

EGMⁿ: The Sequential Endogenous Grid Method

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Heterogeneous agent models with multiple decision choices are often solved using inefficient grid search methods that require a large number of points and are time intensive. This paper provides a novel method for solving such models using an extension of the endogenous grid method (EGM) that uses Gaussian Process Regression (GPR) to interpolate functions on unstructured grids. First, separating models into smaller, sequential problems allows the problems to be more tractable and easily analyzed. Second, using an exogenous grid of post-decision states and solving for an endogenous grid of pre-decision states that obey a first order condition greatly speeds up the solution process. Third, since the resulting endogenous grid can often be curvilinear at best and unstructured at worst, GPR provides an efficient and accurate method for interpolating the value, marginal value, and policy functions. Applied sequentially to each decision within the overarching problem, the method is able to solve heterogeneous agent models with multiple decision choices in a fraction of the time and with less computational resources than are required by standard grid search methods currently used. This paper also illustrates how this method can be applied to a number of increasingly complex models. Software is provided in the form of a Python module under the HARK package.

PDF: [SequentialEGM.pdf \(Current Version\)](#)
html: <https://alanlujan91.github.io/SequentialEGM/>
GitHub: <https://github.com/alanlujan91/SequentialEGM>

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1 Introduction

1.1 Background

Macroeconomic modeling aims to describe a complex world of agents interacting with each other and making decisions in a dynamic setting. The models are often very complex, requiring strong underlying assumptions to be made, and use a lot of computational power to solve. One of the most common methods to solve these complex problems is to use a grid search method to solve the model. The endogenous grid method (EGM) developed by [Carroll \(2006\)](#) allows dynamic optimization problems to be solved in a more computationally efficient and faster manner than the previous method of convex optimization using grid search. Many problems that before took hours to solve became much easier to solve and allowed macroeconomists and computational economists to focus on estimation and simulation. However, the endogenous grid method is limited to a few specific classes of problems. Recently, the classes of problems to which EGM can be applied has been expanded¹, but with every new method comes a new set of limitations. This paper introduces a new approach to EGM in a multivariate setting. The method is called Sequential EGM (or EGMⁿ) and introduces a novel way of breaking down complex problems into a sequence of simpler, smaller, and more tractable problems, along with an exploration of new multidimensional interpolation methods that can be used to solve these problems.

1.2 Literature Review

[Carroll \(2006\)](#) first introduced the endogenous grid method as a way to speed up the solution of dynamic stochastic consumption-savings problems. The method consists of starting with an exogenous grid of post-decision states and using the inverse of the first order condition to find the optimal consumption policy that rationalizes such post-decision states. Given the optimal policy and post-decision states, it is straightforward to calculate the initial pre-decision state that leads to the optimal policy. Although this method is certainly innovative, it only applied to a model with one control variable and one state variable. [Barillas and Fernández-Villaverde \(2007\)](#) further extend this method by including more than one control variable in the form of a labor-leisure choice, as well as a second state variable for stochastic persistence.

[Hintermaier and Koeniger \(2010\)](#) introduce a model with collateral constraints and non-separable utility and solve using an EGM method that allows for occasionally binding constraints among endogenous variables. [Jørgensen \(2013\)](#) evaluates the performance of the endogenous grid method against other methods for solving dynamic stochastic optimization problems and finds it to be fast and efficient. [Maliar and Maliar \(2013\)](#) develop the Envelope Condition Method based on a similar idea as the endogenous grid method, avoiding the need for costly numerical optimization and grid search. However, their model is limited to infinite horizon problems as it is a forward solution method.

¹[Barillas and Fernández-Villaverde \(2007\)](#); [Maliar and Maliar \(2013\)](#); [Fella \(2014\)](#); [White \(2015\)](#); [Iskhakov, Jørgensen, Rust, and Schjerning \(2017\)](#), among others.

Further development into a multivariate endogenous grid method expanded the ability of researchers to solve models efficiently. White (2015) formally characterized the conditions for the Endogenous Grid Method and developed an interpolation method for structured non-rectilinear, or curvilinear, grids. Iskhakov (2015) additionally establishes conditions for solving multivariate models with EGM, requiring the invertibility of a triangular system of first order conditions. Ludwig and Schön (2018) also develops a novel interpolating method using Delaunay triangulation of the resulting unstructured endogenous grid. However, the authors show that the gains from avoiding the grid search method are often offset by the costly construction of the triangulation.

For the papers discussed above, continuity and smoothness of the value and first order conditions are a strict requirement. Fella (2014) first introduced a method to solve non-convex problems using the endogenous grid method. The idea is based on evaluating necessary but not sufficient candidates for the first order condition in overlapping regions of the state space. Arellano, Maliar, Maliar, and Tsyrennikov (2016) use the Envelope Condition Method to solve a sovereign default risk model with similar efficiency gains to EGM. Iskhakov, Jørgensen, Rust, and Schjerning (2017) further advances the methodology by using extreme errors to solve discrete choice problems with endogenous grid method. These methods however were only applied to a single control variable and a single state variable. Druedahl and Jørgensen (2017) introduces the *G2EGM* to handle non-convex problems with more than 1 control variable and more than 1 state variable. This method is also capable of handling occasionally binding constraints which previous multivariate EGM methods were not.

Clausen and Strub (2020) formalize the applicability of the endogenous grid method and its extensions to discrete choice models and discuss the nesting of problems to efficiently find accurate solutions. Druedahl (2021) similarly suggest the nesting of problems to efficiently use the endogenous grid method within problems with multiple control variables. However, while these nested methods reduce the complexity of solving these models, they often still require grid search methods as is the case with Druedahl (2021).

1.3 Research Question

The purpose of this paper is to describe a new method for solving dynamic optimization problems efficiently and accurately while avoiding convex optimization and grid search methods with the use of the endogenous grid method and first order conditions. The method is called Sequential EGM (or EGMⁿ) and introduces a novel way of breaking down complex problems into a sequence of simpler, smaller, and more tractable problems, along with an exploration of new multidimensional interpolation methods that can be used to solve these problems. This paper also illustrates an example of how Sequential EGM can be used to solve a dynamic optimization problem in a multivariate setting.

