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MODELLING THE IMPACT OF RISK FACTORS ON DIGITAL PORTFOLIO RETURNS: A BAYESIAN APPROACH

МОДЕЛЮВАННЯ ВПЛИВУ РИЗИК-ФАКТОРІВ НА ДОХІД ЦИФРОВОГО ПОРТФЕЛЯ: БАЙЄСІВСЬКИЙ ПІДХІД

The article addresses the problem of modeling the impact of risk factors on the income generated by a portfolio of digital intellectual assets under uncertainty and limited information. The relevance of the research lies in the growing role of digital assets in the structure of the modern economy, the specific nature of their circulation, the lack of historical data, high volatility, and the significant individualization of management strategies. In order to overcome the limitations of traditional risk assessment approaches (such as VaR/EaR methodologies), the author proposes a logic-probabilistic model based on Bayesian Belief Networks (BBNs). This model describes causal relationships between key risk factors (demand, creative productivity, sales frequency) and portfolio income, taking into account both internal and external influences. Particular attention is paid to behavioral aspects of decision-making, including the influence of heuristics, cognitive biases, and bounded rationality of the author/investor. The model incorporates hyperbolic discounting, loss aversion, endowment effect, and diminishing sensitivity – factors that significantly affect the subject's motivation to replenish the portfolio. The proposed model enables both forward and backward probabilistic inference, which allows not only to forecast income based on the given values of risk factors, but also to diagnose the potential causes of actual revenue deviations. The paper highlights the advantages of BBNs in risk modeling under informational asymmetry and incomplete data, especially their ability to adapt to new empirical inputs. Using the author's model, the portfolio structure was analyzed by grouping assets according to demand characteristics. It was demonstrated that the so-called «top-performing group» has the most significant impact on risk metrics. It is established that the key determinant of performance is not only market conditions but also the author's strategy of portfolio renewal and management. The proposed approach can be used as a decision support tool in digital asset management and may be adapted to other types of intangible assets in the creative economy.

Keywords: *digital intellectual assets, bayesian belief networks, risk metrics, logic-probabilistic modeling, behavioral factors.*

У статті розглянуто проблему моделювання впливу ризик-факторів на дохід цифрового портфеля інтелектуальних активів в умовах невизначеності та обмеженої інформації. Актуальність дослідження обумовлена зростанням ролі цифрових активів у структурі сучасної економіки, специфікою їх обігу, нестачею історичних даних, високою волатильністю та значною індивідуалізацією стратегій управління. З метою подолання обмежень традиційних підходів до оцінювання ризиків (зокрема, методологій VaR/EaR), автором запропоновано логіко-імовірнісну модель, побудовану на основі байєсівських мереж довіри (БСД). Така модель дозволяє описати причинно-наслідкові зв'язки між ключовими факторами ризику (попит, творча продуктивність, частота продажів) та доходом, що генерується портфелем цифрових інтелектуальних активів, з урахуванням як внутрішніх, так і зовнішніх впливів. Особливу увагу приділено поведінковим аспектам прийняття рішень, які включають вплив евристик, когнітивних викривлень та обмеженої раціональності автора/інвестора. У моделі враховано гіперболічне дисконтування, ефект втрат, ефект володіння, евристику чутливості, що зменшується, які істотно впливають на мотивацію суб'єкта до поповнення портфеля. Запропонована модель реалізує як прямий, так і зворотний імовірнісний висновок, що дозволяє не лише прогнозувати дохід залежно від заданих значень ризик-факторів, а й діагностувати по-

тенційні причини відхилень фактичного доходу. Висвітлено переваги застосування БСД для моделювання ризику в умовах інформаційної асиметрії та неповної інформації, зокрема, здатність моделі до адаптації на основі нових емпіричних даних. На основі авторської моделі проаналізовано структуру портфеля, яка включає групи активів за ознакою попиту, а також показано, що найбільший вплив на ризик-метрики має група так званих «рекордсменів». Визначено, що ключовим фактором результативності є не лише ринкові умови, а й стратегія автора щодо оновлення та управління власним портфелем. Запропонований підхід може бути використаний як інструмент підтримки прийняття управлінських рішень у сфері цифрових активів, а також адаптований до інших видів нематеріальних активів у креативній економіці.

