuum of family units is divided such that λ corresponds to the percentage of medium and low-skilled workers and $(1-\lambda)$ to high-skilled workers.

The first-order conditions are the following, and they give us the equations that determine the labor supply for each type of worker:

$$\theta_{1i}N_{1i,t}^{\nu_{1i}}(j) = W_{1i,t},\ i = 1, 2; \tag{16}$$

$$\theta_2 N_{2,t}^{\nu_2}(j) = W_{2,t}. \tag{17}$$

Given our assumption of perfect foresight, we can express the consumption Euler equation for high-skilled workers as follows:

$$\left(C_{2,t}(j) - \theta_2\frac{N_{2,t}^{1+\nu_2}(j)}{1+\nu_2}\right)^{-\sigma} = \beta\left(C_{2,t+1}(j) - \theta_2\frac{N_{2,t+1}^{1+\nu_2}(j)}{1+\nu_2}\right)^{-\sigma}\widetilde{R}_t, \tag{18}$$

where $\widetilde{R}_t$ is the real interest rate. Based on the same assumption of perfect foresight, we can derive the uncovered interest rate parity (UIP) adjusted by the country risk premium, Ω_t which determines the evolution of the real exchange rate over time:

$$E_t = \frac{E_{t+1}\widetilde{R}_t^*\Omega_t}{\widetilde{R}_t}. \tag{19}$$

C. Investment in the non-robotic sector

We assume a simple form of capital accumulation, in which firms $l \in [0,1]$ maximize the benefits of leasing capital subject to market prices, adjustment costs, and depreciation at every moment in time. These firms decide not only how much capital to build, but also the intensity of its use—measured by the variable μ_t. Thus, the stock of capital used by goods-producing firms is $\widetilde{K}_t(l) = \mu_t K_t(l)$. We define investment and adjustment costs as $I_t(l)$ and $\phi_t(l)$; this function fulfills the standard properties: $\phi_t(\delta) = \delta$ and $\phi_t'(\delta) = 1.0$. The maximization problem of capital-producing firms is then:

$$\max_{\{I_t(l),\mu_t(l)\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \Lambda_{0,t} \left(\widetilde{Z}_t(l) K_t(l) - I_t(l) \right), \tag{20}$$

where $\widetilde{Z}_t(l) = Z_t \mu_t(l)$ subject to:

$$K_{t+1}(l) = (1-\delta_t(l))K_t(l) + \phi\left(\frac{I_t(l)}{K_t(l)}\right) K_t(l), \ \textit{and} \tag{21}$$

$$\delta_t(l) = \delta + \xi \left(\frac{\mu_t(l)^{\eta^{MU}+1} - 1}{\eta^{MU}+1} \right), \tag{22}$$

where $\Lambda_{0,t}$ is the compound interest rate between 0 and t and $\delta_t(l)$ is the depreciation rate of the capital stock, which depends on the capital utilization $\mu_t(l)$ of each firm l. We arbitrarily set the parameter ξ such that $\mu(l) = 1$ in steady state.

The first-order conditions of the non-robotic investment of firm are the equilibrium condition for investment:

$$1 = Q_t(l)\phi_t'(l). \tag{23}$$

where $Q_t(l)$ is Tobin's Q for firm l in the non-robotic sector, which depends on both the future present values of the capital rental price:

$$Q_t(l) = \frac{1}{\widetilde{R}_t} \left\{ \widetilde{Z}_{t+1}(l) + Q_{t+1}(l) \left[(1-\delta_t(l)) + \phi_{t+1}(l) - \phi_t' \left(\frac{I_{t+1}(l)}{K_t(l)} \right) \right] \right\}, \tag{24}$$

and the decision rule for the capital utilization rate:

$$\frac{Z_t}{Q_t(l)} = \xi \mu_t(l)^{\eta^{NU}}. \tag{25}$$

D. Investment in the robotic sector

We follow a similar strategy to model investment in robots by assuming a continuum of firms $s \in [0,1]$. However, we consider three mutually exclusive cases: all the robots are imported; robots are produced domestically; and robots are imported, but they help the productivity of high-skilled workers. In this subsection, we develop only the first alternative. We return to the other two cases after defining the equilibrium of the economy. The maximization problem of robot-using firms is:

$$\max_{\left\{M_t^R(s), \mu_t^R(s)\right\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \Lambda_{0,t} \left(\widetilde{P}_t^R(s) R_t(s) - M_t^R(s)\right), \tag{26}$$

where $\widetilde{P}^R(s) = P^R \mu^R(s)$, $\mu^R(s)$ is the utilization rate of robot stock; and $M^R(s)$ are imports of robots for firm s, subject to:

$$R_{t+1}(s) = \left(1 - \delta_t^R(s)\right) R_t(s) + \phi^R \left(\frac{M_t^R(s)}{R_t(s)}\right) R_t(s), \text{ and} \tag{27}$$

$$\delta_t^R(s) = \delta^R + \xi^R \left(\frac{\mu_t^R(s)^{\eta_R^{MU}+1} - 1}{\eta_R^{MU} + 1}\right). \tag{28}$$

The first-order condition is the following, which is the equilibrium condition for investment in robots for firm s:

$$E_t P_t^S = Q_t^R(s) \phi_t'^R(s), \tag{29}$$

where P^S is the robot import price in foreign currency (in real term); $Q^R(s)$ is Tobin's Q for firm s in the robotic sector; $\phi^R(s)$ is the adjustment cost on the robot investment $M^R(s)$, which fulfills the same properties as in the non-robotic sector for each firm s; and $\delta^R(s)$ is the depreciation rate for robot capital stock, $R(s)$. Tobin's Q and the decision rule for the robotic capital utilization rate are defined as before:

(30)
$$Q_t^R(s) = \frac{1}{\widetilde{R}_t}\left\{\widetilde{P}_{t+1}^R(s) + Q_{t+1}^R(s)\left[\left(1-\delta_t^R(s)\right) + \phi_{t+1}^R(s) - \phi_t'^R\left(\frac{M_{t+1}^R(s)}{R_t(s)}\right)\right]\right\},$$

$$\frac{P_t^R}{Q_t^R(s)} = \xi^R \mu_t^R(s)^{\eta_R^{MU}}. \tag{31}$$

E. Exports, equilibrium, and country risk premium

Since our focus is on small open developing economies, output should be equal to domestic demand plus exports of goods and services:

$$Y_t = C_t + G_t + I_t^T + X_t^T. \tag{32}$$

where $Y_t = \int Y_t(i)di$, $C_t = \int_0^\lambda \sum_{i=1}^2 C_{1i,t}(j)dj + \int_\lambda^1 C_{2,t}(j)dj$, $I_t^T = \int I_t(l)dl$, $N_{2,t} = \int N_{2,t}(i)di = \frac{1}{(1-\lambda)}\int_\lambda^1 N_{2,t}(j)dj$, and $N_{1i,t} = \int N_{1i,t}(i)di = \frac{1}{\lambda}\int_0^\lambda N_{1i,t}(j)dj$, $i = 1, 2$. Total exports are composed of non-commodity goods and commodities. We model the first types of goods as follows:

$$X_t = \left(P_t^{X^*}\right)^{-\eta^*} Y_t^*, \tag{33}$$

where η^* is the demand elasticity in foreign markets and Y_t^* is foreign output. We assume that the price of exports is set in dollars on the international market (Gopinath et al. (2020)), which in turn is equal to the constant markup over the marginal cost in dollars in real terms:

$$P_t^{X^*} = \mu^* \frac{MC_t^R}{E_t}. \tag{34}$$

The real marginal cost in domestic currency is:

$$MC_t^R = \Lambda \widetilde{Z}_t^{\alpha_1} E_t^{\alpha_2} \widetilde{P}_t^{y\alpha_3} W_{2,t}^{\alpha_4}, \tag{35}$$

where $\mu^* = \frac{\eta^*}{\eta^*-1}$ and $\Lambda = \left(\frac{1}{\alpha_1}\right)^{\alpha_1}\left(\frac{1}{\alpha_2}\right)^{\alpha_2}\left(\frac{1}{\alpha_3}\right)^{\alpha_3}\left(\frac{1}{\alpha_4}\right)^{\alpha_4}$. We assume constant returns to scale, thus the marginal costs are the same for each firm.

