4.2. DYNAMIC OPTIMIZATION OF THE INVESTMENT PORTFOLIO MANAGEMENT TRAJECTORY

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Abstract. The task of control from the position of mathematical tools application is discussed, economic statement and mathematical model of optimization problem are formulated, the sequential realization of the research aim – the mechanism of optimal portfolio management strategy formation – is presented. The results of dynamic optimization of decisions made at each step form the optimum law of the portfolio management. Scientific novelty of the study consists in the fact that the constructed portfolio takes into account the real incompleteness of the initial data on the processes of change in the yields of securities; there is no need to build a set of effective portfolios and indifference curves that characterize the risk appetite of investors; private characteristics are not used as the main criteria that determine the structure of the optimal portfolio of securities.

Keywords: portfolio investment, securities management, dynamic system, decision making, differential equations, optimization.

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Динамическая оптимизация траектории управления инвестиционным портфелем

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Аннотация. В статье проводится обсуждение задачи управления портфельными инвестициями с точки зрения математического инструментария. Сформулированы экономическая постановка и математическая модель задачи оптимизации, представлена последовательная реализация цели исследования – механизма формирования оптимальной стратегии управления портфелем ценных бумаг. Результатами динамической оптимизации, которая применяется на каждом из шагов решения, образуют оптимальный механизм управления портфелем. Научная новизна исследования состоит в учете реальной неполноты исходных данных о процессах изменения доходностей ценных бумаг; отсутствует необходимость построения множества эффективных портфелей и кривых безразличия, характеризующих склонность инвестора к риску; в качестве основного критерия, определяющего структуру оптимального портфеля ценных бумаг не используются частные характеристики.

Ключевые слова: портфельные инвестиции, управление ценными бумагами, динамическая система, принятие решений, дифференциальные уравнения, оптимизация.

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INTRODUCTION

The financial sector is the element linking all sectors of the economy into a single mechanism. The securities market as a mechanism for transforming savings into investment is today the sphere in which the main financial sources of economic growth are formed, investment resources needed in the economy are concentrated and distributed. The study of portfolio investment management processes in financial assets is important, first of all, from the point of view of solving the general problem of investment: a well-functioning mechanism of portfolio investment largely determines the functioning of the entire economic system, which determines the relevance of the topic of this paper. In the framework of the Russian economy, the formation of effective risk management models for investment portfolios is of particular importance, since the level of investment risks, unfortunately, still remains quite high. The returns that can be obtained in the relevant sector of the market can be many times higher than those on bank deposits, but risks can be substantially reduced with a balanced, calculated approach.

The profit-making laws are well known to everyone. However, their knowledge is not a sufficient and universal condition for solving the problem of securities income because real market processes are stochastic in nature. This problem is essentially a mathematical one and requires methods adequate to its economic nature. Therefore, the study of the problem of portfolio investment management optimization should be considered as one of the areas of application of applied mathematics in the economic environment.

In the scientific literature the problem of portfolio investment management strategy choice is considered within the framework of modern portfolio theory. On the issues related to this problem in the modern economic literature accumulated a vast methodological potential, in Russia and abroad published a lot of scientific papers, but the effectiveness of its use is largely determined by the adequacy of the methods and models used when making a particular investment decision. The works of Russian scientists V. Zhizhilev, Y.F. Kasimov, E.M. Chetyrkin, A.S. Shvedov, V.V. Kapitonenko, A.S. Shapkin, A.F. Ereshko, A.O. Nedosekin, L. Slutskin and others. G. Markowitz, W. Sharp, G. Alexander, L.J. Gitman, C. Redhead, R. Vince and others have devoted their works to portfolio analysis and portfolio management. It should be noted, however, the insufficient degree of coverage of the issues related to the interaction of information and analytical sides of the portfolio investment management process, as well as with the peculiarities of investment decisions in conditions of insufficient fulfillment of requirements for the qualitative characteristics of information.

The object of the study is an investment securities portfolio. The subject is the process of investment portfolio structure management under uncertainty, as well as methods and models of its optimization.

The securities market is a dynamic system. It is possible to construct a model of market functioning in the form of a stochastic differential system. Differential equations are essentially mathematical models of dynamic systems; their solutions describe the random processes of changing the coordinates of a moving object on a trajectory. A mathematical model of such systems can be the so-called shaping filters. Shaping filters are difference equations that have a random process like white noise on the right-hand side (input) and a statistically colored random process on the left-hand side (output), which is their solution.

