

These notes loosely follow Fernández-Villaverde and Levintal (2018) “Solution Methods for Models with Rare Disasters” but omits several features, such as recursive preferences and disaster risk.

# 1 Model

## 1.1 Household

The model admits a representative agent, so I directly write households’ problem as the representative agent’s. The representative household solves, in the cashless limit,

$$\max_{C_t, L_t, B_t, X_t, K_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \exp(\eta_{\beta,t}) \left( \frac{C_t^{1-\gamma}}{1-\gamma} - \varphi \exp(\eta_{L,t}) \frac{L_t^{1+\nu}}{1+\nu} \right) \quad (1)$$

subject to the budget constraint

$$C_t + \frac{B_t}{P_t} + X_t \leq W_t L_t + R_{K,t} K_{t-1} + R_{t-1} \frac{B_{t-1}}{P_t} + F_t + T_t, \quad (2)$$

where  $C_t$  is consumption,  $B_{t-1}$  nominal bonds,  $X_t$  investment,  $W_{N,t}$  the real wage,  $L_t$  labor,  $R_{KN,t}$  the gross real rental rate on capital,  $K_{t-1}$  capital,  $R_t$  the gross nominal interest rate on bonds,  $F_t$  real profits from firms, and  $T_t$  real lump-sum transfers from the government. The price of the final consumption good is  $P_t$ . Markets are assumed complete, but securities are in zero net supply. Because there is a representative agent, I may omit the Arrow securities from the budget constraint. My notation treats  $B_{t-1}$  and  $K_{t-1}$  as the stocks of bonds and capital present at time  $t$ , while  $B_t$  and  $K_t$  are the chosen stocks of bonds and capital for the following period. I adopt this notation so that all time  $t$  choices are dated at time  $t$  rather than having to differentiate between the predetermined time- $t$  variables from the endogenous controls.

Investment for capital follows the law of motion

$$K_t = (1 - \delta) K_{t-1} + \Phi \left( \frac{X_t}{K_{t-1}} \right) K_{t-1}. \quad (3)$$

The Lagrangian for the household is

$$\begin{aligned} \mathcal{L} = & \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \exp(\eta_{\beta,t}) \left[ \frac{C_t^{1-\gamma}}{1-\gamma} - \varphi \exp(\eta_{L,t}) \frac{L_t^{1+\nu}}{1+\nu} \right] \\ & + \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \exp(\eta_{\beta,t}) \lambda_t \left[ W_t L_t + R_{K,t} K_{t-1} + R_{t-1} \frac{B_{t-1}}{P_t} + F_t + T_t - C_t - \frac{B_t}{P_t} - X_t \right] \\ & + \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \exp(\eta_{\beta,t}) \lambda_t Q_t \left[ (1 - \delta) K_{t-1} + \Phi \left( \frac{X_t}{K_{t-1}} \right) K_{t-1} - K_t \right], \end{aligned}$$

which implies first-order conditions

$$\begin{aligned}
0 &= C_t^{-\gamma} - \lambda_t \\
0 &= -\varphi \exp(\eta_{L,t}) L_t^\nu + \lambda_t W_t \\
0 &= -\exp(\eta_{\beta,t}) \lambda_t + \beta \mathbb{E}_t [\exp(\eta_{\beta,t+1}) \lambda_{t+1} R_t] \\
0 &= -\exp(\eta_{\beta,t}) \lambda_t + \exp(\eta_{\beta,t}) \lambda_t Q_t \Phi' \left( \frac{X_t}{K_{t-1}} \right) K_{t-1} \frac{1}{K_{t-1}} \\
0 &= -\exp(\eta_{\beta,t}) \lambda_t Q_t + \beta \mathbb{E}_t [\exp(\eta_{\beta,t+1}) \lambda_{t+1} R_{K,t+1}] \\
&\quad \beta \mathbb{E}_t \left[ \exp(\eta_{\beta,t+1}) \lambda_{t+1} Q_{t+1} \left( 1 - \delta + \Phi' \left( \frac{X_{t+1}}{K_t} \right) K_t \left( -\frac{X_{t+1}}{K_t^2} \right) + \Phi \left( \frac{X_{t+1}}{K_t} \right) \right) \right]
\end{aligned}$$

The first two equations can be combined by isolating  $\lambda_t$ , which obtains the intratemporal consumption-labor condition

$$C_t^{-\gamma} W_t = \varphi \exp(\eta_{L,t}) L_t^\nu,$$

Using  $\lambda_t = C_t^{-\gamma}$  and defining the gross inflation rate  $\Pi_t \equiv P_t/P_{t-1}$ , I can obtain the Euler equation for households

$$\begin{aligned}
\exp(\eta_{\beta,t}) \frac{C_t^{-\gamma}}{P_t} &= \beta \mathbb{E}_t \left[ \exp(\eta_{\beta,t+1}) \frac{C_{t+1}^{-\gamma}}{P_{t+1}} R_t \right] \\
1 &= \beta \mathbb{E}_t \left[ \frac{\exp(\eta_{\beta,t+1}) C_{t+1}^{-\gamma} R_t}{\exp(\eta_{\beta,t}) C_t^{-\gamma} \Pi_{t+1}} \right].
\end{aligned}$$

I can further simplify the Euler equation by defining the (real) stochastic discount factor

$$M_{t+1} = \beta \frac{\exp(\eta_{\beta,t+1}) C_{t+1}^{-\gamma}}{\exp(\eta_{\beta,t}) C_t^{-\gamma}}$$

After dividing through by  $\exp(\eta_{\beta,t}) \lambda_t$  and re-arranging, the investment condition becomes

$$1 = Q_t \Phi' \left( \frac{X_t}{K_{t-1}} \right).$$

Finally, after dividing through by  $\exp(\eta_{\beta,t}) \lambda_t$ , the first-order condition for next-period capital is

$$Q_t = \mathbb{E}_t \left[ M_{t+1} \left( R_{K,t+1} + Q_{t+1} \left( 1 - \delta + \Phi \left( \frac{X_{t+1}}{K_t} \right) - \Phi' \left( \frac{X_{t+1}}{K_t} \right) \frac{X_{t+1}}{K_t} \right) \right) \right].$$

In summary, households' optimality conditions are

$$C_t^{-\gamma} W_t = \varphi \exp(\eta_{L,t}) L_t^\nu, \quad (4)$$

$$M_{t+1} = \beta \frac{\exp(\eta_{\beta,t+1}) C_{t+1}^{-\gamma}}{\exp(\eta_{\beta,t}) C_t^{-\gamma}}, \quad (5)$$

$$1 = \beta \mathbb{E}_t \left[ M_{t+1} \frac{R_t}{\Pi_{t+1}} \right], \quad (6)$$

$$1 = Q_t \Phi' \left( \frac{X_t}{K_{t-1}} \right), \quad (7)$$

$$Q_t = \mathbb{E}_t \left[ M_{t+1} \left( R_{K,t+1} + Q_{t+1} \left( 1 - \delta + \Phi \left( \frac{X_{t+1}}{K_t} \right) - \Phi' \left( \frac{X_{t+1}}{K_t} \right) \frac{X_{t+1}}{K_t} \right) \right) \right]. \quad (8)$$

