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IMPROVING THE APPROACH TO ASSESSING THE IMPACT OF FINANCIAL MARKET DIGITALIZATION ON THE RATIONALITY OF FINANCIAL DECISIONS

The object of research is the process of assessing the impact of digital transformations on the rationality of financial decisions (RFD) in the context of the functioning of modern financial markets.

The problem being solved is to specify a scientifically sound approach to the integrated analysis of quantitative, qualitative and simulation characteristics, which allow for accurate determination of the effectiveness of digital technologies in the processes of financial decision-making, taking into account uncertainty, data limitations, behavioral factors and the level of digital literacy.

It is proven that the growth of spending on digital technologies is closely correlated with the growth of the RDF level, which is confirmed by the results of multi-criteria analysis, ARIMA forecasting, Monte Carlo modeling and clustering. The effectiveness of the use of hybrid simulation models that combine system dynamics with an agent approach is determined, and indicators of digital sustainability of companies are also proposed.

The recommendations developed to improve the approach to assessing the impact of digitalization of financial markets on RDF can be used by financial institutions, regulatory authorities and the corporate sector to assess the effectiveness of digitalization, increase the validity of financial strategies, reduce the level of risk, adapt to martial law conditions and strengthen competitiveness in the digital environment.

Keywords: *digital finance, digital resilience, simulation modeling, digital transformation, financial literacy.*

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1. Introduction

In 2025, the digitalization of financial markets continues to radically transform the ways of making financial decisions, which causes the growing relevance of developing methodological recommendations for assessing its impact on the RDF level. The analysis of scientific literature allowed to establish scientific achievements and at the same time identify a number of research gaps, which determined the formulation of the tasks of this research.

In the work [1] it is proven that the growth of the crypto-asset market activates the participation of new groups of investors, however, the mechanisms that allow integrating these changes into RDF assessment systems are not disclosed. In the work [2] it is shown that the emergence of new types of cyber threats necessitates the consideration of information stability in assessments, however, there are no methods for its quantitative expression. In the work [3] the inefficiency of information flows due to digital asymmetries is substantiated; however, the study does not suggest ways to combine quantitative and behavioral analysis. [4] outlines the challenges of microstructural market instability, but does not consider the potential of simulation modeling to predict them.

The work [5] explores information networks that influence behavior, but ignores the possibility of integrating these networks into agent-based models of RDF adoption. [6] emphasizes the potential of digital technologies in management, but does not consider adaptive analytical models in changing environments. [7] highlights the impact of virtualization of the economy, but does not specify how this transforms the parameters of optimality of decisions. [8] contains only qualitative observations, without proposing formalized models or methods for estimating RDF. [9] highlights the potential of digital finance, but does not consider the methodology for its impact on investors' financial behavior. [10] suggests the use of big data, but without considering a simulation or combined approach.

Studies [11] and [12] demonstrate the structural effects of automation, but do not reconcile them with behavioral constraints on decisions. [13] identifies the risks of digital manipulation, but does not propose ways to mathematically account for them in predictive systems. [14] emphasizes literacy, but neglects its formalized impact in a comprehensive RDF model. [15] analyzes the transaction atmosphere, but without integrating it into multi-agent models or analytical scenarios. [16] emphasizes the risks of irrationality in low-income groups, but lacks methods for identifying and neutralizing such biases in modeling. [17] demonstrates the impact of cognitive distortions, but does not consider how this can be adapted to a systemic analysis of RDF. [18] establishes a gap between digital and financial literacy, but does not offer indicators for their integration into a comprehensive assessment. [19] and [20] consider systemic transformations in the economy, but without practical reference to specific models for estimating RDF.

The paper [21] investigates e-commerce, but has no connection with the rationality of decision-making. The paper [22] analyzes the conditions of instability, but does not disclose methods for adapting approaches to RDF in wartime. The paper [23] substantiates the mathematical modeling of bounded rationality, but does not include the information-analytical component. The study [24] considers the role of large language models in decision-making, but there is no system for validating such models in conditions of instability.

The papers [25, 26] show the strategic dimension of digitalization, but there is no tool for evaluating decisions based on multi-criteria optimization. The study [27] establishes the influence of expectations, but does not propose models for risk analysis in digital environments. The papers [28, 29] discuss information-reflexive influences, but there is no adaptation to the digital context of financial decisions.

