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Enhancing the Teaching of Statistics: Portfolio Theory, an Application of Statistics in Finance

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Abstract

In this paper we present an application of statistics using real stock market data. Most, if not all, students have some familiarity with the stock market (or at least they have heard about it) and therefore can understand the problem easily. It is the real data analysis that students find interesting. Here we explore the building of efficient portfolios through optimization using examples of two and three stocks, and how covariance and correlation can help the investor to diversify his or her risk. We discuss why diversification works, but also the problems that arise in portfolio management. Stock market data can be incorporated at any level of statistics, from lower division, to upper division, to graduate courses of Mathematics and Statistics. From our experience, students find this topic very interesting and often they want to enroll in other courses related to this area.

1 Introduction

When we teach our courses we often ask ourselves “I need to find a nice real data set to show my students why what we teach is useful and applicable.” In addition, the latest recommendations of many international pedagogical resources in probability and statistics (e.g., SurfStat (SurfStat), the Chance Project (ChanceProject), GAISE Report (GAISEReport), ASA (ASA), USCOTS (USCOTS), ARTIST (ARTIST), IASE, etc.) suggest that undergraduate students enrolled in probability and statistics courses should use to real-world problems and have the opportunity to practice using hands-on experiences in generating, collecting and displaying data, as well as trained in model-design, analysis and result interpretation (Cox, 1998; Dinov et al, 2006; Hawkins, 1997; Taplin, 2003; Teugels, 1997). One application students find very interesting is the use of stock market data to build efficient portfolios.

This application can easily be used when we teach the topic of covariance, correlation and regression. An instructor may argue that without knowledge of finance it is not easy to use financial data. However, we will show below that knowledge of finance is not necessary. Not only will many students find this topic very interesting and often some of them continue and enroll in other courses to explore other statistical models in finance, this application can be used in lower division courses, where students do not have very strong mathematical background, upper division courses, where students have good mathematical skills, and graduate level courses. Very few statistics textbooks present stock market data examples with applications to portfolio management for example, DeGroot and Schervish (2002) briefly mention it in their textbook which is aimed for a mathematical statistics course. Stock market data can be used to explain variation as well. Presenting the fluctuations in the price of a stock and then constructing the histogram of the returns of a stock is a good way to introduce the topic. Data can be found on the web at <http://finance.yahoo.com>, or instructors can obtain accounts (for themselves and their students) and use the following site <http://wrds.wharton.upenn.edu>, which is one of the most comprehensive stock market databases.

2 Mean and variance of the returns of a stock

Closing prices (Figure 1) show how the IBM stock fluctuates from January 2000 to December 2005. We can mention here the high volatility (variance) that is exhibited in stocks. Let us define the return at time t of a stock as follows:

$$R_t = \frac{P_t - P_{t-1}}{P_{t-1}} \quad (1)$$

where P_t, P_{t-1} are the closing stock prices at time t and $t-1$ respectively. One can use daily, weekly, or monthly returns but in portfolio management, we usually use monthly returns. The previous definition for the return of a stock is a common one to obtain returns of stocks. For example, if the stock's closing price at the beginning of last month was \$50 while at the beginning of this month it is \$51 then the return during this period is 2%. Also, we will define the mean and the variance of the returns of stock i as

$$\bar{R}_i = \frac{1}{n} \sum_{t=1}^n R_{it}, \quad \sigma_i^2 = \frac{1}{n-1} \sum_{t=1}^n (R_{it} - \bar{R}_i)^2 \quad (2)$$

and the covariance between the returns of stocks i and j as

$$\text{cov}(R_i, R_j) = \sigma_{ij} = \frac{1}{n-1} \sum_{t=1}^n (R_{it} - \bar{R}_i)(R_{jt} - \bar{R}_j) \quad (3)$$