The analysis of exports is a crucial issue in the model, because while the fall in the robot import price is a negative shock at the labor level due to the replacement of less qualified workers, it is a positive shock that reduces marginal costs and therefore improves export competitiveness in international markets.

The incentives to adopt the new technology derive from the tough competition between countries to maintain their market share, which makes adoption more of a necessity than an option. As mentioned in the introduction, several authors argue and find evidence that in order to compete in developed-country markets, with demanding and sophisticated consumers, export industries need to use high-quality inputs, distribution, transportation, and advertising (Bastos, Silva, and Verhoogen (2018); Brambilla, Lederman, and Porto (2012); Matsuyama (2007)). Robots, including artificial intelligence, are part of these inputs and requirements for satisfying these more sophisticated consumers than those present in developing countries.

This last point calls into question the feasibility of imposing prohibitive taxes on the importation of robots. Indeed, under the extreme assumption that we can completely isolate the economy from robot imports by imposing tariffs, the competitiveness of the export sector will be reduced. As discussed in our analysis of the results of the model simulations, there are alternatives to imposing tariffs that do not reduce the competitiveness of this sector, through improvements to human capital.

Then, total exports are the sum of intermediate and commodity exports:

$$X_t^T = E_t X_t + E_t P_t^{CO} QCO_t, \tag{36}$$

where P^{CO} is the commodity price and QCO is commodity production, which in turn depends on the commodity price. Total imports will be equal to:

$$M_t^T = E_t M_t + E_t P_t^S M_t^R. \tag{37}$$

where $M_t = \int M_t(i)di$ and $M_t^R = \int M_t^R(i)di$. The robot import price is predetermined according to the following form:

$$P_t^R = \left(\bar{P}_t^R\right)^{1-\rho^{PS}} \left(P_{t-1}^R\right)^{1-\rho^{PS}} e^{\mu^{PS}}, \tag{38}$$

where μ^{PS} could be a temporary or permanent shock. Since we assume that the robotics revolution is here to stay, we assume that the economy will face a permanent drop in this price through μ^{P^S}.

Overall, the economy's current account will be equal to:

$$C_t + I_t^T + G_t \leq GDP_t + \frac{E_t}{E_{t+1}} \frac{B_{t+1}^*}{\Omega_t R_t^*} - B_t^*, \tag{39}$$

where total investment, GDP, and consumption are defined as follows:

$$I_t^T = I_t, \tag{40}$$

$$GDP_t = Y_t - M_t^T, \tag{41}$$

$$C_t = (1-\lambda) C_{2,t} + \lambda \left(C_{11,t} + C_{12,t} \right), \tag{42}$$

$$G_t = T_t + \frac{B_{t+1}}{\widetilde{R}_t} + \frac{E_t}{E_{t+1}} \frac{B_{t+1}^{G^*}}{\Phi R_t^*} - B_t - B_t^{G^*}. \tag{43}$$

where $B_t = \int_\lambda^1 B_t(j)dj$ and $B_t^* = \int_\lambda^1 B_t^*(j)dj + B_t^{G^*}$. As in Schmitt-Grohé and Uribe (2003), we close the model by assuming that the country risk premium function, Ω_t, depends on total country external debt over real GDP as a measure of country risk:

(44)

$$\Omega_t = 1 + \underbrace{\Psi_1 \left[e^{\left(\frac{B_t^*}{GDP_t} - \frac{B^*}{GDP} \right)} - 1 \right]}_{Country\ Risk} \underbrace{+ \Psi_2 \left[e^{\left(\frac{B_{t+1}^*}{Q_t K_{t+1} + Q_t^R R_{t+1}} - \frac{B^*}{QK + Q^R R} \right) \left(\frac{E_t}{E_{t+1}} \right)} - 1 \right]}_{Financial\ Accelerator\ Effect}.$$

The second term in the risk premium function corresponds to the financial accelerator proposed by Gertler, Gilchrist, and Natalucci (2007) for a small open economy. This term connects the exchange rate with financial distress (measured by the value of external debt, including expectations of real exchange rate depreciation) with respect to the value of robotic and non-robotic capital (as a measure of the economy's collateral). Both effects produce an upward-sloping supply of funds, indicating that the economy faces financial frictions in the external credit markets. These assumptions highlight once again that we are modeling underdevelopment not only at the level of trade, but also at the level of finance, where these countries also face constraints. Thus, these are necessary assumptions to explain the true dynamics of the robotics revolution in these countries over time.

For the sake of simplicity, we further assume that the shares of government spending and natural resource exports remain constant relative to GDP:

$$G_t = \left(\frac{G}{GDP}\right) GDP_t, \tag{45}$$

$$QCO_t = \left(\frac{QCO}{GDP}\right) QCO_t. \tag{46}$$

Finally, the model is completed with the definition of competitive equilibrium with imperfections in both trade and financial markets, which is calibrated, solved, and simulated in section.

DEFINITION 1: *Imperfect competitive Price equilibrium.*
An imperfect competitive price equilibrium is a set of prices in real terms:

$$\left\{W_{11,t}, W_{12,t}, W_{2,t}, Z_t, E_t, \widetilde{R}_t, R_t^*, Q_t, Q_t^R, P_t^{X^*}, P_t^S, P_t^R, P_t^{CO}\right\}_{t=0}^{\infty},$$

such that a fraction $(1-\lambda)$ *of* j *households (made up of high-skilled workers) maximizes utility, all* i *intermediate-goods producers maximize profits in the domestic and foreign markets, all* l *and* s *capital producers maximize profits, markets clear, and the current account restriction is fulfilled. A fraction* λ *of* j *households who cannot optimize at a specific point in time (low-skilled workers) use a simple consumption rule.*

In this definition of equilibrium, agents take as given a technological constraint, external activity, domestic and external financial frictions (including the country risk premium), government expenditure, initial debt, initial capital, and all shocks.

F. Alternative cases of robotic investment

Without a doubt, the alternative of only importing robots is the most likely scenario in developing countries, at least in the short and medium terms. The lack of research in pure and applied sciences due to deficient support from both the private sector and the government is a reality in these countries, which has led to companies importing much of the more complex machinery and to colleges and universities having modest development in areas such as science, management, and engineering.

To accurately measure this gloomy scenario, we propose two alternatives. First, we model the opposite scenario, in which the country can produce robots instead of importing them. Although this is a distant scenario for many developing countries, it correctly indicates how much it will cost those countries if they decide not to invest adequately in human capital and new technologies relative to developed countries. This allows us to quantify not only the absolute impact within a developing country, but also the gap with the developed world and its implications.

Second, we explore an intermediate and more hopeful scenario for developing countries: robots are imported, but they are complementary to highly skilled workers. This scenario could be achieved after an adjustment period in which these workers are trained to use the imported robotic equipment.

