

# The GEModelTools Package for Solving HANK Models in Python

Jeppe Druedahl  
Emil Holst Partsch

## Abstract

This note provides an overview of the GEModelTools package for solving general equilibrium models easily in Python using the sequence-space method.

You can learn how to use the package following these steps:

1. Read this document
2. Install the package
3. Run the example notebooks
4. Read the commented code for the example notebooks
5. Implement your own model

**Course:** [Adv. Macro: Heterogenous Agent Models](#)

**Literature:** [Boppart et al. \(2018\)](#) and [Auclert et al. \(2021\)](#).

## Structure:

**Section 1** describes the class of models considered

**Section 2** explains the required user inputs and available methods

**Section 3** explains how to efficiently compute the household Jacobian

**Section 4** explains additional features

**Section 5** provides basic troubleshooting

## Code:

Package: [github.com/NumEconCopenhagen/GEModelTools](https://github.com/NumEconCopenhagen/GEModelTools)

Notebooks: [github.com/NumEconCopenhagen/GEModelToolsNotebooks](https://github.com/NumEconCopenhagen/GEModelToolsNotebooks)

**Requirements:** Rely on EconModel and ConSav.

Packages:

[github.com/NumEconCopenhagen/EconModel](https://github.com/NumEconCopenhagen/EconModel)

[github.com/NumEconCopenhagen/ConsumptionSaving](https://github.com/NumEconCopenhagen/ConsumptionSaving)

Notebooks:

[github.com/NumEconCopenhagen/EconModelNotebooks](https://github.com/NumEconCopenhagen/EconModelNotebooks)

[github.com/NumEconCopenhagen/ConsumptionSavingNotebooks](https://github.com/NumEconCopenhagen/ConsumptionSavingNotebooks)

# 1 Model class

In this section, we describe the class of general equilibrium models with heterogeneous agents the package is designed solve, and explain how to use the *sequence space method* developed in [Auclert et al. \(2021\)](#) to solve them. The starting point is a model with *perfect foresight*, where the *non-linear transition path* can be found given the initial distribution of agents and a sequence of exogenous shocks. Next, we show how to solve for the *linearized impulse responses*. These impulse responses are equal to those from a model with *aggregate risk* once it is linearized and certainty equivalence holds. This implies that the sequence space method can be used to simulate time-series data for aggregate variables and the distribution of agents. Throughout this note a simple *Heterogeneous Agent Neo-Classical* (HANC) is used as an example. In Appendix A a *Heterogeneous Agent New Keynesian* with *Search-And-Matching* (HANK-SAM) is considered.

## 1.1 Model class

We consider economies where:

1. Time is discrete (index  $t$ ).
2. There is a continuum of households (index  $i$ , when needed).
3. There is *perfect foresight* wrt. all aggregate variables,  $\mathbf{X}$ , indexed by  $\mathcal{N}$ ,

$$\mathbf{X} = \{\mathbf{X}_t\}_{t=0}^\infty = \{\mathbf{X}^j\}_{j \in \mathcal{N}} = \{X_t^j\}_{t=0, j \in \mathcal{N}},$$

where  $\mathcal{N} = \mathcal{Z} \cup \mathcal{U} \cup \mathcal{O}$ , and  $\mathcal{Z}$  are *exogenous shocks*,  $\mathcal{U}$  are *unknowns*,  $\mathcal{O}$  are *outputs*, and  $\mathcal{H} \in \mathcal{O}$  are *targets*.

4. The model structure is described in terms of a set of *blocks* indexed by  $\mathcal{B}$ , where each block has inputs,  $\mathcal{I}_b \subset \mathcal{N}$ , and outputs,  $\mathcal{O}_b \subset \mathcal{O}$ , and there exists functions  $h^o(\{\mathbf{X}^i\}_{i \in \mathcal{I}_b})$  for all  $o \in \mathcal{O}_b$ .
5. The blocks are *ordered* such that (i) each output is *unique* to a block, (ii) the first block only have shocks and unknowns as inputs, and (iii) later blocks only additionally take outputs of previous blocks as inputs. This implies the blocks can be structured as a *directed acyclical graph* (DAG).
6. The number of targets are equal to the number of unknowns, and an *equilibrium* implies  $\mathbf{X}^o = 0$  for all  $o \in \mathcal{H}$ . Equivalently, the model can be summarized by an *target equation system* from the unknowns and shocks to the targets,

$$\mathbf{H}(\mathbf{U}, \mathbf{Z}) = \mathbf{0}, \tag{1}$$

and an *auxiliary model equation* to infer all variables

$$\mathbf{X} = \mathbf{M}(\mathbf{U}, \mathbf{Z}). \quad (2)$$

A *steady state* satisfy

$$\mathbf{H}(\mathbf{U}_{ss}, \mathbf{Z}_{ss}) = 0 \text{ and } \mathbf{X}_{ss} = \mathbf{M}(\mathbf{U}_{ss}, \mathbf{Z}_{ss}).$$

7. The *discretized household block* can be written recursively as

$$\mathbf{v}_t = v(\underline{\mathbf{v}}_{t+1}, \mathbf{X}_t^{hh}) \quad (3)$$

$$\underline{\mathbf{v}}_t = \Pi(\mathbf{X}_t^{hh}) \mathbf{v}_t \quad (4)$$

$$\mathbf{D}_t = \Pi(\mathbf{X}_t^{hh})' \underline{\mathbf{D}}_t \quad (5)$$

$$\underline{\mathbf{D}}_{t+1} = \Lambda(\underline{\mathbf{v}}_{t+1}, \mathbf{X}_t^{hh})' \mathbf{D}_t \quad (6)$$

$$\mathbf{a}_t^* = \mathbf{a}^*(\underline{\mathbf{v}}_{t+1}, \mathbf{X}_t^{hh}) \quad (7)$$

$$\mathbf{Y}_t^{hh} = \mathbf{y}(\underline{\mathbf{v}}_{t+1}, \mathbf{X}_t^{hh})' \mathbf{D}_t \quad (8)$$

where

$\underline{\mathbf{D}}_0$  is given

$$\mathbf{X}_t^{hh} = \{\mathbf{X}_t^i\}_{i \in \mathcal{I}_{hh}}$$

$$\mathbf{Y}_t^{hh} = \{\mathbf{X}_t^o\}_{o \in \mathcal{O}_{hh}},$$

where respectively  $\underline{\mathbf{v}}_t$  and  $\underline{\mathbf{D}}_t$  and  $\mathbf{v}_t$  and  $\mathbf{D}_t$  are the value functions and distributions *before* and *after* the realization of the idiosyncratic states with transition matrix  $\Pi(\mathbf{X}_t^{hh})$ ,  $\mathbf{a}_t^*$  is the policy functions,  $\mathbf{Y}_t$  is aggregated outputs with  $y(\underline{\mathbf{v}}_{t+1}, \mathbf{X}_t^{hh})$  as individual level measures.

8. Given the sequence of shocks,  $\mathbf{Z}$ , there exists a *truncation period*,  $T$ , such all variables return to steady state beforehand.

It is straightforward to numerically evaluate the model starting from the shocks and unknowns going forward block by block along the directed acyclical graph (DAG). Derivatives can also be calculated along this graph to construct Jacobians. Computationally, the central challenge is to compute the derivatives of the household block. This can be done efficiently as explained below in section 3 with the so-called »fake new algorithm« from Auclert et al. (2021). With the sequence-space Jacobians, the truncated equation system,  $\mathbf{H}(\mathbf{U}, \mathbf{Z}) = 0$ , can be solved straightforwardly with a quasi-Newton solver (e.g. using Broyden's method).