Ключові слова: *цифрові інтелектуальні активи, digital intellectual assets, байєсівські мережі довіри, bayesian belief networks, ризик-метрики, risk metrics, логіко-імовірнісне моделювання, logic-probabilistic modeling, поведінкові фактори, behavioral factors.*

Formulation of the problem. In today's rapidly developing digital economy, the problem of effective management of digital intellectual assets formed in copyright or investment portfolios is becoming particularly relevant. Unlike traditional financial instruments, digital assets have a different nature of circulation, are characterised by a high level of uncertainty, insufficient historical statistical data and significant behavioural variability on the part of economic entities. In these conditions, classical approaches to risk assessment and income forecasting, such as VaR (Value at Risk) or EaR (Earnings at Risk) methodologies, are not effective enough, as they do not take into account the structural asymmetry of the portfolio, non-linearity of cause and effect relationships and behavioural factors. The problem of risk assessment is particularly acute in the case of forming portfolios of digital images or other copyrighted objects, where income is determined not only by price factors but also by the frequency of sales, creative productivity of the author, market reaction to new assets, etc. In such circumstances, it is extremely important to build an adaptive model that allows taking into account a complex set of risk factors, as well as making both direct and reverse probabilistic conclusions about income in the face of incomplete or unclear information.

The presence of subjective assessments, behavioural heuristics, limited rationality and dependence on the author's individual experience necessitate the use of flexible logical and probabilistic tools capable of modelling risk metrics under conditions of multifactorial uncertainty. In this regard, the scientific problem of developing an approach to modelling the impact of risk factors on the income of a digital portfolio using Bayesian trust networks as an effective tool for formalising complex relationships and supporting management decisions in the digital economy arises.

Analysis of recent achievements and publications. Over the past decade, the issue of risk management in the digital economy has become the subject of active scientific discussion due to the proliferation of intangible assets, digitalisation of creative activity and the emergence of new investment instruments. Researchers pay special attention to the development of risk assessment methods under conditions of uncertainty, limited data and asymmetry of information. Among Ukrainian scholars, I. Blank, T. Vasylieva, O. Amosha, and I. Mnykh made a significant contribution to the development of approaches to economic risk assessment, considering risks in the financial management system and focusing on the importance of adaptive methods of analysing risk metrics. In the field of digital economy, the transformation of the nature of assets has been actively studied in recent years, in particular in the works of N. Rebryk, O. Ivanilova, L. Buriak, which address the issues of accounting, valuation and monetisation models of digital assets. Among foreign researchers, the key developments are in the field of Bayesian Networks and logical-probabilistic risk modelling. The work of Judea Pearl has become fundamental to the development of tools for causal analysis using graph models. Researchers such as Koller & Friedman, Neil, Fenton & Nielson have paid considerable attention to the use of BCA in finance, proving the effectiveness of BCA in risk management, in particular in the face of insufficient or incomplete information. A separate area of research is behavioural economics, in particular the works of Daniel Kahneman, Amos Tversky, and Richard Thaler, which describe the impact of heuristics and cognitive distortions on decision-making under risk. It is the combination of these approaches - Bayesian models and behavioural patterns - that has become the basis for building modern decision support systems in the digital environment.

Despite significant theoretical developments, there is a certain gap in modern science regarding the adaptation of Bayesian methods to the analysis of income and risks of digital intellectual assets, in particular, graphic images used in media, marketing, and design. At the same time, the importance and volume of such assets in the modern market is growing, which necessitates the use of appropriate mathematical and instrumental tools that allow not only to analyse returns but also to take into account the complex structure of risks, behavioural characteristics of portfolio holders and market dynamics.

The purpose of the article is to develop and test a logical-probabilistic model based on Bayesian trust networks to assess the impact of the main risk factors on the income of a portfolio of digital intellectual assets under conditions of uncertainty, taking into account both the structural heterogeneity of assets and the behavioural characteristics of management entities.