1.4 Methodology

The sequential endogenous grid method consists of 3 major parts: First, the problem to be solved should be broken up into a sequence of smaller problems that themselves don't add any additional state variables or introduce asynchronous dynamics with respect to the uncertainty. If the problem is broken up in such a way that uncertainty can happen in more than one period, then the solution of this sequence of problems might be different from the aggregate problem due to giving the agent additional information about the future by realizing some uncertainty. Second, I evaluate each of the smaller problems to see if they can be solved using the endogenous grid method. This evaluation is of greater scope than the traditional endogenous grid method, as it allows for the resulting exogenous grid to be non-regular. If the sub-problem can not be solved with EGM, then convex optimization is used. Third, if the exogenous grid generated by the EGM is non-regular, then I use a multidimensional interpolation method that takes advantage of machine learning tools to generate an interpolating function. Solving each subproblem in this way, the sequential endogenous grid method is capable of solving complex problems that are not solvable with the traditional endogenous grid method and are difficult and time consuming to solve with convex optimization and grid search methods.

1.5 Contributions

The Sequential Endogenous Grid Method is capable of solving multivariate dynamic optimization problems in an efficient and fast manner by avoiding grid search. This should allow researchers and practitioners to solve more complex problems that were previously not easily accessible to them, but more accurately capture the dynamics of the macroeconomy. By using advancements in machine learning techniques such as Gaussian Process Regression, the Sequential Endogenous Grid Method is capable of solving problems that were not previously able to be solved using the traditional endogenous grid method. Additionally, the Sequential Endogenous Grid Method often sheds light onto the problem by breaking it down into a sequence of simpler problems that were not previously apparent. This is because intermediary steps in the solution process generate value and marginal value functions of different pre- and post-decision states that can be used to understand the problem better.

1.6 Outline

The first section below presents a basic model that illustrates the sequential endogenous grid method in 1 dimension. Then section 2 introduces a more complex method with 2 state variables to demonstrate the use of machine learning tools to generate an interpolating function. In section 3 I present the unstructured interpolation methods using machine learning in more detail. Section 4 discusses the theoretical requirements to use the Sequential Endogenous Grid Method. Finally, section 5 concludes with some limitations and future work.

2 The Sequential Endogenous Grid Method

The baseline problem which I will use to demonstrate the Sequential Endogenous Grid Method (EGMⁿ) is a discrete time version of Bodie, Merton, and Samuelson (1992) where a consumer has the ability to adjust their labor as well as their consumption in response to financial risk. The objective consists of maximizing the present discounted lifetime utility of consumption and leisure.

$$\max \mathbb{E}_t \left[\sum_{n=0}^{T-t} \beta^n u(C_{t+n}, Z_{t+n}) \right] \quad (1)$$

In particular, this example makes use of a utility function that is based on Example 1 in the paper, which is that of additively separable utility of labor and leisure as

$$u(C, Z) = u(C) + v(Z) = \frac{C^{1-\rho}}{1-\rho} + \nu^{1-\rho} \frac{Z^{1-\zeta}}{1-\zeta} \quad (2)$$

where the term $\nu^{1-\rho}$ is introduced to allow for a balanced growth path as in Mertens and Ravn (2011). The use of additively separable utility is ad-hoc, as it will allow for the use of multiple endogenous grid method steps in the solution process.

This model represents a consumer who begins the period with a level of bank balances b_t and a given wage offer θ_t . Subsequently, they are able to choose consumption, labor intensity, and a risky portfolio share with the objective of maximizing their utility of consumption and leisure, as well as their future wealth.

The problem can be written in normalized recursive form² as

$$\begin{aligned} v_t(b_t, \theta_t) &= \max_{\{c_t, z_t, s_t\}} u(c_t, z_t) + \beta \mathbb{E}_t [\Gamma_{t+1}^{1-\rho} v_{t+1}(b_{t+1}, \theta_{t+1})] \\ &\text{s.t.} \\ \ell_t &= 1 - z_t \\ m_t &= b_t + \theta_t \ell_t \\ a_t &= m_t - c_t \\ \mathbb{R}_{t+1} &= \mathbb{R} + (\mathbb{R}_{t+1} - \mathbb{R}) \varsigma_t \\ b_{t+1} &= a_t \mathbb{R}_{t+1} / \Gamma_{t+1} \end{aligned} \quad (4)$$

in which ℓ_t is the time supplied to labor net of leisure, m_t is the market resources totaling bank balances and labor income, a_t is the amount of saving assets held by the consumer, and ς_t is the risky share of assets, which induce a \mathbb{R}_{t+1} return on portfolio

²As in Carroll (2009), where utility of normalized consumption and leisure is defined as

$$u(c_t, z_t) = P_t^{1-\rho} \frac{c_t^{1-\rho}}{1-\rho} + \nu P_t^{1-\rho} \frac{z_t^{1-\zeta}}{1-\zeta} \quad (3)$$

that results in next period's bank balances b_{t+1} normalized by next period's permanent income Γ_{t+1} .

2.1 Restating the problem sequentially

We can make a few choices to create a nested problem which will allow us to use multiple endogenous grid method steps in sequence. First, the agent decides their labor-leisure trade-off and receives a wage. Their wage plus their previous bank balance then becomes their market resources. Second, given market resources, the agent makes a pure consumption-saving decision. Finally, given an amount of savings, the consumer then decides their risky portfolio share.

Starting from the beginning of the period, we can define the labor-leisure problem as

$$\begin{aligned}
v_t(b_t, \theta_t) &= \max_{z_t} v(z_t) + \tilde{\mathbf{v}}_t(m_t) \\
&\text{s.t.} \\
0 &\leq z_t \leq 1 \\
\ell_t &= 1 - z_t \\
m_t &= b_t + \theta_t \ell_t
\end{aligned} \tag{5}$$

The pure consumption-saving problem is then

$$\begin{aligned}
\tilde{\mathbf{v}}_t(m_t) &= \max_{c_t} u(c_t) + \beta \mathbf{v}_t(a_t) \\
&\text{s.t.} \\
0 &\leq c_t \leq m_t \\
a_t &= m_t - c_t
\end{aligned} \tag{6}$$

Finally, the risky portfolio problem is

$$\begin{aligned}
\mathbf{v}_t(a_t) &= \max_{\varsigma_t} \mathbb{E}_t [\Gamma_{t+1}^{1-\rho} v_{t+1}(b_{t+1}, \theta_{t+1})] \\
&\text{s.t.} \\
0 &\leq \varsigma_t \leq 1 \\
\mathbb{R}_{t+1} &= \mathbf{R} + (\mathbf{R}_{t+1} - \mathbf{R})\varsigma_t \\
b_{t+1} &= a_t \mathbb{R}_{t+1} / \Gamma_{t+1}
\end{aligned} \tag{7}$$

This sequential approach is explicitly modeled after the nested approach explored in [Druehl \(2021\)](#). However, I will offer additional insights that expand on NEGM. An important observation is that now, every single choice is self contained to a sub-problem, and although the structure is specifically chosen to minimize the number of state variables at every stage, the problem does not change by this structural imposition. This is because there is no additional information or realization of uncertainty that happens between decisions, as can be seen by the expectation operator being in the

last sub-problem. From the perspective of the consumer, these decisions are essentially simultaneous, but a careful organization into sub-period problems enables us to solve the model more efficiently and can provide key economic insights. In this problem, as we will see, a key insight will be the ability to explicitly calculate the marginal value of wealth and the Frisch elasticity of labor.

