PROJECT TITLE IN CAPITAL LETTERS

A Project Report Submitted

for the Course

MA498 Project I

by

Mohammed Bilal Girach

(Roll No. 150123024)

Shashank Oberoi

(Roll No. 150123047)

to the

DEPARTMENT OF MATHEMATICS

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

GUWAHATI - 781039, INDIA

November 2018

CERTIFICATE

This is to certify that the work contained in this project report entitled Title of the project report submitted by Name of the Student (Roll No.: xxxxxxxxx) to the Department of Mathematics, Indian Institute of Technology Guwahati towards partial requirement of Bachelor of Technology in Mathematics and Computing has been carried out by him/her under my supervision.

It is also certified that this report is a survey work based on the references in the bibliography.

OR

It is also certified that, along with literature survey, a few new results are established/computational implementations have been carried out/simulation studies have been carried out/empirical analysis has been done by the student under the project.

Turnitin Similarity: __ %

Guwahati - 781 039   (Dr./Prof. Name of the Supervisor)

November 2018   Project Supervisor

ABSTRACT

The main aim of the project ....

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Investment in an individual security always has an associated risk, which can be minimized through diversification, a process involving investment in a portfolio consisting of several securities. In accordance with this notion, Markowitz [17, 18] introduced the mean-variance model for optimum allocation of weights to the securities comprising a portfolio. Mean and covariance matrix of returns of securities are used as the measures for giving a quantitative sense to the return and the risk of the portfolio respectively. Despite the theoretical simplicity of the approach of Markowitz model based on risk-return trade-off, there are several drawbacks associated with incorporating it in a practical setup.

Theoretically, Markowitz based portfolio optimization can result in assigning extreme weights to the securities comprising a portfolio. However, investment in securities can't be made in such extreme positions like large short positions if one takes the active trading into account. Such kind of scenarios can be avoided by introducing appropriate constraints on the weights. Black and Litterman [6] argue that there is an added disadvantage since

there are high chances of the optimal portfolio lying in the neighborhood of the imposed constraints. Thus, imposition of constraints leads to strong dependence of the constructed portfolio upon the constraints. For example, disallowing short sales often results in assigning zero weights to many securities and largely positive weights to the securities having small market capitalizations.

One of the most significant demerits of the mean-variance model is the sensitivity issue associated with risk and return parameters of the individual securities of a portfolio. These parameters are estimated using mean and standard deviation of returns. While computing these estimates, historical data of returns is usually taken into account in order to calculate the sample mean and the sample variance. The historical data neglects various other market factors and is not an accurate representation for estimates of future returns. Taking into account the above reasons, Michaud [19] argues that the mean-variance analysis tends to maximize the impact of estimation errors associated with the return and the risk parameters for the securities. As a result, Markowitz portfolio optimization often overweighs (underweighs) the securities having higher (lower) expected return, lower (higher) variance of returns and negative (positive) correlation between their returns. Labelling the model as "estimation-error maximizers", he states that it often leads to financially counter-intuitive portfolios, which, in some cases, perform worse than the equal-weighted portfolio. Broadie [7] investigates the error maximization property of mean-variance analysis. Accordingly, he conducts a simulation based study to compare the estimated efficient frontier with the actual frontier computed using true parameter values. He observes that points on the estimated efficient frontier show superior performance as

compared to the corresponding points on the actual frontier. He supports his argument of over-estimation of expected returns of optimal portfolios through his simulated results of obtaining the estimated frontier lying above the actual frontier. Additionally, he points out that non-stationarity in the data of returns can further increase the errors in computing the efficient frontier. Chopra and Ziemba [9] perform the sensitivity analysis of performance of optimal portfolios by studying the relative effect of estimation errors in means, variances and covariances of security returns, taking the investors' risk tolerance into consideration as well. They observe that at a high risk tolerance (to be defined in later chapters) of around fifty, cash equivalent loss for estimation errors in means is about eleven times greater than that for errors in variances or covariances. Accordingly, they point out that if the investors have superior estimates for means of security returns, they should prefer using them over the sample means calculated from historical data. Best and Grauer [3, 4] also arrived at similar conclusions by studying the sensitivity of weights of optimal portfolios with respect to changes in estimated means of returns on individual securities. Further, on imposition of no short selling constraint on the securities, they observe that a small change in estimated mean return of an individual security can assign zero weights to almost half the securities comprising a portfolio.

The discussed research works arrive at a common conclusion that the optimal portfolios are extremely sensitive towards the estimated values of input parameters, particularly expected returns on individual securities. In order to address this issue, there has been significant progress in recent years in the area of robust portfolio optimization. Several methods have been proposed in this area.

3

We are particularly interested in the approaches falling in the category related to enhancing robustness by optimizing the portfolio performance in worst-case scenarios.

Significant efforts have been made towards formulating these kinds of approaches from Markowitz based mean-variance analysis. However, no rigorous framework has been observed that could establish these approaches at par with Markowitz optimization in terms of portfolio performance. Ceria and Stubbs [8] introduce a methodology for robust portfolio optimization, taking into account the estimation errors in input parameters while formulating the optimization problem. The approach involves minimizing the worst case return for a given confidence region. They observe that the constructed robust portfolios perform superior in comparison to those constructed using mean-variance analysis in most of the cases but not in each month with certainty. Utilizing the above framework, Scherer[21] shows that robust methods don't lead to significant change in the efficient set. Constructing an example, he shows that robust portfolio underperforms out of the sample in comparison to Markowitz portfolio, especially in the case of low risk aversion and high uncertainty aversion. He also argues that performance of robust portfolio is dependent upon the consistency between uncertainty aversion and risk aversion which is quite complicated. Santos[20] performs similar experiments and concludes stating better performance of robust optimization in comparison to the portfolios constructed using mean-variance analysis in the case of simulated data unlike the real market data.

