

# 1 The Dynamic Portfolio Choice Setting

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This section covers the basics of modern portfolio theory and components of the dynamic portfolio choice problem with transaction costs. This section leans heavily on Cai, Judd and Xu (2020) and Gaegauf, Scheidegger and Trojani (2023), bridging the model from the former, with the framework of the latter.

## 1.1 Asset and goods market

We consider a financial market with  $k$  risky assets and one risk-free asset, making the asset space  $D = 1 + k$  dimensions. The risk-free asset, such as a bond or a bank deposit, yields a constant gross return  $R_f = e^{r\Delta t}$ , where  $r$  is the annual interest rate and  $\Delta t = \frac{T}{N}$  is the length of one investment period.

The  $k$  risky assets can be considered as listed stocks, subject to proportional transaction costs. For each reallocation of wealth in a risky asset, a transaction cost of  $\tau \in [0, 1]$  is incurred as a percentage of the traded amount. The stochastic one-period gross-return vector of the risky assets is denoted as  $\mathbf{R} = (R_1, R_2, \dots, R_k)^\top$ , and the corresponding net-return vector is  $\mathbf{r} = (r_1, r_2, \dots, r_k)^\top$ .

In the goods market, there is a single non-durable consumption good,  $C$ , which is consumed at each time point  $t$ . The fraction of wealth allocated to consumption at time  $t$  is denoted  $c_t$ , the fraction allocated to risky assets is  $\mathbf{x}_t = (x_{1,t}, x_{2,t}, \dots, x_{k,t})^\top$ , and the fraction allocated to the risk-free asset is denoted  $b_t$ . Thus,  $\mathbf{x}_t \in \mathbb{R}^k$  and  $b_t \in \mathbb{R}$ .

## 1.2 Asset dynamics

I follow Cai, Judd and Xu (2013) for the asset dynamics. The total composition of risky assets is assumed to follow a multivariate log-normal distribution:

$$\log(\mathbf{R}) \sim \mathcal{N}\left(\left(\mu - \frac{\sigma^2}{2}\right) \Delta t, (\mathbf{\Lambda} \mathbf{\Sigma} \mathbf{\Lambda}) \Delta t\right), \quad (1)$$

where  $\mu$  is the drift vector,  $\sigma^2$  is a column vector of the variance  $\sigma_i^2$ ,  $\mathbf{\Sigma}$  is the correlation matrix, and  $\mathbf{\Lambda} = \text{diag}(\sigma_1, \sigma_2, \dots, \sigma_k)$  is the diagonal matrix of volatilities. Following Cai, Judd and Xu (2013) we utilize the Cholesky decomposition of the correlation matrix,  $\mathbf{\Sigma} = \mathbf{L} \mathbf{L}^\top$ , where  $\mathbf{L} = (L_{i,j})_{k \times k}$  is a lower triangular matrix. Hence, for each risky asset  $i$ , the log-return is:

$$\log(R_i) = \left(\mu_i - \frac{\sigma_i^2}{2}\right) \Delta t + \sigma_i \sqrt{\Delta t} \sum_{j=1}^i L_{i,j} z_j, \quad (2)$$

where  $z_i$  are independent standard normal random variables.

### 1.3 Transaction costs and portfolio reallocation

Rebalancing incurs proportional transaction costs  $\tau \in [0, 1]$ , which are paid based on the amount bought or sold of each risky asset. Reallocation decisions are made just before  $t_j + \Delta t$ , such that  $\mathbf{x}_t$  is the portfolio of risky assets right before reallocation.  $\delta_{i,t}$  denotes the change in portfolio allocation of asset  $i$ , and  $\delta_{i,t}W_t$  is thus the currency amount traded in asset  $i$ . Hence  $\delta_{i,t} > 0$  implies buying asset  $i$ , and  $\delta_{i,t} < 0$  implies selling asset  $i$ . Proportional transaction costs imply that the cost function associated with rebalancing is:

$$\psi(\delta_{i,t}W_t) = \tau|\delta_{i,t}W_t| \quad (3)$$

I decompose the decision variable  $\delta_{i,t}$ , representing the fraction of wealth used to trade risky asset  $i$ , into buying ( $\delta_{i,t}^+$ ) and selling ( $\delta_{i,t}^-$ ) components to ensure tractability<sup>1</sup>:

$$\delta_{i,t} = \delta_{i,t}^+ - \delta_{i,t}^-, \quad \delta_{i,t}^+, \delta_{i,t}^- \geq 0.$$