Alternatively, the model can be solved to a first order by total differentiating equation (1)

$$\mathbf{H}_U d\mathbf{U} + \mathbf{H}_Z d\mathbf{Z} = 0 \Leftrightarrow d\mathbf{U} = \underbrace{-\mathbf{H}_U^{-1} \mathbf{H}_Z}_{\equiv \mathbf{G}_U} d\mathbf{Z}, \quad (9)$$

where we refer to  $\mathbf{G}_U$  as the *general equilibrium solution matrix*. By also total differentiating equation (2), the remaining linearized impulse responses can be calculated as

$$\begin{aligned} d\mathbf{X} &= \mathbf{M}_U d\mathbf{U} + \mathbf{M}_Z d\mathbf{Z} \\ &= \underbrace{(-\mathbf{M}_U \mathbf{H}_U^{-1} \mathbf{H}_Z + \mathbf{M}_Z)}_{\equiv \mathbf{G}} d\mathbf{Z}. \end{aligned}$$

where  $\mathbf{G}$  is the full *general equilibrium matrix*.

## 1.2 Example: A simple HANC-model

We now consider how a simple HANC-model fits into this setup.

**Firms.** A representative firm rent capital,  $K_{t-1}$ , and hire labor,  $L_t$ , to produce goods, with the production function

$$Y_t = \Gamma_t K_{t-1}^\alpha L_t^{1-\alpha}, \quad (10)$$

where  $\Gamma_t$  is technology and considered an exogenous shock. Capital depreciates with the rate  $\delta$ . Profit maximization by

$$\max_{K_{t-1}, L_t} Y_t - w_t L_t - r_t^k K_{t-1}$$

implies the standard pricing equations

$$r_t^k = \alpha \Gamma_t (K_{t-1}/L_t)^{\alpha-1} \quad (11)$$

$$w_t = (1 - \alpha) \Gamma_t (K_{t-1}/L_t)^\alpha \quad (12)$$

where  $r_t^k$  is rental rate of capital and  $w_t$  is the wage rate. The implied (real) interest rate is  $r_t = r_t^k - \delta$ .

**Households.** Households are heterogeneous ex ante with respect to their discount factor,  $\beta_i$ , and ex post with respect to their productivity,  $z_t$ , and assets,  $a_{t-1}$ . Each period household exogenously supply  $z_t$  units of labor, and choose consumption  $c_t$  subject to a no-borrowing constraint. Households have *perfect foresight* wrt. to the interest rate and

the wage rate,  $\{r_t, w_t\}_{t=0}^\infty$ , and solve the problem

$$\begin{aligned}
v_t(\beta_i, z_t, a_{t-1}) &= \max_{a_t, c_t} \frac{c_t^{1-\sigma}}{1-\sigma} + \beta \mathbb{E}_t[v_{t+1}(\beta_i, z_{t+1}, a_t)] \\
&\text{s.t.} \\
a_t + c_t &= (1 + r_t)a_{t-1} + w_t z_t \\
\log z_t &= \rho_z \log z_{t-1} + \psi_t, \psi_t \sim \mathcal{N}(\mu_\psi, \sigma_\psi), \mathbb{E}[z_t] = 1 \\
a_t &\geq 0,
\end{aligned} \tag{13}$$

where implicitly  $v_t(\beta_i, z_t, a_{t-1}) = v(\beta_i, z_t, a_{t-1}, \{r_\tau, w_\tau\}_{\tau=t}^\infty)$ . We denote optimal policy functions by  $a_t^*(\beta_i, z_t, a_{t-1})$  and  $c_t^*(\beta_i, z_t, a_{t-1})$ .

The household problem is discretized, and optimal savings function,  $a^*$ , is computed on sorted grids for  $\beta_i$ ,  $z_t$  and  $a_{t-1}$  generically denoted  $\mathcal{G}_x = \{x^0, x^1, \dots, x^{\#x-1}\}$ . The transition probabilities for  $z_t$  are denoted  $\pi_{i_{z-}, i_z} = \Pr[z_t = z^{i_z} | z_{t-1} = z^{i_{z-}}]$ . We consider  $\underline{\mathbf{D}}_t$  and  $\mathbf{D}_t$  to be histograms in terms of probability masses at each grid point. The following updating algorithm can now be used given  $\underline{\mathbf{D}}_t$

1. Stochastic simulation: For each  $i_\beta$ ,  $i_z$  and  $i_{a-}$  calculate

$$\mathbf{D}_t(\beta^{i_\beta}, z^{i_z}, a^{i_{a-}}) = \sum_{i_{z-}=0}^{\#z-1} \pi_{i_{z-}, i_z} \underline{\mathbf{D}}_t(\beta^{i_\beta}, z^{i_{z-}}, a^{i_{a-}})$$

2. Initial zero mass: Set  $\underline{\mathbf{D}}_{t+1}(\beta^{i_\beta}, z^{i_z}, a^{i_a}) = 0$  for all  $i_\beta$ ,  $i_{z+}$  and  $i_a$
3. Choice simulation: For each  $i_\beta$ ,  $i_z$  and  $i_{a-}$  do

- (a) Find  $\iota \equiv \text{largest } i_a \in \{0, 1, \dots, \#a - 2\}$  such that  $a^{i_a} \leq a_t^*(\beta^{i_\beta}, z^{i_z}, a^{i_{a-}})$
- (b) Calculate  $\omega = \frac{a^{\iota+1} - a^*(z^{i_z}, a^{i_{a-}})}{a^{\iota+1} - a^\iota} \in [0, 1]$
- (c) Increment  $\underline{\mathbf{D}}_{t+1}(\beta^{i_\beta}, z^{i_z}, a^\iota)$  with  $\omega \mathbf{D}_t(\beta^{i_\beta}, z^{i_z}, a^{i_{a-}})$
- (d) Increment  $\underline{\mathbf{D}}_{t+1}(\beta^{i_\beta}, z^{i_z}, a^{\iota+1})$  with  $(1 - \omega) \mathbf{D}_t(\beta^{i_\beta}, z^{i_z}, a^{i_{a-}})$

This algorithm first use the exogenous transition probabilities,  $\pi_{i_{z-}, i_z}$ , to simulate forward from the beginning-of-period distribution,  $\underline{\mathbf{D}}_t$ , to the choice-relevant distribution,  $\mathbf{D}_t$ . It secondly derives the next-period beginning-of-period distribution,  $\underline{\mathbf{D}}_{t+1}$ , by distributes probability mass to the neighboring grids points of the optimal savings choice (indexed by  $\iota$ ) using linear weights,  $\omega$ . In matrix form the simulation can be written as The histogram method can be

$$\begin{aligned}
\mathbf{D}_t &= \Pi'_z \underline{\mathbf{D}}_t \\
\underline{\mathbf{D}}_{t+1} &= \Lambda_t \mathbf{D}_t
\end{aligned}$$

where the stochastic transition matrix  $\Pi'_z$  is derived from the  $\pi_{i_{z-}, i_z}$ 's, and the choice transition matrix is derived from the  $\iota$ 's and  $\omega$ 's.