## 1.2 Production

**Final Producers** There is a representative final goods firm which sells consumption goods in a competitive market. It aggregates intermediate goods using the CES technology

$$Y_t = \left( \int_0^1 Y_t(j)^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon}{\epsilon-1}}$$

where  $\epsilon > 1$  so that inputs are substitutes. Profit maximization for the final good firm is

$$\max_{Y_t(j)} P_t \left( \int_0^1 Y_t(j)^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon}{\epsilon-1}} - \int_0^1 P_t(j) Y_t(j) dj.$$

The FOC for  $Y_t(j)$  is

$$\begin{aligned} 0 &= P_t \frac{\epsilon}{\epsilon-1} \left( \int_0^1 Y_t(j)^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{1}{\epsilon-1}} \frac{\epsilon-1}{\epsilon} Y_t(j)^{-\frac{1}{\epsilon}} - P_t(j) \\ 0 &= \left( \int_0^1 Y_t(j)^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{1}{\epsilon-1}} Y_t(j)^{-\frac{1}{\epsilon}} - \frac{P_t(j)}{P_t} \\ 0 &= \left( \int_0^1 Y_t(j)^{\frac{\epsilon-1}{\epsilon}} dj \right)^{-\frac{\epsilon}{\epsilon-1}} Y_t(j) - \left( \frac{P_t(j)}{P_t} \right)^{-\epsilon} \\ Y_t(j) &= \left( \frac{P_t(j)}{P_t} \right)^{-\epsilon} Y_t. \end{aligned}$$

Plugging this quantity into the identity

$$P_t Y_t = \int_0^1 P_t(j) Y_t(j) dj$$

and simplifying yields the price index

$$P_t = \left( \int_0^1 P_t(j)^{1-\epsilon} dj \right)^{\frac{1}{1-\epsilon}}.$$

**Intermediate Producers** Intermediate goods are producing according to the Cobb-Douglas technology

$$Y_t(j) = A_t K_{t-1}^\alpha(j) L_t^{1-\alpha}(j).$$

Intermediate producers minimize cost subject to the constraint of meeting demand and Calvo price rigidities. Formally,

$$\min_{K_{t-1}(j), L_t(j)} R_{K,t} K_{t-1}(j) + W_t L_t(j) \quad \text{s.t.} \quad A_t K_{t-1}^\alpha(j) L_t^{1-\alpha}(j) \geq \left( \frac{P_t(j)}{P_t} \right)^{-\epsilon} Y_t.$$

The RHS of the inequality constraint is the demand from final goods producers for intermediate  $j$ . The Lagrangian is

$$\mathcal{L} = R_{K,t} K_{t-1}(j) + W_t L_t(j) + MC_t(j) \left( \left( \frac{P_t(j)}{P_t} \right)^{-\epsilon} Y_t - A_t K_{t-1}^\alpha(j) L_t^{1-\alpha}(j) \right),$$

so the first-order conditions are

$$\begin{aligned} 0 &= R_{K,t} - MC_t(j) \alpha A_t \left( \frac{L_t(j)}{K_{t-1}(j)} \right)^{1-\alpha} \\ 0 &= W_t - MC_t(j) (1-\alpha) A_t \left( \frac{K_{t-1}(j)}{L_t(j)} \right)^\alpha, \end{aligned}$$

hence the optimal capital-labor ratio satisfies

$$\begin{aligned} \frac{R_{K,t}}{\alpha A_t (K_{t-1}(j)/L_t(j))^{\alpha-1}} &= \frac{W_t}{(1-\alpha) A_t (K_{t-1}(j)/L_t(j))^\alpha} \\ \frac{K_{t-1}(j)}{L_t(j)} &= \frac{\alpha}{1-\alpha} \frac{W_t}{R_{K,t}}. \end{aligned}$$

Since the RHS does not vary with  $j$ , all firms choose the same capital-labor ratio. Given this optimal ratio, the marginal cost satisfies

$$\begin{aligned} MC_t &= \frac{R_{K,t}}{\alpha A_t} \left( \frac{K_{t-1}}{L_t} \right)^{1-\alpha} \\ &= \frac{R_{K,t}}{\alpha A_t} \left( \frac{\alpha}{1-\alpha} \frac{W_t}{R_{K,t}} \right)^{1-\alpha} \\ &= \left( \frac{1}{1-\alpha} \right)^{1-\alpha} \left( \frac{1}{\alpha} \right)^\alpha \frac{W_t^{1-\alpha} R_{K,t}^\alpha}{A_t}. \end{aligned}$$

It follows that

$$\begin{aligned} R_{K,t} K_{t-1} + W_t L_t &= \left( \frac{R_{K,t}}{A_t} \left( \frac{K_{t-1}}{L_t} \right)^{1-\alpha} + \frac{W_t}{A_t} \left( \frac{L_t}{K_{t-1}} \right)^\alpha \right) (A_t K_{t-1}^\alpha L_t^{1-\alpha}) \\ &= (\alpha MC_t + (1-\alpha) MC_t) Y_t(j) = MC_t Y_t(j). \end{aligned}$$

Therefore, (real) profits for an intermediate producer become

$$F_t(j) = \frac{P_t(j)}{P_t} Y_t(j) - MC_t Y_t(j).$$

In addition to the capital-labor choice, firms also have the chance to reset prices in every period with probability  $1 - \theta$ . This problem can be written as

$$\max_{P_t(j)} \mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \frac{\exp(\eta_{\beta,t+s})}{\exp(\eta_{\beta,t})} \frac{u'(C_{t+s})}{u'(C_t)} \left( \frac{P_t(j)}{P_{t+s}} \left( \frac{P_t(j)}{P_{t+s}} \right)^{-\epsilon} Y_{t+s} - mc_{t+s} \left( \frac{P_t(j)}{P_{t+s}} \right)^{-\epsilon} Y_{t+s} \right),$$

where I have imposed that intermediate output equals demand. The first-order condition is

$$\begin{aligned} 0 = & (1 - \epsilon) P_t(j)^{-\epsilon} \mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \frac{\exp(\eta_{\beta,t+s})}{\exp(\eta_{\beta,t})} \frac{u'(C_{t+s})}{u'(C_t)} (P_{t+s})^{-(1-\epsilon)} Y_{t+s} \\ & + \epsilon P_t(j)^{-\epsilon-1} \mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \frac{\exp(\eta_{\beta,t+s})}{\exp(\eta_{\beta,t})} \frac{u'(C_{t+s})}{u'(C_t)} mc_{t+s} P_{t+s}^{\epsilon} Y_{t+s} \end{aligned}$$