The total transaction cost is then given by  $\tau \sum_{i=1}^k (\delta_{i,t}^+ + \delta_{i,t}^-)W_t$ . And the transaction cost function is therefore a function of each trading direction:

$$\psi(\delta_{i,t}^+, \delta_{i,t}^-, W_t) = \tau(\delta_{i,t}^+ + \delta_{i,t}^-)W_t \quad (4)$$

Following the reallocation, the remaining wealth is allocated between the risk-free asset and consumption. Notation of rebalancing is henceforth simplified using vectors to  $\boldsymbol{\delta}_t = \boldsymbol{\delta}_t^+ - \boldsymbol{\delta}_t^-$  with  $\boldsymbol{\delta}_t^+ = (\delta_{1,t}^+, \delta_{2,t}^+, \dots, \delta_{k,t}^+)$ . We have that  $\boldsymbol{\delta}_t$  is the *net change* in the risky positions, and  $\boldsymbol{\delta}_t^+ + \boldsymbol{\delta}_t^-$  is the *cumulative change* in the risky positions.

### 1.4 Investor preferences and problem

The investor operates over a finite horizon of  $T$  years, during which the aim is to maximize expected utility. Following Cai, Judd and Xu (2013), the investment horizon is discretized into  $N$  equally spaced periods, each with a duration of  $\Delta t = \frac{T}{N}$ . At each time point  $t_j$ , for  $j = 0, 1, \dots, N$ , where  $t_0 = 0$  and  $t_N = T$ , the investor has the opportunity to adjust the portfolio allocations right before  $t_j + \Delta t$ . Reallocation is costly, and the investor is subject to proportional transaction costs. If consumption is included the investor may also choose to consume a non-durable good at each time point.

For notational simplicity, i now use  $t$  to denote these time points unless specifically referring to  $t_j$ . The investor's preferences are modeled using a constant relative risk

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<sup>1</sup>Gaegauf, Scheidegger and Trojani (2023) note that this ensures differentiability. This approach is common and found in earlier work such as Akian, Menaldi and Sulem (1996), who likewise note that this ensures that the variable is continuous from origin in the positive real set.

aversion (CRRA) utility function:

$$u(C_t) = \begin{cases} \frac{C_t^{1-\gamma}}{1-\gamma} & \text{if } \gamma \neq 1, \\ \log(C_t) & \text{if } \gamma = 1, \end{cases} \quad (5)$$

where  $C_t$  is consumption and  $c_t$  is the fraction of wealth  $W_t$  spent on consumption at time  $t$ . Hence  $c_t = C_t/W_t$ , and lowercase notation is henceforth used to denote variables as fractions of wealth.  $\gamma$  is the coefficient of relative risk aversion. The objective is to maximize the expected utility of consumption and wealth over the investor's lifetime:

$$\max_{\mathbf{x}_t, b_t, c_t} \mathbb{E} \left[ \sum_{i=0}^{N-1} \beta^i u(C_i) \Delta t + \beta^N u(W_N) \right], \quad (6)$$

where  $\beta$  is the discount factor,  $\mathbf{x}_t$  is the allocation to risky assets,  $b_t$  is the allocation to the risk-free asset, and  $W_t$  is the investor's wealth at time  $t$ .