The aggregate supply of savings can be calculated as

$$\begin{aligned}
A_t^{hh} &= \int a_t^*(\beta_i, z_t, a_{t-1}) d\mathbf{D}_t \\
&= \sum_{i_\beta} \sum_{i_z} \sum_{i_a} a_t^*(\beta_i, z_t, a_{t-1}) \mathbf{D}_t(\beta^{i_\beta}, z^{i_z}, a^{i_a}) \\
&= \mathbf{a}_t^{*'} \mathbf{D}_t
\end{aligned} \tag{14}$$

and aggregate consumption can be calculated as

$$\begin{aligned}
C_t^{hh} &= \int c_t^*(\beta_i, z_t, a_{t-1}) d\mathbf{D}_t \\
&= \sum_{i_\beta} \sum_{i_z} \sum_{i_a} c_t^*(\beta_i, z_t, a_{t-1}) \mathbf{D}_t(\beta^{i_\beta}, z^{i_z}, a^{i_a}) \\
&= \mathbf{c}_t^{*'} \mathbf{D}_t
\end{aligned} \tag{15}$$

**Market clearing.** Market clearing requires

$$\begin{aligned}
\text{Capital: } K_t &= A_t^{hh} \\
\text{Labour: } L_t &= \int z_t d\mathbf{D}_t = 1 \\
\text{Goods: } Y_t &= C_t^{hh} + K_t - K_{t-1} + \delta K_{t-1}
\end{aligned}$$

**Stationary equilibrium.** The *stationary equilibrium* (steady state for aggregate variables) for a given  $\Gamma_{ss}$  is

1. Quantities  $K_{ss}$  and  $L_{ss}$ ,
2. prices  $r_{ss}$  and  $w_{ss}$ ,
3. a distribution  $\mathbf{D}_{ss}$  over  $z_{t-1}$  and  $a_{t-1}$
4. and policy functions  $a_{ss}^*(z_t, a_{t-1})$  and  $c_{ss}^*(z_t, a_{t-1})$

are such that

1. Firms maximize profits,  $r_{ss} = \alpha A_{ss} (K_{ss}/L_{ss})^{\alpha-1}$  and  $w_{ss} = (1 - \alpha) A_{ss} \left( \frac{r_{ss} + \delta}{\alpha A_{ss}} \right)^{\frac{\alpha}{\alpha-1}}$
2.  $a_{ss}^*(\bullet)$  and  $c_{ss}^*(\bullet)$  solves the household problem with  $\{r_{ss}, w_{ss}\}_{t=0}^\infty$
3.  $\mathbf{D}_{ss} = \Lambda'_{ss} \Pi'_{ss} \mathbf{D}_{ss}$  is the invariant distribution implied by the household problem
4. The capital market clears, i.e.  $K_{ss} = \int a_{ss}^*(\beta_i, z_t, a_{t-1}) d\mathbf{D}_{ss}$
5. The labor market clears, i.e.  $L_{ss} = \int z_{ss} d\mathbf{D}_{ss} = 1$
6. The goods market clears, i.e.  $Y_{ss} = \int c_{ss}^*(\beta_i, z_t, a_{t-1}) d\mathbf{D}_{ss} + \delta K_{ss}$

This is a root-finding problem, which can be solved as follows:

1. Guess on  $r_{ss}$
2. Calculate  $w_{ss}$
3. Solve the infinite horizon household problem
4. Simulate until convergence of  $\mathbf{D}_{ss}$
5. Calculate supply  $A_{ss}^{hh} = \mathbf{a}_{ss}^{*'} \mathbf{D}_{ss}$
6. Calculate demand  $K_{ss} = \left( \frac{r_{ss} + \delta}{\alpha Z_{ss}} \right)^{\frac{1}{\alpha-1}} L_{ss}$
7. If for some tolerance  $\epsilon$

$$\left| A_{ss}^{hh} - K_{ss} \right| < \epsilon$$

then stop, otherwise update  $r_{ss}$  appropriately and return to step 2

**Transition path.** In terms of the general formulation above, we can write the model in terms of

1. Shocks:  $\mathbf{Z} = \{\mathbf{\Gamma}\}$
2. Unknowns:  $\mathbf{U} = \{\mathbf{K}\}$
3. Targets:  $\{K_t - A_t^{hh}\}$  (asset market clearing)
4. Aggregate variables:  $\mathbf{X} = \{\mathbf{\Gamma}, \mathbf{K}, \mathbf{r}, \mathbf{w}, \mathbf{L}, \mathbf{C}, \mathbf{Y}, \mathbf{A}^{hh}, \mathbf{C}^{hh}\}$
5. Household inputs:  $\mathbf{X}_t^{hh} = \{\mathbf{r}, \mathbf{w}\}$
6. Household outputs:  $\mathbf{Y}_t^{hh} = \{\mathbf{A}^{hh}, \mathbf{C}^{hh}\}$

This implies the equation system

$$\begin{aligned} \mathbf{H}(\mathbf{K}, \mathbf{\Gamma}) &= \mathbf{0} \Leftrightarrow \\ \left[ \begin{array}{c} A_t^{hh} - K_t \end{array} \right] &= \left[ \begin{array}{c} 0 \end{array} \right], \quad \forall t \in \{0, 1, \dots, T-1\} \end{aligned} \tag{16}$$

where we have

$$\begin{aligned} L_t &= 1 \\ r_t &= \alpha \Gamma_t (K_{t-1} / L_t)^{\alpha-1} - \delta \\ w_t &= (1 - \alpha) \Gamma_t \left( \frac{r_t + \delta}{\alpha \Gamma_t} \right)^{\frac{\alpha}{\alpha-1}} \\ A_t^{hh} &= \mathbf{a}_t^{*'} \mathbf{D}_t \\ \mathbf{D}_t &= \Pi_z' \mathbf{D}_t \\ \mathbf{D}_{t+1} &= \Lambda_t \mathbf{D}_t \\ \mathbf{D}_0 &\text{ is given} \end{aligned}$$

The sequence-space solution method described above can therefore be used to find the non-linear transition for an arbitrary sequence for  $\Gamma_t$ . The full Jacobians can be written as

$$\mathbf{H}_K = \mathcal{J}^{A^{hh},r} \mathcal{J}^{r,K} + \mathcal{J}^{A^{hh},w} \mathcal{J}^{w,K} - \mathbf{I} \quad (17)$$

$$\mathbf{H}_Z = \mathcal{J}^{A^{hh},r} \mathcal{J}^{r,Z} + \mathcal{J}^{A^{hh},w} \mathcal{J}^{w,Z} \quad (18)$$

where  $\mathcal{J}^{A^{hh},\bullet}$  are the Jacobians of the household problem, which must be found numerically, and  $\mathcal{J}^{\bullet,K}$  and  $\mathcal{J}^{\bullet,Z}$  are the Jacobians of the firm block, which can in principle be found analytically.

### 1.3 Aggregate risk and simulation

The sequence-space solution method above was used to solve with *perfect foresight* with respect to all aggregate variables. The linearized impulse responses can, however, be shown to also be the linearized impulse responses in a model with aggregate risk, where  $\mathbf{Z}_t$  is a  $MA(\infty)$  process with coefficient  $d\mathbf{Z}_s$  for  $s \in \{0, 1, \dots\}$  driven by the innovation  $\epsilon_t$ .

For a time series of the innovations,  $\tilde{\epsilon}_t$ , the resulting time series of the shocks and all endogenous variables can be computed *with truncation* by

$$d\tilde{\mathbf{Z}}_t = \sum_{s=0}^T d\mathbf{Z}_s \tilde{\epsilon}_{t-s} \quad (19)$$

$$d\tilde{\mathbf{X}}_t = \sum_{s=0}^T d\mathbf{X}_s \tilde{\epsilon}_{t-s} \quad (20)$$

where  $d\mathbf{X}_s$  is the value of the impulse response function  $s$  periods after the shock has arrived.