All robots are produced domestically. — The alternative case in which the robots are produced in the country can be easily modeled by assuming that the price of the robots continues to be determined in the international markets, that is, that the robots can be produced with the same efficiency as abroad, but using national resources.

Equation (29) becomes:

$$P_t^S = Q_t^R(s)\phi_t^{\prime R}(s).$$

At the same time, M_t^R are no longer imports but are the part of national investment that is dedicated to accumulating the stock of robots. In other words, total investment is:

$$I_t^T = I_t^T + P_t^S M_t^R.$$

To compare the previous model (henceforth, case A) with the case in this section (case B), we assume that both start from the same steady state or initial values. The main difference between case A and case B is that in the latter, the economy's resources are used to invest in robots.

Robots are imported but contribute to high-skilled workers´ productivity. — An intermediate alternative between cases A and B is to assume that workers benefit from the incorporation of robots, that is, the use of robots and labor are complementary, not substitutes as in case A. We call this case C. The production function (1) is now:

$$Y_t(i) = A_1 K_{t-1}^{\alpha_1}(i) M_t^{\alpha_2}(i) \widetilde{Y}_t^{\alpha_3}(i) \left(R_t^{\frac{N_{2,t}}{N_{2,t}+N_{11,t}+N_{12,t}} - \tau} N_{2,t}(i) \right)^{\alpha_4},$$

where the robot stock affects the productivity of high-skilled workers depending on the proportion of these workers in the total workforce; otherwise, this effect is negligible. One technical difference is that the parameter τ is only a constant to ensure that the steady state is equal to the initial steady state of the other two cases.

Consequently, workers who do not compete with robots benefit from using them—for example, engineers who are more productive because they learn to build robots or workers who learn to program the robots using artificial intelligence algorithms. In other words, the introduction of robots is also a positive externality, which in the production function can permanently affect the economy's GDP growth rate and marginal costs. However, we impose an additional limitation on this traditional notion from the endogenous growth literature: the positive effect of robots in case C is only important if highly skilled workers are a significant fraction of the workforce; otherwise, the effect is diluted.

G. Welfare

The aggregate utility function would be equal to the weighted sum of the utility functions of each type of worker:

$$U_t = (1-\lambda) U_{2,t} + \lambda (U_{11,t} + U_{12,t}). \tag{47}$$

where $\lambda (U_{11,t} + U_{12,t}) = \int_0^\lambda \sum_{i=1}^2 U_{1i,t}(j)dj$ and $(1-\lambda) U_{2,t} = \int_\lambda^1 U_{2,t}(j)dj$.

Therefore, the total welfare of the economy constitutes the sum of the present utility and the present value of future utilities:

$$W_t = U_t + \beta W_{t+1}. \tag{48}$$

III. Results

The results of the model are obtained by simulating a small open developing economy. We use the Chilean economy as the base case for calibrating the model parameters, basically because of data availability (see table A.1. in the Appendix A.1). It could, however, be any other developing economy that fulfills three general conditions: (i) a labor market with a limited number of high-skilled workers and a minor stock of robots; (ii) a country open to trade in both differentiated goods and commodities, whose prices are fixed in dollars on the international markets; and (iii) only partial flow of foreign debt due to financial frictions that limit the possibilities of smoothing consumption and financing investment. In this sense, one of the additional contributions of this study is to propose a fairly general methodology—which can be easily modified—to measure the medium and long-term impacts of robots in any economy with the above conditions.

As mentioned, one of the important characteristics of Chile—which it shares with many other developing economies—is that the current stock of robots is extremely low, in addition to the typical characteristics of developing countries (insufficient infrastructure, low quality health and education for a significant percentage of the population, low pensions, etc.)[1]. Consequently, the simulations that we present in this section consist in analyzing how an economy with this initial situation evolves through the years following a substantial drop in the robot import price. In other words, we look at how these machines gradually populate the labor market, changing key relative prices, the real marginal cost of production, and finally the long-term imperfect competitive equilibrium defined in the previous section.

To be able to solve the model, we assume that agents internalize that once the robotic revolution occurs, the import price of robots falls permanently by 50%. In this regard, we take as a reference for this fall the evolution of robot prices since 1990 (see Tilley (2017)). Since it is a drastic change in an exogenous variable within the model, it is not possible or desirable to linearize the model. Therefore, the model—that is, the set of equations in differences represented by the first-order conditions, the equilibrium condition, and the current account of the economy—is solved simultaneously using the standard Newton's method with sparse matrices (Heer and Maussner (2009)). For the application of this method, we take the current steady state of the Chilean economy as our initial values. Since the calculation of this equilibrium is complex, we present the details in the Appendix A.1.

For the sake of simplicity, we present the results in two parts: macroeconomic and firm-level variables (disaggregated into robotic and non-robotic capital) and household variables (disaggregated into the labor market and welfare). Tables 1–2 present the results for case A, where all robots are imported. As shown in table 1, despite the low number of robots when the robot price drops, GDP falls continuously for ten years, reaching an accumulated contraction of up to 10%. Given that the potential GDP of the Chilean economy is approximately 2.5%, four years of potential growth are lost in these ten years. The economy accommodates the drop in the robot price with a reduction in the real interest rate and an increase in the real exchange rate, as if this were a negative external shock.

[1]The robot share is currently around 0.46%, according to the World LA KLEMS database.

Despite these adjustments, both consumption and private aggregate investment fall, especially the latter. The negative aggregate impact more than offsets the productivity gains of the robots in these years, and only after two decades does the economy gradually recover. The cost-saving effects of robots lead to increased exports in intermediate goods, and the low robot prices cause imports to grow from the first year.

Next, the effects on the labor market are dramatic but expected for this representative developing economy (see table 2). The results parallel the literature for developed countries: medium and low-skilled jobs fall steadily in conjunction with real wages. Within this group, women are the most affected, a critical result because women are concentrated in this group of workers in this country. The distributional effects are also dramatic: although the group of more qualified workers suffers a decrease in employment and work in the first three years, the positive effects of robots on productivity quickly favor these workers starting in the fourth year. From that moment on, their employment and wages increase, systematically widening the gap between high-skilled workers and the rest of the labor force. The effects on welfare are evident (table 2): the impact of robots is devastating for medium and low-skilled workers, who never recover.

On the firms side (table 1), the reaction is spectacular in terms of investment in robots, which in case A includes imports. Although the initial stock of these machines is marginal, it grows extraordinarily in the first ten years, before stabilizing. This result is expected because the price drop has been assumed to be permanent, without falling again in the next 40 years. In contrast, non-robotic investment falls initially and only starts to recover after about ten years, as productivity gains from robots are transferred to different sectors of the economy.

Undoubtedly, this last assumption is controversial, as the prices of these machines, like many other new technologies, can be expected to continue falling over time. We assume a permanent drop for reasons of simplicity, but it is straightforward to simulate alternative paths with subsequent price cuts in our model. The dynamics of the different variables for each new simulated drop will parallel the above results in the first ten years.