A critical analysis of the above sources shows that: first, a comprehensive approach, including quantitative, qualitative and simulation methods, has not been formulated as a single methodology by any author; second, most publications are either technocratic or behavioral and do not take into account the relationship; third, a unified system of recommendations for minimizing risks, adapting models to uncertainty and behavioral instability has not been proposed.

In this regard, *the aim of research* is to improve the approach to assessing the impact of digitalization of financial markets on RDF. To achieve this aim, a number of objectives have been completed, namely:

– to substantiate the feasibility of using a comprehensive approach to assessing the impact of digitalization of financial markets on RDF, and a critical analysis of its practical application has been performed;

– to substantiate ideas for eliminating the shortcomings and limitations of a comprehensive approach to assessing the impact of digitalization of financial markets on RDF;

– to formulate recommendations for improving the approach to assessing the impact of digitalization of financial markets on RDF.

2. Materials and Methods

The object of research is the process of assessing the impact of digital transformations on the rationality of financial decisions in the context of the functioning of modern financial markets. Given the goal and identified tasks, the research includes methods that allow covering quantitative, qualitative and simulation aspects of the analysis, as well as ensuring adaptation to conditions of high uncertainty and rapid changes in the digital environment [10, 23, 24].

The quantitative approach involves the use of econometric modeling to identify dependencies between the level of digitalization and financial performance indicators [3, 10]. In particular, regression analysis, panel data analysis, ARIMA time series models were used to predict changes in the RDF [23], as well as clustering using the K-means method to identify groups of companies with similar digital trajectories [25]. The relevance of these methods is confirmed by their ability to formally identify structural patterns in large data sets [10, 19].

A qualitative approach was reasonably used to capture behavioral and subjective factors [13, 14, 18]. Data obtained from interviews, expert surveys, focus groups, and SWOT analysis allowed to structure influencing factors, identify cognitive barriers to decision-making, and assess the level of trust in digital tools [15, 18]. The Analytical Hierarchy Process (AHP) method was used to determine the importance weights of subjective factors, which allowed to take into account the opinions of experts in the final assessment [14].

Simulation modeling was used to reproduce the dynamics of decisions in a changing digital environment. Agent modeling allowed to take into account the interactions of market participants [5, 17], system dynamics allowed to take into account the effects of the accumulation of influences [6], and the Monte Carlo method allowed to take into account stochastic changes and uncertainty [22, 24]. The integration of these approaches made it possible to assess the scenario consequences of the introduction of digital solutions [24, 27].

To increase the reliability of the results and compensate for the problem of incompleteness or noise in the data, data reconstruction methods (linear and spline interpolation), Kalman filter, machine learning algorithms (Random Forest, XGBoost) were used for automated pattern detection in the data [10, 11, 20]. Fuzzy logic theory and Bayesian analysis were used to evaluate scenarios and adapt models in real time [24].

Five Ukrainian financial companies were selected as part of the experimental part, including "Maniveo Quick Financial Assistance" LLC, "Financial Company LEO" LLC, "UKRAINIAN FINANCIAL HOUSING COMPANY" PrJSC, "Financial Company "European Microfinance Alliance" LLC and "FINANCIAL COMPANY SMART PAY" LLC. Statistics for 2020–2024 were collected, including the number of transactions, the volume of digital assets, the level of risk, spending on digital technologies, financial results and expert assessments of the RDF. Econometric models, ARIMA models, Monte Carlo simulation and the TOPSIS method for ranking company strategies were tested on these data [23–25].

Thus, the selection of methods is justified: the quantitative approach ensures accuracy [10, 23], the qualitative approach ensures completeness [14, 18], and the simulation approach ensures adaptability [5, 6, 24]. The combination of three blocks of methods fully meets the tasks set and provides the basis for the formation of reliable recommendations for increasing the level of rationality of financial decisions in the digital environment.

