Seminar - Markowitz Portfolio Optimization

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Theoretical Part

Problem Description

In the realm of financial portfolio management, the Markowitz portfolio optimization problem is a classical and essential topic. The primary objective is to allocate weights to different assets in a portfolio to maximize the expected return while minimizing the overall portfolio risk. Let's consider a portfolio with n assets. The goal is to find the optimal set of weights for these assets.

Formalization

Let:

$$\begin{aligned} r_i &: \text{Expected return of asset } i \\ \sigma_i &: \text{Volatility (risk) of asset } i \\ w_i &: \text{Weight of asset } i \text{ in the portfolio} \end{aligned}$$

The objective is to find the vector of weights $\mathbf{w} = [w_1, w_2, \ldots, w_n]$ that maximizes the expected portfolio return μ while minimizing the portfolio risk σ_p:

$$
\begin{aligned}
\text{Maximize} \quad & \mu = \sum_{i=1}^{n} r_i w_i \\
\text{Subject to} \quad & \sigma_p = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \sigma_i \sigma_j \rho_{ij}} \quad \text{(Portfolio risk)} \\
& \sum_{i=1}^{n} w_i = 1 \quad \text{(Sum of weights equals 1)} \\
& w_i \geq 0 \quad \text{(Non-negativity constraint)}
\end{aligned}
\tag{1}
$$

Where:

$$\rho_{ij} : \text{Correlation coefficient between assets } i \text{ and } j$$

An other formulation of the problem is to minimize the portfolio risk σ_p while achieving a target expected return μ:

The objective is to find the vector of weights $\mathbf{w} = [w_1, w_2, \ldots, w_n]$ that minimizes the portfolio risk σ_p while achieving a given expected portfolio return μ:

$$
\begin{aligned}
\text{Minimize} \quad & \sigma_p = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \sigma_i \sigma_j \rho_{ij}} \quad \text{(Portfolio risk)} \\
\text{Subject to} \quad & \mu = \sum_{i=1}^{n} r_i w_i \quad \text{(Expected portfolio return)} \\
& \sum_{i=1}^{n} w_i = 1 \quad \text{(Sum of weights equals 1)} \\
& w_i \geq 0 \quad \text{(Non-negativity constraint)}
\end{aligned}
\tag{2}
$$

In our problem we only want to minimize the portfolio risk σ_p.

After modifying the objective function to be unconstrained, we obtain the following problem formulation:

$$
\text{Minimize} \quad \sigma_p^2 = \frac{1}{(\sum_{k=1}^{n} e^{x_k})^2} \sum_{i=1}^{n} \sum_{j=1}^{n} e^{x_i} e^{x_j} \sigma_i \sigma_j \rho_{ij} \quad \text{(Portfolio risk)} \tag{3}
$$

With the variable change:

$$w_i = \frac{e^{x_i}}{\sum_{j=1}^{n} e^{x_j}} \tag{4}$$

We also calculate the derivate of the objective function:

$$\frac{\partial}{\partial x_n}\sigma_p^2 = \frac{-2e^{x_n}}{(\sum_{k=1}^{N} e^{x_k})^3} \sum_{i=1}^{N}\sum_{j=1}^{N} e^{x_i} e^{x_j} \sigma_i \sigma_j \rho_{ij} + 2\sigma_n e^{x_n} \sum_{j=1}^{N} e^{x_j} \sigma_j \rho_{nj} \tag{5}$$

Numerical Part

Selected Optimization Methods

1. Method 1: [Insert Method 1 Name]
2. Method 2: [Insert Method 2 Name]

Algorithm Implementation

Below are the basic functions describing the two chosen algorithms:

Method 1: [Insert Method 1 Name]

[Insert code or pseudocode for Method 1 implementation]

Method 2: [Insert Method 2 Name]

[Insert code or pseudocode for Method 2 implementation]

Results and Analysis

We have applied both methods to the Markowitz portfolio optimization problem and obtained the following results:

[Insert results, tables, or graphs]

Interpretation

[Provide interpretation of the results]

Comparison

To compare the two methods, we analyze factors such as computational time and the number of iterations:

[Insert comparison results]

Annexe : Objective function and constraints

Objective function

For solving the Markowitz portfolio optimization problem, we have chosen two numerical optimization methods:

I order to simplify the problem, we will first forget about the expected return constraint. We will only focus on minimizing the portfolio risk σ_p.

$$\begin{aligned} \text{Minimize} \quad & \sigma_p = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \sigma_i \sigma_j \rho_{ij}} \quad \text{(Portfolio risk)} \\ \text{Subject to} \quad & \sum_{i=1}^{n} w_i = 1 \quad \text{(Sum of weights equals 1)} \\ & w_i \geq 0 \quad \text{(Non-negativity constraint)} \end{aligned} \tag{6}$$