Divide by  $P_t(j)^{-\epsilon}/(\exp(\eta_{\beta,t})u'(C_t))$ , apply the abuse of notation that  $\prod_{u=1}^0 \Pi_{t+u} = 1$ , and re-arrange to obtain

$$\begin{aligned} P_t(j) &= \frac{\epsilon}{\epsilon - 1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \exp(\eta_{\beta,t+s}) u'(C_{t+s}) mc_{t+s} P_{t+s}^{\epsilon} Y_{t+s}}{\mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \exp(\eta_{\beta,t+s}) u'(C_{t+s}) P_{t+s}^{\epsilon-1} Y_{t+s}} \\ &= \frac{\epsilon}{\epsilon - 1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \exp(\eta_{\beta,t+s}) u'(C_{t+s}) mc_{t+s} P_t^{\epsilon} (\prod_{u=1}^s \Pi_{t+u})^{\epsilon} Y_{t+s}}{\mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \exp(\eta_{\beta,t+s}) u'(C_{t+s}) P_t^{\epsilon-1} (\prod_{u=1}^s \Pi_{t+u})^{\epsilon-1} Y_{t+s}} \\ \frac{P_t(j)}{P_t} &= \frac{\epsilon}{\epsilon - 1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \exp(\eta_{\beta,t+s}) u'(C_{t+s}) mc_{t+s} (\prod_{u=1}^s \Pi_{t+u})^{\epsilon} Y_{t+s}}{\mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \exp(\eta_{\beta,t+s}) u'(C_{t+s}) (\prod_{u=1}^s \Pi_{t+u})^{\epsilon-1} Y_{t+s}}. \end{aligned}$$

This expression gives the optimal (real) reset price  $P_t^* \equiv P_t(j)/P_t$  (note that the RHS does not depend on  $j$ ). Define

$$\begin{aligned} S_{1,t} &= \mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \exp(\eta_{\beta,t+s}) u'(C_{t+s}) mc_{t+s} Y_{t+s} \left( \prod_{u=1}^s \Pi_{t+u} \right)^{\epsilon}, \\ S_{2,t} &= \mathbb{E}_t \sum_{s=0}^{\infty} (\beta\theta)^s \exp(\eta_{\beta,t+s}) u'(C_{t+s}) Y_{t+s} \left( \prod_{u=1}^s \Pi_{t+u} \right)^{\epsilon-1}. \end{aligned}$$

Using these definitions, I may write the optimal reset price more compactly as

$$P_t^* = \frac{\epsilon}{\epsilon - 1} \frac{S_{1,t}}{S_{2,t}}$$

where  $S_{1,t}$  and  $S_{2,t}$  satisfy the recursions

$$\begin{aligned} S_{1,t} &= \exp(\eta_{\beta,t}) u'(C_t) MC_t Y_t + \theta \beta \mathbb{E}_t \Pi_{t+s}^{\epsilon} S_{1,t+1} \\ S_{2,t} &= \exp(\eta_{\beta,t}) u'(C_t) Y_t + \theta \beta \mathbb{E}_t \Pi_{t+s}^{\epsilon-1} S_{2,t+1}. \end{aligned}$$

These recursions can be further rewritten as

$$\begin{aligned}\frac{S_{1,t}}{\exp(\eta_{\beta,t})u'(C_t)} &= MC_t Y_t + \theta \beta \mathbb{E}_t \left[ \frac{\exp(\eta_{\beta,t+1})u'(C_{t+1})}{\exp(\eta_{\beta,t})u'(C_t)} \Pi_{t+s}^\epsilon \frac{S_{1,t+1}}{\exp(\eta_{\beta,t+1})u'(C_{t+1})} \right] \\ \frac{S_{2,t}}{\exp(\eta_{\beta,t})u'(C_t)} &= Y_t + \theta \beta \mathbb{E}_t \left[ \frac{\exp(\eta_{\beta,t+1})u'(C_{t+1})}{\exp(\eta_{\beta,t})u'(C_t)} \Pi_{t+s}^{\epsilon-1} \frac{S_{2,t+1}}{\exp(\eta_{\beta,t+1})u'(C_{t+1})} \right],\end{aligned}$$

By defining  $\tilde{S}_{1,t} \equiv S_{1,t}/(\exp(\eta_{\beta,t})u'(C_t))$  and  $\tilde{S}_{2,t} \equiv S_{2,t}/(\exp(\eta_{\beta,t})u'(C_t))$ , I can simplify these recursions into the form I use for the numerical solution.

From this section, we obtain the following five equilibrium conditions:

$$MC_t = \left( \frac{1}{1-\alpha} \right)^{1-\alpha} \left( \frac{1}{\alpha} \right)^\alpha \frac{W_t^{1-\alpha} R_{K,t}^\alpha}{A_t}, \quad (9)$$

$$\frac{K_{t-1}}{L_t} = \frac{\alpha}{1-\alpha} \frac{W_t}{R_{K,t}}, \quad (10)$$

$$P_t^* = \frac{\epsilon}{\epsilon-1} \frac{\tilde{S}_{1,t}}{\tilde{S}_{2,t}}, \quad (11)$$

$$\tilde{S}_{1,t} = MC_t Y_t + \theta \mathbb{E}_t [M_{t+1} \Pi_{t+1}^\epsilon \tilde{S}_{1,t+1}], \quad (12)$$

$$\tilde{S}_{2,t} = Y_t + \theta \mathbb{E}_t [M_{t+1} \Pi_{t+1}^{\epsilon-1} \tilde{S}_{2,t+1}]. \quad (13)$$

### 1.3 Monetary Policy

I specify the monetary policy rule as the following Taylor rule

$$\frac{R_t}{R} = \left( \frac{R_{t-1}}{R} \right)^{\phi_R} \left( \left( \frac{\Pi_t}{\Pi} \right)^{\phi_\pi} \left( \frac{Y_t}{Y_{t-1}} \right)^{\phi_y} \right)^{1-\phi_R} \exp(\eta_{R,t}) \quad (14)$$

Any proceeds from monetary policy are distributed as lump sum to the representative household.

### 1.4 Aggregation

The price level is currently characterized as the integral

$$P_t^{1-\epsilon} = \int_0^1 P_t(j)^{1-\epsilon} dj.$$

To represent the model entirely in terms of aggregates, notice that, without loss of generality, we may re-order the fraction  $\theta$  of firms which cannot reset prices to the top of the interval so that

$$P_t^{1-\epsilon} = (1-\theta)(P_t^*)^{1-\epsilon} + \int_{1-\theta}^1 P_{t-1}(j)^{1-\epsilon} dj.$$

The latter term can be further simplified under the law of large numbers assumption that a positive measure of firms which cannot change their price still comprise a representative sample of all firms, yielding

$$P_t^{1-\epsilon} = (1-\theta)(P_t^*)^{1-\epsilon} + \theta \int_0^1 P_{t-1}(j)^{1-\epsilon} dj = (1-\theta)(P_t^*)^{1-\epsilon} + \theta P_{t-1}^{1-\epsilon}.$$

Dividing by  $P_{t-1}^{1-\epsilon}$  implies

$$\Pi_t^{1-\epsilon} = (1-\theta)(P_t^* \Pi_t)^{1-\epsilon} + \theta. \quad (15)$$

The price dispersion term can similarly be re-written in terms of aggregates by distinguishing which firms get to change prices.