The effects of the introduction of robots in the developing economy become more evident if we compare the above results with case B, in which robots are produced domestically, as they are in developed countries (see tables 3–4). Under this scenario, the economy is simply evolving toward incredible growth rates. Consumption suffers (table 3), but it is driving all types of investment, while the productivity gains from incorporating robots drive robotic and non-robotic production, exports of goods, and imports of all types of inputs. Obviously, this is a very unlikely counterfactual scenario in developing economies, but it serves

Table 1—Case A: Macroeconomic Variables and Firms Investment

Year	Robot price	GDP	Consumption	Investment	Imports	Exports	Real exchange rate	Real interest rate	Non-robotic investment	Robotic investment
1	-50	-1.17	-0.33	-4.42	2.23	2.77	1.03	-0.76	-4.42	450.73
2	-50	-1.19	-0.39	-3.77	2.81	2.94	1.09	-0.79	-3.77	516.48
3	-50	-1.18	-0.45	-3.18	3.31	3.17	1.16	-0.84	-3.18	568.85
4	-50	-1.13	-0.50	-2.64	3.71	3.41	1.24	-0.89	-2.64	607.59
5	-50	-1.06	-0.54	-2.14	4.03	3.65	1.30	-0.94	-2.14	633.89
6	-50	-0.97	-0.58	-1.66	4.27	3.86	1.36	-0.99	-1.66	649.75
7	-50	-0.87	-0.61	-1.20	4.44	4.06	1.41	-1.04	-1.20	657.40
8	-50	-0.76	-0.63	-0.77	4.57	4.22	1.45	-1.07	-0.77	658.99
9	-50	-0.64	-0.65	-0.36	4.66	4.36	1.48	-1.10	-0.36	656.40
10	-50	-0.53	-0.66	0.04	4.72	4.47	1.51	-1.12	0.04	651.13
15	-50	-0.03	-0.64	1.67	4.88	4.81	1.56	-1.13	1.67	615.10
20	-50	0.35	-0.56	2.86	5.04	5.02	1.58	-1.07	2.86	590.86
25	-50	0.67	-0.46	3.79	5.26	5.24	1.62	-0.97	3.79	580.70
30	-50	0.98	-0.33	4.64	5.55	5.52	1.67	-0.87	4.64	578.95
35	-50	1.30	-0.21	5.54	5.90	5.86	1.74	-0.75	5.54	581.98
40	-50	1.67	-0.07	6.59	6.33	6.27	1.83	-0.62	6.59	588.20

Note: In case A, all robots are imported.

Source: Authors' calculation, based on the model in section II.

Table 2—Case A: Labor Market and Household Welfare

Year	Jobs				Wages				Utility	
	Medium and low-skilled			High-skilled	Medium and low-skilled			High-skilled	Medium and low-skilled	
	All	Male	Female		All	Male	Female		Male	Female
1	-0.42	-0.34	-0.70	-0.18	-0.56	-0.63	-0.29	-0.18	-0.01	-0.12
2	-0.68	-0.55	-1.15	-0.12	-0.91	-1.03	-0.47	-0.12	-0.02	-0.20
3	-0.94	-0.76	-1.58	-0.05	-1.25	-1.42	-0.65	-0.05	-0.03	-0.27
4	-1.19	-0.96	-2.00	0.01	-1.58	-1.80	-0.82	0.01	-0.04	-0.34
5	-1.42	-1.15	-2.38	0.08	-1.89	-2.14	-0.98	0.08	-0.05	-0.41
6	-1.63	-1.32	-2.73	0.14	-2.17	-2.46	-1.13	0.14	-0.05	-0.47
7	-1.82	-1.47	-3.04	0.20	-2.42	-2.74	-1.26	0.20	-0.06	-0.53
8	-1.98	-1.60	-3.32	0.25	-2.63	-2.99	-1.37	0.25	-0.06	-0.58
9	-2.13	-1.72	-3.56	0.31	-2.83	-3.21	-1.47	0.31	-0.07	-0.62
10	-2.25	-1.82	-3.76	0.36	-2.99	-3.39	-1.56	0.36	-0.07	-0.66
15	-2.64	-2.13	-4.40	0.57	-3.50	-3.97	-1.83	0.57	-0.09	-0.78
20	-2.77	-2.24	-4.63	0.73	-3.68	-4.17	-1.92	0.73	-0.09	-0.82
25	-2.78	-2.25	-4.64	0.88	-3.69	-4.19	-1.93	0.88	-0.09	-0.83
30	-2.73	-2.21	-4.55	1.03	-3.62	-4.11	-1.89	1.03	-0.09	-0.81
35	-2.64	-2.13	-4.40	1.19	-3.50	-3.97	-1.83	1.19	-0.09	-0.78
40	-2.52	-2.03	-4.20	1.38	-3.34	-3.79	-1.74	1.38	-0.08	-0.74

Note: In case A, all robots are imported.

Source: Authors' calculation, based on the model in section II.

to illustrate the gaps that could arise between these and small developed countries following the introduction of robotic technology. In a horizon of only four decades, the gap may become unbridgeable not only with this group of countries, but with the developed world in general.

Even in this incredible scenario B, it takes three decades to reverse the negative effect on medium and low-skilled workers. Thus, the impact of robots is so positive that even these workers improve their position, especially women, but only in the long run. Without a doubt this illustrates the importance of investment in human capital: basically, a country can only take advantage of the productivity increases that these machines introduce into the economy, measured in their low prices, if labor and robots are complementary. Otherwise, the introduction of robots becomes a veritable war of extermination against medium and low-skilled humans.

It is important to clarify a crucial point in the simulation of model B. The force behind the results of this simulation is the productivity gains from producing an input—the robots—at a very low cost. This pushes the rest of the economy, through greater demand for resources to produce these machines. Although it is a virtuous circle, decreasing returns continue to operate, which, according to equation (1), will limit expansion at some point. This virtuous circle would be permanent if model B included the endogenous growth mechanism that is in model C, as explained in section II. In other words, even without this mechanism, which is likely to develop in the productive system over time, the gains from being able to produce inputs at very low prices allow for significant economic growth. Thus, the differences between models A and B should be even greater if we included the endogenous growth mechanism in model B.

Is there a middle way? In tables 5–6, we simulate case C, in which all the robots are imported, but they are complemented by high-skilled workers. This scenario can be interpreted as developing countries taking some steps to improve their human capital in order to increase the complementarity between the labor force and the robots. The results are intermediate at the macroeconomic level, but some of the negative results of the first two scenarios remain. First, medium and low-skilled workers continue to be adversely affected, giving rise to the same distributional effects that hurt this group of workers. Second, the gap with small developed countries, although smaller, remains large at the end of the forty years.

A comparison of the simulations of cases B and C shows that in the horizon analyzed, not even the endogenous growth mechanism in model C is capable of producing a growth effect that exceeds the gains of producing robots domestically. In other words, it is not enough to know how to handle robots and take advantage of the positive externalities produced by these machines; domestic production is a key factor for offsetting the economic impact of the replacement of medium and low-skilled workers. Furthermore, as mentioned above, both alternatives should possess this mechanism in the very long term. However, isolating the effect of the price drop in case B—without the endogenous growth mechanism—allows us to clearly highlight the importance of producing robots without taking into account the associated externalities. Indeed, the virtuous circle produced with other sectors of the economy makes the difference, because of the magnitude of the resources mobilized for the direct production of robots.

