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Military spending and economic growth: A post-Keynesian model

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Abstract

One important criticism of models of military spending and growth is that they focus on the direct impact, ignoring critical indirect impacts through, for example, income distribution. This article introduces a post-Keynesian model incorporating military spending that allows workers and capitalists to have different marginal propensities to consume. The model suggests first that civilian spending is more likely to increase the productive capacity of the economy due to higher human capital and, second, that military spending and civilian spending will have different effects on the profit share and the wage share.

While the economic *effects of military spending* can be explained by various theoretical approaches such as the Neoclassical, Keynesian, Institutional, and Marxist (Dunne and Coulomb, 2008; Elveren, 2019), empirical works on the *effect on growth* mainly use the neoclassical growth models (Dunne et al., 2005). The models on the nexus of military spending and economic growth include the Feder-Ram model[1]; the Deger-type model[2]; the endogenous growth model[3]; the augmented Solow growth model[4]; the new macroeconomic model[5]; and a small open economy stochastic growth model[6]. Some major criticism noted in Dunne et al. (2005) and Alexander (2015), include taking either supply-side or demand-side of the economy into account, the arbitrary inclusion of variables into the estimated equation, the unsound interpretation of coefficients of the estimated variables, and ignoring major features of the economies.

One important feature that is often ignored is inequality. There are several channels through which military spending affects income (or pay) inequality.[7] First, military spending can lead to higher aggregate demand and employment in the economy, which benefits the poor relatively more in peaks thereby reducing income inequality. Second, depending on its composition, military spending may increase or decrease income inequality. Since pay is higher in defense and defense-related industries (e.g., R&D) that employ skilled labor, increasing military spending is likely to increase the wage gap. However, an increase in less well paid military personnel may be associated with lower income inequality. Finally, increasing military spending is likely to be at the expense of social spending and so increase inequality.

There have been some studies on the nexus of military spending and income inequality. Abell (1994) was an early attempt to investigate the interaction between military spending and income inequality for the U.S., but the first

1 Feder (1983); Biswas and Ram (1986).
2 Smith (1980); Deger and Smith (1983); Deger (1986).
3 d’Agostino et al. (2020).
4 Knight et al. (1996).
5 Atesoglu (2002).
6 Shin-Chyang et al. (2016).
7 Ali (2007); Elveren (2012).

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One important criticism of models of military spending and growth is that they focus on the direct impact, ignoring critical indirect impacts through, for example, income distribution. The model suggests that functional income distribution is a key channel by which military spending affects economic growth—workers and capitalists have differing marginal propensities to consume.

comprehensive work is Ali (2007). Using a dataset provided by the University of Texas Inequality Project, that calculates inequality in the manufacturing sector using the Theil index as a basic indicator of income inequality, Ali (2007) showed a significant association between military spending and income inequality for global panel data for the years 1987 to 1997. His results were confirmed by researchers for different time periods, country groups, and model specifications.[8] These studies examined the impact of military spending on income (or pay) inequality, not the impact of military spending on economic growth in the context of income inequality, which was the focus of Töngür and Elveren (2016). They used an augmented Solow growth model with effective human capital stock, a function of education level, and income inequality. However, their model did not specify a connection between military spending and income inequality—treating them as two independent variables.

This article develops a post-Keynesian model to examine the nexus of military spending, inequality, and economic growth. It considers the different impacts of civilian government spending and military spending, as workers and capitalists are assumed to have different marginal propensities to consume. The key aspect of post-Keynesian approaches is that the production of goods adjusts itself to the demand for goods. In other words, the economy (i.e., growth) is demand-determined and not constrained by supply. Investment is not determined by savings, but causes it. It does not require prior savings nor prior deposits because the causality runs from loans to deposits.[9] Entrepreneurs and firms make their investment decisions independently from the level of savings in the economy. Since the future is unknown and unpredictable, firms invest based on their confidence in the economy (e.g., their sentiment about demand and profitability, "animal spirits" as Keynes put it) as well as on financial factors.[10] Investment, private or public, affects aggregate demand through multiplier effects.

Another important aspect of post-Keynesian approach is the central role of capitalists' and workers' propensity to consume and save. Investment is a function of capacity utilization and profit and the propensity to save differs across different income classes.[11] That is, in contrast to the mainstream approach, where the demand side of the economy is ignored, the distribution of income between capital and labor plays a key role in the post-Keynesian framework.

