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CHALLENGES IN THE EFFICIENCY ANALYSIS OF HIGH-TECH LONG-TERM INVESTMENT PROJECTS UNDER MODERN STOCHASTIC ECONOMIC CONDITIONS

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Abstract. *The accurate evaluation of investment projects in modern business environments remains a significant challenge. This is driven, on the one hand, by the increasing stochasticity of the economic environment and, on the other hand, by the growing complexity of business projects, which requires more accurate estimation, particularly for long-term operations. Consequently, key parameters of business analysis, such as the discount rate, market supply and demand, and sales volume, require more advanced modeling approaches. Therefore, there is a need for a new paradigm for investment evaluation. The proposed paradigm is based on representing key parameters as continuous functions with stochastic components, while the investment analysis process itself is formulated in terms of ordinary differential equations. The application of this approach enables a more comprehensive assessment of the robustness of investment projects through Monte Carlo simulations with respect to the stochastic properties of the economic environment.*

Keywords: *high-tech long-term investments, business project, discount rate, ordinary differential equations, Furrier series, net present value, profit index, Monte-Carlo tests*

Traditional approaches to investment project evaluation are still largely based on discounted cash flow, net present value, and related deterministic capital-budgeting indicators. However, recent studies increasingly emphasize that such methods are often insufficient under modern uncertainty [1-3], since they treat key inputs as fixed or scenario-based quantities and therefore do not fully reflect the dynamic character of real economic environments [3]. One approach to improving the accuracy of accounting for stochastic factors in mathematical models of financial and economic forecasting is the use of ordinary differential equations (ODEs) with input parameters represented by Fourier series [1, 2] and stochastic processes [4], as well as the application of uncertain differential equations (UDEs) [3]. For example, in

[1], a model was proposed for evaluating key economic indicators, including net present value and the profit index, which are used to assess the efficiency of investment projects. The model is formulated in terms of ordinary differential equations incorporating a time-varying discount rate with periodic components representing political risks, modeled via Fourier series. In turn, the supply and demand coefficients derived from marketing studies, which are used as input parameters in the differential equations [1], are estimated using various regression models based on the least squares method. The developed methodology has demonstrated good performance in forecasting an investment project related to the sale of gasoline electrical generators. However, since supply and demand are represented by regression models, a key limitation is the requirement for sufficiently large datasets on the sales of similar products over a given time period. The availability of sufficiently large statistical datasets from marketing studies is difficult to ensure for new types of products that have recently entered the market, which may impose certain limitations on the methodology [1].

In subsequent studies, ODE-based mathematical models were extended by introducing two types of systems [2]: (1) for forecasting projects with long preparation and development phases and a short implementation phase, and (2) for forecasting projects characterized by time-periodic cash flows [4]. In addition, in [4], a stochastic component modeled as white noise was introduced into the discount rate. Given the incorporation of stochastic parameters into the governing equations, the next step is to employ Monte Carlo methods for repeated statistical simulations.

Considering current trends, probabilistic techniques, particularly Monte Carlo simulation, are widely used in investment appraisal. For example, Pawlak [5] proposed a real-options valuation method based on double Monte Carlo simulation for flexible and multi-stage projects, showing that managerial flexibility and multiple sources of risk can be incorporated more effectively than in static appraisal schemes. Similarly, Tveter et al. [6] demonstrated that Monte Carlo procedures can replace point estimates in cost-benefit analysis with ranges and confidence intervals, which may materially change decision outcomes. In applied project domains, Vilani et al. [7] also combined capital-budgeting techniques, Monte Carlo simulation, and real-options analysis into an integrated appraisal framework for agricultural investments.

Given the increasing relevance of Monte Carlo methods, additional stochastic components are introduced into the systems of differential equations (1) and (2) as follows:

$$\begin{aligned}
&\frac{dV}{dt} = V_{cur},\\
&\frac{dCF}{dt} = V_{cur} \cdot P \cdot k_{n.} - V_{cur} \cdot CP + CP \cdot V_{cur} \cdot k_{\alpha},\\
&NPV = CF \cdot e^{-rt} - I_{oi} \cdot e^{\varphi \cdot t},\\
&PI = \frac{CF \cdot e^{-(r+\varphi)t}}{I_{oi}};
\end{aligned} \qquad (1)$$

$$\begin{aligned}
&\frac{dV}{dt} = V_{cur},\\
&\frac{dCF}{dt} = V_{cur} \cdot P \cdot k_{n.} - V_{cur} \cdot CP + CP \cdot V_{cur} \cdot k_{\alpha},\\
&\frac{dPVI}{dt} = \left(V_{cur} \cdot P \cdot k_{n.} - V_{cur} \cdot CP + CP \cdot V_{cur} \cdot k_{\alpha}\right) \cdot e^{-rt},\\
&NPV = PVI - I_{oi} \cdot e^{\varphi \cdot t},\\
&PI = PVI / I_{oi} \cdot e^{\varphi \cdot t},
\end{aligned} \qquad (2)$$