To simulate a panel of household, we need to know how the policy functions change. Let  $\partial \mathbf{a}_{i_g}^* / \partial X_k^{hh}$  be the derivative of the policy function at grid point  $i_g$  to a  $k$  periods ahead shock to input  $X^{hh}$ . The impulse responses for each grid point then is then computed using the product rule

$$da_{i_g,s}^* = \sum_{s'=s}^{T-1} \sum_{X^{hh} \in \mathbf{X}^{hh}} \frac{\partial a_{i_g}^*}{\partial X_{s'-s}^{hh}} dX_{s'-s}^{hh}.$$

The time path of the policy can then be computed as

$$\mathbf{a}_{i_g}^* = \sum_{s=0}^T da_{i_g,s}^* \tilde{\epsilon}_{t-s},$$

and a panel of households can be simulated using the standard updating rule for the distribution.



### 1.3.1 Simple HANC-model

Assume that  $\Gamma_t$  is an AR(1) process driven by Gaussian shocks with standard deviation  $\sigma$  then  $d\mathbf{Z} = d\mathbf{\Gamma} = \begin{bmatrix} 1 & \rho & \rho^2 & \cdots \end{bmatrix}'$  and  $\epsilon_t \sim \mathcal{N}(0, 1)$  and the general formular above applies.

## 2 Using the GEModelClass

The central tool in GEModelTools is the GEModelClass, which is an add-on to the basic EconModelClass (documented [here](#)). An example of the setup is shown in Listing 1. The three methods .settings(), .setup() and .allocate() are all called automatically when the model is created.

A model of the GEModelClass consists of the following list of namespaces:

1. **Parameters:** .par
2. **Steady state:** .ss
3. **Transition path:** .path
4. **Simulation:** .sim
5. **Initial state:** .ini

The user is required to specify some **variable lists** in .settings() for:

1. **Aggregate variables:** .varlist.  
Used as path.VARNAME.
2. **Household grids:** .grid\_hh.  
Used as par.VARNAME\_grid.
3. **Household inputs, direct:** .inputs\_hh.  
Must be in .varlist.
4. **Household inputs, to transition matrix:** .inputs\_hh\_z.  
Must be in .varlist.
5. **Household outputs:** .outputs\_hh.  
Must *not* be in .varlist.  
The aggregate variable VARNAME.upper()\_hh is added to .varlist.
6. **Household policy functions:** .pols\_hh.  
Must be subset of .outputs\_hh.
7. **Household intertemporal variables:** .intertemps\_hh.  
Must *not* be in .varlist.
8. **Shocks:** .shocks.  
Must be in .varlist.
9. **Unknowns:** .unknowns.  
Must be in .varlist.
10. **Targets:** .targets.  
Must be in .varlist.

The user must choose the following **settings** in .setup():

1. **Number of exogenous *fixed* states:** par.Nfix
2. **Number of exogenous *stochastic* states:** par.Nz

3. **Number of grid points for endogenous variables:** `par.Nendo1, par.Nendo2,...`  
where `endo1, endo2,...`, is in `.grids_hh`
4. **Length of transition period:** `par.T`
5. **Length of simulation:** `par.simT`
6. **For each shock in .shocks:**  
Initial jump: `par.jump_SHOCKNAME`  
Persistence: `par.rho_SHOCKNAME`  
Standard deviation: `par.std_SHOCKNAME`
7. **Optional solver settings:**  
`par.max_iter_solve, par.max_iter_simulate, par.max_iter_broyden`  
`par.tol_solve, par.tol_simulate, par.tol_broyden`

Define `sol_shape = (par.Nfix, par.Nfix, par.Nendo1, par.Nendo1, ...)`.

In `.allocate()` the internal **method** `.allocate_GE()` can now be called to allocate:

1. **Exogenous grids and transition matrices:**  
`par.z_grid, shape=(par.Nz,)`  
`ss.z_trans, shape=(par.Nfix, par.Nz, par.Nz)`  
`ss.Dz, shape=(par.Nfix, par.Nz,)`  
`ini.Dz, shape=(par.Nfix, par.Nz,)`  
`path.z_trans, shape=(par.T, par.Nz, par.Nz)`  
`path.Dz, shape=(par.T, par.Nfix, par.Nz,)`  
`sim.z_trans, shape=(par.simT, par.Nz, par.Nz)`  
`sim.Dz, shape=(par.simT, par.Nfix, par.Nz,)`  
**Remark:** `path.z_trans[t]` is the transition matrix from  $\underline{D}_t$  to  $D_t$
2. **Beginning-of-period distribution,  $\underline{D}_t$ :**  
`ss.Dbeg, shape=sol_shape`  
`ini.Dbeg, shape=sol_shape`  
`path.Dbeg, shape=(par.T, *sol_shape)`  
`sim.Dbeg, shape=(par.simT, *sol_shape)`
3. **Choice-relevant distribution,  $D_t$ :**  
`ss.D, shape=sol_shape`  
`path.D, shape=(par.T, *sol_shape)`  
`sim.D, shape=(par.simT, *sol_shape)`
4. **Household outputs in .outputs\_hh:**  
`ss.OUTPUTNAME, shape=sol_shape`  
`path.OUTPUTNAME, shape=(par.T, *sol_shape)`  
`sim.OUTPUTNAME, shape=(par.simT, *sol_shape)` (only `.pols_hh`)  
Aggregated variables:  
`ss.OUTPUTNAME.upper()_hh, scalar`  
`path.OUTPUTNAME.upper()_hh, shape=(par.T,)`

sim.OUTPUTNAME.upper()\_hh, shape=(par.simT,) (only .pols\_hh)  
sim.OUTPUTNAME.upper()\_hh\_from\_D, shape=(par.simT,) (only .pols\_hh)

5. **Aggregate variables in .varlist:**

ss.VARNAME, scalar  
ini.VARNAME, scalar  
path.VARNAME, shape=(par.T, len(inputs\_endo) × par.T)  
sim.VARNAME, shape=(par.simT,)

**Remark:**

path.VARNAME[0, t] is the value in period  $t$ .  
path.VARNAME[i, t] for  $i > 0$  should be considered *undefined behavior*.

6. **Household Jacobian, .jac\_hh:**

jac\_hh[(OUTPUTNAME.upper()\_hh, INPUTNAME)], each shape=(par.T, par.T)

7. **Full Jacobian, .jac:**

jac[(OUTPUTNAME, INPUTNAME)], each shape=(par.T, par.T)

8. **Solution matrix:**

$H_U$ :  $H_U$ , with shape shape=(par.T, par.T)  
 $H_Z$ :  $H_Z$ , with shape shape=(par.T, par.T)  
 $G_U$ :  $G_U$ , with shape shape=(par.T, par.T)

9. **Impulse-responses of linearized model, .IRF:**

IRF[(OUTPUTNAME, SHOCKNAME)], each shape=(par.T,)

Finally, the user must also provide the following **methods**:

1. `.prephare_hh_ss()` (method), which creates the grids for all the variables in `.par`, creates the transition matrix `ss.z_trans`, choose the initial distributions `ss.Dz` and `ss.Dbeg`, and choose the initial guesses for all variables in `.intertemps_hh()` in `.ss`. This is called each time we solve for the steady state of the household problem using in `.solve_hh_ss()`.
2. `.find_ss()` (method), which solves for the steady state, i.e. fills `ss`, and solve and simulate the household problem in steady state (call `.solve_hh_ss()` and `.simulate_hh_ss()`, see below).