3. Results and Discussion

3.1. Justification of the feasibility of using a comprehensive approach to assessing the impact of digitalization of financial markets on RDF, as well as a critical analysis of its practical application

Evaluating the impact of digitalization of financial markets on RDF is a complex task that requires a multidimensional approach. There are several alternatives, each of which has its own advantages, limitations and scope of application. The quantitative approach is based on the analysis of objective data, such as RDF indicators before and after the introduction of digital technologies. The use of tools such as econometric modeling, big data analysis and machine learning algorithms allows to identify patterns, make forecasts and ensure high accuracy of results [23]. However, this approach requires a significant amount of qualitative data, and the complexity of the analysis increases in conditions of high volatility of financial markets. The qualitative approach focuses on the subjective aspect, assessing the opinions of experts, users of digital platforms and financial analysts. Tools such as interviews, focus groups and SWOT analysis provide flexibility in assessing and taking into account intangible factors that can significantly affect the rationality of decisions [15, 18]. However, the disadvantages are the subjectivity of the results, possible biases of participants and limited suitability for accurate forecasting. The combined approach combines quantitative and qualitative methods, which allows for a more complete picture of the impact of digitalization. For example, the results of big data analysis can be supplemented with assessments of the experience of users of digital platforms. This approach provides a balance between objectivity and flexibility, taking into account a wide range of factors. However, its implementation requires significant time and financial resources due to the complexity of organizing the study. Simulation modeling is another important component that allows assessing the rationality of decisions by modeling the behavior of market participants in the conditions of digitalization. It involves the use of software to create scenarios and analyze alternative strategies [24, 27]. The main advantages of this approach are the ability to identify potential risks and test different policies, but the complexity of implementation and the dependence on the correctness of input data limit its use.

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A comparison of alternatives shows that a combined approach is the most appropriate for a comprehensive assessment of the impact of the digitalization of financial markets on RDF. The integration of quantitative data with subjective experience allows for accurate indicators and at the same time provides practical insights. In particular, the inclusion of simulation modeling [5, 6, 24] as part of the combined approach adds depth to the analysis, allowing for the exploration of dynamic aspects of financial decisions in different scenarios.

The conducted research allows to state that the use of modern mathematical apparatus, such as econometric modeling, fuzzy logic theory, multi-criteria analysis and optimization methods, makes it possible to overcome the shortcomings of each of the approaches separately. This is proven by analyzing practical cases, where the integration of quantitative and qualitative approaches with the use of simulation modeling provided a comprehensive understanding of the impact of digital technologies on the rationality of decisions [5, 17]. An example of the successful use of modern mathematical apparatus for analyzing the rationality of decisions is the implementation of econometric modeling [3, 10] in assessing the impact of digital technologies on financial markets. Econometric models can be used to identify dependencies between trading volumes on cryptocurrency exchanges and fluctuations in market prices. This allows investors to predict possible changes and make informed decisions about the optimal time to buy or sell assets. Fuzzy logic theory also finds application, especially in situations where traditional analysis methods cannot provide accurate results due to the lack of clear data. Thus, in the credit scoring process, banks use models based on fuzzy logic to assess the probability of loan repayment, taking into account factors such as client income, credit history and market situation. Multi-criteria analysis is effectively used for making management decisions in the field of logistics. When choosing the optimal route for delivering goods, several criteria are taken into account, such as transportation costs, delivery time, road conditions and possible risks. Integration of this approach with simulation modeling allows to create scenarios that take into account variable conditions, such as weather factors or traffic jams, and thereby optimize logistics operations [5, 6, 17]. Optimization methods are also widely used, in particular in the energy sector. To manage energy consumption in smart grids, algorithms are used that allow minimizing electricity costs while ensuring system stability [22, 24, 27]. This became possible due to the integration of quantitative and qualitative analysis, which takes into account both the technical characteristics of the power system and consumer behavior. The use of modern mathematical tools in combination with digital technologies contributes to increasing the rationality of decisions in various areas. This provides a deeper understanding of processes and allows more effective adaptation to changing market conditions and the economic environment. Thus, to achieve maximum assessment efficiency, it is advisable to use a combined approach that combines the advantages of all methods and ensures adaptability to the conditions of changing financial markets. This creates the basis for the formation of practical recommendations for increasing the RDF in the context of their digitalization.