2.2 The portfolio decision problem

As useful as it is to be able to use the EGM step more than once, there are clear problems where the EGM step is not applicable. This basic labor-portfolio choice problem demonstrates where we can use an additional EGM step, and where we can not. Now, we go over a sub-problem where we can not use the EGM step.

In reorganizing the labor-portfolio problem into subproblems, we assigned the utility of leisure to the leisure-labor sub-problem and the utility of consumption to the consumption-savings sub-problem. There are no more separable convex utility functions to assign to this problem, and even if we re-organized the problem in a way that moved one of the utility functions into this subproblem, they would not be useful in solving this sub-problem via EGM as there is no direct relation between the risky share of portfolio and consumption or leisure. Therefore, the only way to solve this sub-problem is through standard convex optimization and root-finding techniques.

Restating the problem in compact form:

$$\mathbf{v}_t(a_t) = \max_{\varsigma_t} \beta \mathbb{E}_t \left[\Gamma_{t+1}^{1-\rho} \mathbf{v}_{t+1} (a_t(\mathbf{R} + (\mathbf{R}_{t+1} - \mathbf{R})\varsigma_t), \theta_{t+1}) \right] \quad (8)$$

The first order condition with respect to the risky portfolio share is:

$$\beta \mathbb{E}_t \left[\Gamma_{t+1}^{-\rho} \mathbf{v}_{t+1}^b (b_{t+1}, \theta_{t+1}) a_t (\mathbf{R}_{t+1} - \mathbf{R}) \right] = 0 \quad (9)$$

Finding the optimal risky share requires numerical optimization and root-solving.

To close out the problem, we can calculate the envelope condition as:

$$\mathbf{v}'_t(a_t) = \beta \mathbb{E}_t \left[\Gamma_{t+1}^{-\rho} \mathbf{v}_{t+1}^b (b_{t+1}, \theta_{t+1}) \mathbf{R}_{t+1} \right] \quad (10)$$

2.2.1 A note on avoiding taking expectations more than once.

We could instead define the portfolio choice sub-problem as:

$$\mathbf{v}_t(a_t) = \max_{\varsigma_t} \check{\mathbf{v}}(a_t, \varsigma_t) \quad (11)$$

where

$$\begin{aligned}
\check{\mathbf{v}}_t(a_t, \varsigma_t) &= \beta \mathbb{E}_t [\Gamma_{t+1}^{1-\rho} \mathbf{v}_{t+1}(b_{t+1}, \theta_{t+1})] \\
\mathbb{R}_{t+1} &= \mathbf{R} + (\mathbf{R}_{t+1} - \mathbf{R})\varsigma_t \\
b_{t+1} &= a_t \mathbb{R}_{t+1} / \Gamma_{t+1}
\end{aligned} \tag{12}$$

In this case, the process is similar. The only difference is that we don't have to take expectations more than once. Given the next period's solution, we can calculate the marginal value functions as:

$$\begin{aligned}
\check{\mathbf{v}}_t^a(a_t, \varsigma_t) &= \beta \mathbb{E}_t [\Gamma_{t+1}^{-\rho} \mathbf{v}'_{t+1}(b_{t+1}, \theta_{t+1}) \mathbb{R}_{t+1}] \\
\check{\mathbf{v}}_t^\varsigma(a_t, \varsigma_t) &= \beta \mathbb{E}_t [\Gamma_{t+1}^{-\rho} \mathbf{v}'_{t+1}(b_{t+1}, \theta_{t+1}) a_t (\mathbf{R}_{t+1} - \mathbf{R})]
\end{aligned} \tag{13}$$

If we are clever, we can calculate both of these in one step. Now, the optimal risky share can be found by the first order condition and the envelope condition evaluated at the optimal risky share.

$$\text{F.O.C.:} \quad \check{\mathbf{v}}_t^\varsigma(a_t, \varsigma_t^*) = 0 \quad \text{E.C.:} \quad \mathbf{v}_t^a(a_t) = \check{\mathbf{v}}_t^a(a_t, \varsigma_t^*) \tag{14}$$

The consumption-saving EGM follows Carroll (2006) but I will cover it for exposition.

2.3 Consumption-Savings

We can begin the solution process by restating the consumption-savings subproblem in a more compact form, substituting the market resources constraint and ignoring the no-borrowing constraint for now. The problem is:

$$\tilde{\mathbf{v}}_t(m_t) = \max_{c_t} u(c_t) + \mathbf{v}_t(m_t - c_t) \tag{15}$$

To solve, we derive the first order condition with respect to c_t which gives the familiar Euler equation:

$$u'(c_t) = \mathbf{v}'_t(m_t - c_t) = \mathbf{v}'_t(a_t) \tag{16}$$

Inverting the above equation is the (first) EGM step.

$$\mathbf{c}_t(a_t) = u'^{-1}(\mathbf{v}'_t(a_t)) \tag{17}$$

Given the utility function above, the marginal utility of consumption and its inverse are

$$u'(c) = c^{-\rho} \quad u'^{-1}(x) = x^{-1/\rho}. \tag{18}$$

Carroll (2006) demonstrates that by using an exogenous grid of $[a]$ points we can find the unique $\mathbf{c}_t([a])$ that optimizes the consumption-saving problem, since the first

order condition is necessary and sufficient. Further, using the market resources constraint, we can recover the exact amount of market resources that is consistent with this consumption-saving decision as

$$\mathbf{m}_t([a]) = \mathbf{c}_t([a]) + [a] \quad (19)$$

This $\mathbf{m}_t([a])$ is the “endogenous” grid that is consistent with the exogenous decision grid a_t . Now that we have a $(\mathbf{m}_t([a]), \mathbf{c}_t([a]))$ pair for each $a \in [a]$, we can construct an interpolating consumption function for market resources points that are off-the-grid.