Chapter 2

Robust models

All the real world optimizing problems inevitably have uncertain parameters embedded in them. In order to tackle such problems, a framework called "Stochastic Programming" [5] is used, which can model such problems having uncertain parameters. These models take the probability distributions of the underlying data into consideration. To improve the stability of the solutions, robust methods such as re-sampling techniques, robust estimators and Bayesian approaches were developed. One of the approaches is **robust optimization**, which is used when the parameters are known to lie in a certain range. In this section, we explain some robust models with worst-case optimization approaches for a given objective function within a predefined "uncertainty" set.

The concept of uncertainty sets was introduced by Soyster [22], where he uses a different definition for defining a feasible region of a convex programming problem. The convex inequalities are replaced by convex sets with a condition that the finite sum of convex sets again should be within another convex set. In another way, he defines a new linear programming prob-

lem(LPP) with uncertain truth value, but it is bound to lie within a defined convex set. Later, El Ghaoui and Lebret [11] extend these uncertainty sets to define a robust formulation while tackling the least-squares problem having uncertain parameters, but they are bounded matrices. In their work, they describe the problem of finding a worst-case residual and refer the solution as a robust least-squares solution. Furthermore, they show that it can be computed via semi-definite or second order cone programming. El Ghaoui, Oustry, and Lebret [12] further study how to integrate bounded uncertain parameters in semidefinite programming. They introduce robust-formulations for semidefinite programming and provide sufficient conditions to guarantee the existence of such robust solutions. Ben-Tal and Nemirovski [1] mainly focus on the uncertainty related with *hard* constraints and which are *ought* to be satisfied, irrespective of the representation of the data. They suggest a methodology where they replace an actual uncertain linear programming problem by its robust counterpart. They show that the robust counterpart of a linear programming problem with the ellipsoidal uncertainty set is computationally attractive, as it reduces to a polynomial time solvable conic quadratic program. Additionally, they use interior points methods [2] to compute the solutions efficiently. Along the same lines, Goldfarb and Iyengar [14], focus on the robust convex quadratically constrained programs which are a subclass of the robust convex programs of Ben-Tal and Nemirovski [1]. They mainly work on finding uncertainty sets which structures this subclass of programs as second-order cone programs.

In its early phases, the major directions of research were to introduce robust formulations and to build uncertainty sets for robust counterparts of the LPP as they are computationally attractive. Once the basic framework of

robust optimization was established, it is now applied across various domains such as learning, statistics, finance and numerous areas of engineering.

2.1   Uncertainty sets

The determination of the structure of the uncertainty sets, so as to obtain computationally tractable solutions has been a key step in robust optimization. In the real world, even the distribution of asset returns has an uncertainty associated. In order to address this issue, a most frequently used technique is to find an estimate of the uncertain parameter and to define a geometrical bound around it. Empirically, historical returns are used to compute the estimates of these uncertain parameters. For a given optimization problem, determining the geometry of the uncertainty set is a difficult task. Accordingly, in this section, we discuss a couple of popular types of uncertainty sets which are used in portfolio optimization.

In literature, there are many extensions of uncertainty sets varying from simple polytopes to statistically derived conic-representable sets. A *polytopic* [13] uncertainty set which resembles a "box", it is defined as

$$U_\delta(\hat{\mathbf{a}}) = \{\mathbf{a} : |a_i - \hat{a}_i| \leq \delta_i, i = 1, 2, 3, ..., N\}, \tag{2.1}$$

where $\mathbf{a} = (a_i, a_2, ..., a_N)$ is a vector of values of uncertain parameters of dimension N and $\hat{\mathbf{a}} = (\hat{a_1}, \hat{a_2}, ..., \hat{a_N})$ is generally the estimate for $\mathbf{a}$.

There is another class of uncertainty sets which takes the second moment of the distribution into account. Such type of sets are called *ellipsoidal*

uncertainty sets. One of the most popular way of defining them is

$$U(\hat{\mathbf{a}}) = \left\{ \mathbf{a} : \mathbf{a} = \hat{\mathbf{a}} + \mathbf{P}^{1/2}\mathbf{u}, \|\mathbf{u}\| \leq 1 \right\}, \qquad (2.2)$$

where the choice of $\mathbf{P}$ is driven by the optimization problem. The main motivation to use such kind of sets is that they come up naturally when one tries to estimate uncertain parameters using techniques like regression. Additionally, these sets take probabilistic properties into account. We further discuss how to model the uncertainties for some of the financial indicators.

2.1.1 Uncertainty in expected returns

Recently, many attempts have been made to model the uncertainty in the expected returns because of several reasons. When compared with variances and covariances, it is known that the effect on the performance of portfolio due to the estimation error is more in case of expected returns. Though it is unlikely that the future returns of the assets are equal to the estimated value of expected return, one can foresee that they will be within a certain range of the estimated return. Accordingly, one can define uncertainty sets in such a way so that expected values lie inside the geometric bound around the estimated value, say $\hat{\boldsymbol{\mu}}$.