Compared to the general model formulation above the code, currently, only allows for a structure with the household block and pre- and post-blocks. The user must provide the following **jitted**<sup>1</sup> **functions**:

1. **Bellman iteration** (function), `.solve_hh_bakcwards()` which iterates one step backwards in the household problem. Arguments must be:  
`par` and `z_trans` (transition matrix in period  $t$ ).

---

<sup>1</sup> The function should be decorated with `@numba.njit`.

all variables in `.inputs_hh`, `.outputs_hh` and `.intertemps_hh`.

all variables in `.intertemps_hh` with suffix `_plus`.

2. **Evaluate block before household block** (function), `.block_pre()`. Inputs must be: `(par, ini, ss, path, ncols)`, where `ncols` is 1 or `len(unknowns)×par.T`, and the latter is used to evaluate the path simultaneously for all one step changes. After this block has been evaluated all paths in `.inputs_hh` and `.inputs_hh_z` must be filled.
3. **Evaluate block after household block** (function), `.block_post()`. Same requirements as `.block_pre()`. Can rely on paths in `.outputs_hh`.

Additionally, the user can provide a jitted function for calculating a time-varying transition matrix:

1. **Transition function** (function), `.fill_z_trans()` which calculates transition matrix. Arguments must be `par`, `z_trans` and all elements in `.inputs_hh_z`.

The following internal methods are **now available**:

1. `.solve_hh_ss()`: Solve household problem in steady state  $\rightarrow$  `ss.VARNAME`.
2. `.simulate_hh_ss()`: Simulate household problem in steady state  $\rightarrow$  `ss.D` and `ss.VARNAME.upper()_hh` for all variables in `.outputs_hh`.
3. `.solve_hh_path()`: Solve household problem  $\rightarrow$  `path.VARNAME`
4. `.simulate_hh_path()`: Simulate household problem  $\rightarrow$  `path.D` and `path.VARNAME.upper()_hh` for all variables in `.outputs_hh`.
5. `.compute_jacs(skip_hh=False, skip_shocks=False)`:  
Compute the Jacobians  $\rightarrow$  `jac_hh`, `H_U`, `H_Z`, and `jac`.
6. `.find_transition_path()`: Find transition path  $\rightarrow$  `path`.
7. `.find_IRFs(reuse_G_U=False)`: Find linearized impulse-response  $\rightarrow$  `IRF[VARNAME]`.
8. `.simulate(skip_hh=False, reuse_G_U=False)`: Simulate model  $\rightarrow$  `sim.VARNAME`.

The default for the *impulses-responses* is to consider AR(1) shocks given by `par.jump_VARNAME` and `par.rho_VARNAME`. Both solution methods `.find_transition_path()` and `.find_IRFs_path()` also accepts a dictionary like `shock_specs={dSHOCKE:CUSTOMPATH}` as input, where `CUSTOMPATH` is an arbitrary path for the shocks for which to compute the solution.

The default for the *simulation* is to consider AR(1) shocks given by `par.std_VARNAME` and `par.rho_VARNAME`. The aggregated household variables also exists in a version with suffix `_from_D`, where the response is calculated by linearizing the policy function and then aggregating explicitly.

```

1 from EconModel import EconModelClass
2 from GEModelTools import GEModelClass
3
4 class MyModelClass(EconModelClass, GEModelClass):
5
6     def settings(self):
7
8         self.grids_hh = [] # grids
9         self.pols_hh = [] # policy functions
10        self.inputs_hh = [] # inputs to hh problem, direct
11        self.inputs_hh_z = [] # ... inputs to transition matrix
12        self.outputs_hh = [] # output of hh problem
13        self.intertemps_hh = [] # intertemporal variables in hh problem
14
15        self.shocks = [] # exogenous inputs
16        self.unknowns = [] # endogenous inputs
17        self.targets = [] # targets
18        self.varlist = [] # all variables
19
20        self.fill_z_trans = None
21        self.solve_hh_backwards_step = solve_hh_backwards_step
22        self.block_pre = block_pre
23        self.block_post = block_post
24
25    def setup(self):
26
27        par = self.par
28        par.Nfix = 1
29        par.Nz = 7
30        par.NVARNAME = 100 # number of grid points
31        par.jump_VARNAME = -0.01 # initial jump
32        par.rho_VARNAME = 0.8 # AR(1) coefficient
33        par.std_VARNAME = 0.01 # standard deviation
34        par.T = 500 # length of path
35        par.simT = 1000 # length of simulation
36
37    def allocate(self):
38
39        self.allocate_GE()
40
41    def prepare_hh_ss(self): pass
42    def find_ss(self): pass
43

```

Listing 1: Example: Setup

### 3 Efficient computation of the household Jacobian

In this section, we explain how the Jacobian of the household block can be computed efficiently. This algorithm is fully generic, and the package can be used without understanding this section in detail.

The household block can be summarized as

$$\mathbf{Y}^{hh} = hh(\mathbf{X}^{hh}). \quad (21)$$

We are interested in finding the Jacobian around the steady state, i.e.

$$\mathcal{J}^{hh} = \frac{dhh(\mathbf{X}_{ss}^{hh})}{d\mathbf{X}^{hh}}. \quad (22)$$

We let  $\mathcal{J}_{t,s}^{hh,o,i}$  denote the derivative of output  $o$  to input  $i$  at time  $t$  for a shock at time  $s$ . Let  $\bullet_t^{s,i}$  denote a variable in the equation system (3)-(8) when all inputs are at their steady state value *except in period  $s$* , where there is an infinitesimal shock  $dx$  to input variable  $i$ . We then write

$$\underline{\mathbf{D}}_{t+1}^{s,i} = \left(\Lambda_t^{s,i}\right)' \left(\Pi_t^{s,i}\right)' \underline{\mathbf{D}}_t^{s,i} \quad (23)$$

$$\mathbf{Y}_t^{hh,s,i} = \left(\mathbf{y}_t^{s,i}\right)' \left(\Pi_t^{s,i}\right)' \underline{\mathbf{D}}_t^{s,i} \quad (24)$$

**Building blocks.** The value function equations (3) and (4) are forward looking so

$$\begin{aligned} \mathbf{v}_t^{s,i} &= \mathbf{v}_{ss} \text{ for } t > s \\ \underline{\mathbf{v}}_t^{s,i} &= \underline{\mathbf{v}}_{ss} \text{ for } t > s \end{aligned}$$

Additionally, only the time span until the shock arrives matter so

$$\begin{aligned} \mathbf{v}_t^{s,i} &= \mathbf{v}_{t-1}^{s-1,i} \text{ for } t \leq s \\ \underline{\mathbf{v}}_t^{s,i} &= \underline{\mathbf{v}}_{t-1}^{s-1,i} \text{ for } t \leq s \end{aligned}$$

This carries over to  $\mathbf{y}_t^{s,i}$  and  $\Lambda_t^{s,i}$  such that for all  $t, s \geq 0$

$$\mathbf{y}_t^{s,i} = \begin{cases} \mathbf{y}_{ss} & t > s \\ \mathbf{y}_{T-1-(s-t)}^{T-1,i} & t \leq s \end{cases} \text{ and } \Lambda_t^{s,i} = \begin{cases} \Lambda_{ss} & t > s \\ \Lambda_{T-1-(s-t)}^{T-1,i} & t \leq s \end{cases}. \quad (25)$$

We finally have for all  $t, s \geq 0$  that

$$\Pi_t^{s,i} = \begin{cases} \Pi_{ss} & t \neq s \\ \Pi_{T-1,ss}^{T-1,i} & t = s \end{cases} \quad (26)$$

This implies that  $\mathbf{y}_t^{s,i}$ ,  $\Lambda_t^{s,i}$  and  $\Pi_t^{s,i}$  can all be found for any  $t$  and  $s$  once  $\Pi_{T-1,ss}^{T-1,i}$  is known and  $\mathbf{y}_t^{T-1,i}$  and  $\Lambda_t^{T-1,i}$  is known for  $t \in \{0, 1, \dots, T-1\}$ . This only requires a single backwards iteration from a shock in period  $T-1$  for each input.