Kalecki independently developed a macroeconomic framework that is similar to Keynes's income-expenditure model and established the fundamentals of the effect of income distribution on economic growth.[12] Accordingly, the relative shares of wage and profit in the economy are determined by markup pricing of oligopolistic firms. In turn, these relative shares would have different effects on economic growth as they affect aggregate demand to different degrees. While in Kaleckian economics markup pricing is a given, determined by bargaining power issues, neo-Kaleckian models make income distribution a function of capacity utilization, which is determined by investment and savings. Income distribution plays a central role in determining aggregate demand, and thereby, economic growth.[13] In the same tradition, Joan Robinson (1956; 1962) developed a growth model that differed from Kalecki by assuming full capacity utilization in the long run rather than assuming capacity utilization was endogenous. In this

8 Inter alia: Vadlamannati (2008); Lin and Ali (2009); Ali (2012); Elveren (2012); Meng et al. (2015); Wolde-Rufael (2016a and b); Michael and Stelios (2020); Biscione and Caruso (2021).
9 Lavoie (2006: 58).
10 Stockhammer and Onaran (2022).
11 We acknowledge that post-Keynesian is a general concept that covers various approaches. For example, one may contest that Kalecki was more wage-led and that the notion of an independent investment function is strictly Robinsonian. However, for the purpose of this article we think it is acceptable to use the general concept of post-Keynesian.
12 Kalecki (1954).
13 Bhaduri and Marglin (1990; Blecker (1989).

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Robinsonian growth model, the rate of profit is the key variable for investment, which determines the rate of accumulation and growth.[14]

Following this approach, the next section develops a growth model that emphasizes the demand effect of military spending on growth via the impact of the profit rate in investment decisions, where military investment is autonomous. This provides an appropriate framework to incorporate a military sector and examine the nexus of military spending, inequality, and economic growth. The next section presents the model and then the concluding section discusses the main insights that can be drawn from this model.

A post-Keynesian model for the nexus of military spending and economic growth

Elveren (2023) adapted the growth model of Onaran *et al*. (2022) to incorporate the military sector and examine the effect of military spending on economic growth through gender inequality. This model focuses on how civilian expenditures and military spending would have different impact on economic growth. Starting from aggregate output (Y_t), which is the sum of total wage bill WB_t and profits (R_t).

(1) $Y_t = WB_t + R_t$

The total wage bill (WB_t) is a function of wages in the civilian sector (w_t^C), employment in the civilian sector (E_t^C), wages in the military sector (w_t^M), employment in the military sector (E_t^M), where superscripts C and M refers to the civilian and the military, respectively. For simplicity, we assume that the military sector is a totally public sector and government military spending refers to arms production and payment to military personnel.

(2) $WB_t = w_t^C E_t^C + w_t^M E_t^M$

In line with Onaran et al. (2022) we define all wage rates in terms of hourly real wages and employment in terms of total hours worked by persons. We assume that the average wage in arms production, which is high-tech production, is higher than that of military personnel and of workers in the civilian sector[15]. The wage gap (α_t) for the C and M sectors is then defined as:

(3) $\alpha_t = \dfrac{w_t^M}{w_t^C} > 1$

Aggregate output (Y_t) is

(4) $Y_t = C_t^C + I_t + G_t^C + G_t^M + X_t - M_t$,

where C_t^C is household consumption in the civilian sector, I_t is private investment expenditures, G_t^C is government spending in the civilian sector, G_t^M is government spending in the military sector, X_t is exports of goods and services, and M_t is imports of goods and services. We assume that share of private military companies in private investment is negligible, so that all military spending in the economy is covered by government spending in the military sector, and there is no investment in the military sector.[16]

Government spending in the military sector is determined by fiscal policy decisions, targeted as a share of aggregate output κ_t^M, and constitutes the military component of public sector output in the previous year Y_{t-1}^M.

14 Stockhammer (1999).
15 The wages of military personnel may be lower than the average wage in civilian sector in some countries. However, our model focuses on the military production and since military production is a very high-tech production it is plausible to assume that wages in arms production are higher. For example, Vaze et al. (2017) show that there is a wage premium in defense industry in the U.K. This, however, does not necessarily imply that profits are lower in the defense industry. In fact, some show that profit rates in the defense industry in the U.S. are inherently higher due to the market power (Peltier, 2021).
16 We make this simplifying assumption here and leave it to future studies to investigate the effect of relaxing it.

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Therefore:

(5) $Y_t^M = G_t^M = \kappa_t^M Y_{t-1}$

(6) $Y_t^C = Y_t - G_t^M = Y_{t-1}(1 - \kappa_t^M)$

Hours of employment in both the civilian and the military sector are determined by output and labor productivity in the relevant sectors. The structuralist characteristics of the model suggest that employment is demand-constrained, which results in excess capacity and involuntary unemployment in the economy, and that supply is determined by the capital stock.