In a simple scenario, one can define possible intervals for the expected returns of each individual asset by using box uncertainty set. Mathematically, it can be expressed as

$$U_{\boldsymbol{\delta}}(\hat{\boldsymbol{\mu}}) = \left\{ \boldsymbol{\mu} : |\mu_i - \hat{\mu}_i| \leq \delta_i, i = 1, 2, 3, ..., N \right\}, \qquad (2.3)$$

where δ_i represents the value which determines the confidence interval region

for individual assets. Clearly from the above expression, for the asset i, the estimated error has an upper bound limit of δ_i. On incorporating the box uncertainty set in the robust formulation of Markowitz model having the constraints that involve no short selling and the sum of the weights equalling unity, the following max-min problem

$$\max_{\mathbf{x}} \left\{ \min_{\boldsymbol{\mu} \in U_{\delta}(\hat{\boldsymbol{\mu}})} \boldsymbol{\mu}^{\top} \mathbf{x} - \lambda \mathbf{x}^{\top} \Sigma \mathbf{x} \right\} \text{ such that } \mathbf{x}^{\top} \mathbf{1} = 1 \text{ and } \mathbf{x} \geq 0, \qquad (2.4)$$

transforms to a maximization problem

$$\max_{\mathbf{x}} \quad \hat{\boldsymbol{\mu}}^{\top} \mathbf{x} - \lambda \mathbf{x}^{\top} \Sigma \mathbf{x} - \boldsymbol{\delta}^{\top} |\mathbf{x}| \quad \text{such that } \mathbf{x}^{\top} \mathbf{1} = 1 \text{ and } \mathbf{x} \geq 0, \qquad (2.5)$$

where $\mathbf{1}$ represents the unity vector.

The most popular choice is to use ellipsoidal uncertainty set, as it takes the second moments into account. Uncertainty in expected return using ellipsoidal uncertainty set is expressed as

$$U_{\delta}(\hat{\boldsymbol{\mu}}) = \left\{ \boldsymbol{\mu} : (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})^{\top} \Sigma_{\boldsymbol{\mu}}^{-1} (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}}) \leq \delta^2 \right\}, \qquad (2.6)$$

where Σ_{μ} is a variance-covariance matrix of the estimation error of expected returns of the assets. Again, solving (2.4) with ellipsoid uncertainty set yields

$$\max_{\mathbf{x}} \left\{ \hat{\boldsymbol{\mu}}^{\top} \mathbf{x} - \lambda \mathbf{x}^{\top} \Sigma_{\boldsymbol{\mu}} \mathbf{x} - \delta \sqrt{\mathbf{x}^{\top} \Sigma_{\boldsymbol{\mu}} \mathbf{x}} \right\} \text{ such that } \mathbf{x}^{\top} \mathbf{1} = 1 \text{ and } \mathbf{x} \geq 0. \tag{2.7}$$

While dealing with the box uncertainty, it is assumed that the returns follow normal distribution as it eases the task of computing the desired confidence intervals for each individual asset. For the same reason, if the uncer-

tainty set follows ellipsoid model, the underlying distribution is assumed to be tracing a χ^2 distribution with the number of assets being the degrees of freedom (df). Accordingly, for $100(1 - \alpha)\%$ confidence level, δ is defined in the following manner

$$\delta^2 = \chi_N^2(\alpha) \tag{2.8}$$

where $\chi_N^2(\alpha)$ is the inverse of a chi square distribution with N degrees of freedom.

2.1.2 Separable Uncertainty Set

As mentioned earlier, portfolio performance is more sensitive towards estimation error in mean returns of assets in comparison to variances and covariances of asset returns. This is one of the major reasons behind research works laying less emphasis upon the uncertainty set for covariance matrix of asset returns. Box uncertainty set for covariance matrix of returns is defined on similar lines as that for expected returns. Lower bound $\underline{\Sigma}_{ij}$ and upper bound $\overline{\Sigma}_{ij}$ can be specified for each entry Σ_{ij} of the covariance matrix. Using this methodology, the constructed box uncertainty set for covariance matrix is expressed in the following form:

$$U_\Sigma = \{\Sigma : \underline{\Sigma} \leq \Sigma \leq \overline{\Sigma}, \ \Sigma \succeq 0\}. \tag{2.9}$$

In the above equation, the condition $\Sigma \succeq 0$ implies that Σ is a symmetric positive semidefinite matrix. This condition is necessary in most of the robust optimization approaches, particularly those involving Markowitz model as the basic theoretical framework.

Ttnc and Koenig [23] discuss a method to solve the robust formulation

of Markowitz optimization problem having non-negativity constraints upon the weights of assets. They define the uncertainty set for covariance matrix as per above equation and uncertainty set for expected returns as $U_{\boldsymbol{\mu}} = \{\boldsymbol{\mu} : \underline{\boldsymbol{\mu}} \leq \boldsymbol{\mu} \leq \overline{\boldsymbol{\mu}}\}$, where $\underline{\boldsymbol{\mu}}$ and $\overline{\boldsymbol{\mu}}$ represent lower and upper bounds on mean return vector $\boldsymbol{\mu}$ respectively . Accordingly, the robust optimization problem

$$\max_{\mathbf{x}} \left\{ \min_{(\boldsymbol{\mu},\Sigma)\in(U_{\boldsymbol{\mu}},U_{\Sigma})} \boldsymbol{\mu}^{\top}\mathbf{x} - \lambda\mathbf{x}^{\top}\Sigma\,\mathbf{x} \right\} \text{ such that } \mathbf{x}^{\top}\mathbf{1} = 1 \text{ and } \mathbf{x} \geq 0, \quad (2.10)$$

can be formulated as following:

$$\max_{\mathbf{x}} \left\{ \underline{\boldsymbol{\mu}}^{\top}\mathbf{x} - \lambda\mathbf{x}^{\top}\,\overline{\Sigma}\,\mathbf{x} \right\} \text{ such that } \mathbf{x}^{\top}\mathbf{1} = 1 \text{ and } \mathbf{x} \geq 0. \quad (2.11)$$

Above approach involves the use of "separable" uncertainty sets, which implies, the uncertainty sets for mean returns and covariance matrix are defined independent of each other.