For later use, we define the following objects:

$$\begin{aligned}\mathcal{Y}_{0,s}^{o,i} &\equiv \frac{dY_0^{o,s,i}}{dx} = \frac{(d\mathbf{y}_0^{o,s,i})'}{dx} (\Pi_{ss})' \underline{\mathbf{D}}_{ss} + \begin{cases} \mathbf{y}_{ss}^o \frac{(d\Pi_0^{s,i})'}{dx} \underline{\mathbf{D}}_{ss} & \text{if } s = 0 \\ 0 & \text{else} \end{cases} \\ \underline{\mathcal{D}}_{1,s}^i &\equiv \frac{d\underline{\mathbf{D}}_1^{s,i}}{dx} = \frac{(d\Lambda_0^{s,i})'}{dx} (\Pi_{ss})' \underline{\mathbf{D}}_{ss} + \begin{cases} \Lambda_{ss}' \frac{(d\Pi_0^{s,i})'}{dx} \underline{\mathbf{D}}_{ss} & \text{if } s = 0 \\ 0 & \text{else} \end{cases} \\ \mathcal{E}_t^o &\equiv (\Pi_{ss} \Lambda_{ss})^t \Pi_{ss} \mathbf{y}_{ss}^o,\end{aligned}$$

where  $\mathcal{Y}_{0,s}^{o,i}$  and  $\underline{\mathcal{D}}_{1,s}^i$  are derivatives of the outputs and the distribution at respectively time 0 and time 1 to a shock at time  $s$ , and  $\mathcal{E}_t^o$  is an expectation vector. The cost of computing  $\mathcal{Y}_{0,s}^{o,i}$  and  $\underline{\mathcal{D}}_{1,s}^i$  for  $s \in \{0, 1, \dots, T-1\}$  are similar to a full forward simulation for  $T$  periods. The cost of computing  $\mathcal{E}_s^o$  is negligible in comparison and can be done recursively,  $\mathcal{E}_t^o = \Pi_{ss} \Lambda_{ss} \mathcal{E}_{t-1}^o$  with  $\mathcal{E}_0^o = \Pi_{ss} \mathbf{y}_{ss}^o$ .

*The task is to build the full Jacobian from these building blocks.* To do this, we first need to take the total derivative of (23) and (24) around the steady state

$$d\underline{\mathbf{D}}_{t+1}^{s,i} = \Lambda_{ss}' \Pi_{ss}' d\underline{\mathbf{D}}_t^{s,i} + (d\Lambda_t^{s,i})' \Pi_{ss}' \underline{\mathbf{D}}_{ss} + \Lambda_{ss} d\Pi_t^{s,i} \underline{\mathbf{D}}_{ss} \quad (27)$$

$$dY_t^{o,s,i} = (\mathbf{y}_{ss}^o)' \Pi_{ss}' d\underline{\mathbf{D}}_t^{s,i} + (d\mathbf{y}_t^{o,s,i})' \Pi_{ss}' \underline{\mathbf{D}}_{ss} + (\mathbf{y}_{ss}^o)' (d\Pi_t^{s,i})' \underline{\mathbf{D}}_{ss} \quad (28)$$

**Edge of the Jacobian** First consider the effect on output at time 0 from a shock at time  $s$ . We immediately have

$$\mathcal{J}_{0,s}^{hh,i,o} = \frac{dY_0^{o,s,i}}{dx} = \mathcal{Y}_s^{o,i} \quad (29)$$

Next consider the effect on output at time  $t \geq 1$  from a shock at time 0. Combining equation (27) with only the time span mattering in equations (25)-(26) implies for  $t \geq 2$

$$\begin{aligned}d\underline{\mathbf{D}}_t^{0,i} &= \Lambda_{ss}' \Pi_{ss}' d\underline{\mathbf{D}}_{t-1}^{0,i} \\ &\quad + \underbrace{(d\Lambda_{t-1}^{0,i})'}_{=0} \Pi_{ss}' \underline{\mathbf{D}}_{ss} + \Lambda_{ss}' \underbrace{(d\Pi_t^{0,i})'}_{=0} \underline{\mathbf{D}}_{ss} \\ &= \Lambda_{ss}' \Pi_{ss}' d\underline{\mathbf{D}}_{t-1}^{0,i} \\ &\quad \vdots \\ &= (\Lambda_{ss}' \Pi_{ss}')^{t-1} d\underline{\mathbf{D}}_1^{0,i}.\end{aligned} \quad (30)$$

Combining (28) with only the time span mattering in equation (25)-(26), and the above



equation (33) implies for  $t \geq 1$ ,

$$\begin{aligned}
dY_t^{o,0,i} &= (\mathbf{y}_{ss}^o)' \Pi'_{ss} d\mathbf{D}_t^{0,i} \\
&\quad + \underbrace{(d\mathbf{y}_t^{o,0,i})'}_{=0} \mathbf{D}_{ss} + \Lambda'_{ss} \underbrace{(d\Pi_t^{0,i})'}_{=0} \mathbf{D}_{ss}. \\
&= (\mathbf{y}_{ss}^o)' \Pi'_{ss} d\mathbf{D}_t^{0,i} \\
&= (\mathbf{y}_{ss}^o)' \Pi'_{ss} (\Lambda'_{ss} \Pi'_{ss})^{t-1} d\mathbf{D}_1^{0,i}
\end{aligned} \tag{31}$$

Combining equation (30) and (31) implies for  $t \geq 1$

$$\mathcal{J}_{t,0}^{hh,i,o} = \frac{dY_t^{o,0,i}}{dx} = (\mathcal{E}_{t-1}^o)' \mathcal{D}_0^i \tag{32}$$

**Inner parts of the Jacobian.** Combining (27) with only the time span mattering in equations (25)-(26), implies for  $t, s \geq 1$

$$\begin{aligned}
d\mathbf{D}_t^{s,i} - d\mathbf{D}_{t-1}^{s-1,i} &= \Lambda'_{ss} \Pi'_{ss} (d\mathbf{D}_{t-1}^{s,i} - d\mathbf{D}_{t-2}^{s-1,i}) \\
&\quad + \underbrace{(d\Lambda_{t-1}^{s,i} - d\Lambda_{t-2}^{s-1,i})'}_{=0} \Pi'_{ss} \mathbf{D}_{ss} + \Lambda'_{ss} \underbrace{(d\Pi_{t-1}^{s,i} - d\Pi_{t-2}^{s-1,i})'}_{=0} \mathbf{D}_{ss} \\
&= \Lambda'_{ss} \Pi'_{ss} (d\mathbf{D}_t^{s,i} - d\mathbf{D}_{t-1}^{s-1,i}) \\
&\quad \vdots \\
&= (\Lambda'_{ss} \Pi'_{ss})^{t-1} \left( d\mathbf{D}_1^{s,i} - \underbrace{d\mathbf{D}_0^{s-1,i}}_{=0} \right) \\
&= (\Lambda'_{ss} \Pi'_{ss})^{t-1} d\mathbf{D}_1^{s,i}
\end{aligned} \tag{33}$$

where  $\mathbf{D}_0 = \mathbf{D}_{ss}$  implies  $d\mathbf{D}_0^{s-1,i} = 0$  in the next to last line.