The envelope condition will be useful in the next section, but for completeness is defined here.

$$\tilde{\mathbf{v}}'_t(m_t) = \mathbf{v}'_t(a_t) = \mathbf{u}'(c_t) \quad (20)$$

2.4 Labor-Leisure

The labor-leisure sub-problem can be restated more compactly as:

$$\mathbf{v}_t(b_t, \theta_t) = \max_{z_t} v(z_t) + \tilde{\mathbf{v}}_t(b_t + \theta_t(1 - z_t)) \quad (21)$$

The first order condition with respect to leisure implies the labor-leisure Euler equation

$$v'(z_t) = \tilde{\mathbf{v}}'_t(m_t)\theta_t \quad (22)$$

The marginal utility of leisure and it's inverse are

$$v'(z) = \nu z^{-\zeta} \quad v'^{-1}(x) = (x/\nu)^{-1/\zeta} \quad (23)$$

Using an exogenous grid of $[m]$ and $[\theta]$, we can find leisure as

$$\mathfrak{z}_t([m], [\theta]) = v'^{-1}(\tilde{\mathbf{v}}'_t([m])[\theta]) \quad (24)$$

In this case, it's important to note that there are conditions on leisure itself. An agent with a small level of market resources m might want to work more than their available time endowment, especially at higher levels of income θ , if the utility of leisure is not enough to compensate for their low wealth. In these situations, the optimal unconstrained leisure might be negative, so we must impose a constraint on the optimal leisure function. This is similar to the treatment of an artificial borrowing constraint in the pure consumption sub-problem. From now on, let's call this constrained optimal function $\hat{\mathfrak{z}}_t([m], [\theta])$, where

$$\hat{\mathfrak{z}}_t([m], [\theta]) = \max[\min[\mathfrak{z}_t([m], [\theta]), 1], 0] \quad (25)$$

Then, we derive labor as $\mathfrak{l}_t(m_t, \theta_t) = 1 - \hat{\mathfrak{z}}_t(m_t, \theta_t)$. Finally, for each θ_t and m_t as an exogenous grid, we can find the endogenous grid of bank balances as $\mathfrak{b}_t(m_t, \theta_t) = m_t - \theta_t \mathfrak{l}_t(m_t, \theta_t)$.

The envelope condition is simply

$$v_t^b(b_t, \theta_t) = \tilde{\mathfrak{v}}'_t(m_t) = v'(z_t)/\theta_t \quad (26)$$

2.5 Alternative Parametrization

An alternative formulation for the utility of leisure is to state it in terms of the disutility of labor as in (references)

$$v(\ell) = -\zeta \frac{\ell^{1+\nu}}{1+\nu} \quad (27)$$

In this case, we can restate the problem as

$$v(z) = -\zeta \frac{(1-z)^{1+\nu}}{1+\nu} \quad (28)$$

The marginal utility of leisure and it's inverse are

$$v'(z) = \zeta(1-z)^\nu \quad v'^{-1}(x) = 1 - (x/\zeta)^{1/\nu} \quad (29)$$

3 The EGMⁿ in Higher Dimensions

3.1 A more complex problem

The problem above demonstrates the simplicity of solving problems sequentially. However, as constructed, the problem has only 1 state variable and 1 post-decision state variable per stage. Can EGMⁿ be used to solve higher dimensional problems? In short, yes, but it requires additional thought on interpolation.

For a demonstration, we now turn to the problem of a worker saving up for retirement. This worker must consume, save, and deposit resources into a tax-advantaged account that can not be liquidated until retirement. In the recursive problem, the worker begins a new period with a liquid account of market resources m_t and an illiquid account of retirement savings n_t . The worker maximizes their utility by choosing consumption c_t and pension deposit d_t . The pension deposit is set aside on a retirement account that is exposed to a risky return, while their post-consumption liquid assets accrue risk-free interest every period. The worker additionally receives an income which faces a permanent (Γ_{t+1}) and a transitory (θ_{t+1}) shock every period. At the age of 65, the worker is retired and their assets are liquidated, at which point the state reduces to one liquid account of market resources. The worker's recursive problem is:

$$\begin{aligned}
v_t(m_t, n_t) &= \max_{c_t, d_t} u(c_t) + \beta \mathbb{E}_t [\Gamma_{t+1}^{1-\rho} v_{t+1}(m_{t+1}, n_{t+1})] \\
\text{s.t. } & c_t \geq 0, \quad d_t \geq 0 \\
& a_t = m_t - c_t - d_t \\
& b_t = n_t + d_t + g(d_t) \\
m_{t+1} &= a_t \mathbf{R} / \Gamma_{t+1} + \theta_{t+1} \\
n_{t+1} &= b_t \mathbf{R}_{t+1} / \Gamma_{t+1}
\end{aligned} \tag{30}$$

This problem can subsequently be broken down into 3 stages: a pension deposit stage, a consumption stage, and an income shock stage.

In the deposit stage, the worker begins with market resources and a retirement savings account. The worker must maximize their value of liquid wealth l_t and retirement balance b_t by choosing a pension deposit d_t , which must be positive. The retirement balance b is the cash-value of their retirement account plus their pension deposit and an additional amount $g(d_t)$ that provides an incentive to save for retirement. As we'll see, this additional term will allow us to use the endogenous grid method to solve this sub-problem.

$$\begin{aligned}
v_t(m_t, n_t) &= \max_{d_t} \tilde{v}_t(l_t, b_t) \\
\text{s.t. } & d_t \geq 0 \\
& l_t = m_t - d_t \\
& b_t = n_t + d_t + g(d_t)
\end{aligned} \tag{31}$$

After making their pension decision, the worker begins their consumption stage with liquid wealth l_t and retirement balance b_t . From their liquid wealth, the worker must choose a level of consumption to maximize utility and continuation value w_t . After consumption, the worker is left with post-decision states that represent liquid assets a_t and retirement balance b_t , which passes through this problem unaffected because it can't be liquidated until retirement.

$$\begin{aligned}
\tilde{v}_t(l_t, b_t) &= \max_{c_t} u(c_t) + \beta w_t(a_t, b_t) \\
\text{s.t. } & c_t \geq 0 \\
& a_t = m_t - c_t - d_t \\
& b_t = n_t + d_t + g(d_t)
\end{aligned} \tag{32}$$