2.1.3   Joint Uncertainty Set

There are certain drawbacks associated with separable uncertainty sets. Lu [16] argues that such kind of uncertainty sets don't take the knowledge of actual confidence level into consideration. Secondly, separable uncertainty sets don't incorporate the joint behavior of mean returns and covariance matrix. As a result, these uncertainty sets are completely or partially similar to box uncertainty sets. This is one of the major reasons behind robust portfolios being conservative or highly non-diversified as observed in numerous computations. In order to address these drawbacks, Lu proposes a "joint uncertainty set". This uncertainty set is constructed as per desired confidence level using a statistical procedure that takes the factor model [15] for asset

returns into consideration.

Delage and Ye [10] define a joint uncertainty set that takes into consideration the uncertainty in distribution of asset returns as well as moments (mean returns and covariance matrix of returns). The proposed uncertainty set having confidence parameters, $\gamma_1 \geq 0$ and $\gamma_2 \geq 1$, is given by:

$$
\begin{aligned}
(\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})^\top \, \hat{\Sigma}^{-1} \, (\boldsymbol{\mu} - \hat{\boldsymbol{\mu}}) &\leq \gamma_1, \\
E[(\mathbf{r} - \hat{\boldsymbol{\mu}})(\mathbf{r} - \hat{\boldsymbol{\mu}})^\top] &\leq \gamma_2 \hat{\Sigma}.
\end{aligned}
\tag{2.12}
$$

In the above equation, $\hat{\boldsymbol{\mu}}$ and $\hat{\Sigma}$ represent the estimates of mean return vector and covariance matrix of asset returns respectively, and $\mathbf{r}$ is the random return vector. Using this uncertainty set, they formulate the portfolio optimization problem as a Distributionally Robust Stochastic Program (DRSR). Accordingly, they demonstrate that the problem is computationally tractable by solving it as a semidefinite program.

Chapter 3

Experiments

We analyse the performance of robust portfolio optimization methods discussed in previous chapter in a practical setup involving domestic market data and simulated data. Experimental analysis are performed under two scenarios: number of stocks is 31 and number of stocks is 98. This is done in order to observe the effect of increase in number of stocks on the performance of robust methods with respect to the Markowitz model.

For the first scenario, we construct the market data using the daily log-returns obtained from the data containing "Adjusted Close Price" of 31 stocks comprising BSE30 (data source: Yahoo Finance). We have considered the period from December 18, 2017 to September 30, 2018 comprising a total of 194 active trading days. Corresponding to this market data, we prepare two sets of simulated data for 31 assets by sampling returns from a multivariate normal distribution with mean and covariance matrix set equal to those obtained from BSE30 market data. The first set comprises of number of samples same as the daily log-return observations in BSE30 market data whereas the second set comprises of 1000 samples. We use two types of sim-

ulated data in order to study the impact of number of samples in simulated data on the portfolio optimization approaches. Additionally, we compare the performance of robust optimization approaches visavis Markowitz approach in the case of market data as well as simulated data in each scenario in order to analyse whether worst-case portfolio optimization approaches are useful in real market setup.

For the scenario involving greater number of stocks, we utilize daily adjusted close price data of 98 stocks comprising BSE100 with the period spanning from December 18, 2016 to September 30, 2018. On similar lines as the first scenario, two sets of simulated data are constructed using multivariate normal distribution.

The robust portfolio optimization approaches that we have taken into consideration for analysing their performance with respect to Markowitz model (**Mark**) are as follows:

1. Robust Model involving box uncertainty set in expected return (**Box**)

2. Robust Model involving ellipsoidal uncertainty set in expected return (**Ellip**)

3. Robust Model involving separable uncertainty set (**Sep**)

The performance of the robust optimization approaches mentioned above are studied by taking into consideration the "Sharpe Ratio" of the portfolios constructed having λ representing risk-aversion in the ideal range (2-4). In order to compute Sharpe Ratio, we assume the annualized riskfree rate equal to 6%. In the following sections, we perform qualitative analysis of the computational results observed in case of two scenarios as discussed above.

14

3.1 Performance with $N = 31$ assets

Figure 3.1 and Table 3.1 present the efficient frontier and performance of portfolios constructed using Markowitz model (Mark) and three robust models, on applying these models to the simulated returns with 1000 samples. We observe that efficient frontiers for Ellip and Sep models lie below the one for Mark model. This supports the argument made by Broadie regarding over-estimation of efficient frontier in case of Markowitz model [7]. Overlap of efficient frontiers for Mark and Box models indicates that utilizing box uncertainty set for robust optimization does not prove to be of much use in this case. This claim is supported quantitatively from Table 3.1 as well as since the average Sharpe ratio for portfolios constructed in the ideal range of risk-aversion is same in case of both the models.
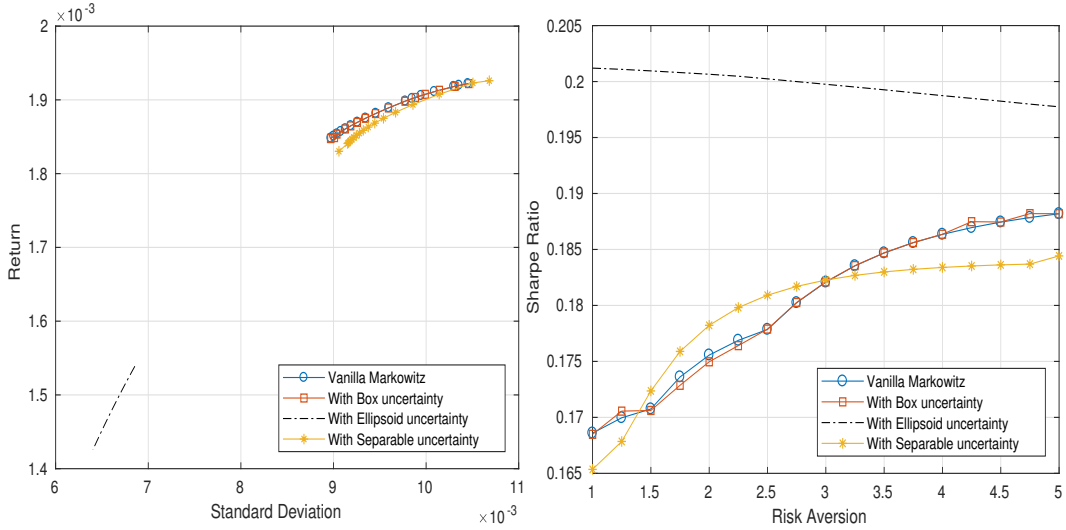