The employment in the civilian sector C is output over labor productivity sector C (T_t^C),

(7) $E_t^C = \frac{Y_t^C}{T_t^C} = \frac{(1 - \kappa_t^M)Y_t}{T_t^C}$

We assume that productivity in the military sector is constant[17] but that productivity in the civilian sector (T_t^C) changes over time and is a function of government spending in the civilian sector (e.g., education and health spending), as follows[18]:

(8) $log\ T_t^C = t_0 + t_1 log(w_{t-1}^C E_{t-1}^C)$

Government spending on the military G_t^M can be written as follows:

(9) $G_t^M = \kappa_t^M Y_t = w_t^M E_t^M + G_t^A$,

where G_t^A is an autonomous component, referring to spending on arms rather than personnel.

The profit income (R_t^M) in the military sector is the surplus after wage payments,

(10) $R_t^M = Y_t^M - w_t^M E_t^M - G_t^A$

and the military profit share (π_t^M) is the share of profit in total output and depends on productivity in the sector:

(11) $\pi_t^M = \frac{Y_t^M - w_t^M E_t^M - G_t^A}{Y_t^M}$

Similarly, the profit income (R_t^C) in the civilian sector is the surplus after wage payments,

(12) $R_t^C = Y_t(1 - \kappa_t^M) - w_t^C E_t^C$

and the profit share (π_t^C) is:

(13) $\pi_t^C = \frac{Y_t(1 - \kappa_t^M) - w_t^C E_t^C}{Y_t(1 - \kappa_t^M)}$

On the demand-side household consumption is a function of wage and profits. In the civilian sector it depends on the differences in the marginal propensities to consume (MPC) out of wage and profits[19]:

17 We acknowledge that productivity in the military sector changes over time. However, given that productivity growth is likely to be smaller in the military sector than the civilian sector, we assume for simplicity that productivity in the military sector is constant.
18 Equation 8 is defined in logs since the impact of government spending in the civilian sector on productivity might be non-linear.
19 We specify equations 14 and 15 in logs since the effects of the variables in question might be non-linear (i.e., between consumption and its determinants, and between private investment and its determinants, respectively).

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(14) $log\ C_t^C = c_0 + c_R log\ [R_t^C(1 - t_t^R)] + c_W log\ [(w_t^C E_t^C)(1 - t_t^W)]$,

where t_t^R is the implicit tax rate for profits and t_t^W is the implicit tax rate for wages.

Private investment I_t is a function of the after-tax π_t^M and π_t^C, GDP, and public debt/GDP $(\frac{D}{Y})_t$:

(15) $logI_t = i_0 + i_1 logY_t + i_2 log[\pi_t^M(1 - t_t^R)] + i_3 log[\pi_t^C(1 - t_t^R)] + i_4 log(\frac{D}{Y})_t$

The public debt (D_t) is determined by the public debt in the previous period (D_{t-1}) , the interest rate (r_{t-1}), plus the total government expenditures in t, minus the taxes collected on profits, wages, and consumption:

(16) $D_t = (1 + r_{t-1})D_{t-1} + G_t^C + G_t^M - t_t^W WB_t - t_t^R(R_t^C + R_t^M) - t_t^C C_t^C$,

where t_t^C is the implicit tax rate on consumption.[20] The public debt to GDP ratio refers to possible effects of public debt on investment. Higher public debt may crowd-out private investment, or it may increase private investment (i.e., crowding-in) if public spending leads to higher productivity.[21]

Exports are a function of prices of exports relative to foreign prices and foreign income (Y_{world}) and the exchange rate (ε), imports are a function of Y^C and domestic prices relative to import prices. For simplicity, we assume that the country has a military industry and does not need to import, so the marginal propensity to import is zero.

The wage share is considered as the real unit labor cost, so when the profit share decreases (wage share increases), exports decrease and imports increase. The magnitude of the effect is determined by the pass through from the wage share to nominal unit labor costs and prices, and the price elasticity of exports and imports. For simplicity, exports and imports are defined as reduced form functions of π:

(17) $logX_t = x_0 + x_1 logY_t^{world} + x_2 log\ \pi_t^C + x_3 log\pi_t^M + x_4 log\varepsilon_t$

(18) $logM_t = n_0 + n_1 logY_t^C + n_2 log\pi_t^C + n_3 log\pi_t^M + n_4 log\varepsilon_t$

The effect of κ_t^M on output can be shown as follows (explicit forms of the derivations are provided in the Appendix):