### 1.5 Intertemporal portfolio choice without transaction costs

When there are no transaction costs (no market frictions) the investor can freely rebalance the portfolio. This reduces the problem to a classic portfolio optimization problem formulated by Merton (1969) and Merton (1971). For a more detailed treatment, see Björk (2019). In this setting, the investor dynamically allocates wealth between  $k$  risky assets and a risk-free asset to maximize utility over a finite horizon  $[0, T]$ .

The investor's wealth  $W_t$  can be allocated between a risk-free asset and  $k$  risky assets. Consumption is a non-durable good that can be purchased at each time point  $t$ .  $r$  is the risk-free rate,  $\boldsymbol{\mu}$  is the vector of expected returns on the risky assets, and  $C_t$  represents consumption at time  $t$ . The investor's preferences follow a constant relative risk aversion (CRRA) utility function.

Without transaction costs, the optimal portfolio allocation, known as the Merton point is:

$$\mathbf{x}_t^* = \frac{1}{\gamma} \boldsymbol{\Sigma}^{-1} (\boldsymbol{\mu} - r), \quad (7)$$

where  $\gamma$  is the coefficient of relative risk aversion, and  $\boldsymbol{\Sigma}$  is the covariance matrix of the risky assets' returns. This provides a time-independent optimal allocation that serves as a benchmark for models incorporating frictions such as transaction costs.

### 1.6 The general class of dynamic portfolio choice with transaction costs and intertemporal consumption

Now consider when transaction costs are present, and the investor can consume a non-durable good at each time point. The solution to the dynamic portfolio choice problem

is no longer given by the closes form solution of the Merton point. Considering the components presented in this section, the class of dynamic portfolio optimization problems, given one risk free asset and  $k$  risky assets, can be formulated by the following Bellman equation, Bellman (1958)<sup>2</sup>:

$$V_t(W_t, \mathbf{x}_t, \theta_t) = \max_{c_t, \boldsymbol{\delta}_t^+, \boldsymbol{\delta}_t^-} \{u(c_t W_t) \Delta t + \beta \mathbb{E}_t [V_{t+\Delta t}(W_{t+\Delta t}, \mathbf{x}_{t+\Delta t}, \theta_{t+\Delta t})]\}, \quad t < T \quad (8)$$

Given some initial level of wealth  $W_0$  and portfolio allocation  $\mathbf{x}_0$ .  $\theta_t$  is a vector of stochastic variables, which the gross one period risk free return, and risky return depends on, i.e  $\mathbf{R}(\theta_t)$  and  $R_f(\theta_t)$ . These could cover the drift  $\mu$ , volatility  $\sigma^2$ , correlation of the risky assets  $\Sigma$ , and the risk free return  $r$  or only some of these, dependent on the model. Notice that future wealth and allocations are stochastic, as they depend on the future realization of  $\theta_t$ .

Notice that consumption and reallocation are decision variables, whereas bond holding are not (Explicitly). This is because bond holdings can be determined as the residual wealth, after consumption and reallocation decisions are made:

$$b_t W_t = \left(1 - \mathbf{1}^\top \cdot \mathbf{x}_t\right) W_t - \mathbf{1}^\top \cdot \boldsymbol{\delta}_t W_t - \psi(\boldsymbol{\delta}_t^+, \boldsymbol{\delta}_t^-, W_t) - c_t W_t \quad (9)$$

Where  $\psi(\cdot)$  is the transaction cost function, and  $\mathbf{1}$  is a vector of ones.

The dynamics of the state variables follow Schober, Valentin and Pflüger (2022) and are given by:

$$W_{t+\Delta t} = b_t W_t R_f(\theta_t) + ([\mathbf{x}_t + \boldsymbol{\delta}_t] W_t)^\top \cdot \mathbf{R}(\theta_t) \quad (10)$$

$$\mathbf{x}_{t+\Delta t} = \frac{([\mathbf{x}_t + \boldsymbol{\delta}_t] W_t) \odot \mathbf{R}(\theta_t)}{W_{t+\Delta t}} \quad (11)$$