If in the planning period the portfolio optimization problem is solved *N* times and *N* decisions are made, then a discrete dynamic portfolio management strategy is implemented (by increasing the number of controls, in the limit $N \to \infty$ one can obtain a continuous management process in the form of some trajectory of control actions). Let us consider the discrete strategy as a more realistic one.

The portfolio restructuring procedure usually involves additional transaction costs. When dealing in securities, an investor pays a commission to the stock exchange. The commission is charged on each act – both sale and purchase – which must be taken into account when determining the sale and purchase price. When deciding whether to rotate (reposition) financial instruments, costs must be taken into account (measure the projected increment in the value of financial instruments and the unavoidable costs associated with their rotation).

In order to achieve the best results at some point in time, all decisions made at any point in time must be optimal with respect to future developments, i.e., to perform the task at each step, the future values of returns on marketable financial instruments should be best predicted and final decisions taken at any point in time based on the results of dynamic optimization with respect to future developments in market events.

A control problem in which no information about the current state of the system at the time of the decision is used in decision-making, i.e. the optimal control can be determined in advance, is called an open-loop optimal control problem. Meanwhile, under market conditions, information is updated and supplemented constantly and, fortunately, in relation to portfolio management, it is objectively possible to form more efficient strategies, i.e., involving consideration of current information. Its use makes it possible to achieve a higher quality of management. Therefore, this paper focuses on the problem of optimizing the control of a dynamic system using feedback.

1. THE OPTIMIZATION PROBLEM OF A PORTFOLIO MANAGEMENT STRATEGY

Let us consider portfolio management on the time interval $[0, N-1]$, where the index $i \in [0, N-1]$ corresponds to the trading session number. Let's assume that Q types of securities circulate in the market in the $[0, N-1]$ time interval. For each security of *j-th* kind at step i we will compare its price with $X(i, j)$. The change of prices from session to session is described by a discrete-time Markov process. The values $X(i, j)$ take discrete values. The price vector at step *i* will be denoted as $X(i)$. At any moment of time all *Q* types of securities are available to a market participant $i \in [0, N-1]$. If some security *j* first appeared in trading at session *i*, its price for all previous sessions $i' < i$ is defined as $X(i', j) = 0$. If *i* – is the last of the trading sessions preceding the redemption of *j* security, then for all $i' > i$ $X(i', j) = 0$. Securities of type *j* can be sold or bought at step *i* at price $X(i, j)$. The current state of the portfolio under management is modelled by the vector $(U_{i,1}, U_{i,2}, \ldots, U_{i,Q})$, where $U_{i,j}$ – is the number of securities of *j-th* type in the portfolio at time *i*. Let us denote by the value $S(i, j)$ value of *j-th* type of securities in the portfolio at step *i*:

$$S(i, j) = X(i, j) \cdot U_{i,j} \,. \quad (1)$$

For arbitrary session *i* let's denote by $u'_{i,j}$ the number (for the price $X(i, j)$) of securities of *j-th type* in the portfolio before buying and selling operations, by $u''_{i,j}$ – the number of securities of the same type after this operations, assuming $u'_{i,j} \geq 0$, $u''_{i,j} \geq 0$ and, obviously, $u''_{i,j} = u'_{i+1,j}$. The control at step *i* is defined by selection

$$\frac{u''_{i,j}}{\sum_{k=1}^{Q} u''_{k,j}} \,.$$

The set of such control functions U_i let's call a control strategy, and the set of such strategies let's denote by Ψ.

Using S_i' and S_i'' let's denote the value of the portfolio before and after control in epe session *i* respectively. Then $S_i' = \sum_{j=1}^{Q} S_{i,j}'$, $S_i'' = \sum_{j=1}^{Q} S_{i,j}''$. The profit (i.e., portfolio return) based on the results of the session

$$w_i = \sum_{j=1}^{Q} S_{i,j}'' - \sum_{j=1}^{Q} S_{i,j}' . \quad (2)$$

Cumulative gain $W = \sum_{i=1}^{N} w_i$ at any control will remain a random variable, so we should choose such a vector of controls, at which the average value of the random gain *W* will be maximal $\overline{W} = M[W] = \sum_{i=1}^{N} \overline{w}_i$, where $\overline{w}_i$ - is an average gain at *the i-th* step. The aim of control – is to choose such an optimal control U^*, consisting of optimal controls U_1^*, U_2^*, ..., U_N^* of each step, so that the addictive criterion of the return on investment $\overline{W}$ over a period of time $[0, N-1]$ turns to the maximum.