Figure 3.1: Efficient Frontier plot and Sharpe ratio plot for different portfolio optimization models in case of Simulated Data with 1000 samples (31 assets)

λ	SR_{Mark}	SR_{Box}	SR_{Ellip}	SR_{Sep}
2	0.176	0.175	0.201	0.178
2.5	0.178	0.178	0.2	0.181
3	0.182	0.182	0.2	0.182
3.5	0.185	0.185	0.199	0.183
4	0.186	0.186	0.199	0.183
Avg	0.181	0.181	0.2	0.182

Table 3.1: Comparison of different portfolio optimization models in case of Simulated Data with 1000 samples (31 assets)

From Table 3.1, we infer that Sep model performs at par with Mark model if we take into consideration the average Sharpe Ratio. This is evident from Figure 3.1 as well since Mark model starts outperforming Sep model in terms Of Sharpe ratio after risk-aversion crosses 3. On the other hand, Ellip model outperforms all the models including Mark model in the entire ideal range of risk-aversion.

On conducting the simulation study with same number of samples as in case of market data (Figure 3.2 and Table 3.2), we observe similar results on comparing Box model with Mark model. However, we could observe slight inconsistency in performance of Box model as evident from the Sharpe Ratio plot. The efficient frontiers for Sep and Ellip model lie below that for Mark model.
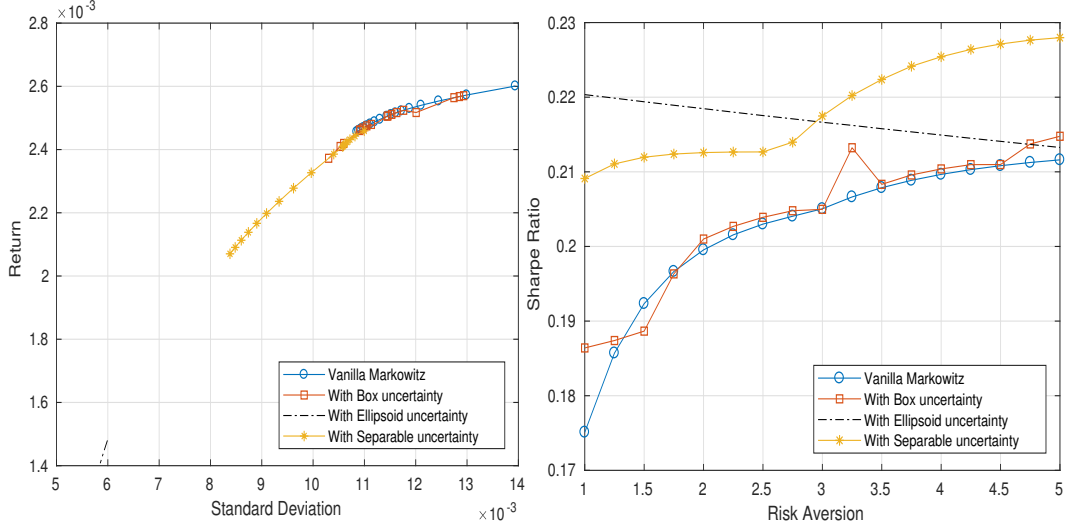
Figure 3.2: Efficient Frontier plot and Sharpe ratio plot for different portfolio optimization models in case of Simulated Data with same number of samples as market data (31 assets)

λ	SR_{Mark}	SR_{Box}	SR_{Ellip}	SR_{Sep}
2	0.2	0.198	0.218	0.213
2.5	0.203	0.204	0.218	0.213
3	0.205	0.207	0.217	0.217
3.5	0.208	0.209	0.216	0.222
4	0.21	0.21	0.215	0.225
Avg	0.205	0.206	0.217	0.218

Table 3.2: Comparison of different portfolio optimization models in case of Simulated Data with same number of samples as market data (31 assets)

We also infer that Sep and Ellip model outperform Mark model in terms of Sharpe Ratio in the ideal range of risk-aversion. However, it is difficult to compare the performance of Sep model with that of Ellip model in this case since the average Sharpe Ratio for both of them is almost same.