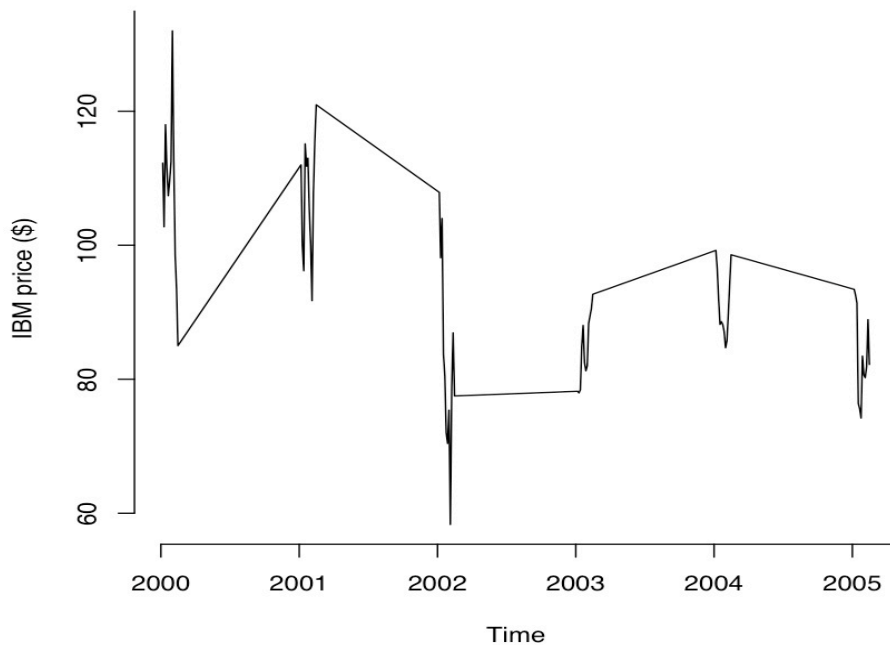


Figure 1: IBM closing price, January 2000 - December 2005.

In some finance textbooks, instead of the denominator being $n - 1$ (expressions (2) and (3)), they use n which is based on the maximum likelihood estimates (Rice, 1995). The corresponding histogram of the returns of IBM from January 2000 to December 2005 is shown in Figure 2. Investing in the stock market always bears some risk, large or small, depending on the variance of the returns of the stock. A stock that has large variance may make you rich but may also make you poor! Therefore, risk is synonymous with variance and because investors are risk averse they want to minimize risk. Suppose now that the investor has two stocks and wants to make an investment. There are many possibilities of course. One of them is to invest all his available funds in the first stock and nothing in the second, or vice versa, another possibility is to invest 50% of his funds in the first stock and the other 50% in the second stock (equal allocation), etc. Which investment should he choose? We will answer this below.

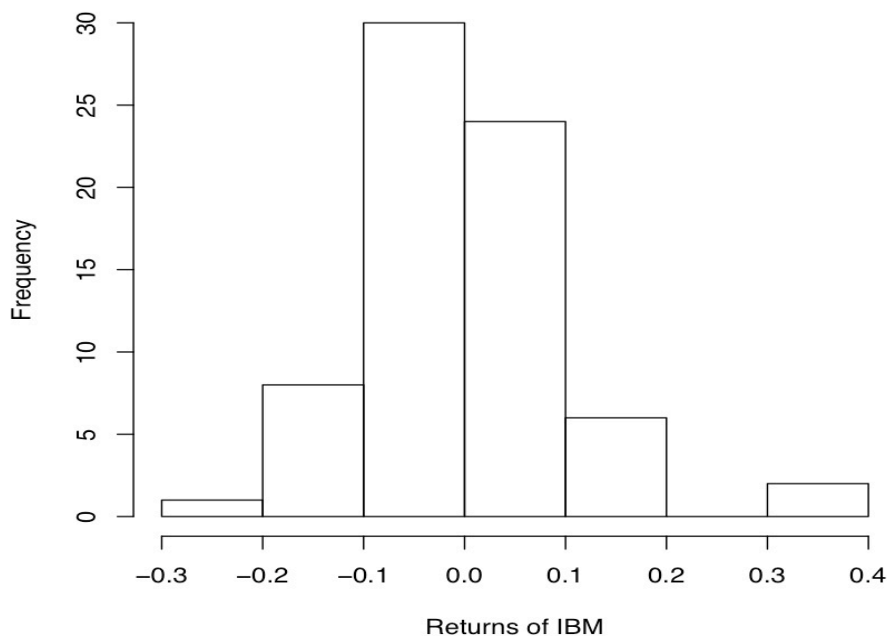


Figure 2: Returns of IBM, January 2000 - December 2005.