(19) $$\frac{dY_t}{dk_t^M} = \frac{\frac{\partial C_t^C}{\partial k_t^M} + \frac{\partial I_t}{\partial k_t^M} + \frac{\partial G_t^C}{\partial k_t^M} + \frac{\partial G_t^M}{\partial k_t^M} + \frac{\partial X_t}{\partial k_t^M} - \frac{\partial M_t}{\partial k_t^M} - \frac{\partial Y_t}{\partial k_t^M}}{1 - \Phi}$$

(20) $$\Phi = \frac{\partial C_t^C}{\partial Y_t} + \frac{\partial I_t}{\partial Y_t} + \frac{\partial G_t^C}{\partial Y_t} + \frac{\partial G_t^M}{\partial Y_t} + \frac{\partial X_t}{\partial Y_t} - \frac{\partial M_t}{\partial Y_t}$$

20 It is worth noting that military spending directly affects public debt. Pempetzoglou (2021) reviews the literature on the military spending and external debt, which is the sum of private sector debt and public debt. Increasing military spending can lead to higher debt for three ways: It may increase domestic or foreign borrowing; it may expand external debt if arms are imported; and it may increase debt even if the country produces its own arms, but it is dependent on some imported intermediate goods. Most of the studies suggest that higher military spending is associated with higher debt, and causality is running from military spending to debt (inter alia Dunne et al., 2019; Caruso and Di Domizio, 2017).

21 Our model considers debt, not the deficit per se. Running budget deficit increases debt, which can be considered as accumulated deficits. Also, according to Ricardian equivalence theorem, an increase in debt leads to a decline in consumption as people adjust their consumption by anticipating an increase in tax in future, keeping aggregate demand the same. However, empirical evidence is not supportive of the theorem (see for example Stanley (1998) and Hayo and Nuemeier (2017)).

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The model suggests two main reasons why the effect of military spending and civilian spending on output might be different. First, civilian spending in terms of education and health spendings increase productivity, which in turn increases the productive capacity of the economy due to higher human capital in the long run. Second, military spending and civilian spending can have different effects through the profit share and wage share. An increase in the wage share can boost economic growth because workers' propensity to consume is higher than that of capitalists, but can also have negative effects. First, a higher wage share and so a lower profit share can reduce capitalists' incentive to invest and, second, it can reduce the firms' competitiveness in international markets, thereby decreasing exports.

Based on the benchmark model of Bhaduri and Marglin (1990), a number of empirical studies have investigated whether the positive effects of wage-led growth or the negative effects dominate.[22] In a comprehensive analysis, Oyvat *et al.* (2020) found that countries that are more open to trade, that have higher wage inequality, higher private credit-to-GDP ratios, and greater household debt/GDP ratios are more likely to see profit-led growth.[23] In this context, the size and decomposition of military spending on growth can be important. A recent study by Becker and Dunne (2021) is critical because, instead of using general military spending data that covers expenditures on arms, infrastructure, military personnel, etc., the authors decompose military spending data to show that, for 34 major countries for 1970-2019, it is the negative correlation between military personnel expenditures and growth that drives the overall negative effect on growth. Moreover, it has been shown with a circuit of capital model that the military sector, compared to the civilian sector, is inherently associated with higher profit rates due to shorter realization lags.[24] Therefore, the ultimate effect on output depends on whether growth regime is wage-led or profit-led. That is, on the one hand, rising wage share can increase economic growth since workers have a larger marginal propensity to consume compared to capitalists; on the other hand, it creates disincentives for private investment and reduces the international competitiveness of domestic firms. If the positive impact of wage share through higher consumption is larger than its negative impact through private investment then the regime is called wage-led, otherwise it is profit-led. Therefore, our model suggests that functional income distribution is a key channel by which military spending affects economic growth.

Conclusion

The goal of this article was to develop a post-Keynesian model to examine the impact of military spending on economic growth that allows for the fact that military spending may have a different impact on economic growth than civilian expenditure—as they affect income distribution differently. The model shows that civilian expenditure is likely to have a higher positive impact on growth because it increases aggregate demand more—as most of this spending goes to workers whose higher marginal propensity to consume is higher than that of capitalists.

While introducing the income distribution channel is a valuable contribution, we acknowledge that our model is, of necessity, based on simplistic assumptions on productivity and investment in the military sector. It could be improved by relaxing them, but at the cost of increasing complexity. Future work will aim to address this.

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22 Blecker (2016); Stockhammer (2017); Oyvat et al. (2020).

23 It is worth noting that the controversy between profit-led versus wage-led models is not of concern here as the goal is to emphasize the relationship between military spending and potential output.

24 Realization lags refer to the number of periods required on average to turn value as finished products into sales flow (Elveren, 2022).

