Index-tracking portfolio optimization model

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Abstract

In the present tutorial report we examine the theory and computational aspects behind the index-tracking portfolio optimization model. This model is compared with Markowitz mean-variance model. This report is distributed with an example in C using the NAG C Library.

1 Introduction

Index-tracking is a form of passive fund management. The index-tracking problem is the problem of reproducing the performance of a stock market index by considering a portfolio of assets comprised on the index. This approach differs from the full replication strategy, where a fund purchases all the stocks that make up a particular market index. A passively managed fund whose objective is to reproduce the return on an index is known as an index fund, or a tracker fund. The classical index-tracking approach represents the problem in a least square framework with errors computed using a sample of historical data. A new approach described in [1], which this report is based on, replaces the classical risk measure of portfolio variance by the variance of tracking errors between stochastic index return and the return on the portfolio selection. In this report we formulate the index-tracking portfolio optimization model and present an illustrative example where we compare the presented model with the classical Markowitz mean-variance portfolio optimization model.

2 Index-tracking Optimization Model

Consider a market index $M$ and select a portfolio $P$ with $n$ assets. $P$ reproduces the performance of the market index if the return on $P$, denoted by $r_P$, follows very closely the return of the index, denoted by $r_M$, at every unit time period. Thus, the goal is to obtain the $P$ that minimizes the variance of the difference between both returns, $r_P$ and $r_M$. Denote the return on asset $i$ by $r_i$ and its mean by $\mu_i$, for $i = 1, 2, \ldots, n$. The variance-covariance matrix of assets returns is denoted by $V$, where $\sigma_{ij}$ denotes the covariance between the returns of two assets, and $\sigma_{ii}$ the variance of $r_i$. The covariance between asset returns and market index returns is given by $\sigma_{iM} = \text{Cov}(r_i, r_M)$. The beta of asset $i$ relative to $M$ is given by

$$\beta_i = \frac{\sigma_{iM}}{\sigma_M^2}$$

where $\sigma_M^2$ denotes the variance of the market index returns. As previously stated, the index-tracking model aims to minimize $\text{Var}(r_P - r_M) = \sigma_P^2 + \sigma_M^2 - 2\sigma_{PM}\beta_P$, the so-called measure of goodness of the index-tracking portfolio. Thus, the optimization problems is formulated as

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follows:

\[
\begin{align*}
\text{minimize} & \quad \frac{1}{2} x^T V x - \sigma^2_M \beta^T x \\
\text{subject to} & \quad \sum_{i=1}^{n} \mu_i x_i = m \\
& \quad \sum_{i=1}^{n} x_i = 1
\end{align*}
\]  \hspace{1cm} (2)

and \(-1 \leq x_i \leq 1, i \in \{1, \ldots, n\}\). Therefore, we need to solve a constrained convex quadratic programming problem (QP). Given that the matrix \(V\) is symmetric positive semi-definite and dense, we select the solver \texttt{e04ncf}. The following measures are used to determine the characteristics of the optimal portfolio

- Portfolio variance: \(\sigma^2_P = x^T V x\).
- Portfolio beta: \(\beta_P = \sum_{i=1}^{n} \beta_i x_i\).
- Portfolio \(P\) (measure of goodness): \(\text{Var}(r_p - r_M) = \sigma^2_P + \sigma^2_M - 2\sigma^2_M \beta_P\).

Note that the tracking-efficient (TE) portfolio is equivalent to Markowitz mean-variance (MV) portfolio when the linear term \(-\sigma^2_M \beta^T x\) is removed from the objective function. A review of the basic Markowitz portfolio optimization theory and solution using the NAG Library can be found in [2].

3 Example

We present a simple example to illustrate the described methodology. We select seven technology stocks in order to track the S&P 500 index. The data for this example was downloaded from Yahoo Finance [3] using a Python script with the module \texttt{urllib2}. For this example we downloaded monthly prices from January 2009 to January 2016, see Figure 1. From a sample of historical data we can compute the one-period returns for each stock by using the well-known formula

\[
r_t = \frac{\text{price}_t - \text{price}_{t-1}}{\text{price}_{t-1}}.
\]  \hspace{1cm} (3)

Having the returns we can easily determine the mean vector, standard deviation vector, covariance matrix and beta vector, see Table 1 and 2.

![Figure 1: Monthly prices for seven technology stocks from January 2009 to January 2016.](image-url)
Following the example in [1], we set the desired portfolio mean \( m = \mu_M \), where \( \mu_M \) represents S&P 500 index mean return. Table 3 shows that the index-tracking model, using the market index mean, reduces the number of short positions in the portfolio with respect to Markowitz portfolio. Markowitz portfolio has two short positions (CSCO and ORCL) whereas the index-tracking portfolio has only one short position (AAPL). In addition, the index-tracking portfolio tends to reduce extreme positions, for example IBM changes the long position from 72.1% to a more conservative 44.9%.

Table 1: Mean, standard deviation and beta.

<table>
<thead>
<tr>
<th>Asset</th>
<th>Mean (( \mu )) (%)</th>
<th>Std. dev (( \sigma )) (%)</th>
<th>Beta (( \beta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSPC</td>
<td>1.11</td>
<td>4.15</td>
<td>-</td>
</tr>
<tr>
<td>AAPL</td>
<td>2.82</td>
<td>7.44</td>
<td>1.026</td>
</tr>
<tr>
<td>CSCO</td>
<td>1.08</td>
<td>7.8</td>
<td>1.250</td>
</tr>
<tr>
<td>GOOG</td>
<td>2.00</td>
<td>7.3</td>
<td>0.975</td>
</tr>
<tr>
<td>IBM</td>
<td>0.72</td>
<td>4.57</td>
<td>0.595</td>
</tr>
<tr>
<td>MSFT</td>
<td>1.79</td>
<td>6.78</td>
<td>0.994</td>
</tr>
<tr>
<td>ORCL</td>
<td>1.21</td>
<td>6.96</td>
<td>1.199</td>
</tr>
<tr>
<td>YHOO</td>
<td>1.49</td>
<td>8.47</td>
<td>0.941</td>
</tr>
</tbody>
</table>

Table 2: Variance-covariance matrix \( V \).