In other words, *it is necessary* to find such a dynamic sequence of decisions to invest in financial instruments that would provide the investor with the maximum return during the period from the beginning of the planning period to the end of the period. The strategy must give an unambiguous answer to what proportions should be invested in which financial instruments at which points in time. It is an algorithm for making optimal investment decisions.

Feedback is information fed into the controlled system through measurement channels that objectively contain «noise», or measurement errors. The measurement channel is the current information about security price quotes.

In this paper we consider a linear market model in the form of systems of difference equations. We will use instrument returns as coordinates of the market state vector. The scheme for solving the optimal control problem is as follows:

1. Definition of a mathematical model of the system in relation to which management is performed – i.e., the investor's market portfolio model (in the form of a stochastic differential system model).
2. Using optimal algorithms for forecasting random processes (i.e., the future state of the market, and hence the desired investment portfolio) in order to process feedback information in an optimal (according to some criterion) way to obtain optimal (according to some criterion) estimates of the current – at the time of decision-making – state of the system.
3. Dynamic optimization of decisions regarding future developments in the market through the use of dynamic programming algorithms (development of control actions on the system based on information about its current state).

General statement of the problem of optimal control of a dynamical system using feedback: the optimal control path of a dynamical system must be found based on the condition of reaching an extremum of the target function (in the form of the so-called Boltz problem)

$$J = \int_{t_0}^{t_1} I(X,U,t)dt + F(X_1,t_1) \to \underset{U(t,X(t))}{extremum}, \quad (3)$$

the system dynamics description conditions in the form of a vector matrix differential equation of the form

$$\dot{X} = f\left[X, U\left(\hat{X}(t)\right), t\right], \quad (4)$$

initial conditions

$$t_0, X(t_0) = X_0 \quad (5)$$

and control cconstraints of the kind

$$\left\{U\left[t, \hat{X}(t)\right]\right\} \in U . \quad (6)$$

2. BUILDING A MATHEMATICAL MODEL OF THE PROBLEM

The algorithm for constructing a mathematical model of the random processes to which the dynamics of the investment portfolio states are related is as follows:

- Statistical market research that involves obtaining estimates of the mathematical expectations of random processes, autocovariance and mutual-covariance functions (mixed moments) of individual financial instruments.
- Determination of the parameters of the difference equations of the shaping filters generating random processes and their construction. It is sufficient to limit the difference equations of the shaping filters to no higher than 2nd order.

Autonomous stochastic differential systems are systems where the coefficients of the difference equations are not time-dependent but are constant. We will consider the model in discrete time in the form of an autonomous stochastic differential system. The vector-matrix differential equation will be

$$\dot{X} = AX + B \cdot m_X(t) + V(t)$$

$$X = X(t_0) \text{ при } t = t_0 . \quad (7)$$

The vector quantity *X is* of dimensionality $(N \times 1)$ and describes the state of the dynamical system. The matrix A of the coefficients of the difference equation (7) is of dimension $(N \times N)$; it will be shown below how its form is determined. The structure and values of the elements of the matrix B are chosen so as to satisfy the condition of the function reproduction astatism $m_X(t)$. $m_X(t)$ – a vector function of the mathematical expectation of a vector random process $X(t)$. $V(t)$ – a vector normal white noise random process with mathematical expectation equal to zero. The vector differential equation is equivalent to a system of scalar differential equations.

The values of the market state vector for two consecutive moments of time are related by the formula for the general solution of this equation. If F is the transition matrix for matrix A, then for two consecutive time moments we obtain:

$$X(t_{i+1}) = \Phi(t_{i+1}, t_i) X(t_i) + \int_{t_i}^{t_{i+1}} \Phi(t_{i+1}, \tau)[B(\tau)U(\tau) + V(\tau)]d\tau \quad (8)$$

The control action will be assumed to be piecewise constant: $U(t) = U(t_i), t_i \le t \le t_{i+1}$. For simplicity let's denote $X(t_i) = X(i)$, $\Phi(t_{i+1}, t_i) = \Phi(i+1, i)$. Since the control is piecewise constant, we can take the $U(t_i) = U(i)$ out from the integral and assume $B(i) = \int_{t_i}^{t_{i+1}} \Phi(t_{i+1}, \tau) B(\tau) d\tau$. In addition, assume that $V(i) = \int_{t_i}^{t_{i+1}} \Phi(t_{i+1}, \tau) V(\tau) d\tau$, to obtain a discrete version of the white noise random process.