In a real market setup involving stocks comprising BSE30, we observe that

efficient frontier for Box model almost overlaps with that for Mark model. However, the performance of Box model in terms of Sharpe ratio is quite inconsistent as evident from the plot in Figure 3.3. Efficient frontier for Sep model lies below that that for Mark model and the gap between the plots widens upto great extent incase of Ellip model.
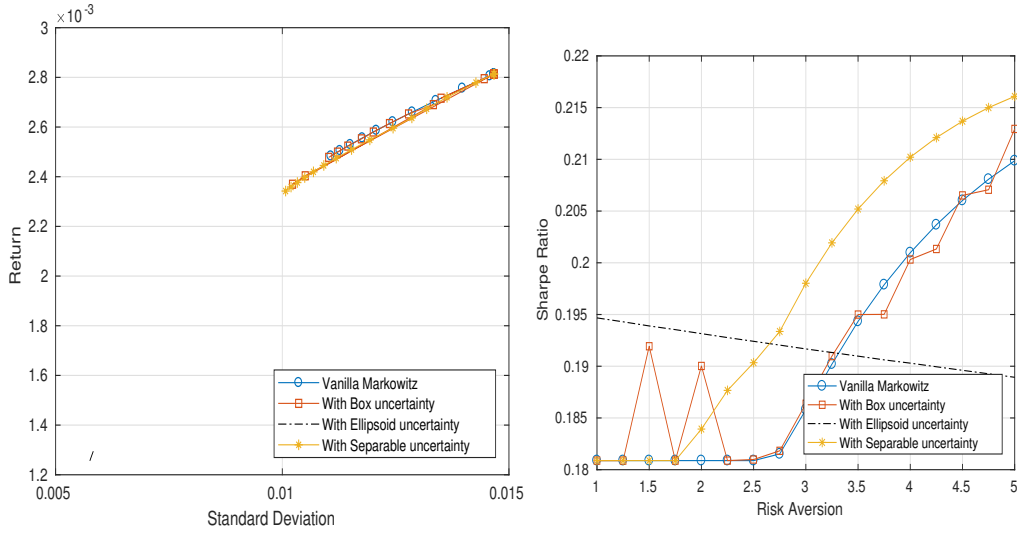

Figure 3.3: Efficient Frontier plot and Sharpe ratio plot for different portfolio optimization models in case of Market Data (31 assets)

λ	SR_{Mark}	SR_{Box}	SR_{Ellip}	SR_{Sep}
2	0.181	0.181	0.193	0.186
2.5	0.181	0.181	0.192	0.193
3	0.186	0.191	0.192	0.202
3.5	0.194	0.195	0.191	0.209
4	0.201	0.202	0.19	0.213
Avg	0.189	0.19	0.192	0.2

Table 3.3: Comparison of different portfolio optimization models in case of Market Data (31 assets)

We also observe that Sep model outperforms Mark model in the ideal range of risk-aversion on taking the Sharpe Ratio into consideration as the

performance measure. This is not true in case of Ellip Model as evident from the Sharpe ratio plot in Figure 3.3. Even from Table 3.3, we observe that average Sharpe ratio for Ellip model is only slightly greater than that for Markowitz. Thus, unlike the simulated data, Sep model performs superior in comparison to Ellip model when applied to market data.

A common observation that could be inferred from three cases considered in the scenario involving less number of assets is Sep and Ellip model perform superior or equivalent in comparison to Markowitz model in the ideal range of risk-aversion.

3.2 Performance with $N = 98$ assets

On applying robust model along with the Markowitz model on a simulated data having 1000 samples, we observe results similar to the corresponding case in previous scenario when we compare Box model with Markowitz model. This is evident from the coinciding plots of the efficient frontier and the Sharpe ratio for both the models in Figure 3.4.
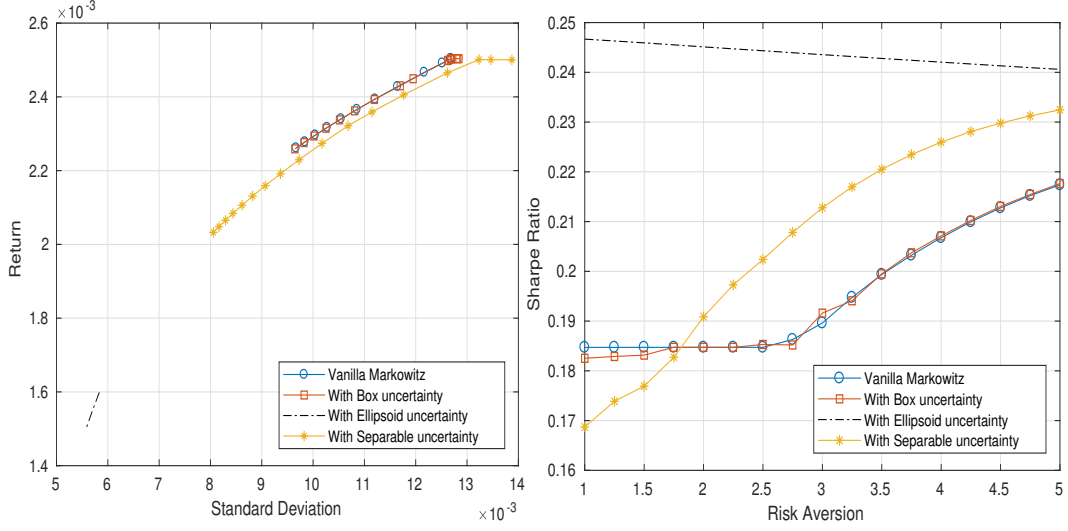
Figure 3.4: Efficient Frontier plot and Sharpe ratio plot for different portfolio optimization models in case of Simulated Data with 1000 samples (98 assets)

λ	SR_{Mark}	SR_{Box}	SR_{Ellip}	SR_{Sep}
2	0.185	0.185	0.245	0.191
2.5	0.185	0.185	0.244	0.202
3	0.19	0.192	0.244	0.213
3.5	0.199	0.199	0.243	0.221
4	0.207	0.207	0.242	0.226
Avg	0.193	0.194	0.244	0.21

Table 3.4: Comparison of different portfolio optimization models in case of Simulated Data with 1000 samples (98 assets)

Contrary to the similar case in scenario involving less number of assets (31 assets), we observe that not only Ellip model but Sep model also outperforms Mark model taking into consideration the portfolios constructed in the ideal range of risk-aversion. From Table 3.4, we infer that Ellip model performs superior in comparison to Sep model in terms of greater average Sharpe ratio.