Combining (28) with only the time span mattering in equation (25)-(26), and the above equation (33), implies for  $t, s \geq 1$

$$\begin{aligned}
dY_t^{o,s,i} - dY_{t-1}^{o,s-1,i} &= (\mathbf{y}_{ss}^o)' \Pi'_{ss} (d\mathbf{D}_t^{s,i} - d\mathbf{D}_{t-1}^{s-1,i}) \\
&\quad + \underbrace{(d\mathbf{y}_t^{o,s,i} - d\mathbf{y}_{t-1}^{o,s-1,i})'}_{=0} \Pi'_{ss} \mathbf{D}_{ss} + \mathbf{y}_{ss}^o \underbrace{(d\Pi_t^{s,i} - d\Pi_{t-1}^{s-1,i})'}_{=0} \mathbf{D}_{ss} \\
&= (\mathbf{y}_{ss}^o)' \Pi'_{ss} (d\mathbf{D}_t^{s,i} - d\mathbf{D}_{t-1}^{s-1,i}) \\
&= (\mathbf{y}_{ss}^o)' \Pi'_{ss} (\Lambda'_{ss} \Pi'_{ss})^{t-1} d\mathbf{D}_1^{s,i} \\
&= (\mathcal{E}_{t-1}^o)' d\mathbf{D}_1^{s,i}
\end{aligned} \tag{34}$$

Combining (33) and (34) for  $t, s \geq 1$  implies

$$\begin{aligned}\mathcal{J}_{t,s}^{hh,i,o} - \mathcal{J}_{t-1,s-1}^{hh,i,o} &= \frac{dY_t^{o,s,i} - dY_{t-1}^{o,s-1,i}}{dx} \Leftrightarrow \\ \mathcal{J}_{t,s}^{hh,i,o} &= \mathcal{J}_{t-1,s-1}^{hh,i,o} + (\mathcal{E}_{t-1}^o)' \underline{\mathcal{D}}_s^i\end{aligned}\quad (35)$$

**Recursive formulation** Define the object

$$\mathcal{F}_{t,s}^{i,o} \equiv \begin{cases} \mathcal{Y}_s^{o,i} & t = 0 \\ (\mathcal{E}_{t-1}^o)' \underline{\mathcal{D}}_s^i & t \geq 1 \end{cases} \quad (36)$$

Combining equations (29), (32) and (35), the household Jacobian can be written recursively by

$$\mathcal{J}_{t,s}^{i,o} = \sum_{k=0}^{\min\{t,s\}} \mathcal{F}_{t-k,s-k}^{i,o} \quad (37)$$

## 4 Additional features

The following methods are available:

1. `.show_IRFS(...)`  
Show IRFs.
2. `.compare_IRFS(...)`  
Compare IRFs across models.
3. `.decompose_hh_path(...)`  
Decompose household transition path (varying inputs and initial distribution)
4. `.print_unpack_varlist(...):`  
Print unpacking of all variables for use in `.block_pre(...)` and `.block_post(...)`.
5. `.test_hh_z_path(...):`  
Test time-invariance when inputs are at their steady state values.
6. `.test_hh_path(...):`  
Test time-invariance when inputs are at their steady state values.
7. `.test_jacs(...):`  
Compare Jacobians calculated with a direct and the fake news algorithm.
8. `.test_path(...):`  
Test time-invariance when inputs are at their steady state values.

## 5 Troubleshooting

**The transition path cannot be found.** Considering the following

1. Use finer tolerances for finding the steady state  
par.tol\_solve ↓  
par.tol\_simulate ↓
2. Extend the transition period  
par.T ↑
3. Decrease the size and persistence of the size  
par.jump\_VARNAME ↓  
par.rho\_VARNAME ↓
4. Change other parameters making the model more stable  
(e.g. more strict Taylor rule, less sticky prices/wages)

## References

- Auclert, A., Bardóczy, B., Rognlie, M., and Straub, L. (2021). Using the Sequence-Space Jacobian to Solve and Estimate Heterogeneous-Agent Models. *Econometrica*, 89(5):2375–2408.
- Boppart, T., Krusell, P., and Mitman, K. (2018). Exploiting MIT shocks in heterogeneous-agent economies: the impulse response as a numerical derivative. *Journal of Economic Dynamics and Control*, 89:68–92.

## A HANK model with endogenous idiosyncratic risk

**Households** The real interest rate and the after-tax wage income as employed are now denoted  $r_t$  and  $w_t^h$ . We additionally assume the households are members of a union, which determines its labor supply, and pays out wages and unemployment benefits. Finally, households are now assumed to have ex ante heterogeneous discount factors,  $\beta_i$ .

The Bellman equation for the household problem is

$$\begin{aligned}
v_t(\beta_i, u_t, e_t, a_{t-1}) &= \max_{c_t, a_t \geq 0} \frac{c_t^{1-\rho}}{1-\rho} + \beta_i \mathbb{E}_t[v_{t+1}(\beta_i, u_{t+1}, e_{t+1}, a_t)] \\
&\text{s.t.} \\
c_t + a_t &= (1 + r_t)a_{t-1} + \phi^{u_t} w_t^h e_t \\
\log e_t &= \rho_e \log e_{t-1} + \psi_t, \psi_t \sim \mathcal{N}(\mu_\psi, \sigma_\psi), \mathbb{E}[e_t] = 1 \\
\Pr[u_{t+1} = 1 \mid u_t = 0] &= \pi_{t+1}^{EU} \\
\Pr[u_{t+1} = 0 \mid u_t = 1] &= \pi_{t+1}^{UE} \\
a_t &\geq 0.
\end{aligned} \tag{38}$$

We have  $z_t = (u_t, e_t)$ . From a perfect foresight sequence space perspective, the value function can be written

$$v_t(u_t, e_t, a_{t-1}) = v\left(u_t, e_t, a_{t-1}; \{r_\tau^h, w_\tau^h, \pi_\tau^{EU}, \pi_\tau^{UE}\}_{\tau=t}^\infty\right).$$

The average discount factor is  $\bar{\beta} = \int \beta_i \mathbf{D}_t$ .

**Firms** The firm  $j$  has the production function  $y_{jt} = Z_t n_{jt}$ . Price setting frictions with Rotemberg adjustment implies a standard New Keynesian Phillips Curve (NKPC),

$$(1 - \epsilon) + \epsilon w_t / Z_t = \theta (\Pi_t - 1) \Pi_t - \bar{\beta} \theta (\Pi_{t+1} - 1) \Pi_{t+1} \frac{Y_{t+1}}{Y_t}. \tag{39}$$

Adjustment costs are considered virtual, and dividends are given by

$$d_t = Y_t - w_t N_t. \tag{40}$$

The dividends are fully taxed away by the government.