$$\begin{aligned} V_t^p &= \int_0^{1-\theta} (P_t^*)^{-\epsilon} dj + \int_{1-\theta}^1 \left( \frac{P_{t-1}(j)}{P_t} \right)^{-\epsilon} dj \\ &= \int_0^{1-\theta} (P_t^* \Pi_t)^{-\epsilon} \left( \frac{1}{\Pi_t} \right)^{-\epsilon} dj + \int_{1-\theta}^1 \left( \frac{P_{t-1}(j)}{P_{t-1}} \right)^{-\epsilon} \left( \frac{P_{t-1}}{P_t} \right)^{-\epsilon} dj \\ &= (1-\theta)(P_t^* \Pi_t)^{-\epsilon} \Pi_t^\epsilon + \Pi_t^\epsilon \int_{1-\theta}^1 \left( \frac{P_{t-1}(j)}{P_{t-1}} \right)^{-\epsilon} dj. \end{aligned}$$

By invoking the law of large assumptions applied to any positive measure subset of firms, we must have

$$\int_{1-\theta}^1 \left( \frac{P_{t-1}(j)}{P_{t-1}} \right)^{-\epsilon} dj = \theta \int_0^1 \left( \frac{P_{t-1}(j)}{P_{t-1}} \right)^{-\epsilon} dj = \theta V_{t-1}^p.$$

Thus, we acquire

$$V_t^p = \Pi_t^\epsilon ((1-\theta)(P_t^* \Pi_t)^{-\epsilon} + \theta V_{t-1}^p) \quad (16)$$

## 1.5 Equilibrium

To close the model, I need to specify the functional form for investment, aggregate shocks, and market-clearing conditions.

Following Jermann (1998), I assume the investment function takes the concave form

$$\Phi \left( \frac{X_t}{K_{t-1}} \right) = \frac{\bar{X}^{1/\chi}}{1-1/\chi} \left( \frac{X_t}{K_{t-1}} \right)^{1-1/\chi} - \frac{\bar{X}}{\chi(\chi-1)} \quad (17)$$

where  $\bar{X} = \delta\chi/(\chi+1)$  is the steady-state investment rate (per unit of capital). The first derivative of  $\Phi(\cdot)$  w.r.t.  $X_t/K_{t-1}$  is

$$\Phi' \left( \frac{X_t}{K_{t-1}} \right) = \bar{X}^{1/\chi} \left( \frac{X_t}{K_{t-1}} \right)^{-1/\chi}. \quad (18)$$

This functional form implies the law of motion

$$\begin{aligned}
K_t &= \left( 1 - \delta + \frac{\bar{X}^{1/\chi}}{1 - 1/\chi} \left( \frac{X_t}{K_{t-1}} \right)^{1-1/\chi} - \frac{\bar{X}}{\chi(\chi - 1)} \right) K_{t-1} \\
&= \left( 1 + \frac{\bar{X}^{1/\chi}}{1 - 1/\chi} \left( \frac{X_t}{K_{t-1}} \right)^{1-1/\chi} - \delta \left( 1 + \frac{1}{(\chi - 1)(\chi + 1)} \right) \right) K_{t-1} \\
&= \left( 1 + \frac{\bar{X}^{1/\chi}}{1 - 1/\chi} \left( \frac{X_t}{K_{t-1}} \right)^{1-1/\chi} - \delta \left( \frac{\chi^2}{(\chi - 1)(\chi + 1)} \right) \right) K_{t-1} \\
&= \left( 1 + \frac{\bar{X}^{1/\chi}}{1 - 1/\chi} \left( \frac{X_t}{K_{t-1}} \right)^{1-1/\chi} - \frac{\delta \chi^2}{\chi^2(1 - 1/\chi)(1 + 1/\chi)} \right) K_{t-1} \\
&= \left( 1 + \frac{\bar{X}^{1/\chi}}{1 - 1/\chi} \left( \frac{X_t}{K_{t-1}} \right)^{1-1/\chi} - \frac{\bar{X}}{1 - 1/\chi} \right) K_{t-1}.
\end{aligned}$$

If  $K_t = K_{t-1} = K_{ss}$  and  $X_{ss}/K_{ss} = \bar{X}$ , then

$$1 + \frac{\bar{X}^{1/\chi}}{1 - 1/\chi} \bar{X}^{1-1/\chi} - \frac{\bar{X}}{1 - 1/\chi} = 1 + \frac{\bar{X}}{1 - 1/\chi} - \frac{\bar{X}}{1 - 1/\chi} = 1,$$

thus verifying the original conjecture that  $\bar{X}$  represents the steady-state investment rate.

There are four shocks in the model:  $\eta_{A,t}$ ,  $\eta_{\beta,t}$ ,  $\eta_{L,t}$ , and  $\eta_{R,t}$ . Without loss of generality, I assume all shocks follow AR(1) processes with persistence  $\rho_i$  and standard deviation  $\sigma_i$ .

Markets must clear for capital, labor, bonds, final goods, and intermediate goods, . The first three markets clear as a consequence of optimality conditions and the assumption that bonds have zero net supply. To clear the market for final goods, we set the sum of aggregate consumption demand  $C_t$  and investment demand  $X_t$  equal to aggregate supply  $Y_t$ , which satisfies

$$\begin{aligned}
\int_0^1 A_t K_{t-1}^\alpha L_t^{1-\alpha} dj &= \int_0^1 \left( \frac{P_t(j)}{P_t} \right)^{-\epsilon} Y_t dj \\
A_t K_{t-1}^\alpha L_t^{1-\alpha} &= Y_t \int_0^1 \left( \frac{P_t(j)}{P_t} \right)^{-\epsilon} dj = V_t^p Y_t.
\end{aligned}$$

Re-arranging yields the output market-clearing condition

$$C_t + X_t = Y_t, \tag{19}$$

$$Y_t = \frac{A_t K_{t-1}^\alpha L_t^{1-\alpha}}{V_t^p}. \tag{20}$$

It can be shown that  $V_t^p \geq 1$  by applying Jensen's inequality. For our purposes, because the dimensionality of our model is not too large, we add the auxiliary  $Y_t$  variable, even though we could substitute it out of the system of equations.



All together, the full set of endogenous equilibrium conditions are

$$C_t^{-\gamma} W_t = \varphi \exp(\eta_{L,t}) L_t^\nu, \quad (21)$$

$$M_{t+1} = \beta \frac{\exp(\eta_{\beta,t+1}) C_{t+1}^{-\gamma}}{\exp(\eta_{\beta,t}) C_t^{-\gamma}}, \quad (22)$$

$$1 = \mathbb{E}_t \left[ M_{t+1} \frac{R_t}{\Pi_{t+1}} \right], \quad (23)$$

$$1 = Q_t \Phi' \left( \frac{X_t}{K_{t-1}} \right), \quad (24)$$

$$Q_t = \mathbb{E}_t \left[ M_{t+1} \left( R_{K,t+1} + Q_{t+1} \left( 1 - \delta + \Phi \left( \frac{X_{t+1}}{K_t} \right) - \Phi' \left( \frac{X_{t+1}}{K_t} \right) \frac{X_{t+1}}{K_t} \right) \right) \right], \quad (25)$$

$$MC_t = \left( \frac{1}{1-\alpha} \right)^{1-\alpha} \left( \frac{1}{\alpha} \right)^\alpha \frac{W_t^{1-\alpha} R_{K,t}^\alpha}{A_t}, \quad (26)$$

$$\frac{K_{t-1}}{L_t} = \frac{\alpha}{1-\alpha} \frac{W_t}{R_{K,t}}, \quad (27)$$