Table 3—Case B: Macroeconomic Variables and Firms Investment

Year	Robot price	GDP	Consumption	Investment	Imports	Exports	Real exchange rate	Real interest rate	Non-robotic investment	Robotic investment
1	-50	0.70	-1.70	7.49	-0.14	-0.08	-0.11	-1.55	2.41	575.33
2	-50	1.28	-1.66	9.79	0.43	0.36	-0.03	-1.85	3.68	692.02
3	-50	1.88	-1.61	12.08	1.02	0.86	0.07	-2.12	5.06	795.00
4	-50	2.48	-1.55	14.33	1.61	1.39	0.18	-2.36	6.55	880.72
5	-50	3.07	-1.50	16.49	2.19	1.94	0.29	-2.54	8.12	948.39
6	-50	3.65	-1.43	18.56	2.76	2.50	0.41	-2.66	9.74	999.25
7	-50	4.21	-1.37	20.53	3.31	3.06	0.53	-2.74	11.39	1035.68
8	-50	4.76	-1.29	22.42	3.85	3.62	0.65	-2.78	13.06	1060.54
9	-50	5.30	-1.22	24.23	4.38	4.16	0.76	-2.77	14.72	1076.70
10	-50	5.82	-1.13	25.97	4.89	4.70	0.88	-2.74	16.38	1086.68
15	-50	8.36	-0.63	34.21	7.39	7.30	1.42	-2.31	24.46	1104.26
20	-50	11.01	-0.03	42.68	10.00	9.93	1.96	-1.66	32.63	1138.73
25	-50	14.02	0.66	52.36	12.96	12.86	2.54	-0.88	41.66	1212.25
30	-50	17.56	1.42	63.91	16.44	16.29	3.19	0.03	52.23	1323.16
35	-50	21.78	2.27	77.88	20.59	20.36	3.95	1.08	64.89	1471.18
40	-50	26.81	3.20	94.76	25.54	25.22	4.83	2.29	80.10	1660.15

Note: In case B, all robots are produced domestically.

Source: Authors' calculation, based on the model in section II.

Table 4—Case B: Labor Market and Household Welfare

Year	Jobs				Wages				Utility	
	Medium and low-skilled			High-skilled	Medium and low-skilled			High-skilled	Medium and low-skilled	
	All	Male	Female		All	Male	Female		Male	Female
1	-0.07	-0.06	-0.13	0.25	-0.10	-0.11	-0.05	0.25	0.00	-0.02
2	-0.22	-0.18	-0.37	0.54	-0.30	-0.34	-0.15	0.54	-0.01	-0.06
3	-0.38	-0.31	-0.64	0.83	-0.51	-0.58	-0.26	0.83	-0.01	-0.11
4	-0.54	-0.44	-0.91	1.13	-0.72	-0.82	-0.37	1.13	-0.02	-0.15
5	-0.70	-0.56	-1.17	1.42	-0.93	-1.05	-0.48	1.42	-0.02	-0.20
6	-0.84	-0.68	-1.41	1.70	-1.12	-1.27	-0.58	1.70	-0.03	-0.24
7	-0.96	-0.78	-1.62	1.98	-1.28	-1.46	-0.67	1.98	-0.03	-0.28
8	-1.07	-0.86	-1.79	2.25	-1.42	-1.61	-0.74	2.25	-0.03	-0.31
9	-1.15	-0.93	-1.93	2.51	-1.53	-1.74	-0.79	2.51	-0.04	-0.33
10	-1.21	-0.97	-2.03	2.76	-1.61	-1.82	-0.84	2.76	-0.04	-0.35
15	-1.19	-0.96	-1.99	3.98	-1.58	-1.79	-0.82	3.98	-0.04	-0.34
20	-0.75	-0.61	-1.26	5.25	-1.00	-1.14	-0.52	5.25	-0.02	-0.22
25	-0.03	-0.03	-0.06	6.66	-0.05	-0.05	-0.02	6.66	0.00	-0.01
30	0.90	0.73	1.53	8.30	1.21	1.37	0.62	8.30	0.03	0.25
35	2.04	1.64	3.46	10.22	2.73	3.10	1.40	10.22	0.06	0.56
40	3.37	2.71	5.74	12.48	4.51	5.15	2.31	12.48	0.10	0.90

Note: In case B, all robots are produced domestically.

Source: Authors' calculation, based on the model in section II.

Another possibility that we have not considered thus far is what happens if the increase in robots in the big developed trading blocs, such as the United State, Europe, or Asia, translates into a greater demand for goods from developing countries. To consider this last element, we assume that in conjunction with the reduction in robot prices, there is a simultaneous increase in external growth of 0.6%, measured by the average gains in total factor productivity (TFP) calculated by Graetz and Michaels (2018), due to the incorporation of robots in

Table 5—Case C: Macroeconomic Variables and Firms Investment

Year	Robot price	GDP	Consumption	Investment	Imports	Exports	Real exchange rate	Real interest rate	Non-robotic investment	Robotic investment
1	-50	-1.07	0.41	-6.25	2.48	3.09	1.12	-1.53	-6.25	450.73
2	-50	-0.93	0.40	-5.04	3.30	3.43	1.22	-1.63	-5.04	516.48
3	-50	-0.76	0.40	-3.93	4.04	3.84	1.33	-1.73	-3.93	568.85
4	-50	-0.56	0.40	-2.89	4.67	4.27	1.45	-1.82	-2.89	607.59
5	-50	-0.35	0.40	-1.93	5.19	4.69	1.56	-1.90	-1.93	633.89
6	-50	-0.12	0.40	-1.03	5.61	5.08	1.66	-1.97	-1.03	649.75
7	-50	0.11	0.42	-0.20	5.94	5.44	1.74	-2.02	-0.20	657.40
8	-50	0.35	0.43	0.58	6.21	5.76	1.82	-2.07	0.58	658.99
9	-50	0.57	0.45	1.31	6.43	6.03	1.88	-2.10	1.31	656.40
10	-50	0.79	0.48	1.98	6.61	6.28	1.93	-2.12	1.98	651.13
15	-50	1.71	0.65	4.73	7.20	7.10	2.09	-2.09	4.73	615.10
20	-50	2.42	0.87	6.75	7.69	7.67	2.19	-1.96	6.75	590.86
25	-50	3.04	1.11	8.44	8.25	8.23	2.29	-1.80	8.44	580.70
30	-50	3.66	1.36	10.12	8.90	8.87	2.42	-1.61	10.12	578.95
35	-50	4.33	1.62	12.00	9.67	9.62	2.58	-1.40	12.00	581.98
40	-50	5.11	1.90	14.22	10.58	10.52	2.77	-1.16	14.22	588.20

Source: Authors' calculation, based on the model in section II.