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Appendix: Explicit forms of the derivations

$$(19)\quad \frac{dY_t}{dk_t^M} = \frac{\frac{\partial C_t^C}{\partial k_t^M} + \frac{\partial I_t}{\partial k_t^M} + \frac{\partial G_t^C}{\partial k_t^M} + \frac{\partial G_t^M}{\partial k_t^M} + \frac{\partial X_t}{\partial k_t^M} - \frac{\partial M_t}{\partial k_t^M} - \frac{\partial Y_t}{\partial k_t^M}}{1 - \Phi}$$

$$(20)\quad \Phi = \frac{\partial C_t^C}{\partial Y_t} + \frac{\partial I_t}{\partial Y_t} + \frac{\partial G_t^C}{\partial Y_t} + \frac{\partial G_t^M}{\partial Y_t} + \frac{\partial X_t}{\partial Y_t} - \frac{\partial M_t}{\partial Y_t}$$

For equation (19), the derivations are as follows (for simplicity we ignore subscript t in derivation):

$$(21)\quad \frac{\partial C^C}{\partial k^M} = \frac{\partial C^C}{\partial E^C} \cdot \frac{dE^C}{dk^M} + \frac{\partial C^C}{\partial R^C} \cdot \frac{dR^C}{dk^M}$$

$$(22)\quad \frac{\partial C^C}{\partial E^C} = -c_W\, w^C\, \mathrm{e}^{c_0} \left(-R^C\,(t^R-1)\right)^{c_R} (t^W-1) \left(-E^C\, w^C\,(t^W-1)\right)^{c_W-1}$$

$$(23)\quad \frac{\partial C^C}{\partial R^C} = -c_R\, \mathrm{e}^{c_0} \left(-R^C\,(t^R-1)\right)^{c_R-1} (t^R-1) \left(-E^C\, w^C\,(t^W-1)\right)^{c_W}$$

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(24) $$\frac{dC^C}{dk^M} = c_R\, e^{c_0} \left(-R^C\,(t^R-1)\right)^{c_R-1} \left(Y - \frac{Y\,w^C}{T^C}\right)(t^R-1)\left(-E^C\,w^C\,(t^W-1)\right)^{c_W} + \frac{Y\,c_W\,w^C\,e^{c_0}\left(-R^C\,(t^R-1)\right)^{c_R}(t^W-1)\left(-E^C\,w^C\,(t^W-1)\right)^{c_W-1}}{T^C}$$

(25) $$G^M = Y_{t1} \cdot k^M$$

(26) $$\frac{\partial G^M}{\partial k^M} = Y$$

(27) $$G^C = -Y_{t1} \cdot (k^M - 1)$$

(28) $$\frac{\partial G^C}{\partial k^M} = -Y$$

(29) $$I = Y^{i_1}\, e^{i_0} \left(\frac{D}{Y}\right)^{i_4} \left(-\pi^C\,(t^R-1)\right)^{i_3} \left(-\pi^M\,(t^R-1)\right)^{i_2}$$

(30) $$\frac{\partial I}{\partial k^M} = \frac{\partial I}{\partial D}\cdot\frac{dD}{dk^M} + \frac{\partial I}{\partial \pi^C}\cdot\frac{d\pi^C}{dk^M} + \frac{\partial I}{\partial \pi^M}\cdot\frac{d\pi^M}{dk^M}$$

(31) $$\frac{\partial I}{\partial D} = \frac{Y^{i_1}\, i_4\, e^{i_0}\left(\frac{D}{Y}\right)^{i_4-1}\left(-\pi^C\,(t^R-1)\right)^{i_3}\left(-\pi^M\,(t^R-1)\right)^{i_2}}{Y}$$

(32) $$\frac{\partial I}{\partial \pi^C} = -Y^{i_1}\, i_3\, e^{i_0}\left(\frac{D}{Y}\right)^{i_4}\left(-\pi^C\,(t^R-1)\right)^{i_3-1}\left(-\pi^M\,(t^R-1)\right)^{i_2}(t^R-1)$$

(33) $$\frac{\partial I}{\partial \pi^M} = -Y^{i_1}\, i_2\, e^{i_0}\left(\frac{D}{Y}\right)^{i_4}\left(-\pi^C\,(t^R-1)\right)^{i_3}\left(-\pi^M\,(t^R-1)\right)^{i_2-1}(t^R-1)$$