<table>
<thead>
<tr>
<th></th>
<th>AAPL</th>
<th>CSCO</th>
<th>GOOG</th>
<th>IBM</th>
<th>MSFT</th>
<th>ORCL</th>
<th>YHOO</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAPL</td>
<td>0.005528</td>
<td>0.002689</td>
<td>0.001983</td>
<td>0.001417</td>
<td>0.001996</td>
<td>0.002167</td>
<td>0.001418</td>
</tr>
<tr>
<td>CSCO</td>
<td>0.002689</td>
<td>0.006082</td>
<td>0.002637</td>
<td>0.001873</td>
<td>0.002812</td>
<td>0.003305</td>
<td>0.002146</td>
</tr>
<tr>
<td>GOOG</td>
<td>0.001983</td>
<td>0.002637</td>
<td>0.005324</td>
<td>0.001132</td>
<td>0.002193</td>
<td>0.001718</td>
<td>0.001765</td>
</tr>
<tr>
<td>IBM</td>
<td>0.001417</td>
<td>0.001873</td>
<td>0.001132</td>
<td>0.002084</td>
<td>0.001021</td>
<td>0.001571</td>
<td>0.000677</td>
</tr>
<tr>
<td>MSFT</td>
<td>0.001996</td>
<td>0.002812</td>
<td>0.002193</td>
<td>0.001021</td>
<td>0.004599</td>
<td>0.002502</td>
<td>0.001350</td>
</tr>
<tr>
<td>ORCL</td>
<td>0.002167</td>
<td>0.003305</td>
<td>0.001718</td>
<td>0.000471</td>
<td>0.002502</td>
<td>0.004843</td>
<td>0.002146</td>
</tr>
<tr>
<td>YHOO</td>
<td>0.001418</td>
<td>0.002146</td>
<td>0.001765</td>
<td>0.000677</td>
<td>0.001350</td>
<td>0.002146</td>
<td>0.007173</td>
</tr>
</tbody>
</table>

Table 3: Mean-variance and index-tracking optimal portfolios.

<table>
<thead>
<tr>
<th>Ticker</th>
<th>MV</th>
<th>TE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAPL</td>
<td>0.019969</td>
<td>-0.023608</td>
</tr>
<tr>
<td>CSCO</td>
<td>-0.123901</td>
<td>0.072067</td>
</tr>
<tr>
<td>GOOG</td>
<td>0.076037</td>
<td>0.076785</td>
</tr>
<tr>
<td>IBM</td>
<td>0.721647</td>
<td>0.449256</td>
</tr>
<tr>
<td>MSFT</td>
<td>0.171989</td>
<td>0.115741</td>
</tr>
<tr>
<td>ORCL</td>
<td>-0.001755</td>
<td>0.193798</td>
</tr>
<tr>
<td>YHOO</td>
<td>0.136014</td>
<td>0.115961</td>
</tr>
</tbody>
</table>

Table 4 shows the main portfolio measures. The value of the measure of goodness indicates that the TE portfolio tracks the S&P 500 index more closely with \( \text{Var}(r_P - r_M) = 0.000707 \) compared with the MV portfolio, \( \text{Var}(r_P - r_M) = 0.001049 \).

Table 4: Portfolio measures.
3.1 Compilation

The presented problem has been solved using the NAG C Library. For example, to compile it with NAG C Library for Linux Mark 26, CLL6I26DDL, using the gcc compiler follow the instructions below. For other platforms please refer to the appropriate Users’ notes of your NAG C Library, see [https://www.nag.co.uk/doc/inun/cl26.html](https://www.nag.co.uk/doc/inun/cl26.html)

Listing 1: Linux instructions.

```bash
gcc -O3 index_tracking.c -I ../CL26/cll6i26dd1/include/ 
../CL26/cll6i26dd1/lib/libnagc_nag.so -lpthread -lm -o index_tracking.exe
```

Listing 2: To run the example we pass the downloaded data as standard input.

```bash
./index_tracking.exe < index_tracking.txt
```

Listing 3: Example data.

```
7 85
GSPC AAPL CSCO GOOG IBM MSFT ORCL YHOO
1.9E+03 9.8E+01 2.5E+01 7.3E+02 1.3E+02 5.2E+01 3.5E+01 3.1E+01
```

Listing 4: Example output.

```
Optimal portfolio selection:
----------------------------
GSPC: market index
AAPL: -2.36%
CSCO: 7.21%
GOOG: 7.68%
IBM: 44.93%
MSFT: 11.57%
ORCL: 19.38%
YHOO: 11.60%

Portfolio measures:
----------------------------
Portfolio variance : 0.001962
Portfolio beta : 0.864691
Measure of goodness: 0.000707
```

4 Conclusions

In this tutorial report we have described one of the possible approaches for solving the index-tracking optimization problem. Our approach is based on [1] and the resulting quadratic programming problem has been solved using a solver from Chapter E04 of the NAG C Library. Finally, a detailed description of the obtained results and a comparison to Markowitz mean-variance model was presented.

References