$$P_t^* = \frac{\epsilon}{\epsilon-1} \frac{\tilde{S}_{1,t}}{\tilde{S}_{2,t}}, \quad (28)$$

$$\tilde{S}_{1,t} = MC_t Y_t + \theta \mathbb{E}_t [M_{t+1} \Pi_{t+1}^\epsilon \tilde{S}_{1,t+1}], \quad (29)$$

$$\tilde{S}_{2,t} = Y_t + \theta \mathbb{E}_t [M_{t+1} \Pi_{t+1}^{\epsilon-1} \tilde{S}_{2,t+1}], \quad (30)$$

$$\Pi_t^{1-\epsilon} = (1-\theta)(P_t^* \Pi_t)^{1-\epsilon} + \theta, \quad (31)$$

$$V_t^p = \Pi_t^\epsilon ((1-\theta)(P_t^* \Pi_t)^{-\epsilon} + \theta V_{t-1}^p), \quad (32)$$

$$\frac{R_t}{R} = \left( \frac{R_{t-1}}{R} \right)^{\phi_R} \left( \left( \frac{\Pi_t}{\Pi} \right)^{\phi_\pi} \left( \frac{Y_t}{Y_{t-1}} \right)^{\phi_y} \right)^{1-\phi_R} \exp(\eta_{R,t}), \quad (33)$$

$$C_t + X_t = Y_t, \quad (34)$$

$$Y_t = \frac{A_t K_{t-1}^\alpha L_t^{1-\alpha}}{V_t^p}, \quad (35)$$

as well as the law of motion for capital

$$K_t = \left( 1 + \frac{\bar{X}^{1/\chi}}{1-1/\chi} \left( \frac{X_t}{K_{t-1}} \right)^{1-1/\chi} - \frac{\bar{X}}{1-1/\chi} \right) K_{t-1} \quad (36)$$

and the four exogenous processes

$$\eta_{\beta,t+1} = \rho_\beta \eta_{\beta,t} + \sigma_\beta \varepsilon_{\beta,t+1}, \quad (37)$$

$$\eta_{L,t+1} = \rho_L \eta_{L,t} + \sigma_L \varepsilon_{L,t+1}, \quad (38)$$

$$\eta_{A,t+1} = \rho_A \eta_{A,t} + \sigma_A \varepsilon_{A,t+1}, \quad (39)$$

$$\eta_{R,t+1} = \rho_R \eta_{R,t} + \sigma_R \varepsilon_{R,t+1}. \quad (40)$$

## 1.6 Deterministic Steady State

To provide an initial guess for the risk-adjusted linearization and to provide a verification that the model is coded correctly, I determine some reasonable guesses for the deterministic steady state.

Within this subsection, I denote the deterministic steady state values by an absence of a time subscript. The exogenous processes, by construction, have steady states of 0, i.e.  $\eta_\beta = \eta_L = \eta_A = \eta_R = 0$ . Further,  $A = 1$ .

Focusing now on the endogenous equilibrium conditions, from (21),

$$W = \frac{\varphi L^\nu}{C^{-\gamma}}.$$

From (22),

$$M = \beta.$$

From (24), the fact that  $\bar{X}$  is the steady-state investment rate, and the fact that  $\Phi'(\bar{X}) = 1$ ,

$$Q = 1.$$

From (25), first observing that,

$$\Phi(\bar{X}) = \frac{\bar{X}\chi}{\chi - 1} - \frac{\bar{X}}{\chi(\chi - 1)} = \bar{X} \frac{\chi^2 - 1}{\chi(\chi - 1)} = \bar{X} \frac{(\chi - 1)(\chi + 1)}{\chi(\chi - 1)} = \frac{\delta\chi}{\chi + 1} \frac{\chi + 1}{\chi} = \delta,$$

which ensures that  $K$  does indeed remain at steady state, it must be the case that

$$\begin{aligned} 1 &= \beta(R_K + (1 - \delta + \Phi(\bar{X}) - \bar{X})) \\ R_K &= \frac{1}{\beta} + \bar{X} - 1. \end{aligned}$$

Equation (26) remains as it is but with time subscripts removed. From (29),

$$\tilde{S}_1 = MC \cdot Y + \theta\beta\Pi^\epsilon \tilde{S}_1 \Rightarrow \tilde{S}_1 = \frac{MC \cdot Y}{1 - \theta\beta\Pi^\epsilon}.$$

From (30),

$$\tilde{S}_2 = Y + \theta\beta\Pi^{\epsilon-1} \tilde{S}_2 \Rightarrow \tilde{S}_1 = \frac{Y}{1 - \theta\beta\Pi^{\epsilon-1}}.$$

Thus,

$$P^* = \frac{\epsilon}{\epsilon - 1} MC \frac{1 - \theta\Pi^{\epsilon-1}}{1 - \theta\Pi^\epsilon}.$$

From (31),

$$\Pi^{1-\epsilon} = (1 - \theta) (P^* \Pi)^{1-\epsilon} + \theta$$

Note that  $P^*$  depends on  $MC$  and fundamental parameters, hence the above equation pins down  $MC$ , which then pins down the ratio of  $K$  to  $L$ . From (32),

$$\begin{aligned} V^p &= \Pi^\epsilon \left( (1 - \theta) (P^* \Pi)^{-\epsilon} + \theta V^p \right) \\ V^p &= \frac{(1 - \theta) (P^* \Pi)^{-\epsilon}}{\Pi^{-\epsilon} - \theta} = \frac{(1 - \theta) (P^*)^{-\epsilon}}{1 - \theta \Pi^\epsilon}. \end{aligned}$$

From the Taylor rule (33), the steady state interest and inflation rates are  $R$  and  $\Pi$ , respectively, and from the Euler equation (23),  $R$  must satisfy

$$R = \frac{\Pi}{\beta}.$$

From (34),

$$C + X = Y.$$

From (35),

$$Y = \frac{K^\alpha L^{1-\alpha}}{V^p}.$$

As shown previously, the steady-state investment rate is  $\bar{X}$ , hence

$$X = \bar{X}K$$

Finally, I claim that the deterministic steady state reduces to a nonlinear equation in  $L$ . Using the aggregate supply and capital accumulation equations,

$$C + \bar{X}K = \frac{K^\alpha L^{1-\alpha}}{V^p}.$$

The optimal capital-labor ratio implies

$$\begin{aligned} K &= \frac{\alpha}{1 - \alpha} \frac{W}{R_K} L, \\ C + \bar{X}K &= \left( \frac{\alpha}{1 - \alpha} \right)^\alpha \left( \frac{W}{R_K} \right)^\alpha \frac{L}{V^p}. \end{aligned}$$

The intratemporal condition for consumption and labor implies

$$\begin{aligned} K &= \frac{\alpha}{1 - \alpha} \frac{\varphi L^\nu}{C^{-\gamma} R_K} L, \\ C + \delta K &= \left( \frac{\alpha}{1 - \alpha} \right)^\alpha \left( \frac{\varphi L^\nu}{C^{-\gamma} R_K} \right)^\alpha \frac{L}{V^p}. \end{aligned}$$

Given a guess for  $L$ , I can compute  $C$  using these two equations. Given  $C$ , I can compute  $W$ . Given the wage  $W$ , I can compute  $K$  and  $MC$ . Given the marginal cost  $MC$ , I can compute the inflation-related terms.