**Unions** The unions face wage setting costs giving rise to a New Keynesian Wage Phillips Curve (WPC)

$$(1 - \epsilon_w) (1 - \tau_t) w_t + \epsilon_w \frac{v'(N_t)}{u'(C_t)} = \theta_w (\Pi_t^w - \bar{\Pi}^w) \Pi_t^w - \bar{\beta} \theta_w (\Pi_{t+1}^w - \bar{\Pi}^w) \Pi_{t+1}^w \frac{N_{t+1}}{N_t},$$

where  $v'(N_t) = \vartheta N_t^{\frac{1}{\varphi}}$  is an ad hoc marginal disutility of aggregate labor,  $u'(C_t)$  is an ad hoc marginal utility of aggregate consumption,  $C_t^{-\rho}$ ,  $\Pi_t^w = W_t/W_{t-1}$  and  $W_t$  is the nominal wage. The real wage thus is  $w_t = W_t/P_t$ . The adjustment costs are again considered virtual.

We assume an ad hoc processes for unemployment,  $U_t$ , and the job-finding rate implying the separation rate as a residual,

$$U_t = U_{ss}(N_t/N_{ss})^{\varepsilon_U} \quad (41)$$

$$\pi_t^{UE} = \pi_{ss}^{UE}(N_t/N_{ss})^{\varepsilon_{UE}} \quad (42)$$

$$\pi_t^{EU} = \frac{U_t - \pi_t^{UE}U_{t-1}}{1 - U_{t-1}}. \quad (43)$$

Total after-tax wage income received by the union is  $(1 - \tau_t)w_tN_t$ . For a given unemployment replacement rate,  $\phi$ , this implies that the wage rate per productivity unit faced by the households are

$$w_t^h = \frac{(1 - \tau_t)w_tN_t}{\phi U_t + (1 - U_t)}. \quad (44)$$

**Government** The government budget identity in real terms is

$$B_t = (1 + r_t + (d_t - d_{ss})/B_{t-1})B_{t-1} + G_t - \tau_t w_t N_t - d_t,$$

where  $B_t$  is government bonds,  $G_t$  is government consumption, and  $\tau_t w_t N_t$  are total labor taxes.

We assume government debt,  $B_t$ , initially takes the adjustment when fiscal policy,  $G_t$ , is changed. After period  $t_B$  taxes begin to adjust smoothly over  $\Delta_B$  periods,

$$\tau_t = \begin{cases} \tau_{ss} & \text{if } t < t_B \\ (1 - \omega(\tilde{t}))\tau_{ss} + \omega(\tilde{t})\tilde{\tau}_t & \text{if } t \in [t_B, t_B + \Delta_B], \tilde{t} = (t - t_B)/\Delta_B \\ \tilde{\tau}_t & \text{if } t > t_B + \Delta_B, \end{cases} \quad (45)$$

with

$$\begin{aligned} \tilde{\tau}_t &= \tau_{ss}(B_{t-1}/B_{ss})^{\varepsilon_B} \\ \omega(x) &= 3x^2 - 2x^3 \text{ (smooth } S \text{ function)} \end{aligned}$$

**Monetary Policy** Monetary policy is set according to a Taylor Rule,

$$i_t = (1 + r_{ss})\Pi_t^{\varepsilon_\pi} - 1. \quad (46)$$

The Fisher equation implies

$$r_t = \frac{1 + i_{t-1}}{\Pi_t} - 1. \quad (47)$$

**Market clearing** The labor market clears per construction. The goods market clearing condition is

$$Y_t = G_t + C_t. \quad (48)$$

The asset market clearing condition is

$$A_t = B_t. \quad (49)$$

**Equation system** In terms of the general formulation above, we can write the model in terms of

1. Shocks:  $\mathbf{Z} = \{\mathbf{\Gamma}, \mathbf{G}\}$
2. Unknowns:  $\mathbf{U} = \{\mathbf{Y}, \mathbf{w}\}$
3. Targets: WPC and goods market clearing

In sequence space, the model can be summarized as the equation system,

$$\begin{aligned} \mathbf{H}(\{Y_t, w_t, \Gamma_t, G_t\}_{t=0}^T) = \mathbf{0} &\Leftrightarrow \\ \begin{bmatrix} \text{WPC} \\ \text{Goods market clearing} \end{bmatrix} &= \mathbf{0} \\ \begin{bmatrix} (1 - \epsilon_w)(1 - \tau_t)w_t + \epsilon_w \frac{\partial N_t^{\frac{1}{\varphi}}}{C_t^{-\rho}} - [\theta_w (\Pi_t^w - \bar{\Pi}^w) \Pi_t^w - \bar{\beta} \theta_w (\Pi_{t+1}^w - \bar{\Pi}^w) \Pi_{t+1}^w \frac{N_{t+1}}{N_t}] \\ Y_t = G_t + C_t \end{bmatrix} &= \begin{bmatrix} \\ 0 \end{bmatrix} \\ &\forall t \in \{0, 1, \dots, T-1\} \end{aligned}$$

where we solve the NKPC backwards  $t \in \{T-1, T-2, \dots, 0\}$  for  $\Pi_t$

$$(1 - \epsilon) + \epsilon w_t / \Gamma_t - \left[ \theta (\Pi_t - 1) \Pi_t - \bar{\beta} \left( \theta (\Pi_{t+1} - 1) \Pi_{t+1} \frac{Y_{t+1}}{Y_t} \right) \right]$$

and we implicitly have,

$$\begin{aligned}
\Pi_t^w &= w_t/w_{t-1}\Pi_t \\
w_t &= W_t/P_t \\
i_t &= (1 + r_{ss})\Pi_t^{\varepsilon\pi} \\
r_t &= (1 + i_{t-1})/\Pi_t - 1 \\
N_t &= Y_t/\Gamma_t \\
d_t &= Y_t - w_t N_t \\
U_t &= U_{ss}(N_t/N_{ss})^{\varepsilon_U} \\
\pi_t^{UE} &= \pi_{ss}^{UE}(N_t/N_{ss})^{\varepsilon_{UE}} \\
\pi_t^{EU} &= \frac{U_t - \pi_t^{UE}U_{t-1}}{1 - U_{t-1}} \\
B_t &= (1 + r_t)B_{t-1} + G_t - \tau_t w_t N_t - d_t \\
\tau_t &= \begin{cases} \tau_{ss} & \text{if } t < t_B \\ (1 - \omega(\tilde{t}))\tau_{ss} + \omega(\tilde{t})\tilde{\tau}_t & \text{if } t \in [t_B, t_B + \Delta_B], \tilde{t} = (t - t_B)/\Delta_B \\ \tilde{\tau}_t & \text{if } t > t_B + \Delta_B, \end{cases} \\
\tilde{\tau}_t &= \tau_{ss}(B_t/B_{ss})^{\varepsilon_B} \\
\omega(x) &= 3x^2 - 2x^3 \\
w_t^h &= \frac{(1 - \tau_t)w_t N_t}{\phi U_t + (1 - U_t)} \\
A_t &= B_t \\
C_t &= Y_t - G_t \\
\mathbf{D}_t &= \Pi_z(\pi_t^{UE}, \pi_t^{EU})' \underline{\mathbf{D}}_t \\
\underline{\mathbf{D}}_{t+1} &= \Lambda_t \mathbf{D}_t \\
\underline{\mathbf{D}}_0 &\text{ is given}
\end{aligned}$$