Table 6—Case C: Labor Market and Household Welfare

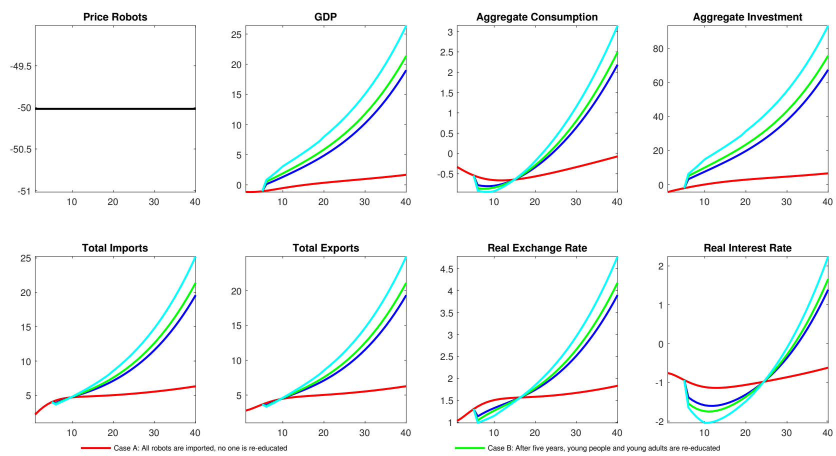
Year	Jobs				Wages				Utility	
	Medium and low-skilled			High-skilled	Medium and low-skilled			High-skilled	Medium and low-skilled	
	All	Male	Female		All	Male	Female		Male	Female
1	-0.37	-0.30	-0.62	-0.11	-0.49	-0.56	-0.25	-0.11	-0.01	-0.10
2	-0.58	-0.47	-0.97	0.04	-0.77	-0.87	-0.40	0.04	-0.02	-0.16
3	-0.79	-0.63	-1.32	0.19	-1.05	-1.19	-0.54	0.19	-0.03	-0.22
4	-0.99	-0.80	-1.66	0.34	-1.31	-1.49	-0.68	0.34	-0.03	-0.28
5	-1.18	-0.95	-1.98	0.48	-1.57	-1.78	-0.81	0.48	-0.04	-0.34
6	-1.35	-1.09	-2.27	0.62	-1.80	-2.04	-0.94	0.62	-0.04	-0.39
7	-1.51	-1.22	-2.52	0.75	-2.00	-2.28	-1.04	0.75	-0.05	-0.44
8	-1.64	-1.33	-2.75	0.87	-2.19	-2.48	-1.14	0.87	-0.05	-0.48
9	-1.76	-1.42	-2.95	0.98	-2.34	-2.66	-1.22	0.98	-0.06	-0.51
10	-1.86	-1.50	-3.12	1.08	-2.47	-2.81	-1.29	1.08	-0.06	-0.54
15	-2.15	-1.73	-3.59	1.50	-2.85	-3.23	-1.49	1.50	-0.07	-0.63
20	-2.19	-1.77	-3.66	1.82	-2.91	-3.30	-1.52	1.82	-0.07	-0.64
25	-2.10	-1.70	-3.52	2.12	-2.79	-3.17	-1.46	2.12	-0.07	-0.62
30	-1.94	-1.57	-3.25	2.42	-2.58	-2.93	-1.35	2.42	-0.06	-0.57
35	-1.73	-1.40	-2.90	2.76	-2.30	-2.61	-1.20	2.76	-0.06	-0.50
40	-1.47	-1.19	-2.46	3.16	-1.96	-2.22	-1.02	3.16	-0.05	-0.43

Source: Authors' calculation, based on the model in section II.

developed countries. We calculate the results only for scenario C, which we now define as case D (see tables B.1.–B.2., in Appendix B.1). As the results show, the increase in external demand from these big trading blocs moderates the effects of the drop in the price of robots, but it in no way compensates for the effects already analyzed for case C.

The specific educational issues of how to increase human capital in developing countries are beyond the scope of this study, especially the endogenous decisions of choosing different levels of human capital, which are quite limited by the poor development of robotics-related fields in the educational system in these countries. To explore the more general issue of the benefits of retraining workers to complement robots, we carry out a second type of simulation in which we simply transpose case A with cases B, C, and D, assuming that the developing economy is initially in the specific situation of case A. Starting in the fourth year, scenarios B, C, and D are gradually transposed on different shares of the workforce, depending on the age of the workers (namely, young people of university age; young people plus young adults; and young people, young adults, and 3% of the remaining workforce). We chose four years because it is the average duration of a college degree in science, engineering, or management. Figures 1, 2, and 3 show the impact of retraining assuming different percentages for the re-educated population. The results clearly show that some of the results of scenario A are reversed, highlighting the benefits that a country can obtain by implementing an accelerated retraining of the population, through investment in technical and college education.

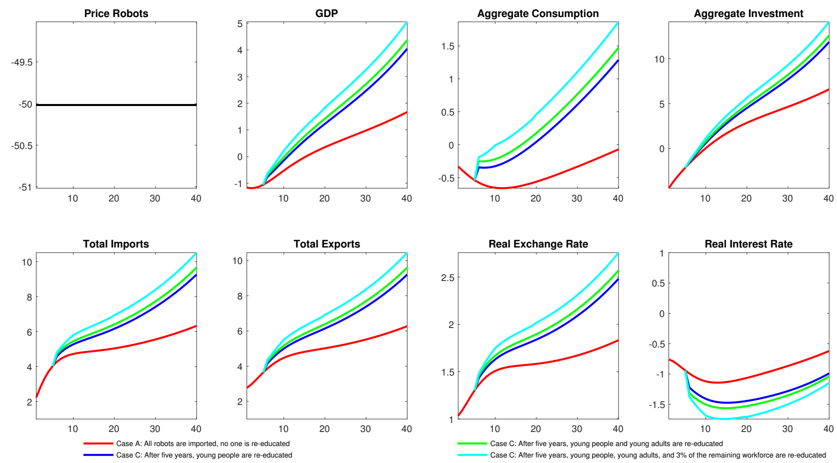
Figure 1. Retraining case B.



Source: Authors' calculation, based on the model in section II.

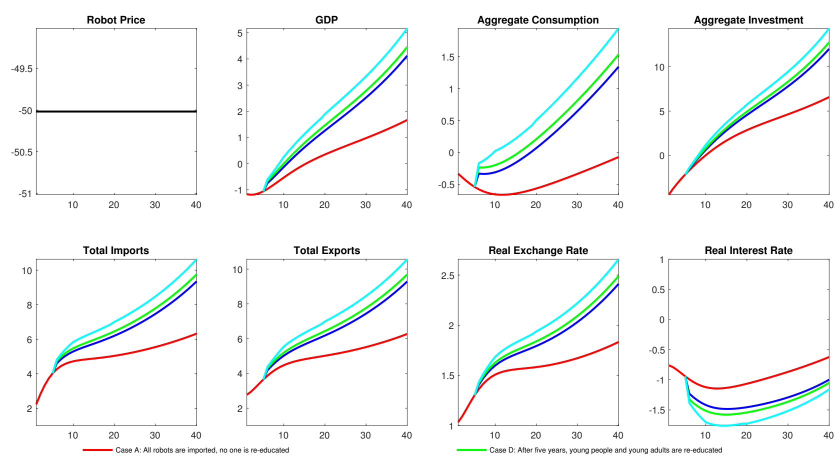
Finally, while our model does not explicitly consider migration between countries, the results of all the simulations suggest that robots would strengthen the incentives for medium and low-skilled workers to migrate to the developed world as a way to combat the poverty brought on by this new technological revolution. From a general equilibrium perspective, this would tend to worsen the fragile situation of medium and low-skilled workers in developed countries mentioned in case B.

Figure 2. Retraining case C.



Source: Authors' calculation, based on the model in section II.

Figure 3. Retraining case D.



Source: Authors' calculation, based on the model in section II.

IV. Conclusion

In this study we quantify the possible effects of the robotics revolution on developing economies. The methodology is general, including not only labor market variables, but also those related to international trade, which are crucial for many of these economies. Some of the results confirm the findings in the literature for developed countries, especially the negative effects on the labor market and the income distribution for medium and low-skilled workers.

However, there are dramatic differences. In the scenario that we have defined as the most likely, robots are massively imported due to a substantial drop in their prices, which causes a substantial negative effect on the economy as a whole in the first decade and a half. Although the productivity gains from the introduction of robots gradually reverse this effect, the negative impact on medium and low-skilled workers is permanent. To prevent this effect, the alternative is to retrain these workers to complement the robots, so that they transition into the group of high-skilled workers. This process takes time, however, since the possibilities for altering human capital endogenously in that direction are limited. It will take time and infrastructure to develop robotics-related programs within the educational system in developing countries.