## 2 Risk-Adjusted Linearization

We now proceed to converting the equilibrium conditions into a suitable form for a risk-adjusted linearization. The system should conform to the representation

$$\begin{aligned} 0 &= \log \mathbb{E}_t [\exp (\xi(z_t, y_t) + \Gamma_5 z_{t+1} + \Gamma_6 y_{t+1})] \\ z_{t+1} &= \mu(z_t, y_t) + \Lambda(z_t, y_t)(y_{t+1} - \mathbb{E}_t y_{t+1}) + \Sigma(z_t, y_t)\varepsilon_{t+1}, \end{aligned}$$

where  $z_t$  are (predetermined) state variables and  $y_t$  are (nondetermined) jump variables. For the remainder of this section, lower case variables are the logs of previously upper case variables, and with a small abuse of notation, let  $s_{1,t} = \log(\tilde{S}_{1,t})$  and  $s_{2,t} = \log(\tilde{S}_{2,t})$ . Additionally, let  $r_{k,t} = \log(R_{K,t})$  and  $v_t = \log(V_t^p)$ .

Equation (21) becomes

$$\begin{aligned} 1 &= \varphi \exp(\eta_{L,t}) \frac{L_t^\nu}{C_t^{-\gamma} W_t} \\ 0 &= \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\varphi) + \eta_{L,t} + \nu l_t - (-\gamma c_t + w_t)}_{\xi} \right) \right]. \end{aligned}$$

Equation (22) will not be used in the system of equations for the risk-adjusted linearization, but it simplifies the other equations. Taking logs and re-arranging yields

$$\begin{aligned} 0 &= \log(\beta) + \eta_{\beta,t+1} + (-\gamma c_{t+1}) - \eta_{\beta,t} - (-\gamma c_t) - m_{t+1} \\ m_{t+1} &= \underbrace{\log(\beta) - \eta_{\beta,t} + \gamma c_t}_{\xi} + \underbrace{\eta_{\beta,t+1} - \gamma c_{t+1}}_{\text{forward-looking}}. \end{aligned}$$

Equation (23) becomes

$$0 = \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\beta) + r_t}_{\xi} + \underbrace{m_{t+1} - \pi_{t+1}}_{\text{forward-looking}} \right) \right].$$

Equation (24) becomes

$$0 = \log \mathbb{E}_t [\exp (q_t + \log (\Phi' (\exp (x_t - k_{t-1}))))].$$

For equation (25), observe that the RHS is not log-linear in the forward-looking variables. To handle this case, I define the new variable

$$\Omega_t = R_{K,t} + Q_t \left( 1 - \delta + \Phi \left( \frac{X_t}{K_{t-1}} \right) - \Phi' \left( \frac{X_t}{K_{t-1}} \right) \frac{X_t}{K_{t-1}} \right). \quad (41)$$

Then (25) can be written as

$$1 = \mathbb{E}_t \left[ \frac{M_{t+1} \Omega_{t+1}}{Q_t} \right]$$

$$0 = \log \mathbb{E}_t [\exp(m_{t+1} + \omega_{t+1} - q_t)].$$

Equation (26) becomes

$$0 = \log \mathbb{E}_t \left[ \exp \left( \underbrace{(1 - \alpha)w_t + \alpha r_{k,t} - a_t - (1 - \alpha) \log(1 - \alpha) - \alpha \log(\alpha) - mc_t}_{\xi} \right) \right].$$

Equation (27) becomes

$$0 = \log \mathbb{E}_t \left[ \exp \left( \underbrace{k_t - l_t - \log \left( \frac{\alpha}{1 - \alpha} \right) - (w_t - r_{k,t})}_{\xi} \right) \right].$$

Like the stochastic discount factor, equation (28) will not be used in the system of equations, but it will be useful to simplify other equations. Taking logs yields

$$p_t^* = \log \left( \frac{\epsilon}{\epsilon - 1} \right) + s_{1,t} - s_{2,t}.$$

Equation (29) becomes

$$\begin{aligned} & \tilde{S}_{1,t} - MC_t Y_t \\ &= \mathbb{E}_t [\exp(\log(\theta) + \log(\beta) + m_{t+1} + \epsilon \pi_{t+1} + s_{1,t+1})] \\ 0 &= \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\theta) + \log(\beta) - \log(\exp(s_{1,t}) - \exp(mc_t) \exp(y_t))}_{\xi} + \underbrace{m_{t+1} + \epsilon \pi_{t+1} + s_{1,t+1}}_{\text{forward-looking}} \right) \right] \end{aligned}$$

and equation (30) becomes

$$0 = \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\theta) + \log(\beta) - \log(\exp(s_{2,t}) - \exp(y_t))}_{\xi} + \underbrace{m_{t+1} + (\epsilon - 1)\pi_{t+1} + s_{2,t+1}}_{\text{forward-looking}} \right) \right].$$

Equation (31) becomes

$$1 = \frac{\Pi_t^{1-\epsilon}}{(1 - \theta)(P_t^* \Pi_t)^{1-\epsilon} + \theta}$$

$$0 = \log \mathbb{E}_t [\exp((1 - \epsilon)\pi_t - \log((1 - \theta) \exp((1 - \epsilon)(p_t^* + \pi_t)) + \theta))].$$

Equation (32) becomes

$$1 = \frac{V_t^p}{\Pi_t^\epsilon((1-\theta)(P_t^*\Pi_t)^{-\epsilon} + \theta V_{t-1}^p)}$$

$$0 = \log \mathbb{E}_t [\exp(v_t - \epsilon\pi_t - \log((1-\theta)\exp(-\epsilon(p_t^* + \pi_t)) + \theta\exp(v_{t-1})))].$$

Equation (33) becomes

$$0 = \log \mathbb{E}_t [\exp(\phi_R r_{t-1} + (1-\phi_R)r + (1-\phi_R)(\phi_\pi(\pi_t - \pi) + \phi_y(y_t - y_{t-1})) + \eta_{R,t} - r_t)].$$

Equation (34) becomes

$$0 = \log \mathbb{E}_t [\exp(y_t - \log(\exp(c_t) + \exp(x_t)))].$$

Equation (35) becomes

$$0 = \log \mathbb{E}_t [\exp(a_t + \alpha k_t + (1-\alpha)l_t - v_t - y_t)].$$

Equation (36) becomes

$$k_t = \log \left( 1 + \frac{\bar{X}^{1/\chi}}{1 - 1/\chi} (\exp(x_t - k_{t-1}))^{1-1/\chi} - \frac{\bar{X}}{1 - 1/\chi} \right) + k_{t-1}.$$

The autoregressive processes (37) to (40) remain as they are.