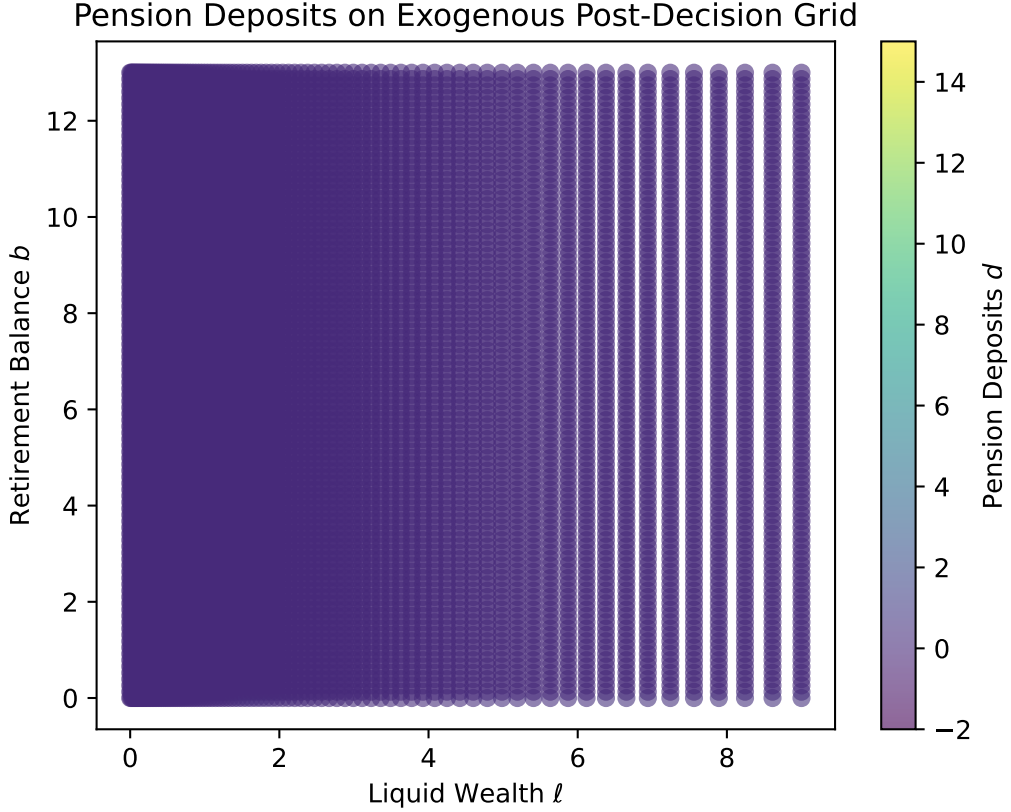
Finally, the post-decision value function w_t represents the value of both liquid and illiquid account balances before the realization of uncertainty regarding the risky return and income shocks. Since we are dealing with a normalized problem, this stage handles the normalization of state variables and value functions into the next period. The advantage of conceptualizing this sub-problem as a separate stage is that we can construct

a function w_t and use it in the prior optimization problems without having to worry about stochastic optimization.

$$\begin{aligned}
w_t(a_t, b_t) &= \mathbb{E}_t [\Gamma_{t+1}^{1-\rho} v_{t+1}(m_{t+1}, m_{t+1})] \\
\text{s.t. } &a_t \geq 0, \quad b_t \geq 0 \\
m_{t+1} &= a_t R / \Gamma_{t+1} + \theta_{t+1} \\
n_{t+1} &= b_t R_{t+1} / \Gamma_{t+1}
\end{aligned} \tag{33}$$

3.2 The pass-through case

As seen in the consumption stage above, the retirement balance b_t passes through the problem unaffected because it can't be liquidated until retirement. In this sense, it is already a post-decision state variable. To solve this problem, we can use a fixed grid of b_t and for each obtain endogenous consumption and ex-ante market resources using the simple endogenous grid method for the consumption problem.



In the deposit stage, both the state variables and post-decision variables are different since both are affected by the pension deposit decision.

First, we can rewrite the pension deposit problem more compactly as:

$$v_t(m_t, n_t) = \max_{d_t} \tilde{v}_t(m_t - d_t, n_t + d_t + g(d_t)) \quad (34)$$

The first order condition is

$$\tilde{v}_t^l(l_t, b_t)(-1) + \tilde{v}_t^b(l_t, b_t)(1 + g'(d_t)) = 0 \quad (35)$$

Rearranging this equation gives

$$g'(d_t) = \frac{\tilde{v}_t^l(l_t, b_t)}{\tilde{v}_t^b(l_t, b_t)} - 1 \quad (36)$$

Assuming that $g'(d)$ exists and is invertible, we can find

$$\mathfrak{d}_t(l_t, b_t) = g'^{-1} \left(\frac{\tilde{v}_t^l(l_t, b_t)}{\tilde{v}_t^b(l_t, b_t)} - 1 \right) \quad (37)$$

Using this, we can back out n_t as

$$\mathfrak{n}_t(l_t, b_t) = b_t - \mathfrak{d}_t(l_t, b_t) - g(\mathfrak{d}_t(l_t, b_t)) \quad (38)$$