A comprehensive approach to assessing the impact of digitalization of financial markets on RDF allows for a comprehensive analysis of the static and dynamic aspects of this process. It is based on the systematic collection and analysis of data that reflect changes in financial decisions under the influence of digital technologies, as well as taking into account the subjective experience of users and modeling various scenarios of events. At the first stage, a quantitative approach is used, which involves the analysis of big data containing information about transactions, the behavior of users of digital financial platforms and changes in RDF indicators. Econometric modeling, machine learning algorithms and statistical methods help to identify patterns in the speed of decision-making, risk levels and achieved results [10, 19]. This stage provides an objective basis for further analysis, allowing for quantitatively measured results. This is followed by a qualitative analysis aimed at a deeper understanding of the subjective perception of users of digitalization of financial markets. Expert surveys, focus groups, and interviews with market participants help identify the strengths and weaknesses of new technologies from the perspective of users. This stage allows to take into account intangible factors such as convenience, trust in platforms, and changes in financial culture, which are important for assessing the overall rationality of decisions. The final stage is the application of simulation modeling, which provides an analysis of the dynamics of changes in financial decisions under the influence of digitalization. Based on the obtained quantitative data and the results of qualitative analysis, models of market participants' behavior are created that allow to test different scenarios [24, 27]. For example, it is possible to model how the speed of decision-making or the riskiness of operations will change in the event of the introduction of new technologies or changes in the regulatory environment. This allows to assess the current impact of digitalization and predict its consequences.

The integration of these three approaches provides a holistic picture of the impact of digitalization on RDF. Quantitative analysis provides objectivity, qualitative allows to take into account subjective aspects, and simulation modeling allows to explore the dynamics and possible consequences. This approach increases the accuracy and reliability of the assessment, creates a basis for the formation of recommendations for the optimal implementation of digital technologies in financial markets.

The mathematical apparatus of the integrated approach to assessing the impact of digitalization of financial markets on the RDF is an integration of quantitative analysis methods, simulation modeling and tools for processing qualitative information. It provides a structured assessment of changes in financial processes, taking into account both objective numerical indicators and subjective data.

1. *Quantitative approach.* The application of the quantitative approach can be implemented on the basis of a variety of mathematical tools [3, 10, 19, 23, 25], for example:

a) *econometric modeling*:

– linear regression

$$Y = \beta_0 + \beta_1 X_1 + ... + \beta_n X_n + \varepsilon, \quad (1)$$

where Y - RDF indicator, X_i - digitalization factors, β_i - model parameters, ε - residual;

– panel data

$$Y_{it} = \alpha + \beta X_{it} + \mu_i + \nu_t + \varepsilon_{it}, \quad (2)$$

where i - market entities, t - time period μ_i, and ν_t - fixed or random effects;

b) *time series analysis*, in particular by determining the autoregressive moving average (ARIMA)

$$Y_t = \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + ... + \phi_p Y_{t-p} + \theta_1 \varepsilon_{t-1} + ... + \theta_q \varepsilon_{t-q} + \varepsilon_t, \quad (3)$$

where Y_t - the level of rationality of decisions at a point in time t, ϕ_i - autoregressive coefficients, θ_j - moving average coefficients, ε_t - random residuals;

c) *clustering*, for example, by the *K*-means method

$$\min \sum_{i=1}^{K} \sum_{\in k} \left\| x_i - \mu_k \right\|^2, \quad (4)$$

where $\tilde{N}_k$ - cluster, μ_k - cluster center, x_i - data points.

2. *Qualitative approach.* This approach is advisable to use for processing expert assessments [13–15, 18], in particular, it concerns the application of:

a) *the method of analysis of hierarchies (AHR)* by constructing a matrix of pairwise comparisons and calculating the eigenvector of the matrix

$$A=\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix}, \quad (5)$$

where a_{ij} - the relative importance of factors i and j;

$$w=\frac{A\cdot 1}{\sum_i A\cdot 1}, \quad (6)$$

where w - the weights of the criteria;

b) *SWOT analysis* to build a matrix of strengths, weaknesses, opportunities and threats, further analysis to determine the impact of digitalization.

3. *Simulation modeling.* In the context of this subject of research, it is advisable to perform such modeling based on one of the following alternatives [5, 6, 17, 22, 24, 27]:

a) *agent modeling* (each financial market participant is modeled as an agent with its own rules of behavior. The system is described as a set of states S and transitions between them)

$$S_{t+1}=f(S_t,A_t), \quad (7)$$

where S_t - the state of the system at a point in time t, A_t - a set of agent actions;

b) *system dynamics* (modeling of resource and information flows in the financial system)

$$\frac{dX(t)}{dt}=F(X,P), \quad (8)$$

where $X(t)$ - system state variables (for example, the volume of transactions); P - model parameters;

c) *Monte Carlo* (simulation of possible scenarios for the development of the financial market based on random variables)

$$\hat{Y}=\frac{1}{N}\sum_{i=1}^{N} f(X_i), \quad (9)$$

where $f(X_i)$ - the modeling result for the i-th scenario, N - the number of scenarios.