Presentation of the main material. Bayesian trust networks (BTN) are directed acyclic graphs in which nodes represent uncertain variables of any nature, and directed links between nodes indicate causal relationships between the relevant variables. Each node in such a network is associated with a probability table that models the relationship with the so-called parent nodes, taking into account all the uncertainties present in these relationships. The BTN theory combines elements of Bayesian probability theory and the notion (assumption) of conditional independence in the representation of relationships between variables. Today, the BTN tools are used in various industries to solve a wide range of tasks related to the numerical assessment of risk metrics and the degree of uncertainty that can be caused by various reasons:

– incomplete knowledge of the research object;

– task conditions characterised by the presence of randomness;

– incomplete understanding of the research area;

– various combinations of the above factors.

Models based on the principles of the BTN are of fundamental importance in machine learning, as Bayesian methods allow you to measure the level of uncertainty in the data and change it based on newly received data. The processes modelled by a BTN can be both static and dynamic. The ultimate goal of building a BTN is to obtain a Probabilistic Inference apparatus that is maximally adapted to the uncertainties and risks of a particular task or subject area in general. Probabilistic inference can be carried out in any direction of the network, in particular: from effects to causes, from causes to effects, and mixed inference is also possible.

In the broadest sense, Bayesian networks are one of the most productive concepts for the formation of expert systems, which are software tools that use expert knowledge to ensure the effective solution of informal problems in a narrow subject area. An expert system can help an expert specialist and sometimes partially replace him or her in solving problems under conditions of uncertainty. An integral part of any expert system is a knowledge base (a structured body of knowledge) about a subject area that determines the behavioural model of experts in the field of study using certain logical inference procedures. Knowledge bases are accumulated in the process of building and operating any expert system of this type. The advantages of using a BTN in comparison with other concepts of building expert systems include:

– relative simplicity of subjective probabilistic assessment of causal relationships from the psychological point of view and intuitive representation in the form of a directed graph;

– interpretation of logical conclusion from the computational point of view due to the presence of theoretical axiomatic apparatus;

– methods underlying the mathematical apparatus of the BTN provide efficient calculation of conditional probabilities.

As shown in the previous sections, the studied portfolios of digital intellectual assets have an asymmetric heterogeneous structure of returns and risk by asset group. For this reason, our logical-probabilistic Bayesian model proposes to take into account the causal relationships between the main components of the portfolio, and not only its significant heterogeneity. As portfolio components, we propose to consider groups of assets grouped on the basis of the same (comparable) demand. The author's logical and probabilistic model was built on the assumption of a continuous flow of assets in the direction from the «waiting group» to the «record group», in the process of which there is a continuous change in the risk metrics of the portfolio.

Initial estimates of the risk metrics of the digital intellectual assets portfolio were made using the VaR (EaR) methodology based on empirical data on the distribution of a random variable of total income over the portfolio. However, further research has shown that the VaR (EaR) methodology does not fully take into account the specific features of the economic circulation of digital intellectual assets, as this methodology does not take into account the structural heterogeneity of the portfolio. To solve this problem, we used the tools of Bayesian trust networks. The results of previous studies of portfolio risk metrics using the VaR (EaR) methodology were used in our Bayesian model.

The flexibility of the BTN toolkit is reflected in the ability to integrate input parameters specified in discrete and/or continuous form, to take into account the different nature of some data, and to use dependencies between different types of variables. Risk factors specific to the intellectual property market have a significant impact on the return on the digital image portfolio. The factors that significantly affect the demand for digital images include: consumer attitudes to photo stocks, the relevance of the subject matter of the assets in the copyright portfolio to the current fashion in web design, advertising, and publishing. The main consumers of the studied digital intellectual assets are designers, web developers, media, bloggers and other media industry participants who use digital intellectual assets in their professional activities. When assessing the risk of traditional financial instruments (securities, currencies), the main risk factor is the price volatility of the instrument. In the original model, taking into account the peculiarities of the circulation of digital intellectual assets, the following risk factors were selected as having a greater impact on the financial result of the portfolio:

– market demand for the author's/investor's images. This is an external factor that depends on the current market situation and reflects the number of sales events of the author's assets over a fixed period of time;

– creative productivity of the author. This is an internal factor that reflects the presence of events of new assets entering the portfolio, on which the author's portfolio size depends.