The jump variables are  $y_t$ ,  $c_t$ ,  $l_t$ ,  $w_t$ ,  $r_t$ ,  $\pi_t$ ,  $q_t$ ,  $x_t$ ,  $r_{k,t}$ ,  $\omega_t$ ,  $mc_t$ ,  $s_{1,t}$ ,  $s_{2,t}$ , and  $v_t$ . The state variables are  $k_{t-1}$ ,  $v_{t-1}$ ,  $r_{t-1}$ ,  $y_{t-1}$ , and the autoregressive processes. The equations defining the evolution of the lags  $v_{t-1}$ ,  $r_{t-1}$ , and  $y_{t-1}$  are obtained by the formula  $z_{(t-1)+1} = z_t$ . This system has three forward difference equations (25), (29), and (30). To ensure accuracy of the risk-adjusted linearization, I derive  $N$ -period ahead forward difference equations for all three.

First, redefine  $\Omega_t$  as

$$\Omega_t = 1 - \delta + \Phi \left( \frac{X_t}{K_{t-1}} \right) - \Phi' \left( \frac{X_t}{K_{t-1}} \right) \frac{X_t}{K_{t-1}}.$$

Then we can write (25) recursively as

$$\begin{aligned} Q_t &= \mathbb{E}_t [M_{t+1}(R_{K,t+1} + Q_{t+1}\Omega_{t+1})] \\ &= \mathbb{E}_t [M_{t+1}R_{K,t+1} + \Omega_{t+1}M_{t+1}\mathbb{E}_{t+1}[M_{t+2}(R_{K,t+2} + Q_{t+2}\Omega_{t+2})]] \\ &= \mathbb{E}_t [M_{t+1}R_{K,t+1}] + \Omega_{t+1}\mathbb{E}_t \mathbb{E}_{t+1} [M_{t+1}M_{t+2}(R_{K,t+2} + Q_{t+2}\Omega_{t+2})]. \end{aligned}$$

By the tower property,

$$\begin{aligned}
Q_t &= \mathbb{E}_t[M_{t+1}R_{K,t+1}] + \Omega_{t+1}\mathbb{E}_t[M_{t+1}M_{t+2}(R_{K,t+2} + Q_{t+2}\Omega_{t+2})] \\
&= \mathbb{E}_t \left[ \left( \sum_{s=1}^2 \left( \prod_{u=1}^{s-1} \Omega_{t+u} \right) \left( \prod_{u=1}^s M_{t+u} \right) R_{K,t+s} \right) + M_{t+1}M_{t+2}Q_{t+2}\Omega_{t+1}\Omega_{t+2} \right] \\
&= \mathbb{E}_t \left[ \left( \sum_{s=1}^2 \left( \prod_{u=1}^{s-1} \Omega_{t+u} \right) \left( \prod_{u=1}^s M_{t+u} \right) R_{K,t+s} \right) + \prod_{s=1}^2 (M_{t+s}\Omega_{t+s}) \mathbb{E}_{t+2}[M_{t+3}(R_{K,t+3} + Q_{t+3}\Omega_{t+3})] \right] \\
&= \mathbb{E}_t \left[ \left( \sum_{s=1}^3 \left( \prod_{u=1}^{s-1} \Omega_{t+u} \right) \left( \prod_{u=1}^s M_{t+u} \right) R_{K,t+s} \right) + \prod_{s=1}^3 (M_{t+s}\Omega_{t+s}) Q_{t+3} \right]
\end{aligned}$$

and so on, with the abuse of notation that  $\prod_{u=1}^0 \Omega_{t+u} = 1$ . Given this recursive structure, define  $D_{Q,t}^{(n)}$  and  $P_{Q,t}^{(n)}$  as

$$\begin{aligned}
D_{Q,t}^{(n)} &= \mathbb{E}_t \left[ \Omega_{t+1} M_{t+1} D_{Q,t+1}^{(n-1)} \right] \\
P_{Q,t}^{(n)} &= \mathbb{E}_t \left[ \Omega_{t+1} M_{t+1} P_{Q,t+1}^{(n-1)} \right]
\end{aligned}$$

with boundary conditions

$$\begin{aligned}
D_{Q,t}^{(0)} &= \frac{R_{K,t+1}}{\Omega_{t+1}} \\
P_{Q,t}^{(0)} &= Q_{t+1}.
\end{aligned}$$

Then I may write the  $N$ -period ahead recursive form of equation (25) as

$$Q_t = \sum_{n=1}^N D_{Q,t}^{(n)} + P_{Q,t}^{(N)}.$$

To see why this recursion works, it is simpler to first verify that  $P_{Q,t}^{(3)}$  is correct:

$$\begin{aligned}
P_{Q,t}^{(1)} &= \mathbb{E}_t [\Omega_{t+1} M_{t+1} Q_{t+1}] \\
P_{Q,t}^{(2)} &= \mathbb{E}_t [\Omega_{t+1} M_{t+1} (\mathbb{E}_{t+1} [\Omega_{t+2} M_{t+2} Q_{t+2}])] \\
&= \mathbb{E}_t \left[ \mathbb{E}_{t+1} \left[ \prod_{s=1}^2 (\Omega_{t+s} M_{t+s}) Q_{t+2} \right] \right] \\
&= \mathbb{E}_t \left[ \prod_{s=1}^2 (\Omega_{t+s} M_{t+s}) Q_{t+2} \right].
\end{aligned}$$

where the second equality for  $P_{Q,t}^{(2)}$  follows from the fact that  $M_{t+1}$  is measurable with respect to the information set at time  $t+1$  and can therefore be moved insided the conditional

expectation  $\mathbb{E}_{t+1}[\cdot]$ . Continuing for one more recursion, I have

$$\begin{aligned} P_{Q,t}^{(3)} &= \mathbb{E}_t \left[ \Omega_{t+1} M_{t+1} \mathbb{E}_{t+1} \left[ \prod_{s=1}^2 (\Omega_{t+1+s} M_{t+1+s}) Q_{t+3} \right] \right] \\ &= \mathbb{E}_t \left[ \prod_{s=1}^3 (\Omega_{t+s} M_{t+s}) Q_{t+3} \right]. \end{aligned}$$

Similarly, for  $D_{Q,t}$ , I have

$$\begin{aligned} D_{Q,t}^{(1)} &= \mathbb{E}_t \left[ \Omega_{t+1} M_{t+1} \frac{R_{K,t+1}}{\Omega_{t+1}} \right] = \mathbb{E}_t [M_{t+1} R_{K,t+1}] \\ D_{Q,t}^{(2)} &= \mathbb{E}_t [\Omega_{t+1} M_{t+1} \mathbb{E}_{t+1} [M_{t+2} R_{K,t+2}]] \\ &= \mathbb{E}_t [\Omega_{t+1} M_{t+1} M_{t+2} R_{K,t+2}] \\ D_{Q,t}^{(3)} &= \mathbb{E}_t [\Omega_{t+1} M_{t+1} \mathbb{E}_{t+1} [\Omega_{t+2} M_{t+2} M_{t+3} R_{K,t+3}]] \\ &= \mathbb{E}_t [\Omega_{t+1} \Omega_{t+2} M_{t+1} M_{t+2} M_{t+3} R_{K,t+3}]. \end{aligned}$$