Where  $\odot$  is the elementwise product (Hadamand product). The terminal value function is given by<sup>3</sup>:

$$V_T(W_T, \mathbf{x}_T, \theta_T) = u(W_T - \psi(\mathbf{x}_T W_T)) \quad (12)$$

Which implies that the investor consumes everything at the terminal period. Finally we note that the optimization problem is subject to the following constraints:

$$\boldsymbol{\delta}_t W_t \geq -\mathbf{x}_t W_t \quad (13)$$

$$b_t W_t \geq 0 \quad (14)$$

$$\mathbf{1}^\top \mathbf{x}_t \leq 1 \quad (15)$$

<sup>2</sup>This is consolidated model of the base model, and with consumption model, of Cai, Judd and Xu (2020), however the cost function is generalized and correlation of returns is included.

<sup>3</sup>Stemming from the infinite sum of discounted utility of interest payments.

The first constraint ensures that the investor does not short sell risky assets, The second constraint is also a no shorting constraint and the third is a no-borrowing constraint. Hence This formulation does not consider leveraged investments. Furthermore we can note that the rebalancing decision (in each direction), is only feasible in the space:

$$\delta_{i,t}^+ \in [0, 1 - x_{i,t}] \quad (16)$$

$$\delta_{i,t}^- \in [0, x_{i,t}] \quad (17)$$

This is a direct formulation of the constraints, already captured in the equations above. The problem can be simplified by normalizing wrt. wealth, and removing wealth as a state variable, since wealth is seperable from the rest of the state space  $\mathbf{x}_t, \theta_t$  as noted by Cai, Judd and Xu (2013).

This is because portfolio optimality is independent of wealth for CRRA utility function. The Bellman equation is then:

$$v_t(\mathbf{x}_t, \theta_t) = \max_{c_t, \delta_t^+, \delta_t^-} \{u(c_t)\Delta t + \beta \mathbb{E}_t [\pi_{t+\Delta t}^{1-\gamma} v_{t+\Delta t}(\mathbf{x}_{t+\Delta t}, \theta_{t+\Delta t})]\}, \quad t < T \quad (18)$$

The normalized bond holdings are then:

$$b_t = 1 - \mathbf{1}^\top \cdot (\mathbf{x}_t - \delta_t - \psi(\delta_t^+, \delta_t^-)) - c_t \Delta t \quad (19)$$

We see that these are still the residual of the wealth after the rebalancing and consumption decision. Where we formulate the transaction cost function  $\psi(\cdot)$  in terms of the buying and selling components, and using changes to allocations proportional to wealth, instead of the prior formulations, where wealth was a direct input. The dynamics are then:

$$\pi_{t+\Delta t} = b_t R_f(\theta_t) + (\mathbf{x}_t + \delta_t)^\top \cdot \mathbf{R}(\theta_t) \quad (20)$$

$$\mathbf{x}_{t+\Delta t} = \frac{(\mathbf{x}_t + \delta_t) \odot \mathbf{R}(\theta_t)}{\pi_{t+\Delta t}} \quad (21)$$

$$W_{t+\Delta t} = \pi_{t+\Delta t} W_t \quad (22)$$

Where we now formulate the problem with regard to the proportional wealth change  $\pi_{t+\Delta t} = \frac{W_{t+\Delta t}}{W_t}$ . The terminal value function is:

$$v_T(\mathbf{x}_T, \theta_T) = u(1 - \psi(\mathbf{x}_T)) \quad (23)$$

The constraints are likewise normalized:

$$\delta_t \geq -\mathbf{x}_t \quad (24)$$

$$b_t \geq 0 \quad (25)$$

$$\mathbf{1}^\top \mathbf{x}_t \leq 1 \quad (26)$$

This class of dynamic portfolio choice problems covers any formulation of the problem, where the transaction cost specification is differentiable, and the utility function allows for separability of wealth and remaining state variables. Later formulations will be based on this class structure, covering the necessary Bellman equation, state dynamics, preferences and transaction costs functions as well as the constraints and any extensions not yet presented.