While the latter mitigates the negative effects within a given economy, it does little to address the gap between developed and developing countries. If these economies cannot produce robots, the differences with small developed economies will be abysmal within four decades, in both aggregate and distributional terms, making it impossible for these developing countries to reach the level of the developed world. This will happen even considering both the incorporation of the traditional endogenous growth mechanism, in which the use of one input (imported robots) produces an increase in the productivity of another input (high-skilled workers), and the positive effects of increased demand for goods from large developed trading blocs, deriving from productivity increases in those countries due to the introduction of robots.

In short, the virtuous circle between the direct production of robots and other sectors of the economy makes the difference, because of the magnitude of the resources mobilized to produce robots.

Appendix A.1. Steady State and Calibrated Parameters

The procedure for calculating the steady state starts with the labor market, because of an important property of the GHH utility function. Since consumption does not appear in the labor supply, parameter can be solved independently from the rest of the model:

$$\alpha = \frac{\kappa}{1+\kappa}, \kappa = \left(\frac{N_{11}}{N_{12}}\right)^{\frac{1}{\epsilon_1}} \left(\frac{W_{11}}{W_{12}}\right), \tag{A.1}$$

where N_{11}, N_{12}, and the gap W_{12}/W_{11} are obtained from the National Statistics Institute (INE), and is from García (2020). Substituting the value of α in equation (16), we get the wage W_{12} of women who are low-skilled workers:

$$\theta_{11} = \frac{\theta_{12}\left(N_{12}\right)^{\nu_{12}}}{N_{11}^{\nu_{11}}} \left(\frac{W_{11}}{W_{12}}\right), \Rightarrow W_{12} = \theta_{12}\left(N_{12}\right)^{\nu_{12}}, \tag{A.2}$$

where, ν_{11} and ν_{12} are from García (2020). The parameters θ_{11} and θ_{12} are calibrated so that the consumption of restricted workers (both men and women) is around 30% of total consumption, as estimated by García (2020). The details of the calculation for θ_{11} and θ_{12} are as follows. The value of consumption is equal to:

$$PobC = W_{11}\widetilde{N}_{11} + W_{12}\widetilde{N}_{12} + Pob_2 C_2, \tag{A.2}$$

where Pob is total population, Pob_2 is the population of high-skilled workers, and $\widetilde{N}_{1i}$ is the aggregate work of the medium and low-skilled workers. Note that $\widetilde{N}_{1i}$ is different from per capita work N_{1i}. Thus, dividing equation (A.2) by Pob yields:

$$C = W_{11}\frac{\widetilde{N}_{11}}{Pob} + W_{12}\frac{\widetilde{N}_{12}}{Pob} + \frac{Pob_2}{Pob}C_2, \ or \tag{A.3}$$

$$C = \lambda\left(C_{11} + C_{12}\right) + \left(1-\lambda\right)C_2, \tag{A.4}$$

where $(1-\lambda) = Pob_2/Pob$. Then, comparing equations (A.3) and (A.4), we have:

$$(C_{11}+C_{12})=\frac{1}{\lambda}\left(W_{11}\frac{\widetilde{N}_{11}}{Pob}+W_{12}\frac{\widetilde{N}_{12}}{Pob}\right). \tag{A.5}$$

The log-linearization of equation (A.4) is:

$$\hat{c}=\lambda\left(\frac{C_{11}}{C}\hat{c}_{11}+\frac{C_{12}}{C}\hat{c}_{12}\right)+(1-\lambda)\frac{C_2}{C}\hat{c}_2. \tag{A.6}$$

From equation (A.5)

$$\lambda\left(\frac{C_{1i}}{C}\right)=\lambda\left(\frac{\frac{1}{\lambda}\frac{W_{1i}\widetilde{N}_{1i}}{Pob}}{C}\right)=\frac{\frac{W_{1i}\widetilde{N}_{1i}}{Pob}}{C},\ i=1,2 \tag{A.7}$$

Then (A.6) can be rewritten as:

$$\hat{c}=\widetilde{\lambda}\left(\hat{c}_{11}+\hat{c}_{12}\right)+\left(1-\widetilde{\lambda}\right)\hat{c}_2, \tag{A.8}$$

where:

$$\widetilde{\lambda}=\frac{W_{11}\widetilde{N}_{11}+W_{12}\widetilde{N}_{12}}{PobC}=\frac{W_{11}\widetilde{N}_{11}/Pob+W_{12}\widetilde{N}_{12}/Pob}{C}. \tag{A.9}$$

On the one hand, equation (A.9) is the share of restricted workers' consumption in total consumption, which García (2020) estimated to be equal to 0.3. From equation (A.2), the value of the wage rates depends on θ_{11} and θ_{12}, so we set these parameters (knowing the value of total per capita consumption, which we explain below) such that the resulting wages produce a result consistent with $\widetilde{\lambda}$. On the other hand, we calibrate λ to take a value of 46%, which is the share of the population that does not have access to credit in Chile. This allows us to calculate:

$$C_{11}=\frac{1}{\lambda}\left(W_{11}N_{11}\right)\ \textit{and} \tag{A.10}$$

$$C_{12} = \frac{1}{\lambda}\left(W_{12}N_{12}\right). \tag{A.11}$$

Also, with the values for W_{11} and W_{12}, we can calculate W_1 from equation (11).

We chose a value of 3.5 for the elasticity of substitution between medium and low-skilled workers and robots, ϵ, estimated by Berg, Buffie, and Zanna (2018). Then, taking the share of robots in the economy, RS, directly from the information provided by the World LA KLEMS database, we can calculate values for P^R , Q^R, and $\widetilde{P}^y$:

$$P^R = \left(W_1^{\epsilon}N_1/RS\right)^{\frac{1}{\epsilon-1}}, \tag{A.12}$$

$$Q^R = \frac{P^R}{\widetilde{r}+\delta^R},\ \textit{and} \tag{A.13}$$

$$\widetilde{P}^Y = \left[\left(P^R\right)^{1-\epsilon} + \left(W_1\right)^{1-\epsilon}\right]^{\frac{1}{1-\epsilon}}. \tag{A.14}$$

The rest of the steady state is more standard. For the production function, we draw on a useful assumption that $Y = 1$ is obtained by choosing an appropriate A_1 from equation (1):

$$\alpha_3 = W_{11}N_{11} + W_{12}N_{12} + P^R,\ \textit{and} \tag{A.15}$$

$$\alpha_4 = LS - \left(W_{11}N_{11} + W_{12}N_{12} + P^R\right), \tag{A.16}$$

where LS is the labor share. Note that the robots take a fraction of that income:

$$\widetilde{Y} = \frac{\alpha_3}{\hat{P}^y}; \tag{A.17}$$

$$M^R = \delta^R R = \delta^R \frac{RS}{P^R}, \tag{A.18}$$

If we assume:

$$E = 1.0, \tag{A.19}$$

and if we use $\frac{EM^T}{GDP} = \frac{M^T}{GDP} = \frac{M^T}{Y-M^T} = \frac{M^T}{1-M^T} = \frac{M+M^R}{1-(M+M^R)}$, then we can calculate:

$$M = \left(\frac{M^T/GDP}{1+M^T/GDP}\right) - M^R, \tag{A.20}$$

$$\alpha_2 = EM = M, \textit{ and} \tag{A.21}$$

$$M^T = EM + EP^S M^R = M + P^S M^R, \tag{A.22}$$

where P^S is also assumed to be equal to 1.0

$$\alpha_1 = 1 - LS - \alpha_2; \tag{A.23}$$

$$K = \alpha_1 \left(\frac{1}{Z}\right); \tag{A.24}$$

$$I = \delta K. \tag{A.25}$$

With these results, we calculated the values of the variables related to high-skilled workers. We know employment adjusted by hours—and divided by the population—of these jobs and the demand for high-skilled workers. Then,

$$W_2 = \frac{\alpha_4}{N_2}. \tag{A.26}$$

From the labor supply of high-skilled workers, the parameter θ_2 is:

$$\theta_2 = \frac{W_2}{N_2^{\nu_2}}. \tag{A.27}$$

With all these values, we can calculate the values of A_1 and parameter τ for case C:

$$A_1 = \frac{1}{K^{\alpha_1} M^{\alpha_2} \widetilde{Y}^{\alpha_3} N^{\alpha_4}}. \tag{A.28}$$