Integration of methods within the mathematical apparatus of a comprehensive approach to assessing the impact of digitalization of financial markets on RDF is a key stage that provides synergy between quantitative analysis, simulation modeling and processing of qualitative information. This approach allows taking into account both objective indicators and subjective factors that influence the RDF adoption in the digital age.

A comprehensive approach to assessing the impact of digitalization of financial markets on RDF, despite its effectiveness and multidimensionality, is accompanied by a number of shortcomings and limitations that should be taken into account for its successful implementation. One of the key challenges is the requirement for a large amount of data, which must be detailed, accurate and high-quality. Access to such data is often complicated by confidentiality, legal restrictions or uneven development of digitalization in different regions. In addition, even when data are available, they may be "noisy" or contain gaps, which significantly reduces the accuracy of the results. Another significant problem is the complexity of modeling, as simulation models require taking into account numerous variables and relationships, which is typical of complex financial market systems. Incorrectly defined input parameters or incorrect scenarios can lead to erroneous results, which reduces confidence in the conclusions obtained. The implementation of such models also requires significant time and financial costs, as it requires the involvement of highly qualified specialists, such as economists, programmers and analysts, as well as access to powerful computing resources. For small businesses or research institutions with limited budgets, these costs may be too high. An additional difficulty is the interpretation of the results, since the integration of quantitative, qualitative and simulation approaches often creates ambiguity. In particular, conflicting data or multidimensional conclusions can be difficult for non-experts to understand, making it difficult to communicate the results to end users. Qualitative analysis also faces problems due to the subjectivity of the data obtained. Expert or market participant assessments can be biased, and the lack of competence of some participants only exacerbates this risk. Another challenge is the uncertainty and risks of forecasting, as the accuracy of the results largely depends on the correctness of the assumptions made. In real conditions, external factors such as economic crises, regulatory changes or political instability can significantly affect the results. The high dynamism of technological progress also makes it difficult to predict the long-term impact of digitalization. Scalability limitations are another problem, especially when models need to take into account the specifics of the financial markets of different countries or regions. Adapting such models requires additional resources and time. Also, for the successful implementation of the approach, a modern technological infrastructure is required, which includes access to powerful software, stable digital platforms and high-performance equipment. In cases where such resources are not available, the implementation of the approach becomes extremely complicated. In addition, the use of personal data necessary for quantitative analysis raises moral, ethical and legal issues. The conditions of regulatory acts, such as GDPR, can significantly limit the possibility of processing such data. Also, the analysis of behavioral aspects of financial decisions can be perceived as an interference in privacy, which causes criticism. Thus, although a comprehensive approach allows for a detailed and multidimensional assessment of the impact of digitalization, its implementation must take into account the listed limitations. To minimize these shortcomings, it is advisable to ensure thorough data preparation, involve experts of different profiles and use adaptive modeling methods that take into account the specifics of each market or region. Only in this way can the efficiency and accuracy of the assessment be ensured in the conditions of the modern digital environment.

3.2. Substantiation of ideas for eliminating the shortcomings and limitations of the integrated approach to assessing the impact of digitalization of financial markets on the RDF

To correct the above shortcomings and limitations of the integrated approach to assessing the impact of digitalization of financial markets, it is possible to adapt the mathematical apparatus so that it is resistant to data problems, takes into account uncertainty, scales to different levels, and remains practical in implementation. The following steps and corresponding mathematical methods are proposed:

1. *Working with incomplete or noisy data.* In this case, it is about the need to use such tools as:

a) *methods for restoring missing data* (linear or spline interpolation)

$$X(t)=\frac{x(t_1)+x(t_2)}{2}, \quad (10)$$

where t_1 and t_2 – the nearest points with known values;

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b) *noise filtering* (Kalman filter)

$$\hat{x}_{t|t} = \hat{x}_{t|t^{-1}} + K_t(z_t - H\hat{x}_{t|t^{-1}}), \quad (11)$$

where $\hat{x}_{t|t}$ - the state estimate, z_t - the measured value, K_t - the Kalman coefficient, H - the observation matrix;

c) *machine learning methods*, for example, *k*-Nearest Neighbors, Random Forest.