As a result, given that $\Phi(i+1, i) = A(i)$, we get:

$$X(t_{i+1}) = X(i) = \Phi(t_{i+1}, t_i) X(t_i) + \int_{t_i}^{t_{i+1}} \Phi(t_{i+1}, \tau)[B(\tau)U(\tau) + V(\tau)]d\tau =$$

$$= A(t_i) X(t_i) + \int_{t_i}^{t_{i+1}} (\Phi(t_{i+1}, \tau) B(\tau) U(\tau) + \Phi(t_{i+1}, t_i) V(\tau)) d\tau = A(i) X(i) + B(i) U(i) + V(i) . \quad (9)$$

This is *a difference shaping filter equation* describing the market process in discrete time.

Let us construct a mathematical model of the securities market, assuming that the process of its functioning is fully determined by the securities circulating in the market, the quotations of all instruments are performed regularly, and the changes in the quotations of the instruments when considered as a function of time are the realizations of random processes. Each of the financial instruments is characterized by its own random process, so the resulting process characterizing the market as a whole will be a vector process.

The target function is

$$J = M \sum_{i=0}^{N-1} W(X_{i+1}, U_i)' \quad (10)$$

where M – mathematical expectation operator; $W(X_{i+1}, U_i)$ – real function, which type depends on the economic sense of the problem to be solved; control vector U_i – value of proportional shares of financial instruments included in the portfolio taking into account the constraints in the formulation of the problem. . The sequence of decisions about the values of proportional shares U_j j forms the investment strategy on the time interval $j = 0,1,..., N-1$.

3. ASSESSING AND FORECASTING MARKET CONDITIONS

The problem of selecting an optimal control strategy can be solved iteratively in two independent steps: optimal estimation and forecasting of the vector of system states, and then dynamic optimization using optimal estimates of the vector of current and future market states.

The algorithm, called *the Kalman filter*, is recognized as optimal in terms of the minimum mean square error of the system state estimation. The structure and parameters of this algorithm are pretuned to the statistical profile of the system to be evaluated. The Kalman filter equations for the unbiased estimation of the current market state are written as follows:

$$X'(i+1) = A(i)\hat{X}(i) + B(i)m(i),$$
$$X'(i_0) = \xi, \quad (11)$$
$$\hat{X}(i) = X'(i) + K(i)\left[Y(i) - X'(i)\right],$$

where $m(i)$ – estimate of the expectation vector of the random process of market returns; $K(i)$ – covariance matrix of estimation errors (filter amplification matrix), determined from recurrent equations

$$P'(i+1) = A(i)\tilde{P}(i)A^T(i) + Q(i)$$
$$K(i) = P'(i)[P'(i) + R(i)]^{-1} \quad (12)$$
$$\tilde{P}(i) = P'(i) - K(i)P'(i)$$

with initial conditions $P'(i) = P(i_0)$; $P(i_0)$ – covariance matrix of the initial vector $X(i_0)$, containing a priori information about the market.

The linear multistep extrapolator, the predictor, which is optimal by the criterion of minimum mean square error of prediction, is determined by solving the differential equation (11). The optimal estimate of the future value of the market state vector is defined as follows:

$$\hat{X}(t) = \phi(t, i+1)\hat{X}(i+1) + \sum_{\tau=i+1}^{t-1} \phi(t,\tau)m(\tau)' \quad (13)$$

where ϕ – is the fundamental matrix of solutions of the homogeneous deffirence equation, corresponding to equation (11); $\hat{X}(i+1)$ – is the optimal estimate of the current market state vector obtained using the Kalman filter.

The one-step predictor implemented by the Kalman filter looks like

$$\hat{X}((i+1)/i) = A(i)\hat{X}(i/(i-1)) + B(i)m(i) + K'(i)\left[Y(i) - \hat{X}(i/(i-1))\right], \quad (14)$$

where the filter gain matrix $K'(i)$ is obtained from equation $K(i) = P'(i)[P'(i) + R(i)]^{-1}$. Covariance matrix for the extrapolation error is the solution of the difference equation

$$P'(i+1) = A(i)P'(i)A^T(i) - A(i)P'(i)\left[P'(i) + N(i)\right]^{-1} P'(i)A^T(i) + Q(i),$$
$$P'(i_0) = P(i_0). \quad (15)$$

The missing estimates $m(\tau)$, $\tau = i+1,..., t-1$ in the multi-step extrapolation formula (13) can be determined by successively applying the one-step predictor (14).

Thus, the algorithms for optimal estimation and prediction of the market state vector are fully defined. The result of their application is a sequence of prediction vectors of market states $\hat{X}(i/i), \hat{X}((i+1)/i), \hat{X}((i+2)/i),..., \hat{X}(t/i)$. This sequence of vectors is the initial information for dynamic optimization of investment decisions.