where V is the production volume (the quantity of manufactured products) or the volume of services/goods (for non-production sectors and retail trade); V_{cur} is the production rate, units per determined time (day, hour, etc.); CP is the production cost (of goods or services); CF is the cash flow; I_{oi} is the initial investment provided by the investor (or the investment at the beginning of the forecasting period); $k_{n.}$ is the expected sales coefficient for the enterprise over the forecast period, determined using expert evaluation methods; k_{α} is the depreciation coefficient, determined using expert evaluation methods depending on the characteristics of the equipment, the type of enterprise, and the depreciation calculation method; r is the discount rate incorporating both deterministic and stochastic components; φ is the investor's interest rate; t is the forecasting time, with the integration step.

Considering that stochastic components are incorporated into the discount rate, it can be written as follows:

$$r_k = f_{pol}^{USA}(t) + f_{pol}^{UA}(t) + R_{inf} + R_{bi} + \sigma_r \xi_k, \qquad (3)$$

where r_k is the current discount rate value in the *k*-th Monte-Carlo run; $f_{pol}^{USA}(t)$ and $f_{pol}^{UA}(t)$ are continuous functions of political risks due to president elections in USA and Ukraine that are modeled by Fourier series [1]; $R_{\inf} \sim U(a_{\inf}, b_{\inf})$ denotes the uniform distribution with minimum value of inflation risk a_{inf} and maximum value of inflation risk b_{inf}; $R_{bi} \sim U(a_{bi}, b_{bi})$ denotes the uniform distribution with minimum value of industry risk coefficient a_{bi} and maximum value of industry risk coefficient b_{bi}; σ_r is the standard deviation characterizing the intensity of stochastic fluctuations of the discount rate; $\xi_k \sim N(0,1)$ represents standard Gaussian white noise.

The variables R_{inf} and R_{bi} are drawn once per Monte Carlo realization and kept fixed over time, while $\xi_k \sim N(0,1)$ is independently sampled at each integration step t_k of the numerical ODE solver for eqs. (1)–(2), thus forming a discrete-time approximation of white noise.

Conclusions

Thus, the ordinary differential equation-based mathematical model has been adapted for Monte Carlo simulations, enabling the incorporation of stochastic components into the investment analysis framework. The proposed approach allows key economic parameters, including the discount rate, inflation, and industry-specific risks, to be represented as random variables and processes. It should be noted that the introduction of stochastic components does not inherently improve the predictive accuracy of the model; rather, it provides a more realistic representation of uncertainty. The primary advantage of the proposed methodology lies in enabling a more rigorous assessment of the robustness and sensitivity of investment projects under uncertain market conditions. The separation of parametric and dynamic uncertainties ensures a consistent and structured modeling framework. Therefore, the developed approach can be effectively used for robust decision-making support in investment project evaluation, particularly in the presence of significant uncertainty.

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ПРОБЛЕМИ АНАЛІЗУ ЕФЕКТИВНОСТІ ВИСОКОТЕХНОЛОГІЧНИХ ДОВГОСТРОКОВИХ ІНВЕСТИЦІЙНИХ ПРОЕКТІВ У СУЧАСНИХ УМОВАХ СТОХАСТИЧНОГО ЕКОНОМІЧНОГО СЕРЕДОВИЩА

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Анотація. *Точна оцінка інвестиційних проєктів у сучасному бізнес-середовищі залишається суттєвою проблемою. Це зумовлено, з одного боку, зростанням стохастичності економічного середовища, а з іншого – підвищенням складності бізнес-проєктів, що потребує більш точного оцінювання, особливо для довгострокових процесів. У зв'язку з цим ключові параметри бізнес-аналізу, такі як ставка дисконтування, ринкові попит і пропозиція, а також обсяги продажів, потребують застосування більш досконалих підходів до моделювання. Тому виникає необхідність у формуванні нової парадигми оцінювання інвестицій. Запропонована парадигма ґрунтується на поданні ключових параметрів у вигляді неперервних функцій зі стохастичними складовими, тоді як сам процес* *інвестиційного аналізу формалізується за допомогою звичайних диференціальних рівнянь. Застосування такого підходу дає змогу здійснювати більш повну оцінку робастності інвестиційних проєктів за допомогою методів Монте-Карло з урахуванням стохастичних властивостей економічного середовища.*

Ключові слова: *високотехнологічні довгострокові інвестиції, бізнес-проєкт, ставка дисконтування, звичайні диференціальні рівняння, ряди Фур'є, чиста приведена вартість, індекс прибутковості, методи Монте-Карло.*