With the above values, we can calculate the real marginal costs of production, MC^r, using equation (35) and the price that is set in foreign markets:

$$P^* = \mu MC^\gamma. \tag{A.29}$$

Now we can calculate the value of variables that are related to national accounts:

$$GDP = 1 - M^T; \tag{A.30}$$

$$G = \frac{G}{GDP} GDP = \underbrace{0.1305}_{Chile\,value} \; GDP. \tag{A.31}$$

We know that commodity exports (mainly mining) in Chile are:

$$\frac{EQCO}{GDP} = \frac{QCO}{GDP} = \underbrace{0.1088}_{Chile\,value} \;, \tag{A.32}$$

$$QCO = \frac{QCO}{GDP} GDP = 0.1088 GDP, \tag{A.33}$$

and non mining exports are:

$$\frac{EX}{GDP} = \frac{EX}{GDP} = 0.31325 - 0.1088. \tag{A.34}$$

From equation (44), the external GDP is calculated to be consistent with equation (33):

$$Y^* = (0.31325 - 0.1088)\left[(P^*)^{\eta^*}\right] GDP. \tag{A.35}$$

We calculate:

$$X = \left[(P^*)^{-\eta^*}\right] Y^*, \tag{A.36}$$

and total exports:

$$EX^T = X^T = EX + EQCO = X + QCO. \tag{A.37}$$

Aggregate consumption and foreign debt complete the calculation of the steady state:

$$C = 1 - X^T - G - I \; and \tag{A.38}$$

$$B^* = \left(\frac{R^*}{r^*}\right)(GDP - C - I - G). \tag{A.39}$$

The calibrated parameters are presented in table A.1..

Table A.1.—Calibrated Parameters Used in the Model

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
A_1	1.20	α_4	0.22	η^{MU}	0.40	σ	2.00
A_2	1.00	β	0.99	η_R^{MU}	1.50	θ_2	66.08
ϕ	4.00	δ	0.01	Ψ_1	0.07	θ_{12}	2.01
ϕ^R	4.00	δ_R	0.03	Ψ_2	0.01	θ_{11}	51.72
α	0.77	ϵ	3.50	μ^*	1.37	ν_{11}	1.88
α_1	0.40	ϵ_1	1.06	λ	0.46	ν_{12}	0.41
α_2	0.23	η^*	3.08	$\widetilde{R}^*$	1.01	ν_2	1.00
α_3	0.15						

Source: The parameters are calibrated based on the steady state describes in this appendix and information indicated in the text.

Appendix B.1. Steady State and Calibrated Parameters

Table B.1.—Case D: Macroeconomic Variables and Firms Investment

Year	Robot price	GDP	Consumption	Investment	Imports	Exports	Real exchange rate	Real interest rate	Non-robotic investment	Robotic investment
1	-50	-1.00	0.46	-6.15	2.55	3.15	1.01	-1.56	-6.15	483.64
2	-50	-0.87	0.46	-4.94	3.38	3.50	1.11	-1.66	-4.94	560.80
3	-50	-0.70	0.45	-3.83	4.11	3.91	1.22	-1.76	-3.83	623.71
4	-50	-0.50	0.45	-2.79	4.74	4.34	1.33	-1.85	-2.79	671.44
5	-50	-0.28	0.46	-1.82	5.26	4.77	1.44	-1.93	-1.82	704.90
6	-50	-0.05	0.46	-0.92	5.69	5.16	1.54	-2.00	-0.92	726.07
7	-50	0.19	0.47	-0.09	6.02	5.52	1.63	-2.05	-0.09	737.43
8	-50	0.42	0.49	0.69	6.29	5.84	1.71	-2.09	0.69	741.42
9	-50	0.64	0.51	1.42	6.51	6.12	1.77	-2.12	1.42	740.23
10	-50	0.86	0.54	2.10	6.69	6.36	1.82	-2.14	2.10	735.66
15	-50	1.79	0.71	4.86	7.29	7.19	1.98	-2.12	4.86	699.36
20	-50	2.51	0.93	6.89	7.78	7.76	2.08	-1.99	6.89	675.77
25	-50	3.13	1.18	8.60	8.35	8.33	2.19	-1.82	8.60	668.91
30	-50	3.76	1.43	10.30	9.00	8.97	2.32	-1.63	10.30	672.63
35	-50	4.44	1.70	12.20	9.78	9.73	2.48	-1.42	12.20	683.06
40	-50	5.23	1.98	14.46	10.71	10.64	2.67	-1.17	14.46	698.74

Source: Authors' calculation, based on the model in section II.

Table B.2.—Case D: Labor Market and Household Welfare

Year	Jobs				Wages				Utility	
	Medium and low-skilled			High-skilled	Medium and low-skilled			High-skilled	Medium and low-skilled	
	All	Male	Female		All	Male	Female		Male	Female
1	-0.34	-0.28	-0.57	-0.08	-0.45	-0.52	-0.24	-0.08	-0.01	-0.10
2	-0.55	-0.44	-0.92	0.07	-0.73	-0.83	-0.38	0.07	-0.02	-0.16
3	-0.76	-0.61	-1.27	0.22	-1.01	-1.15	-0.52	0.22	-0.02	-0.22
4	-0.96	-0.77	-1.61	0.37	-1.28	-1.45	-0.66	0.37	-0.03	-0.28
5	-1.15	-0.93	-1.93	0.52	-1.53	-1.74	-0.80	0.52	-0.04	-0.33
6	-1.32	-1.07	-2.22	0.65	-1.76	-2.00	-0.92	0.65	-0.04	-0.38
7	-1.48	-1.19	-2.48	0.78	-1.97	-2.23	-1.02	0.78	-0.05	-0.43
8	-1.62	-1.30	-2.70	0.90	-2.15	-2.44	-1.12	0.90	-0.05	-0.47
9	-1.73	-1.40	-2.90	1.01	-2.30	-2.61	-1.20	1.01	-0.06	-0.50
10	-1.83	-1.48	-3.07	1.12	-2.44	-2.76	-1.27	1.12	-0.06	-0.53
15	-2.11	-1.71	-3.53	1.54	-2.81	-3.19	-1.46	1.54	-0.07	-0.62
20	-2.15	-1.74	-3.60	1.86	-2.86	-3.25	-1.49	1.86	-0.07	-0.63
25	-2.07	-1.67	-3.46	2.16	-2.75	-3.12	-1.43	2.16	-0.07	-0.61
30	-1.91	-1.54	-3.19	2.47	-2.53	-2.87	-1.32	2.47	-0.06	-0.56
35	-1.69	-1.36	-2.83	2.82	-2.25	-2.55	-1.17	2.82	-0.06	-0.49
40	-1.42	-1.15	-2.39	3.22	-1.89	-2.15	-0.99	3.22	-0.05	-0.41

Source: Authors' calculation, based on the model in section 1.

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