4. DYNAMIC OPTIMISATION ALGORITHM

There are two basic algorithms for making optimal investment decisions. The first is based on the use of a one-step predictor. When applied to the task of managing a portfolio to maximize the incremental value of the portfolio over a given period of time, it consists of the following steps:

1. One-step forecasting of the future value of returns on all traded financial instruments.
2. Making investment decisions. From the market universe of financial instruments, those with the highest projected returns are included in the optimal portfolio in advance.
3. The sequence of these steps is repeated in an iterative pattern for each decision-making step until the portfolio management process is completed.

The second implements optimal stochastic closed-loop control. The depth of prediction should extend from any current point in time to the end of the portfolio management process. However, forecasting in this case loses its practical meaning because the forecasting error will be equal to the variance of the process being evaluated.

Therefore, it is better to use a short-term statistical forecast of the vector of market states at each current moment in time – for 3-5 trading sessions ahead – as a «golden mean» algorithm. On the basis of this forecast, the optimal sequence of decisions is formed, of which only the first one is taken. By the time of opening of the next trading session new statistical information on the market is received, which, theoretically, can devalue the previously made forecast. Therefore, the sequence of optimal investment decisions is formed anew, and only the first decision is taken from it again. The iteration scheme continues until the end of the investment activity.

For any given point in time, the optimal investment strategy is determined based on a standard dynamic optimization algorithm. The optimization is carried out from the last step to the first step in an iterative scheme. The first step corresponds to the current decision point.

Maximization of the incremental value of the portfolio is represented as a sequence of procedures of the form:

$$\max_{U(t-1)}\left\{W\left[\hat{X}(t),U(t-1)\right] \mid \hat{X}(t-1),U(t-2)\right\}$$

$$\max_{U(t-2)}\left\{\max_{U(t-1)} W\left[\hat{X}(t),U(t-1)\right] \mid \hat{X}(t-1),U(t-2) \mid \hat{X}(t-2),U(t-3)\right\} \quad (16)$$

$$\max_{U(1)}\left\{\ldots\max_{U(t-2)}\left\{\max_{U(t-1)} W\left[\hat{X}(t),U(t-1)\right] \mid \hat{X}(t-1),U(t-2) \mid \hat{X}(t-2),U(t-3) \mid \ldots\right\}\right\}$$

On the resulting trajectory, the function $J = M\sum_{i=0}^{N-1} W(\hat{X}_{i+1},U_i)$ reaches the maximum possible value under the specified constraints, therefore, it is commonly called the *extreme of the securities market*. The portfolio management optimization problem is thus solved.

Note that a solution may not exist, or it may not be the only one (in which case, further investigation is needed to find out which of the available solutions can claim to be the solution to the original optimal control problem). But even if the equation has a smooth solution, the control found from this equation is not yet optimal as it may not be admissible. Moreover, in a given class of admissible controls, there is not always one in which the exact lower or upper bound of the criterion is reached. In some cases, it is possible to overcome these difficulties and obtain a solution in analytical or approximate form.

CONCLUSION

This paper builds a mathematical model of the system in relation to which the control is performed, i.e., the investor's market portfolio model (in the form of a stochastic differential system model). We apply optimal algorithms for forecasting random processes (i.e., the future state of the market and, hence, the desired investment portfolio) to optimally process the feedback information to obtain the best estimates of the current – at the time of decision-making – state of the system. Dynamic optimization of decisions regarding future developments in the market is carried out by applying dynamic programming algorithms (development of control actions on the system taking into account information on its current state).

As a result of performance of work the generalized approach to formation of an optimum portfolio of securities has been formed, scientific novelty of research consists that in the constructed portfolio the real incompleteness of initial data on processes of change of returns of securities is considered; there is no necessity of construction of set of effective portfolios and indifference curves characterizing propensity of investor to risk; as the basic criterion defining structure of an optimum portfolio of securities private characteristics are not used risk (yield variance) and expected return (mathematical expectation of return) are not used as the main criterion defining the structure of optimal securities portfolio; the proposed algorithm can be implemented «manually», but the development of appropriate software can significantly simplify the solution of optimization problem.

The following should be noted. Determination of the effective direction of managerial influence on the investment process within the framework of portfolio investment should, one way or another, be based on recognition of the following fact: when working in emerging markets, which undoubtedly include the Russian stock market, it is not always appropriate to rely on generally accepted provisions of portfolio theory, such as evaluation of investment options only on the basis of expected return and risk, understanding of the management process as a sequence of independent static activities, not taking into account transaction costs.

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