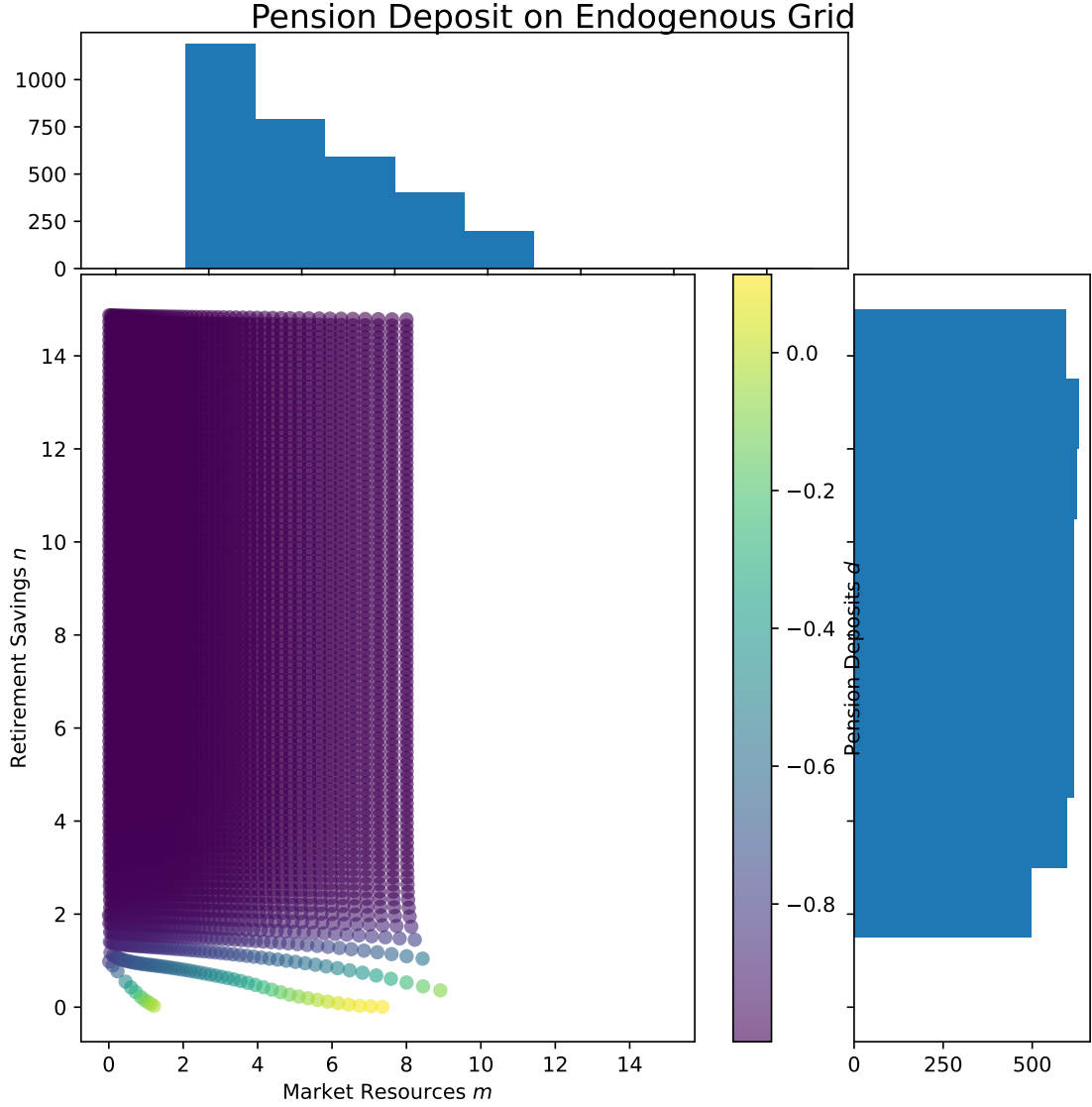
and m_t as

$$\mathfrak{m}_t(l_t, b_t) = l_t + \mathfrak{d}_t(l_t, b_t) \quad (39)$$

In sum, given an exogenous grid (l_t, b_t) we obtain the triple $(\mathfrak{m}_t(l_t, b_t), \mathfrak{n}_t(l_t, b_t), \mathfrak{d}_t(l_t, b_t))$, which we can use to create an interpolator for the decision rule d_t .

To close the solution method, the envelope conditions are

$$\begin{aligned} v_t^m(m_t, n_t) &= \tilde{v}_t^l(l_t, b_t) \\ v_t^n(m_t, n_t) &= \tilde{v}_t^b(l_t, b_t) \end{aligned} \quad (40)$$



3.3 Unstructured Grid Interpolation

To interpolate a function defined on an unstructured grid, we use Gaussian Process Regression as in Scheidegger and Bilionis (2019).

4 Multivariate Interpolation on Non-Rectilinear Grids

This section presents alternative interpolation methods for non-rectilinear grids. First, I present the relatively simpler case of fast warped interpolation on a curvilinear grid, which improves upon the interpolation in White (2015). Then, I present a machine

learning approach to interpolation on unstructured grids based on Gaussian process regression as presented in Scheidegger and Bilonis (2019).

4.1 Warped Homotopic Interpolation Method (WHIM)

Discuss fast warped interpolation.

4.2 Gaussian Process Regression (GPR)

Unstructured interpolation arises in many dynamic programming applications when using the endogenous grid method because the first order conditions might be highly non-linear and non-monotonic, or because boundary constraints induce kinks in the policy and value functions. In these cases, the grid points generated by the EGM step are not evenly spaced, leading to the need for curvilinear interpolation. We saw above an approach to curvilinear interpolation based on White (2015) that is incapable of interpolation on structured grids. A similar approach was presented in Ludwig and Schön (2018) which used Delaunay interpolation. However, this approach is not well suited for our purposes because triangulation can be computationally expensive and slow, often offsetting the efficiency gains from the Endogenous Grid Method.

As an alternative to these methods, I introduce the use of Gaussian process regression (GPR) along with the Endogenous Grid Method. GPR is computationally efficient, and tools exist to easily parallelize and take advantage of hardware such as GPU's.

4.2.1 Gaussian Process Regression

A Gaussian process is a random process for which every subset of random variables is jointly Gaussian or has a multivariate normal distribution.

5 Conditions for using the Sequential Endogenous Grid Method

5.1 Splitting the problem into subproblems

The first step in using the Sequential Endogenous Grid Method is to split the problem into subproblems. This process of splitting up the problem has to be strategic so as to not insert additional complexity to the original problem. If one is not careful when doing this, the sub-problems can become more complex and intractable than the original problem.

To split up the problem, we first count the number of control variables or decisions faced by the agent. Ideally, if the agent has n control variables, then the problem should be split into n subproblems, each handling a different control variable. For counting the number of control variables, it is important to not double count variables which are equivalent and have market clearing conditions. For example, the decision of how much

to consume and how much to save may seem like 2 different choices, but because of the market clearing condition $c + a = m$ they are resolved simultaneously and count as only one decision variable. Similarly, the choice between labor and leisure are simultaneous and count as only one decision.

Having counted our control variables, we look for differentiable and invertible utility functions which are separable in the dynamic programming problem, such as in section 2 of the paper, or differentiable and invertible functions in the constraints, as in section 3 of the paper.

5.1.1 Separable utility functions

In that problem, we have additively separable utility of consumption and leisure, which allows for each of these control variables to be handled by a separate subproblem. So, it makes sense to split the utility between subproblems and attach one to the consumption subproblem and one to the leisure subproblem.

As mentioned in section 2, however, there are only 2 separable utility functions in the problem which have been assigned to 2 sub-problems already. This leaves one control variable without a separable utility function. In that case, there is no more endogenous grid method step to exploit, and this subproblem has to be handled by standard convex optimization techniques such as maximization of the value function (VFI) or finding the root of the Euler equation (PFI).

Now that we have split the problem into conceptual sub-problems, it is important to sequence them in such a way that they don't become more complex than the original problem. The key here is to avoid adding unnecessary state variables. For example, in the consumption-leisure-portfolio problem, if we were to choose consumption first, we would have to track the wage rate into the following leisure sub-problem. This would mean that our consumption problem would be 2-dimensional as well as our labor decision problem. As presented, the choice of order in section 2 ensures that the consumption problem is 1-dimensional, as we can shed the information about the wage rate offer after the agent has made their labor-leisure decision. If we did this the other way, the problem would be more complex and require more computational resources.