To restruct the weight vector to be positive, we can use a variable change:

$$w_i = e^{x_i} \quad \text{with} \quad x_i \in \mathbb{R} \tag{7}$$

The problem becomes:

$$\begin{aligned} \text{Minimize} \quad & \sigma_p = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} e^{x_i} e^{x_j} \sigma_i \sigma_j \rho_{ij}} \quad \text{(Portfolio risk)} \\ \text{Subject to} \quad & \sum_{i=1}^{n} e^{x_i} = 1 \quad \text{(Sum of weights equals 1)} \end{aligned} \tag{8}$$

We can also forget about the square root in the objective function, as it does not change the optimal solution.

$$
\begin{aligned}
&\text{Minimize} \quad \sigma_p^2 = \sum_{i=1}^{n}\sum_{j=1}^{n} e^{x_i} e^{x_j} \sigma_i \sigma_j \rho_{ij} \quad \text{(Portfolio risk)} \\
&\text{Subject to} \quad \sum_{i=1}^{n} e^{x_i} = 1 \quad \text{(Sum of weights equals 1)}
\end{aligned} \tag{9}
$$

Finally we can use the softmax function to ensure that the sum of the weights equals 1, such as:

$$
w_i = \frac{e^{x_i}}{\sum_{j=1}^{n} e^{x_j}} \tag{10}
$$

Leading to the following problem formulation (with softmax):

$$
\text{Minimize} \quad \sigma_p^2 = \frac{1}{(\sum_{k=1}^{n} e^{x_k})^2} \sum_{i=1}^{n}\sum_{j=1}^{n} e^{x_i} e^{x_j} \sigma_i \sigma_j \rho_{ij} \quad \text{(Portfolio risk)} \tag{11}
$$

Derivate of the objective function

Now, let's delve into the derivate of the objective function:

We are going to derive it term by term using the chain rule, we first derive the term outside the sum such as :

$$
\frac{\partial}{\partial x_n} \frac{1}{(\sum_{k=1}^{N} e^{x_k})^2} = \frac{-2e^{x_n}}{(\sum_{k=1}^{N} e^{x_k})^3} \tag{12}
$$

Where N is the number of assets in the portfolio and x_n is the variable we are deriving with respect to.

The second term is a bit more complicated, we will use the product rule:

$$
\frac{\partial}{\partial x_n} \sum_{i=1}^{N}\sum_{j=1}^{N} e^{x_i} e^{x_j} \sigma_i \sigma_j \rho_{ij} = \sum_{i=1}^{N}\sum_{j=1}^{N} (\frac{\partial}{\partial x_n} e^{x_i}) e^{x_j} \sigma_i \sigma_j \rho_{ij} + \sum_{i=1}^{N}\sum_{j=1}^{N} e^{x_i} (\frac{\partial}{\partial x_n} e^{x_j}) \sigma_i \sigma_j \rho_{ij} \tag{13}
$$

Because the two terms are similar, we will only focus on the first one: We can see that the derivate is not null if $i \neq n$:

$$\sum_{i=1}^{N}\sum_{j=1}^{N}(\frac{\partial}{\partial x_n}e^{x_i})e^{x_j}\sigma_i\sigma_j\rho_{ij} = \sum_{j=1}^{N} e^{x_n}e^{x_j}\sigma_n\sigma_j\rho_{nj} = \sigma_n e^{x_n}\sum_{j=1}^{N} e^{x_j}\sigma_j\rho_{nj} \tag{14}$$

We can simplify the two sums by using the fact that $\rho_{ij} = \rho_{ji}$ and $\sigma_i\sigma_j = \sigma_j\sigma_i$:

$$\frac{\partial}{\partial x_n}\sum_{i=1}^{N}\sum_{j=1}^{N} e^{x_i}e^{x_j}\sigma_i\sigma_j\rho_{ij} = 2\sigma_n e^{x_n}\sum_{j=1}^{N} e^{x_j}\sigma_j\rho_{nj} \tag{15}$$

Finally, we can derive the whole objective function:

$$\frac{\partial}{\partial x_n}\sigma_p^2 = \frac{-2e^{x_n}}{(\sum_{k=1}^{N} e^{x_k})^3}\sum_{i=1}^{N}\sum_{j=1}^{N} e^{x_i}e^{x_j}\sigma_i\sigma_j\rho_{ij} + 2\sigma_n e^{x_n}\sum_{j=1}^{N} e^{x_j}\sigma_j\rho_{nj} \tag{16}$$