Since  $P_{Q,t}^{(n)}$  and  $D_{Q,t}^{(n)}$  are time- $t$  conditional expectations, they are measurable at time  $t$ , so they are not forward-looking variables. Thus, to get this version of (25) in the appropriate form, define  $d_{q,n,t} = \log(D_{Q,t}^{(n)})$  and  $p_{q,n,t} = \log(P_{Q,t}^{(n)})$ , and use the following  $2N+1$  equations:

$$0 = \log \mathbb{E}_t \left[ \exp \left( \underbrace{q_t - \log \left( \sum_{n=1}^N \exp(d_{q,n,t}) + \exp(p_{q,n,t}) \right)}_{\xi} \right) \right] \quad (42)$$

$$0 = \begin{cases} \log \mathbb{E}_t \left[ \exp \left( \underbrace{-d_{q,n,t}}_{\xi} + \underbrace{\omega_{t+1} + m_{t+1} + d_{q,n-1,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n > 1 \\ \log \mathbb{E}_t \left[ \exp \left( \underbrace{-d_{q,1,t}}_{\xi} + \underbrace{m_{t+1} + r_{k,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n = 1, \end{cases} \quad (43)$$

$$0 = \begin{cases} \log \mathbb{E}_t \left[ \exp \left( \underbrace{-p_{q,n,t}}_{\xi} + \underbrace{\omega_{t+1} + m_{t+1} + p_{q,n-1,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n > 1 \\ \log \mathbb{E}_t \left[ \exp \left( \underbrace{-p_{q,1,t}}_{\xi} + \underbrace{\omega_{t+1} + m_{t+1} + q_{t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n = 1. \end{cases} \quad (44)$$



For (29), observe that

$$\begin{aligned}
\tilde{S}_{1,t} &= MC_t Y_t + \theta\beta \mathbb{E}_t[M_{t+1}\Pi_{t+1}^\epsilon (MC_{t+1}Y_{t+1} + \theta\beta \mathbb{E}_{t+1}[M_{t+2}\Pi_{t+2}^\epsilon \tilde{S}_{1,t+2}])] \\
&= MC_t Y_t + \theta\beta \mathbb{E}_t[M_{t+1}\Pi_{t+1}^\epsilon MC_{t+1}Y_{t+1} + \theta\beta M_{t+1}\Pi_{t+1}^\epsilon M_{t+2}\Pi_{t+2}^\epsilon \tilde{S}_{1,t+2}] \\
&= MC_t Y_t + \mathbb{E}_t \left[ \sum_{s=1}^1 ((\theta\beta)^s \prod_{u=1}^s (M_{t+u}\Pi_{t+u}^\epsilon)) MC_{t+s} Y_{t+s} \right] + \mathbb{E}_t \left[ \prod_{s=1}^2 (\theta\beta M_{t+s}\Pi_{t+s}^\epsilon) \tilde{S}_{1,t+2} \right].
\end{aligned}$$

Thus, define  $D_{S1,t}^{(n)}$  and  $P_{S1,t}^{(n)}$  as the recursions

$$\begin{aligned}
D_{S1,t}^{(n)} &= \mathbb{E}_t[\theta\beta M_{t+1}\Pi_{t+1}^\epsilon D_{S1,t+1}^{(n-1)}], \\
P_{S1,t}^{(n)} &= \mathbb{E}_t[\theta\beta M_{t+1}\Pi_{t+1}^\epsilon P_{S1,t+1}^{(n-1)}],
\end{aligned}$$

with boundary conditions

$$\begin{aligned}
D_{S1,t}^{(0)} &= MC_t Y_t \\
P_{S1,t}^{(0)} &= \tilde{S}_{1,t}.
\end{aligned}$$

Given these definitions, it follows that

$$\begin{aligned}
D_{S1,t}^{(1)} &= \mathbb{E}_t[\theta\beta M_{t+1}\Pi_{t+1}^\epsilon MC_{t+1}Y_{t+1}] \\
P_{S1,t}^{(1)} &= \mathbb{E}_t[\theta\beta M_{t+1}\Pi_{t+1}^\epsilon \tilde{S}_{1,t+1}] \\
P_{S1,t}^{(2)} &= \mathbb{E}_t[\theta\beta M_{t+1}\Pi_{t+1}^\epsilon \mathbb{E}_{t+1}[\theta\beta M_{t+2}\Pi_{t+2}^\epsilon \tilde{S}_{1,t+2}]] \\
&= \mathbb{E}_t[(\theta\beta)^2 M_{t+1}\Pi_{t+1}^\epsilon M_{t+2}\Pi_{t+2}^\epsilon \tilde{S}_{1,t+2}].
\end{aligned}$$

Thus, defining  $d_{s1,t} = \log(D_{S1,t})$  and  $p_{s1,t} = \log(P_{S1,t})$ , the  $N$ -period ahead recursive form of

(29) results in the  $2N + 1$  equations

$$0 = \log \mathbb{E}_t \left[ \exp \left( \underbrace{s_{1,t} - \log \left( \sum_{n=0}^{N-1} \exp(d_{s1,n,t}) + \exp(p_{s1,n,t}) \right)}_{\xi} \right) \right] \quad (45)$$

$$0 = \begin{cases} \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\theta) + \log(\beta) - d_{s1,n,t}}_{\xi} + \underbrace{m_{t+1} + \epsilon\pi_{t+1} + d_{s1,n-1,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n \geq 1 \\ \log \mathbb{E}_t \left[ \exp \left( \underbrace{d_{s1,0,t} - mc_t - y_t}_{\xi} \right) \right] & \text{if } n = 0. \end{cases} \quad (46)$$

$$0 = \begin{cases} \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\theta) + \log(\beta) - p_{s1,n,t}}_{\xi} + \underbrace{m_{t+1} + \epsilon\pi_{t+1} + p_{s1,n-1,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n > 1 \\ \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\theta) + \log(\beta) - p_{s1,1,t}}_{\xi} + \underbrace{m_{t+1} + s_{1,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n = 1. \end{cases} \quad (47)$$

It is straightforward to show that a similar recursive form applies to (30):

$$0 = \log \mathbb{E}_t \left[ \exp \left( \underbrace{s_{2,t} - \log \left( \sum_{n=0}^{N-1} \exp(d_{s2,n,t}) + \exp(p_{s2,n,t}) \right)}_{\xi} \right) \right] \quad (48)$$

$$0 = \begin{cases} \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\theta) + \log(\beta) - d_{s2,n,t}}_{\xi} + \underbrace{m_{t+1} + (\epsilon - 1)\pi_{t+1} + d_{s2,n-1,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n \geq 1 \\ \log \mathbb{E}_t \left[ \exp \left( \underbrace{d_{s2,0,t} - y_t}_{\xi} \right) \right] & \text{if } n = 0. \end{cases} \quad (49)$$

$$0 = \begin{cases} \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\theta) + \log(\beta) - p_{s2,n,t}}_{\xi} + \underbrace{m_{t+1} + (\epsilon - 1)\pi_{t+1} + p_{s2,n-1,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n > 1 \\ \log \mathbb{E}_t \left[ \exp \left( \underbrace{\log(\theta) + \log(\beta) - p_{s2,1,t}}_{\xi} + \underbrace{m_{t+1} + s_{2,t+1}}_{\text{forward-looking}} \right) \right] & \text{if } n = 1, \end{cases} \quad (50)$$

where terms and boundary conditions are analogously defined.