The non-normalized optimal choices can be obtained by multiplying the normalized choices with the wealth level  $W_t$  at a given time point  $t$ . The no-trade-region (NTR) is in this framework the set of asset allocations where it is sub-optimal to rebalance the portfolio, and is defined as:

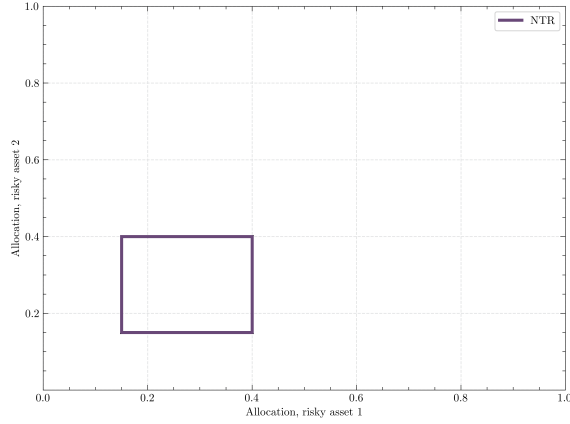
$$\Omega_t = \{\mathbf{x}_t : \delta_t^{+,*}, \delta_t^{-,*} = \mathbf{0}\} \quad (27)$$

Where  $\delta_t^{+,*}, \delta_t^{-,*}$  are the optimal buying and selling policies at time  $t$ . The next section will cover the NTR in more detail.

## 1.7 No Trade Region

The NTR is a region in the risky asset space where it is sub-optimal to rebalance the portfolio. Given the parameters of the model the NTR without consumption is defined as in equation (27). If consumption is included, this definition remains the same, but the consumption decision varies within the NTR. Note that the NTR is independent of the wealth level, but only depends on the wealth allocations. The NTR stems from the introduction of transaction costs, and is a connected set. The shape of the NTR is dependent on the parameters of the model, and can be a complex shape, however for the case of proportional transaction costs and independent risky assets, the NTR for 2 risky assets is a square, as shown by Dybvig and Pezzo (2020) for example. The NTR may extend out of the feasible region, in which case the shape is truncated to the feasible space. For most cases seen in the literature, when consumption is not included, the NTR encapsulates the Merton point. Figure 1.1 illustrates an example of a NTR with two risky assets. The NTR is a key component of the model, and illustrates the trade-off between the utility of rebalancing the portfolio and the cost of doing so. I will go into further detail on the NTR in the next section, where I will discuss the formal properties of the NTR, and how I can leverage key findings from the NTR to solve the dynamic

**Figure 1.1:** Example No Trade Region with  $k = 2$  risky assets.



portfolio choice problem with transaction costs efficiently.

### 1.8 Base problem: Portfolio choice with proportional costs and consumption

Considering the class of problems constructed in the prior section, we can now quickly introduce the basic problem formulation. We consider an investor with CRRA utility function. She can invest in one risk free asset and  $k$  risky assets. Trading is subject to proportional transaction costs hence we have the following cost function (in cumulative terms):

$$\psi(\delta_{i,t}^+, \delta_{i,t}^-) = \tau(\delta_{i,t}^+ + \delta_{i,t}^-) \quad (28)$$

We do not assume that returns are dependent on stochastic parameters, but instead are drawn from a distribution with known parameters. Hence we assume  $\theta_t = \theta$  for all  $t$ . That is that we assume a constant return on the risk free asset, hence  $R_f(\theta_t) = R_f$ , and the risky assets follow a multivariate log-normal distribution, with some mean and covariance matrix. We can now formulate the entire problem given the class structure from section 1.6. The terminal value function is given by equation (23). The system is subject to the constraints of equations (24), (25) and (26), as well as a simple constraint on consumption,  $c_t \geq 0$ . We assume that the position in bond holdings is the residual wealth, and they therefore follow the process in (19). The Bellman equation is therefore:

$$v_t(\mathbf{x}_t, \theta_t) = \max_{c_t, \delta_t^+, \delta_t^-} \{u(c_t)\Delta t + \beta \mathbb{E}_t \left[ \pi_{t+\Delta t}^{1-\gamma} v_{t+\Delta t}(\mathbf{x}_{t+\Delta t}) \right]\}, \quad t < T$$