3 Minimizing the risk of the portfolio

Let R_A and R_B be the returns of stocks A and B respectively, and let x_A, x_B be the proportions of the available funds invested in each of the stocks. Then the resulting portfolio is $x_A R_A + x_B R_B$. A risk averse investor would like to minimize his or her risk; therefore, he or she wants to minimize the variance of the portfolio:

$$\min \text{var}(x_A R_A + x_B R_B)$$

or

$$\min x_A^2 \text{var}(R_A) + x_B^2 \text{var}(R_B) + 2x_A x_B \text{cov}(R_A, R_B)$$

which is subject to the budget constrained $x_A + x_B = 1$. If we incorporate the constraint in the variance of the portfolio we have the following unconstrained minimization (Chvatal, 1983):

$$\min x_A^2 \text{var}(R_A) + (1 - x_A)^2 \text{var}(R_B) + 2x_A(1 - x_A) \text{cov}(R_A, R_B) \quad (4)$$

The unknowns are x_A and x_B . By differentiating with respect to x_A , setting it equal to zero, and solving for x_A we get the following solution for x_A :

$$x_A = \frac{\text{var}(R_B) - \text{cov}(R_A, R_B)}{\text{var}(R_A) + \text{var}(R_B) - 2\text{cov}(R_A, R_B)} \quad (5)$$

and therefore:

$$x_B = \frac{\text{var}(R_A) - \text{cov}(R_A, R_B)}{\text{var}(R_A) + \text{var}(R_B) - 2\text{cov}(R_A, R_B)} \quad (6)$$

Note that the above expressions make sense in the following way. If $\text{var}(R_A) > \text{var}(R_B)$, which means A is riskier than B , we would want to invest more in stock B than in A in order to minimize the risk of the portfolio. The problem of portfolio theory is not very old. Harry Markowitz is considered the pioneer in the area where in the early 1950s he published his work (Markowitz, 1952) to receive the Nobel prize much later in 1990. One question that immediately arises here is that the values of the variances and covariances are only estimates and are based on historical data. How well history predicts the future in stock market is another story, but it is better than having nothing. In the next sections we will present the results when two and three stocks are involved using real stock market data.

4 Portfolio management with two stocks

Monthly stock market data were obtained for the stocks IBM, EXXON-MOBIL, and BOEING (they are traded in the New York Stock Exchange (NYSE)), for the period January 2000 until December 2005. The data were obtained from the Wharton Research Data Services website (Center for Research in Security Prices, CRSP) at <http://wrds.wharton.upenn.edu>. We first obtained the closing monthly prices which are then converted into monthly returns using (1). Figure 3 shows the fluctuations of the closing prices of the three stocks over time and Figure 4 shows the histograms of the returns of the three stocks. The mean returns of the three stocks are presented in Table 1, and the variance-covariance matrix of the returns of the three stocks is presented in Table 2. In this first example, we will use the IBM and BOEING stocks to find the most efficient portfolios.