The consumption sub-problem would be 2-dimensional instead of 1 dimensional, adding more complexity,

$$\begin{aligned} v(b, \theta) &= \max_c u(c) + \tilde{v}(b', \theta) \\ \text{s.t.} \\ b' &= b - c \geq -\theta \end{aligned} \tag{41}$$

while the labor-leisure sub-problem would have an additional constraint

$$\begin{aligned}
\tilde{\mathbf{v}}(b', \theta) &= \max_z v(z) + \mathbf{v}(a) \\
&\text{s.t.} \\
0 &\leq z \leq 1 \\
a &= b' + \theta(1 - z) \geq 0.
\end{aligned} \tag{42}$$

5.1.2 Differentiable and invertible constraints

In section 3, we saw that a problem with a differentiable and invertible constraint can also be used to embed an additional endogenous grid method step.

Therefore, strategic ordering of sub-problems can greatly simplify the solution process and reduce computational burden.

6 Conclusion

This paper introduces a novel method for solving dynamic stochastic optimization problems called the Sequential Endogenous Grid Method (EGMⁿ). Given a problem with multiple decision choices (or control variables), the Sequential Endogenous Grid Method proposes separating the problem into a sequence of smaller sub-problems that can be solved sequentially by using more than one EGM step. Then, depending on the resulting endogenous grid from each sub-problem, this paper proposes different methods for interpolating functions on non-rectilinear grids, called the Warped Homotopic Interpolation Method (WHIM) and the Gaussian Process Regression (GPR) method.

EGMⁿ is similar to the Nested Endogenous Grid Method (NEGM)³ and the Generalized Endogenous Grid Method (G2EGM)⁴ in that it can solve problems with multiple decision choices, but it differs from these methods in that by choosing the subproblems strategically, we can take advantage of multiple sequential endogenous grid method steps to solve complex multidimensional models in a fast and efficient manner. The use of machine learning tools such as the GPR overcomes bottlenecks seen in unstructured interpolation using Delaunay triangulation and other similar methods.

³Druehdahl (2021).

⁴Druehdahl and Jørgensen (2017).

Appendices

A Solving the illustrative G2EGM model with EGMⁿ

A.1 The problem for a retired household

I designate as $w_t(m_t)$ the problem of a retired household at time t with total resources m . The retired household solves a simple consumption-savings problem with no income uncertainty and a certain next period pension of $\underline{\theta}$.

$$\begin{aligned} w_t(m_t) &= \max_{c_t} u(c_t) + \beta w_{t+1}(m_t) \\ \text{s.t.} \\ a_t &= m_t - c_t \\ m_{t+1} &= R_a a_t + \underline{\theta} \end{aligned} \tag{43}$$

Notice that there is no uncertainty and the household receives a retirement income $\underline{\theta}$ every period until death.

A.2 The problem for a worker household

The value function of a worker household is

$$V_t(m_t, n_t) = \mathbb{E}_\epsilon \max \{v_t(m_t, n_t, \mathbb{W}) + \sigma_\epsilon \epsilon_{\mathbb{W}}, v_t(m_t, n_t, \mathbb{R}) + \sigma_\epsilon \epsilon_{\mathbb{R}}\} \tag{44}$$

where the choice specific problem for a working household that decides to continue working is

$$\begin{aligned} v_t(m_t, n_t, \mathbb{W}) &= \max_{c_t, d_t} u(c_t) - \alpha + \beta \mathbb{E}_t [V_{t+1}(m_{t+1}, n_{t+1})] \\ \text{s.t.} \\ a_t &= m_t - c_t - d_t \\ b_t &= n_t + d_t + g(d_t) \\ m_{t+1} &= R_a a_t + \theta_{t+1} \\ n_{t+1} &= R_b b_t \end{aligned} \tag{45}$$

and the choice specific problem for a working household that decides to retire is

$$v_t(m_t, n_t, \mathbb{R}) = w_t(m_t + n_t) \tag{46}$$

A.3 Applying the Sequential EGM

The first step is to define a post-decision value function. Once the household decides their level of consumption and pension deposits, they are left with liquid assets they are saving for the future and illiquid assets in their pension account which they can't access again until retirement. The post-decision value function can be defined as

$$\begin{aligned} \mathbf{v}_t(a_t, b_t) &= \beta \mathbb{E}_t [V_{t+1}(m_{t+1}, n_{t+1})] \\ \text{s.t.} \\ m_{t+1} &= R_a a_t + \theta_{t+1} \\ n_{t+1} &= R_b b_t \end{aligned} \tag{47}$$

Then redefine the working agent's problem as

$$\begin{aligned} v_t(m_t, n_t, \mathbb{W}) &= \max_{c_t, d_t} u(c_t) - \alpha + \mathbf{v}_t(a_t, b_t) \\ a_t &= m_t - c_t - d_t \\ b_t &= n_t + d_t + g(d_t) \end{aligned} \tag{48}$$

Clearly, the structure of the problem remains the same, and this is the problem that G2EGM solves. We've only moved some of the stochastic mechanics out of the problem. Now, we can apply the sequential EGMⁿ method. Let the agent first decide d_t , the deposit amount into their retirement; we will call this the deposit problem, or outer loop. Thereafter, the agent will have net liquid assets of l_t and pension assets of b_t .

$$\begin{aligned} v_t(m_t, n_t, \mathbb{W}) &= \max_{d_t} \tilde{\mathbf{v}}_t(l_t, b_t) \\ \text{s.t.} \\ l_t &= m_t - d_t \\ b_t &= n_t + d_t + g(d_t) \end{aligned} \tag{49}$$

Now, the agent can move on to picking their consumption and savings; we can call this the pure consumption problem or inner loop.

$$\begin{aligned} \tilde{\mathbf{v}}_t(l_t, b_t) &= \max_{c_t} u(c_t) - \alpha + \mathbf{v}_t(a_t, b_t) \\ \text{s.t.} \\ a_t &= l_t - c_t \end{aligned} \tag{50}$$

Because we've already made the pension decision, the amount of pension assets does not change in this loop and it just passes through to the post-decision value function.