(34) $$\frac{dI}{dk^M} = \frac{Y^{i_1}\, i_4\, e^{i_0}\left(\frac{D}{Y}\right)^{i_4-1}\sigma_5^{\,i_3}\,\sigma_4^{\,i_2}\left(Y - Y_{t1} - Y\,t^R + t^R\,\sigma_1 - t^C\left(c_R\,e^{c_0}\,\sigma_6^{\,c_R-1}\,\sigma_1\,(t^R-1)\,\sigma_2^{\,c_W} + \frac{Y\,c_W\,w^C\,e^{c_0}\,\sigma_6^{\,c_R}\,(t^W-1)\,\sigma_2^{\,c_W-1}}{T^C}\right) + \frac{Y\,t^W}{T^C}\right)}{Y}$$
$$- Y^{i_1}\, i_2\, e^{i_0}\,\sigma_3\left(\frac{Y}{Y^M} - \frac{R^M\,Y}{{Y^M}^2}\right)\sigma_5^{\,i_3}\,\sigma_4^{\,i_2-1}(t^R-1)$$
$$- Y^{i_1}\, i_3\, e^{i_0}\,\sigma_3\,\sigma_5^{\,i_3-1}\,\sigma_4^{\,i_2}\left(\frac{R^C}{Y\,(k^M-1)^2} + \frac{\sigma_1}{Y\,(k^M-1)}\right)(t^R-1)$$

where

(35) $$\sigma_1 = Y - \frac{Y\,w^C}{T^C}$$

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(36) $\sigma_2 = -E^C\, w^C\, (t^W - 1)$

(37) $\sigma_3 = \left(\frac{D}{Y}\right)^{i_4}$

(38) $\sigma_4 = -\pi^M\, (t^R - 1)$

(39) $\sigma_5 = -\pi^C\, (t^R - 1)$

(40) $\sigma_6 = -R^C\, (t^R - 1)$

(41) $\frac{dX}{dk^M} = \frac{\partial X}{\partial \pi^C} \cdot \frac{d\pi^C}{dk^M} + \frac{\partial X}{\partial \pi^M} \cdot \frac{d\pi^M}{dk^M}$

(42) $\frac{\partial X}{\partial \pi^C} = Y^{world^{x_1}}\, \varepsilon^{x_4}\, \pi^{C^{x_2-1}}\, \pi^{M^{x_3}}\, x_2\, e^{x_0}$

(43) $\frac{\partial X}{\partial \pi^M} = Y^{world^{x_1}}\, \varepsilon^{x_4}\, \pi^{C^{x_2}}\, \pi^{M^{x_3-1}}\, x_3\, e^{x_0}$

(44) $$\frac{dX}{dk^M} = Y^{world^{x_1}}\, \varepsilon^{x_4}\, \pi^{C^{x_2}}\, \pi^{M^{x_3-1}}\, x_3\, e^{x_0} \left(\frac{Y}{Y^M} - \frac{R^M\, Y}{{Y^M}^2}\right) + Y^{world^{x_1}}\, \varepsilon^{x_4}\, \pi^{C^{x_2-1}}\, \pi^{M^{x_3}}\, x_2\, e^{x_0} \left(\frac{R^C}{Y\,(k^M-1)^2} + \frac{Y - \frac{Y\, w^C}{T^C}}{Y\,(k^M-1)}\right)$$

(45) $\frac{dM}{dk^M} = \frac{\partial M}{\partial Y^C} \cdot \frac{dY^C}{dk^M} + \frac{\partial M}{\partial \pi^C} \cdot \frac{d\pi^C}{dk^M} + \frac{\partial M}{\partial \pi^M} \cdot \frac{d\pi^M}{dk^M}$

(46) $\frac{\partial M}{\partial G^C} = Y^{C^{n_1-1}}\, \varepsilon^{n_4}\, n_1\, \pi^{C^{n_2}}\, \pi^{M^{n_3}}\, e^{n_0}$

(47) $\frac{\partial M}{\partial \pi^C} = Y^{C^{n_1}}\, \varepsilon^{n_4}\, n_2\, \pi^{C^{n_2-1}}\, \pi^{M^{n_3}}\, e^{n_0}$

(48) $\frac{\partial M}{\partial \pi^M} = Y^{C^{n_1}}\, \varepsilon^{n_4}\, n_3\, \pi^{C^{n_2}}\, \pi^{M^{n_3-1}}\, e^{n_0}$

(49) $$\frac{dM}{dk^M} = Y^{C^{n_1}}\, \varepsilon^{n_4}\, n_3\, \pi^{C^{n_2}}\, \pi^{M^{n_3-1}}\, e^{n_0} \left(\frac{Y}{Y^M} - \frac{R^M\, Y}{{Y^M}^2}\right) - Y^{C^{n_1-1}}\, Y_{t1}\, \varepsilon^{n_4}\, n_1\, \pi^{C^{n_2}}\, \pi^{M^{n_3}}\, e^{n_0} + Y^{C^{n_1}}\, \varepsilon^{n_4}\, n_2\, \pi^{C^{n_2-1}}\, \pi^{M^{n_3}}\, e^{n_0} \left(\frac{R^C}{Y\,(k^M-1)^2} + \frac{Y - \frac{Y\, w^C}{T^C}}{Y\,(k^M-1)}\right)$$