Classical methods of managing the risk of a portfolio of traditional financial instruments include diversification of the set of instruments, various hedging methods, selection of instruments with different correlations of returns, etc. However, such methods are not applicable to portfolios of digital intellectual assets, and risk minimisation is possible only by changing the impact of the main risk factors on the portfolio's asset groups. It should also be noted that traditional financial instruments have significant amounts of historical data for many years. Many studies have been devoted to the study of the parameters of value and profitability of individual financial instruments and portfolios of instruments, which confirm the normal or lognormal nature of the distribution of the random variable of profitability. With respect to intellectual assets, especially digital ones, there are significantly fewer historical data sets, while the events occurring in the course of circulation of such assets have a more complex probabilistic nature. In the proposed logical-probabilistic model, the impact of the main risk factors on the key risk metrics is presented as a set of events characterised by:

– a certain frequency of occurrence;
– the impact on certain elements of the portfolio;
– the presence of the level of influence (strength).

In this case, the level of influence can be taken into account (weakened or strengthened) by training a logical-probabilistic model.

The initial simplified version of the logical-probabilistic model is shown in Fig. 1. In this model, the main risk factors affecting a portfolio are traditionally represented as variables in the nodes of a Bayesian network. Each node of the model is characterised by a certain level of probability distribution of events. To adapt the model to a specific author's portfolio and perform calculations, it is necessary to take into account the set of influences for each specific portfolio, determined by its information environment. The resulting node of the model is the revenue R (Revenue) for a portfolio consisting of digital intellectual assets. An increase in this indicator represents the portfolio's response to changes that can be either external, achieved by reducing the impact of risk factors, or internal, through model training. External changes are caused by a decrease in the impact of risk factors and, according to the model logic, affect income indirectly, through the parent nodes of sales S (Sales), creative productivity of the author PR (Productivity) and demand D (Demand).

Node S represents the probability of sales events of assets in the portfolio, arranged by frequency. The frequency of sales is directly related to the demand for assets, since due to the special mechanism of selling digital intellectual assets, the price for homogeneous groups of assets is fixed and the demand for such assets, unlike conventional financial assets, is reflected not in the market price but in the frequency of sales. Each group of assets is characterised by its own probability distribution

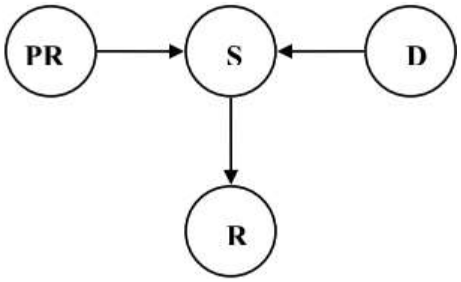

Fig. 1. Simplified network structure (created by the author)

function (these functions may be continuous or discrete), which is affected by certain risk factors, which may have a positive or negative impact. Internal changes are the results of model training, which is caused by the emergence of new data that can be used to refine the modelling forecasts. Training of the author's model is possible because Bayesian methods allow measuring the level of uncertainty in the data and changing it with new data. For example, the performance of the portfolio in the last period.

The sales node S is influenced by risk factors from the parent nodes: market demand D and creative productivity of the author PR. The factor of the author's creative productivity depends on the actions (or inaction) of the author and reflects the intensity of replenishing the portfolio with new assets. The demand factor can be either low or high, and it affects the frequency of asset sales over a certain period. The sales node S, in turn, affects the income node R, which is directly dependent only on the facts of sales. Despite the seeming absence of uncertainty in the creative productivity factor due to the fact that this factor is completely dependent on the author, this factor is subject to uncertainties that depend on the portfolio management strategy. In addition, the process of adding new assets to the portfolio is not stable. As shown above in Section 2, portfolios of digital intellectual assets are inherently inertial.