Figure 3.5 and Table 3.5 present the results of simulation study with same

number of samples as that of market data (BSE100). Results observed on comparing Box model with Mark model are similar to the previous case. In the ideal range of risk aversion, we observe that efficient frontier for Ellip as well as Sep model lie below Mark model. Additionally, both the models perform better than Mark model in terms of the Sharpe Ratio.
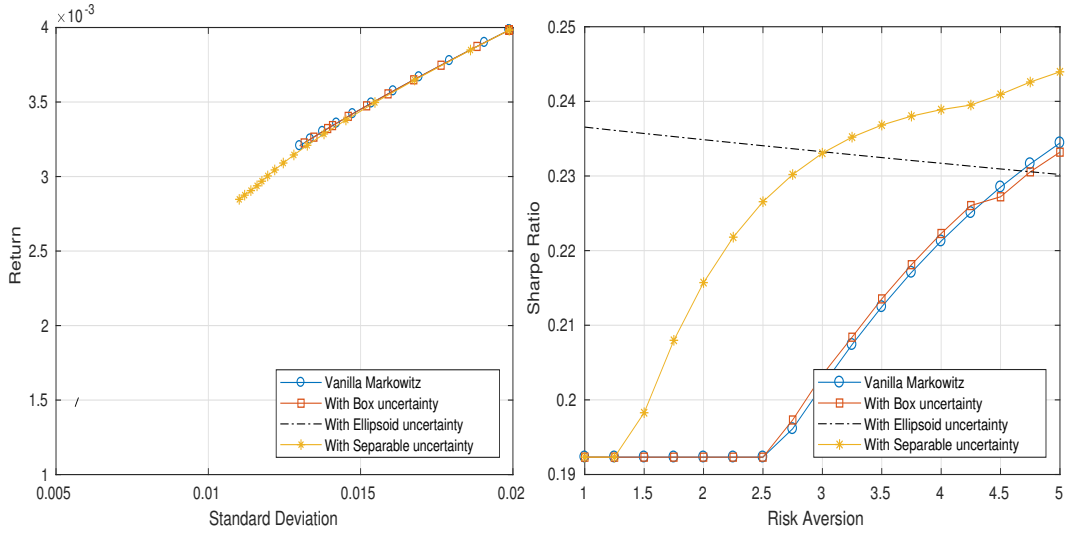

Figure 3.5: Efficient Frontier plot and Sharpe ratio plot for different portfolio optimization models in case of Simulated Data with same number of samples as market data (98 assets)

λ	SR_{Mark}	SR_{Box}	SR_{Ellip}	SR_{Sep}
2	0.192	0.192	0.235	0.216
2.5	0.192	0.192	0.234	0.227
3	0.202	0.203	0.233	0.233
3.5	0.212	0.213	0.232	0.237
4	0.221	0.222	0.232	0.239
Avg	0.204	0.205	0.233	0.23

Table 3.5: Comparison of different portfolio optimization models in case of Simulated Data with same number of samples as market data (98 assets)

From the Sharpe ratio plot in Figure 3.5, it is difficult to compare Sep

and Ellip model since each outperforms the other in a different sub-interval of risk-aversion. Similar values of the average Sharpe ratio in Table 3.5 supports the claim of equivalent performance of these two models in this case.

The results for the case involving the market data (that contains log-returns of stocks comprising BSE100) are shown in Figure 3.6 and Table 3.6. The efficient frontier plot leads to observations similar to the previous case. However, there is a slight inconsistency in the performance of Box model as observed in the Sharpe ratio plot.
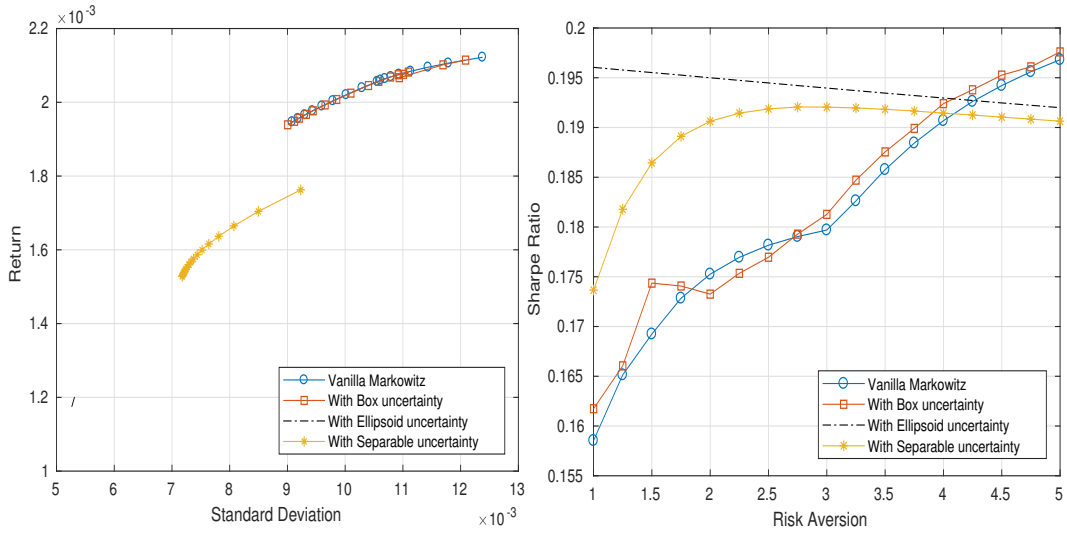
Figure 3.6: Efficient Frontier plot and Sharpe ratio plot for different portfolio optimization models in case of Market Data (98 assets)

Portfolios constructed using Sep and Ellip model outperform the ones constructed using Mark model in the ideal range of risk-aversion. Ellip model performs slightly better than Sep model as evident from the Sharpe Ratio plot. Marginal difference in average Sharpe ratio between these two models supports this inference.