A.4 Solving the problem

A.4.1 Solving the Inner Consumption Saving Problem

Let's start with the pure consumption-saving problem, which we can summarize by substitution as

$$\tilde{\mathbf{v}}_t(l_t, b_t) = \max_{c_t} u(c_t) - \alpha + \mathbf{v}_t(l_t - c_t, b_t) \quad (51)$$

The first order condition is

$$u'(c_t) = \mathbf{v}_t^a(l_t - c_t, b_t) = \mathbf{v}_t^a(a_t, b_t) \quad (52)$$

We can invert this Euler equation as in standard EGM to obtain the consumption function.

$$\mathbf{c}_t(a_t, b_t) = u'^{-1}(\mathbf{v}_t^a(a_t, b_t)) \quad (53)$$

Again as before, $\mathbf{l}_t(a_t, b_t) = \mathbf{c}_t(a_t, b_t) + a_t$. To sum up, using an exogenous grid of (a_t, b_t) we obtain the trio $(\mathbf{c}_t(a_t, b_t), \mathbf{l}_t(a_t, b_t), b_t)$ which provides an interpolating function for our optimal consumption decision rule over the (l, b) grid. Without loss of generality, assume $\mathbf{l}_t = \mathbf{l}_t(a_t, b_t)$ and define the interpolating function as

$$\check{\mathbf{c}}_t(\mathbf{l}_t, b_t) \equiv \mathbf{c}_t(a_t, b_t) \quad (54)$$

For completeness, we derive the envelope conditions as well, and as we will see, these will be useful when solving the next section.

$$\begin{aligned} \tilde{\mathbf{v}}_t^l(l_t, b_t) &= \mathbf{v}_t^a(a_t, b_t) = u'(c_t) \\ \tilde{\mathbf{v}}_t^b(l_t, b_t) &= \mathbf{v}_t^b(a_t, b_t) \end{aligned} \quad (55)$$

A.4.2 Solving the Outer Pension Deposit Problem

Now, we can move on to solving the deposit problem, which we can also summarize as

$$\mathbf{v}_t(m_t, n_t, \mathbb{W}) = \max_{d_t} \tilde{\mathbf{v}}_t(m_t - d_t, n_t + d_t + g(d_t)) \quad (56)$$

The first order condition is

$$\tilde{\mathbf{v}}_t^l(l_t, b_t)(-1) + \tilde{\mathbf{v}}_t^b(l_t, b_t)(1 + g'(d_t)) = 0 \quad (57)$$

Rearranging this equation gives

$$g'(d_t) = \frac{\tilde{\mathbf{v}}_t^l(l_t, b_t)}{\tilde{\mathbf{v}}_t^b(l_t, b_t)} - 1 \quad (58)$$

Assuming that $g'(d)$ exists and is invertible, we can find

$$\mathfrak{d}_t(l_t, b_t) = g'^{-1} \left(\frac{\tilde{\mathfrak{v}}_t^l(l_t, b_t)}{\tilde{\mathfrak{v}}_t^b(l_t, b_t)} - 1 \right) \quad (59)$$

Using this, we can back out n_t as

$$\mathfrak{n}_t(l_t, b_t) = b_t - \mathfrak{d}_t(l_t, b_t) - g(\mathfrak{d}_t(l_t, b_t)) \quad (60)$$

and m_t as

$$\mathfrak{m}_t(l_t, b_t) = l_t + \mathfrak{d}_t(l_t, b_t) \quad (61)$$

In sum, given an exogenous grid (l_t, b_t) we obtain the triple $(\mathfrak{m}_t(l_t, b_t), \mathfrak{n}_t(l_t, b_t), \mathfrak{d}_t(l_t, b_t))$, which we can use to create an interpolator for the decision rule d_t .

To close the solution method, the envelope conditions are

$$\begin{aligned} v_t^m(m_t, n_t, \mathbb{W}) &= \tilde{\mathfrak{v}}_t^l(l_t, b_t) \\ v_t^n(m_t, n_t, \mathbb{W}) &= \tilde{\mathfrak{v}}_t^b(l_t, b_t) \end{aligned} \quad (62)$$

A.5 Is g invertible?

We've already seen that $u'(\cdot)$ is invertible, but is g ?

$$g(d) = \chi \log(1 + d) \quad g'(d) = \frac{\chi}{1 + d} \quad g'^{-1}(y) = \chi/y - 1 \quad (63)$$

A.6 The Post-Decision Value and Marginal Value Functions

$$\begin{aligned} \mathfrak{v}_t(a, b) &= \beta \mathbb{E}_t [V(m_{t+1}, n_{t+1})] \\ &\text{s.t.} \\ m_{t+1} &= R_a a_t + \theta_{t+1} \\ n_{t+1} &= R_b b_t \end{aligned} \quad (64)$$

and

$$\begin{aligned} \mathfrak{v}_t^a(a_t, b_t) &= \beta R_a \mathbb{E}_t [V_{t+1}^m(m_{t+1}, n_{t+1})] \\ &\text{s.t.} \\ m_{t+1} &= R_a a_t + \theta_{t+1} \\ n_{t+1} &= R_b b_t \end{aligned} \quad (65)$$

and

$$\begin{aligned}
\mathbf{v}_t^b(a_t, b_t) &= \beta R_b \mathbb{E}_t [V_{t+1}^n(m_{t+1}, n_{t+1})] \\
&\text{s.t.} \\
m_{t+1} &= R_a a_t + \theta_{t+1} \\
n_{t+1} &= R_b b_t
\end{aligned} \tag{66}$$

A.7 Taste Shocks

From decision choice theory and from DCEGM paper, we know that

$$\mathbb{E}_t [V_{t+1}(m_{t+1}, n_{t+1}, \epsilon_{t+1})] = \sigma \log \left[\sum_{\mathbb{D} \in \{\mathbb{W}, \mathbb{R}\}} \exp \left(\frac{v_{t+1}(m_{t+1}, n_{t+1}, \mathbb{D})}{\sigma_\epsilon} \right) \right] \tag{67}$$

and

$$\mathbb{P}_t(\mathbb{D} \mid m_{t+1}, n_{t+1}) = \frac{\exp(v_{t+1}(m_{t+1}, n_{t+1}, \mathbb{D})/\sigma_\epsilon)}{\sum_{\mathbb{D} \in \{\mathbb{W}, \mathbb{R}\}} \exp \left(\frac{v_{t+1}(m_{t+1}, n_{t+1}, \mathbb{D})}{\sigma_\epsilon} \right)} \tag{68}$$

the first order conditions are therefore

$$\dot{\mathbf{v}}_t^m(m_{t+1}, n_{t+1}) = \sum_{\mathbb{D} \in \{\mathbb{W}, \mathbb{R}\}} \mathbb{P}_t(\mathbb{D} \mid m_{t+1}, n_{t+1}) v_{t+1}^m(m_{t+1}, n_{t+1}, \mathbb{D}) \tag{69}$$

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