The key task of the model is to estimate the resulting factor of the model – the value of income in the node R. This task is solved by forecasting (Causal Reasoning) – setting certain probabilities of parent nodes and, after calculations, determining the probability of certain values in the income node. The model built using BDS also allows for the reverse inference (diagnosis or Evidential Reasoning), which is the process of determining the probabilities of parent nodes (creative productivity, demand) given a given probability value in the income node. Since each node of a logic-probabilistic model is a random variable that represents a probability distribution that is in a certain dependence on the parent nodes, the second task of building a model (after building the graph architecture) is to determine the distribution of the joint probability of the nodes (risk factors) of the model. It is the joint distribution that fixes the dependencies between the nodes in the graph of

the logical-probabilistic model, which allows for both direct and reverse inference.

Dependencies between variables are given by algebraic expressions. If D is a random variable characterising the demand for digital intellectual assets, and PD is a discrete distribution of this probability, then P(D) (D = d) or P(D) (d) is the probability that the argument D will acquire a certain (defined) value d in a specific range of its probable values. We will do the same with the random variables PR, S, and R related to creative productivity, sales, and income. The nature of each distribution and the ranges of its values are separate issues that depend on the specific purposes of the analysis, but regardless, based on the architecture of the BDS, we can write that the value representing the probability that the variables PR, D, S, and R will take on values equal to pr, d, s, r, respectively, is factorised by the equation:

$$P(PR = pr, D = d, S = s, R = r) =$$

$$= P_{PR}(pr) \times P_D(d) \times P_S(s|PR = pr, D = d) \times P_R(r|S = s)$$

where each is the conditional probability that variable I will take on the value i if variable J takes on the value j. To solve this equation, it remains to determine the variables in all nodes of the model. The above algebraic expressions allow us to model the processes occurring in the portfolio of the asset class under study and calculate the probability of obtaining a certain return R of the portfolio.

As our observations have shown, groups of record holders have a greater impact on total return and are more dependent on the asset demand factor than on the transitory mechanism of asset replenishment. Due to the greatest impact of record holders on total return, they have the greatest impact on the risk metric of the entire portfolio. The creative productivity of an author is an indicator that directly depends on the decisions made by the author, his or her actions or inaction. Today, the neoclassical concept of economic theory prevails, according to which economic actors always act rationally, maximising their benefits.

In practice, an economic entity (author, investor) is characterised by an individual approach to justifying decision-making, so it does not behave exclusively rationally, as prescribed by the neoclassical concept, and, moreover, it may make erroneous and irrational decisions. Rational human behaviour implies that under conditions of uncertainty, an economic entity will make a choice in favour of the most optimal option. It is customary to use the theory of probability to assess the optimality of a particular variant of human behaviour, i.e. rational behaviour is considered to be that in which a person weighs all possible options and determines the probability of a favourable outcome for him or her under a particular decision. From the point of view of the neoclassical concept, the most rational behaviour of an author/investor is to continuously replenish the portfolio with new images, i.e. the probability of creative productivity should be 100%. But in practice, this is not the case. The behaviour of a decision maker depends on the way they make decisions: some make decisions after a long time of thinking and evaluating all outcomes and their probabilities, while others make decisions quickly based on their experience and intuition.

Conclusions. The study substantiates the feasibility of using Bayesian trust networks (BTN) to model the risks of a digital portfolio of intellectual assets, in particular, digital images. The proposed logical-probabilistic model allows to take into account both the structural heterogeneity of the portfolio and the impact of the main risk factors, such as market demand and creative productivity of the author, on the final income of the portfolio. The results of the study confirm that classical risk assessment methods, such as VaR or EaR, are limitedly effective for analysing digital assets due to the lack of sufficient historical data, high volatility of parameters, and behavioural heterogeneity of subjects. In turn, Bayesian networks provide a flexible toolkit for working with probabilistic dependencies, which allows modelling both forward and backward inference, assessing the degree of influence of individual factors, and adapting the model based on new data. The model pays special attention to the behavioural aspects of managerial decision-making, which are reflected through the heuristics of self-control, preferences, losses and possession. These aspects play a key role in shaping the level of an author's creative productivity, which, in turn, affects the amount and dynamics of income. This approach allows us to formalise the impact of individual behavioural strategies on the final financial results.

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