The value of x_A using (5) is:

$$x_A = \frac{0.008282 - 0.000030}{0.009930 + 0.008282 - 2(0.000030)} = 0.455,$$

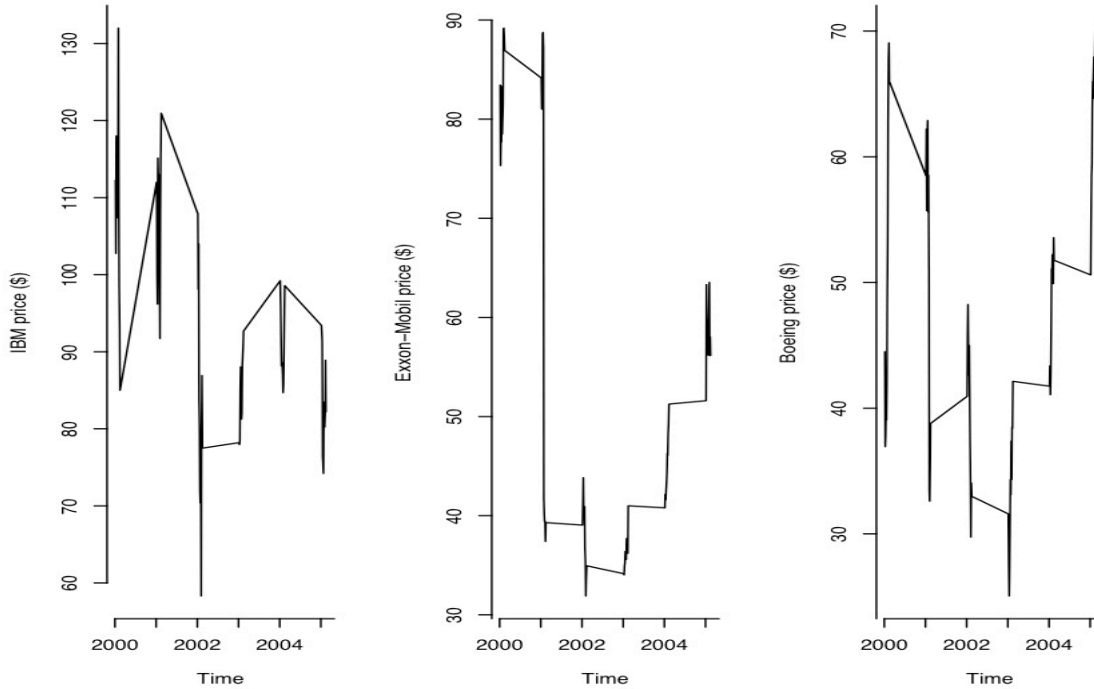


Figure 3: Closing prices of IBM, Exxon-Mobil, Boeing, January 2000 - December 2005.

	Mean	Q_1	Median	Q_3	Min	Max
IBM	0.000307	-0.052343	-0.008992	0.046457	-0.226453	0.353799
EXXON-MOBIL	-0.001167	-0.018680	0.000701	0.033832	-0.521923	0.226938
BOEING	0.010791	-0.043722	0.018433	0.073589	-0.345703	0.174825

Table 1: Descriptive statistics of the returns of IBM, EXXON-MOBIL, BOEING.

and therefore $x_B = 1 - x_A = 1 - 0.455 = 0.545$. Therefore if the investor invests 45.5% of the available funds into IBM and the remaining 54.5% into BOEING, the variance of the portfolio will be minimized and equal to:

$$\text{var}(0.455R_{IBM} + 0.545R_{BOEING}) = 0.004531.$$

The corresponding expected return of this portfolio will be

$$E(0.455R_{IBM} + 0.545R_{BOEING}) = 0.455(0.000307) + 0.545(0.010791) = 0.006025.$$

We already see the benefit of diversification. The combination of 45.5% IBM and 54.5% BOEING gives less risk than the individual stocks. Of course not everyone would invest his