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(50) $$\frac{\partial E^C}{\partial k^M} = -\frac{Y}{T^C}$$

(51) $$\frac{\partial R^C}{\partial E^C} = -w^C$$

(52) $$\frac{\partial R^C}{\partial k^M} = -Y$$

(53) $$\frac{dR^C}{dk^M} = \frac{Y\,w^C}{T^C} - Y$$

(54) $$\frac{dG^M}{dk^M} = Y$$

(55) $$\frac{dG^C}{dk^M} = -Y_{t1}$$

(56) $$E^C = -\frac{Y\,(k^M - 1)}{T^C}$$

(57) $$R^C = \frac{Y\,w^C\,(k^M - 1)}{T^C} - Y\,(k^M - 1)$$

(58) $$\frac{\partial R^M}{\partial G^M} = 1$$

(59) $$\frac{dR^M}{dk^M} = Y$$

(60) $$\frac{\partial \pi^M}{\partial R^M} = \frac{1}{Y^M}$$

(61) $$\frac{\partial \pi^M}{\partial G^M} = -\frac{R^M}{Y^{M^2}}$$

(62) $$\frac{d\pi^M}{dk^M} = \frac{Y}{Y^M} - \frac{R^M\,Y}{Y^{M^2}}$$

(63) $$\frac{\partial \pi^C}{\partial k^M} = \frac{R^C}{Y\,(k^M - 1)^2}$$

(64) $$\frac{\partial \pi^C}{\partial R^C} = -\frac{1}{Y\,(k^M - 1)}$$

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(65) $$\frac{d\pi^C}{dk^M} = \frac{R^C}{Y\,(k^M-1)^2} + \frac{Y - \frac{Y\,w^C}{T^C}}{Y\,(k^M-1)}$$

(66) $$\frac{\partial D}{\partial G^C} = 1$$

(67) $$\frac{\partial D}{\partial G^M} = 1$$

(68) $$\frac{\partial D}{\partial WB} = -t^W$$

(69) $$\frac{\partial D}{\partial R^C} = -t^R$$

(70) $$\frac{\partial D}{\partial R^M} = -t^R$$

(71) $$\frac{\partial D}{\partial C^C} = -t^C$$

(72) $$\frac{dWB}{dk^M} = -\frac{Y}{T^C}$$

(73) $$\frac{dD}{dk^M} = Y - Y_{t1} - Y\,t^R + t^R\,\sigma_1 - t^C\left(c_R\,e^{c_0}\left(-R^C\,(t^R-1)\right)^{c_R-1}\sigma_1\,(t^R-1)\,{\sigma_2}^{c_W} + \frac{Y\,c_W\,w^C\,e^{c_0}\left(-R^C\,(t^R-1)\right)^{c_R}(t^W-1)\,{\sigma_2}^{c_W-1}}{T^C}\right) + \frac{Y\,t^W}{T^C}$$

where

(74) $$\sigma_1 = Y - \frac{Y\,w^C}{T^C}$$

(75) $$\sigma_2 = -E^C\,w^C\,(t^W-1)$$

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For equation (20), the derivations are as follows:

$$\frac{dG^M}{dY} = 0 \tag{76}$$

$$\frac{dG^C}{dY} = 0 \tag{77}$$

$$\frac{dC^C}{dY} = c_R\, \mathrm{e}^{c_0} \left(-R^C\,(t^R-1)\right)^{c_R-1} (k^M-1)\,(t^R-1)\left(-E^C\, w^C\,(t^W-1)\right)^{c_W} \tag{78}$$

$$\frac{dC^C}{dY} = \frac{\partial C^C}{\partial E^C}\cdot\frac{dE^C}{dY} + \frac{\partial C^C}{\partial R^C}\cdot\frac{dR^C}{dY} \tag{79}$$

$$\frac{dX}{dY} = {Y^{world}}^{x_1}\, \varepsilon^{x_4}\, {\pi^C}^{x_2-1}\, {\pi^M}^{x_3}\, x_2\, \mathrm{e}^{x_0}\left(\frac{1}{Y} + \frac{R^C}{Y^2\,(k^M-1)}\right) \tag{80}$$