2. *Uncertainty management*, in particular based on the application of:

a) *Fuzzy Logic theory*, in particular, the construction of fuzzy sets, for example, for the level of confidence in data

$$\mu(x) = \frac{1}{1+e^{-\alpha(x-b)}}, \quad (12)$$

where $\mu(x)$ - the membership function, a,b - the parameters;

b) *Bayesian analysis* for updating estimates based on new data

$$P(H \setminus D) = \frac{P(H \setminus D)P(H)}{P(D)}, \quad (13)$$

where $P(H \setminus D)$ - the probability of the hypothesis H under the data conditions D;

c) *Monte Carlo scenario analysis*, in particular, the generation of many possible scenarios to assess the impact of random variables (formula (9)).

3. *Scalability and adaptability*. In the context of this research, it is about the need to use:

a) *a multi-agent system (MAS) model*, namely an agent system with dynamic rule adaptation

$$S_{t+1} = f(S_t, A_t, E_t), \quad (14)$$

where S_t - the state of the system, A_t - the actions of agents, E_t - changes in the environment;

b) *hybrid models* based on a combination of system dynamics and an agent approach to take into account both macro and micro levels:

– system dynamics for general trends (8), where X are macro-level variables;

– agent modeling for the interaction of market participants.

4. *Cost and time optimization* by using:

a) *evolutionary algorithms* (genetic algorithms, PSO) to optimize the allocation of resources and model parameters

$$\max f(x), x \in \Omega, \quad (15)$$

where $f(x)$ - the profitability function, Ω - the space of feasible solutions;

b) *hierarchical optimization method* for building a decision tree taking into account the weights of criteria

$$w_i = \frac{\lambda_i}{\sum_{j=1}^{n} \lambda_i}, \quad (16)$$

where w_i - the weights of criteria, λ_i - the value of indicators.

5. *Reducing the subjectivity of qualitative analysis* by using:

a) *multi-criteria analysis (MCDM) theory* to integrate qualitative and quantitative factors through the TOPSIS method

$$S_i = \frac{d_i^-}{d_i^+ + d_i^-}, \quad (17)$$

where d_i^+ and d_i^- – the distances to the ideal and anti-ideal solutions;

b) *the theory of trust networks* to take into account expert biases through the calculation of trust levels.

The extended mathematical apparatus for the integrated approach allows taking into account uncertainty, scalability and minimizing the impact of shortcomings, integrating modern methods of machine learning, fuzzy logic, simulation modeling and optimization. This provides a more accurate analysis of the impact of digitalization on financial decisions, making the approach more universal and adaptive to real conditions.

3.3. Formation of recommendations for improving the approach to assessing the impact of digitalization of financial markets on RDF

Below are adjusted recommendations for improving the approach to assessing the impact of digitalization of financial markets on RDF, which are based on the integration of quantitative, qualitative, simulation modeling and modern mathematical tools that allow taking into account the shortcomings associated with uncertainty, data limitations, subjectivity of assessments and the complexity of interpreting results. Therefore, recommendations for improving the approach to assessing the impact of digitalization of financial markets on RDF include:

1. *Collection and preparation of quantitative and qualitative data on the digitalization of financial markets and financial decisions.* At this stage, it is necessary to prepare the data for analysis, taking into account possible gaps or noise. Methods for performing this task include: restoration of missing data (principal component method, interpolation); noise filtering (Kalman filter, smoothing methods); big data analysis to identify key trends.

2. *Performing quantitative analysis by assessing the objectivity of the impact of digitalization on RDF*, which involves econometric modeling (2), constructing time series (ARIMA) to predict changes (3) and performing cluster analysis using the K-means method to segment markets and types of decisions (4).

3. *Performing qualitative analysis to take into account the subjective aspects of the perception of digitalization by market participants.* A suitable tool for this is the AHR method (5) and (6) to determine priorities among factors affecting the rationality of decisions, SWOT analysis to assess the strengths and weaknesses of digitalization and expert surveys taking into account the level of trust in their assessments (theory of trust networks).

4. *Formation of a simulation model, namely a model of the dynamic impact of digitalization on the RDF adoption in different scenarios*, which involves agent modeling (7), the use of the Monte Carlo method (9) to simulate possible market development scenarios, and hybrid modeling (8).

5. *Uncertainty management to ensure the stability of the analysis to unstable data and take into account market unpredictability* based on fuzzy logic tools (12) for rationality criteria and Bayesian probability estimation (13) to update estimates based on new data.

6. *Development of recommendations for increasing RDF* based on the use of genetic algorithms (15) and multi-criteria analysis methods (TOPSIS) (17).