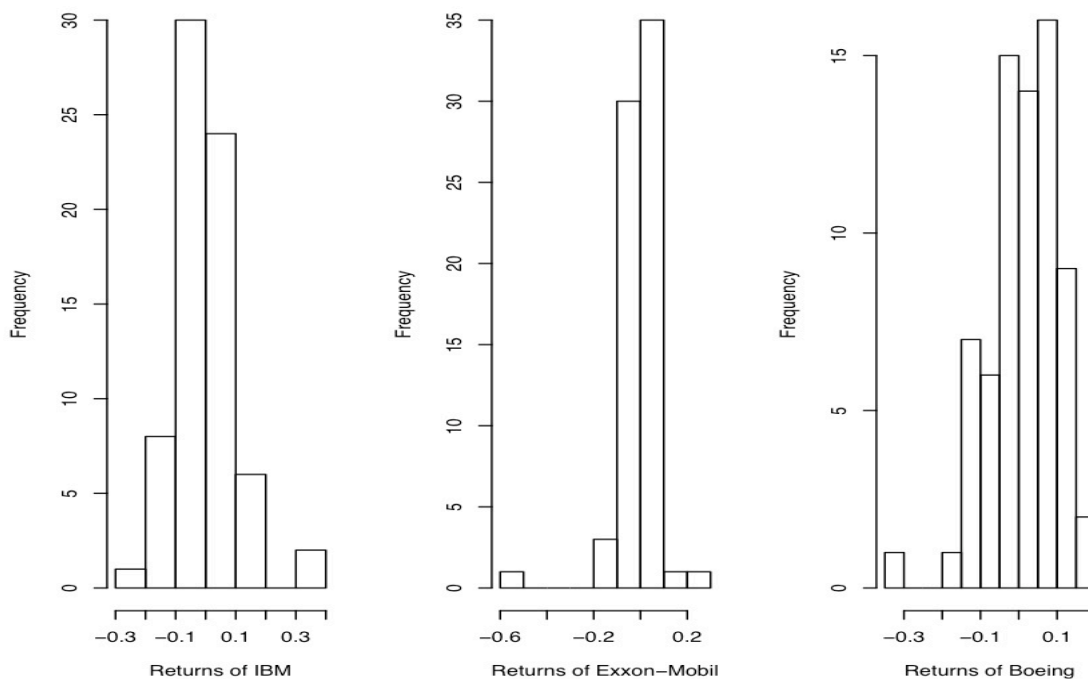


Figure 4: Returns of IBM, Exxon-Mobil, Boeing, January 2000 - December 2005.

or her funds in the above combination of the two stocks because some people can tolerate more risk than the minimum risk. Any other combination of the two stocks, (under the constraint $x_A + x_B = 1$), will give risk higher than the minimum risk that we have found (and of course higher return). We can try many other combinations of x_A and x_B and compute the risk and expected return for each resulting portfolio. Some of these calculations are shown in Table 3. Now, let us plot the expected return against the risk (standard deviation) for each combination (portfolio). This graph is called the portfolio possibilities curve (Figure 5). We

	IBM	EXXON-MOBIL	BOEING
IBM	0.009930		
EXXON-MOBIL	0.001799	0.006744	
BOEING	0.000030	0.001781	0.008282

Table 2: Variance-covariance matrix of IBM, EXXON-MOBIL, BOEING.

a	b	$E(R_p)$	σ_p
1.0	0.0	0.000307	0.099649
0.9	0.1	0.001355	0.090175
0.8	0.2	0.002404	0.081830
0.7	0.3	0.003452	0.074991
0.6	0.4	0.004501	0.070102
0.5	0.5	0.005549	0.067587
0.4	0.6	0.006597	0.067711
0.3	0.7	0.007646	0.070459
0.2	0.8	0.008694	0.075547
0.1	0.9	0.009743	0.082542
0.0	1.0	0.010791	0.091005

Table 3: Expected return and standard deviation on the portfolio for values x_A, x_B .

note here that the efficient portfolios are located on the top part of the graph between the minimum risk portfolio point and the maximum return portfolio point, which is called the efficient frontier. Based on the investor's risk tolerance, his or her portfolio will be located on this efficient frontier (Elton et al, 2003).