$$\frac{dX}{dY} = \frac{\partial X}{\partial \pi^C}\cdot\frac{d\pi^C}{dY} + \frac{\partial X}{\partial \pi^M}\cdot\frac{d\pi^M}{dY} \tag{81}$$

$$\frac{dM}{dY} = {Y^C}^{n_1}\, \varepsilon^{n_4}\, n_2\, {\pi^C}^{n_2-1}\, {\pi^M}^{n_3}\, \mathrm{e}^{n_0}\left(\frac{1}{Y} + \frac{R^C}{Y^2\,(k^M-1)}\right) \tag{82}$$

$$\frac{dM}{dY} = \frac{\partial M}{\partial G^C}\cdot\frac{dG^C}{dY} + \frac{\partial M}{\partial \pi^C}\cdot\frac{d\pi^C}{dY} + \frac{\partial M}{\partial \pi^M}\cdot\frac{d\pi^M}{dY} \tag{83}$$

$$\begin{aligned}\frac{dI}{dY} = {} & Y^{i_1-1}\ i_1\ e^{i_0}\ \sigma_3\ {\sigma_4}^{i_3}\ \sigma_1 - \frac{D\, Y^{i_1}\ i_4\ e^{i_0}\ \sigma_2\ {\sigma_4}^{i_3}\ \sigma_1}{Y^2} \\ & - Y^{i_1}\ i_3\ e^{i_0}\ \sigma_3\ {\sigma_4}^{i_3-1}\ \sigma_1\ \left(\frac{1}{Y} + \frac{R^C}{Y^2\ (k^M-1)}\right)(t^R-1) \\ & + \frac{Y^{i_1}\ i_4\ e^{i_0}\ \sigma_2\ {\sigma_4}^{i_3}\ \sigma_1\ \left(t^R\ (k^M-1) - c_R\ t^C\ e^{c_0}\ \left(-R^C\ (t^R-1)\right)^{c_R-1} (k^M-1)\,(t^R-1)\left(-E^C\ w^C\ (t^W-1)\right)^{c_W}\right)}{Y}\end{aligned} \tag{84}$$

where

$$\sigma_1 = \left(-\pi^M\,(t^R-1)\right)^{i_2} \tag{85}$$

$$\sigma_2 = \left(\frac{D}{Y}\right)^{i_4-1} \tag{86}$$

$$\sigma_3 = \left(\frac{D}{Y}\right)^{i_4} \tag{87}$$

$$\sigma_4 = -\pi^C\,(t^R-1) \tag{88}$$

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(89) $$\frac{dI}{dY} = \frac{\partial I}{\partial Y} + \frac{\partial I}{\partial D} \cdot \frac{dD}{dY} + \frac{\partial I}{\partial \pi^C} \cdot \frac{d\pi^C}{dY} + \frac{\partial I}{\partial \pi^M} \cdot \frac{d\pi^M}{dY}$$

(90) $$\frac{dE^C}{dY} = 0$$

(91) $$\frac{dR^C}{dY} = 1 - k^M$$

(92) $$\frac{\partial \pi^C}{\partial Y} = \frac{R^C}{Y^2(k^M - 1)}$$

(93) $$\frac{d\pi^C}{dY} = \frac{1}{Y} + \frac{R^C}{Y^2(k^M - 1)}$$

(94) $$\frac{d\pi^M}{dY} = 0$$

(95) $$\frac{\partial I}{\partial Y} = Y^{i_1 - 1}\, i_1\, \mathrm{e}^{i_0} \left(\frac{D}{Y}\right)^{i_4} \left(-\pi^C\,(t^R - 1)\right)^{i_3} \left(-\pi^M\,(t^R - 1)\right)^{i_2} - \frac{D\, Y^{i_1}\, i_4\, \mathrm{e}^{i_0} \left(\frac{D}{Y}\right)^{i_4 - 1} \left(-\pi^C\,(t^R - 1)\right)^{i_3} \left(-\pi^M\,(t^R - 1)\right)^{i_2}}{Y^2}$$

(96) $$\frac{\partial I}{\partial Y} = Y^{i_1 - 1}\, i_1\, \mathrm{e}^{i_0} \left(\frac{D}{Y}\right)^{i_4} \left(-\pi^C\,(t^R - 1)\right)^{i_3} \left(-\pi^M\,(t^R - 1)\right)^{i_2} - \frac{D\, Y^{i_1}\, i_4\, \mathrm{e}^{i_0} \left(\frac{D}{Y}\right)^{i_4 - 1} \left(-\pi^C\,(t^R - 1)\right)^{i_3} \left(-\pi^M\,(t^R - 1)\right)^{i_2}}{Y^2}$$

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