With same terminal condition as before, where investments are sold and wealth is consumed.

$$v_T(\mathbf{x}_T) = u(1 - \psi(\mathbf{0}, \mathbf{x}_T))$$

## 1.9 Portfolio choice with fixed costs

I now consider the model, where the investor faces fixed costs when rebalancing the portfolio, instead of proportional costs. Fixed costs are common in practice, and can be seen as a fixed fee for trading, regardless of the traded amount. I consider a slight modification to the classical purely fixed costs, and instead consider fixed costs as a percentage of the wealth. I do this to be able to use the same model structure as in section 1.8, where variables are in fractions of wealth, in order to drop wealth as a state variable.

This is seen previously in (Morton and Pliska 1995), who note that such a fixed cost can be seen as a portfolio management fee. In practice, when setting the level of the fixed cost, i make an implicit assumption on the wealth of the investor, if i want to draw comparisons to common trading fees on the market, as the fixed cost in this scenario is purely fixed. The cost function is then given by:

$$\psi(\boldsymbol{\delta}_t^+, \boldsymbol{\delta}_t^-) = \mathbf{1} \left( \sum_{i=1}^k \delta_{i,t}^+ + \delta_{i,t}^- > 0 \right) \cdot \text{fc} \quad (29)$$

Where  $\text{fc}$  is the fixed cost, and  $\mathbf{1}(\cdot)$  is the indicator function. The fixed cost is only incurred if the investor rebalances the portfolio, and is independent of the traded amount. The normaized bond holdings are therefore given by:

$$b_t = 1 - \mathbf{1}^\top \cdot (\mathbf{x}_t - \boldsymbol{\delta}_t^-) - \psi(\boldsymbol{\delta}_t^+, \boldsymbol{\delta}_t^-) - c_t \Delta t \quad (30)$$

The model otherwise remains the same as in section 1.8, with the same constraints and dynamics, while using the new cost function. Note that in the terminal period, when all investments are sold, the fixed cost is incurred, unless the investor holds no risky assets. Note that for the model to be well defined, the fixed cost must be less than the wealth of the investor, as the fixed cost is a percentage of the wealth. Furthermore, the fixed cost function is not differentiable. Furthermore (Dybvig and Pezzo 2020) notes that the fixed cost only problem, is not a convex optimization problem, and is therefore not as easily solved as the proportional cost problem. I will deal with these issues individually when implementing the model.

## 1.10 Portfolio choice with fixed and proportional costs

The last model i consider is a combination of the two previous models, where the investor faces both fixed and proportional costs. This is a more realistic model, as it combines the two most common types of transaction costs an individual common investor face in the real world, with a fixed brokerage fee and a percentage of the traded amount stemming from bid ask spreads, taxes or commisions (Lesmond, Ogden and Trzcinka 1999). The



cost function is then given by:

$$\psi(\boldsymbol{\delta}_t^+, \boldsymbol{\delta}_t^-) = \mathbf{1} \left( \sum_{i=1}^k \delta_{i,t}^+ + \delta_{i,t}^- > 0 \right) \cdot \text{fc} + \tau(\boldsymbol{\delta}_t^+ + \boldsymbol{\delta}_t^-) \quad (31)$$

The normalized bond holdings are therefore given by:

$$b_t = 1 - \mathbf{1}^\top \cdot (\mathbf{x}_t - \boldsymbol{\delta}_t^-) - \psi(\boldsymbol{\delta}_t^+, \boldsymbol{\delta}_t^-) - c_t \Delta t \quad (32)$$

The model otherwise remains the same as in section 1.8, with the same constraints and dynamics, while using the new cost function.

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