5 Portfolio management with three stocks

When more than two stocks are involved in order to find the minimum risk portfolio we need to minimize:

$$\min var(x_A R_A + x_B R_B + x_C R_C) \tag{7}$$

or

$$\begin{aligned} \min & x_A^2 var(R_A) + x_B^2 var(R_B) + x_C^2 var(R_C) + \\ & 2x_A x_B cov(R_A, R_B) + 2x_A x_C cov(R_A, R_C) + 2x_B x_C cov(R_B, R_C) \end{aligned}$$

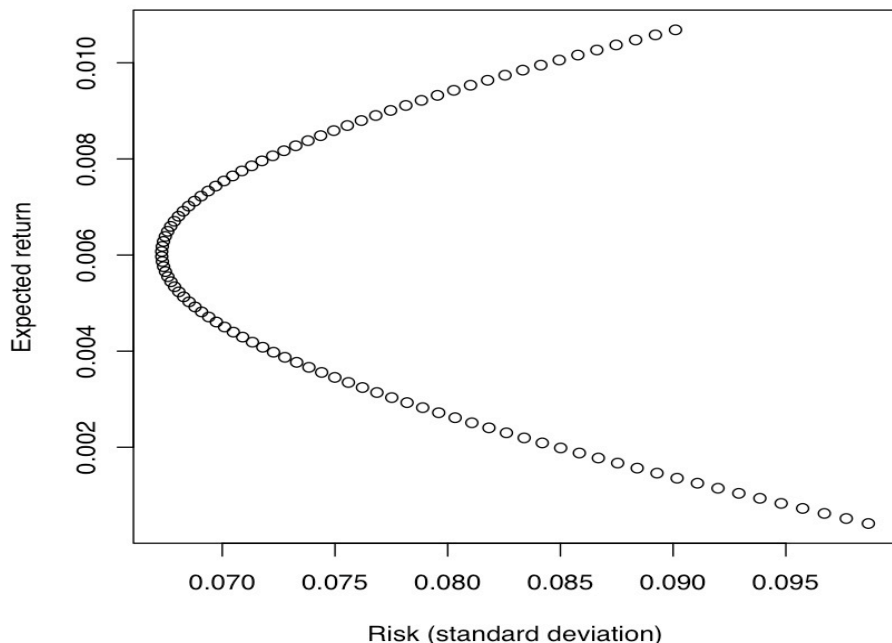


Figure 5: Portfolio possibilities curve for two stocks.

which is subject to the constraint $x_A + x_B + x_C = 1$, where x_A, x_B, x_C are the proportions of the available funds invested in the three stocks A, B, C respectively. The problem becomes more complicate as the number of stocks increases. This can be solved through quadratic programming (Bazarrá, Shetty, 1979), but also much easier using some smart techniques that have been developed (Elton et al, 1977), which will not be discussed in this paper. Here we will only present the graph of the expected return against risk of the portfolio for various values of x_A, x_B, x_C (Figure 6). The three stocks used are IBM, EXXON-MOBIL, and BOEING. Each point on the graph represents a different portfolio. Again, we see that the efficient frontier is the part of the graph that connects the minimum risk portfolio to the maximum return portfolio (concave shape). The solution to the problem is to trace out this efficient frontier because that is where the investor finds his or her efficient portfolios. There are ways to trace out the efficient frontier using the so called excess return to beta ratio, or the excess return to standard deviation ratio (Elton et al, 1977, 2003). We will not discuss these methods here since they are beyond the scope of this paper.