λ	SR_{Mark}	SR_{Box}	SR_{Ellip}	SR_{Sep}
2	0.175	0.173	0.195	0.193
2.5	0.178	0.177	0.194	0.193
3	0.18	0.181	0.194	0.193
3.5	0.186	0.188	0.193	0.192
4	0.191	0.192	0.193	0.192
Avg	0.182	0.182	0.194	0.192

Table 3.6: Comparison of different portfolio optimization models in case of Market Data (98 assets)

We draw a common inference from three cases considered in the scenario involving greater number of assets, i.e, Sep and Ellip model outperform the Markowitz model in the ideal range of risk aversion.

Chapter 4

Conclusions and Comments

4.1 From the view of number of stocks

	S&P BSE30	S&P BSE100
#generated_simulations = 1000	AF	AFG
#generated_simulations = ζ	AX	ALA
Market data	AL	ALB

Table 4.1: The average increase in Sharpe ratio when compared to traditional Markowitz Model by varying the number of stocks in different kinds of scenarios

4.2 From the view of number of samples generated

4.3 From the view of type of the data

	#samples = 1000	#stocks = ζ
S&P BSE30	AF	AFG
S&P BSE100	AX	ALA

Table 4.2: The average increase in Sharpe ratio when compared to traditional Markowitz Model by varying the number of observations generated in different kinds of scenarios.

	Simulated data	Real Market data
S&P BSE30	AF	AFG
S&P BSE100	AX	ALA

Table 4.3: The average increase in Sharpe ratio when compared to traditional Markowitz Model by varying the number of observations generated in different kinds of scenarios.

Bibliography

[1] A. Ben-Tal and A. Nemirovski. Robust convex optimization. *Mathematics of Operations Research*, 23(4):769–805, 1998.

[2] A. Ben-Tal and A. Nemirovski. Robust solutions of uncertain linear programs. *Oper. Res. Lett.*, 25(1):1–13, August 1999.

[3] Michael J. Best and Robert R. Grauer. On the sensitivity of mean-variance-efficient portfolios to changes in asset means: Some analytical and computational results. *The Review of Financial Studies*, 4(2):315–342, 1991.

[4] Michael J. Best and Robert R. Grauer. Sensitivity analysis for mean-variance portfolio problems. *Management Science*, 37(8):980–989, 1991.

[5] John R. Birge and Franois Louveaux. *Introduction to Stochastic Programming (Springer Series in Operations Research and Financial Engineering)*. Springer, 2011.

[6] Fischer Black and Robert Litterman. Global portfolio optimization. *Financial Analysts Journal*, 48(5):28–43, 1992.

[7] Mark Broadie. Computing efficient frontiers using estimated parameters. *Annals of Operations Research*, 45(1):21–58, Dec 1993.

[8] Sebastián Ceria and Robert A Stubbs. Incorporating estimation errors into portfolio selection: Robust portfolio construction. *Journal of Asset Management*, 7(2):109–127, Jul 2006.

[9] Vijay Kumar. Chopra and William T. Ziemba. The effect of errors in means, variances, and covariances on optimal portfolio choice. *The Journal of Portfolio Management*, 19(2):6–11, 1993.

[10] Erick Delage and Yinyu Ye. Distributionally robust optimization under moment uncertainty with application to data-driven problems. *Operations research*, 58(3):595–612, 2010.

[11] L. El Ghaoui and H. Lebret. Robust solutions to least-squares problems with uncertain data. *SIAM Journal on Matrix Analysis and Applications*, 18(4):1035–1064, 1997.

[12] L. El Ghaoui, F. Oustry, and H. Lebret. Robust solutions to uncertain semidefinite programs. *SIAM Journal on Optimization*, 9(1):33–52, 1998.

[13] Frank J. Fabozzi, Petter N. Kolm, Dessislava Pachamanova, and Sergio M. Focardi. *Robust Portfolio Optimization and Management.* Wiley, 2007.

[14] D. Goldfarb and G. Iyengar. Robust convex quadratically constrained programs. *Mathematical Programming*, 97(3):495–515, Aug 2003.

[15] Donald Goldfarb and Garud Iyengar. Robust portfolio selection problems. *Mathematics of operations research*, 28(1):1–38, 2003.

[16] Zhaosong Lu. A new cone programming approach for robust portfolio selection. *Optim. Methods Softw.*, 26(1):89–104, 2006.

[17] Harry M. Markowitz. Portfolio selection. *The journal of finance*, 7(1):77–91, 1952.

[18] Harry M. Markowitz. *Portfolio Selection: Efficient Diversification of Investments*. Yale University Press, 1959.

[19] Richard O. Michaud. The markowitz optimization enigma: Is 'optimized' optimal? *Financial Analysts Journal*, 45(1):31–42, 1989.

[20] Andr Santos. The out-of-sample performance of robust portfolio optimization. *Brazilian Review of Finance*, 8(2):141–166, 2010.

[21] Bernd Scherer. Can robust portfolio optimisation help to build better portfolios? *Journal of Asset Management*, 7(6):374–387, Mar 2007.

[22] A. L. Soyster. Convex programming with set-inclusive constraints and applications to inexact linear programming. *Operations Research*, 21(5):1154–1157, 1973.

[23] Reha H Tütüncü and M Koenig. Robust asset allocation. *Annals of Operations Research*, 132(1-4):157–187, 2004.