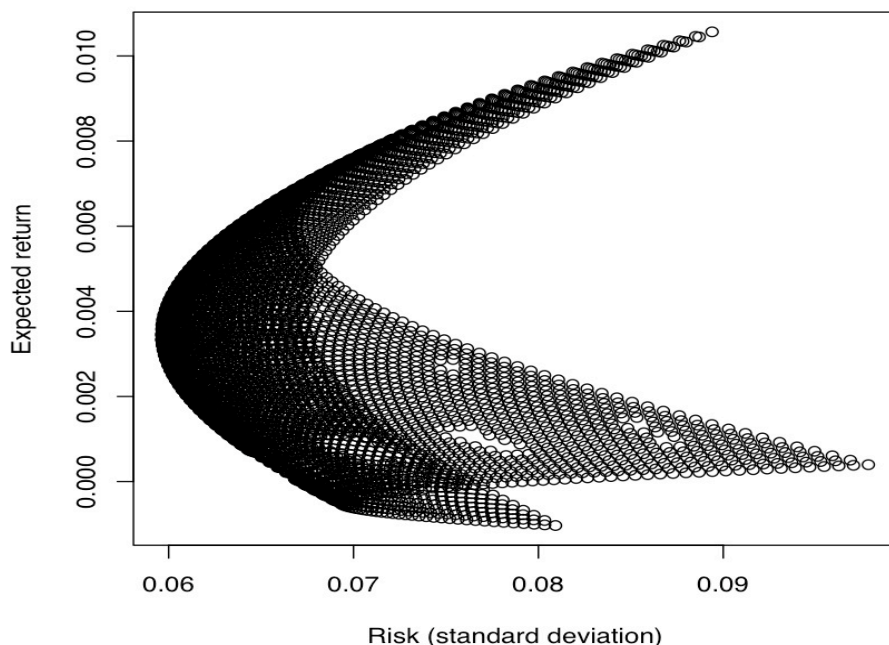


Figure 6: Portfolio possibilities curve for three stocks.

6 Why does diversification work?

We will explain here very briefly (Elton et al, 2003) why investing in more than one securities reduces the risk. Suppose in the portfolio there are n securities. Then, the variance of the return on the portfolio (risk) is:

$$\sigma_p^2 = \sum_{i=1}^n x_i^2 \sigma_i^2 + \sum_{i=1}^n \sum_{j \neq i}^n x_i x_j \sigma_{ij}$$

Let us consider equal allocation into the n securities. This means that $\frac{1}{n}$ of our wealth will be invested in each security. So, $x_i = \frac{1}{n}$ and the above expression becomes:

$$\sigma_p^2 = \sum_{i=1}^n \left(\frac{1}{n}\right)^2 \sigma_i^2 + \sum_{i=1}^n \sum_{j \neq i}^n \left(\frac{1}{n}\right) \left(\frac{1}{n}\right) \sigma_{ij}$$

We can factor out from the first summation $\frac{1}{n}$ and from the second summation $\frac{n-1}{n}$ and since there are all together $n(n-1)$ covariances we have:

$$\sigma_p^2 = \frac{1}{n} \bar{\sigma}_i^2 + \frac{n-1}{n} \bar{\sigma}_{ij}$$

where $\bar{\sigma}_i^2 = \frac{1}{n} \sum_{i=1}^n \frac{\sigma_i^2}{n}$, and $\bar{\sigma}_{ij} = \sum_{i=1}^n \sum_{j \neq i}^n \frac{\sigma_{ij}}{n(n-1)}$. We see that when n is large the risk of the portfolio is approximately equal the average covariance. The individual risk of securities can be diversified away. Even though equal allocation is not the optimum solution it can explain the reduction of risk by holding many securities.

7 Conclusion

We have presented a brief theory on portfolio risk management and why it works. The two examples (with two and three stocks) using real market data can be used in class to enhance the teaching of covariance, correlation, and optimization. There are of course many other issues in portfolio theory that the interested reader may want to explore. For example, one may study some simple techniques for ranking stocks based on the excess return to beta or excess return to standard deviation, constructing portfolios using the single index model, the constant correlation model, the multi-index model, or the multi-group model (Elton et al, 1977). When I first started teaching this topic in my probability and statistics classes (I spent 1-2 lectures), I noticed that students showed a lot of interest in this area. The material was well received by the students who engaged in discussion of the subject. As a result of this, I proposed and taught once a year a new course “Statistical Models in Finance” that attracts many students from Mathematics, Engineering, Statistics, Biostatistics, as well as graduate students from Statistics, Economics, Computer Science, and Engineering. In finishing this paper we would like to mention the many applications of statistics to finance not only portfolio theory but also to areas such as options and futures (binomial theorem and the famous Black-Scholes model, (Hull, 2004)). Some of these topics are advanced and require strong mathematical background but it is worthwhile exploring the teaching possibilities that these topics have to offer.

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