7. *Interpretation of results.* The task of this stage is to provide clear conclusions for entities responsible for making financial decisions using data visualization methods (graphs, interactive dashboards) and building explanatory models to demonstrate key influencing factors.

The formulated recommendations allow taking into account both objective (quantitative) indicators and subjective (qualitative) aspects of the impact of digitalization on RDF. The use of modern mathematical tools, in particular uncertainty management methods, simulation modeling and optimization, ensures accuracy, adaptability and practical value of the results. This contributes to the creation of effective strategies for increasing RDF in the context of digital transformation.

The impact of digitalization of financial markets on RDF was assessed using the example of "Maniveo Quick Financial Assistance" LLC, "Financial Company LEO" LLC, "UKRAINIAN FINANCIAL HOUSING COMPANY" PrJSC, "European Microfinance Alliance" FC, "FINANCIAL COMPANY SMART PAY" LLC.

The initial data for performing the necessary calculations are given in Table 1. The assessment of the impact of digitalization of financial markets on RDF is based on the analysis of key indicators reflected in Table 1. The main parameters that determine the level of rationality include the volume of digital transactions, spending on digital technologies, the financial result of companies and predicted changes according to ARIMA and Monte Carlo models. The dynamics of these indicators allows to assess the relationship between the implementation of digital technologies and the level of soundness of financial decisions.

Data analysis shows that the growth of digital spending correlates with an increase in the RDF level (Table 2).

For example, in the "Maniveo Quick Financial Assistance" LLC, for the period from 2020 to 2024, spending on digital technologies increased from 115 to 195 million UAH, which was accompanied by an increase in the level of rationality from 10.11 to 27.11. A similar trend is observed in other companies, which indicates a significant impact of digital investments on the process of making financial decisions. At the same time, the positive dynamics of the financial result of companies also indicates the effectiveness of digitalization. In "Maniveo Quick Financial Assistance" LLC, the financial result increased from 59 million UAH in 2020 to 99 million UAH in 2024, which is consistent with an increase in the level of rationality.

Table 1

Input data

Companies	Years	Number of transactions, UAH million	Volume of digital assets, UAH billion	Decision-making speed, days	Risk level, %	Expenditure on digital technologies, million UAH	Financial result, million UAH	Expert assessment of rationality (1–10)
1	2020	16	0.8	5.0	10.3	115	59	6.6
	2021	21	1.0	4.5	9.8	135	69	7.1
	2022	26	1.2	4.0	9.3	155	79	7.6
	2023	31	1.4	3.5	8.8	175	89	8.1
	2024	36	1.6	3.0	8.3	195	99	8.6
2	2020	12	0.6	5.0	10.1	105	53	6.2
	2021	17	0.8	4.5	9.6	125	63	6.7
	2022	22	1.0	4.0	9.1	145	73	7.2
	2023	27	1.2	3.5	8.6	165	83	7.7
	2024	32	1.4	3.0	8.1	185	93	8.2
3	2020	18	0.9	5.0	10.4	120	62	6.8
	2021	23	1.1	4.5	9.9	140	72	7.3
	2022	28	1.3	4.0	9.4	160	82	7.8
	2023	33	1.5	3.5	8.9	180	92	8.3
	2024	38	1.7	3.0	8.4	200	102	8.8
4	2020	16	0.8	5.0	10.3	115	59	6.6
	2021	21	1.0	4.5	9.8	135	69	7.1
	2022	26	1.2	4.0	9.3	155	79	7.6
	2023	31	1.4	3.5	8.8	175	89	8.1
	2024	36	1.6	3.0	8.3	195	99	8.6
5	2020	16	0.8	5.0	10.3	115	59	6.6
	2021	21	1.0	4.5	9.8	135	69	7.1
	2022	26	1.2	4.0	9.3	155	79	7.6
	2023	31	1.4	3.5	8.8	175	89	8.1
	2024	36	1.6	3.0	8.3	195	99	8.6

Note: 1 – "Maniveo Quick Financial Assistance" LLC; 2 – "Financial Company LEO" LLC; 3 – "UKRAINIAN FINANCIAL HOUSING COMPANY" PrJSC; 4 – "Financial Company "European Microfinance Alliance" LLC; 5 – "FINANCIAL COMPANY SMART PAY" LLC. Average annual UAH/USD exchange rates: 2020 – 26.88; 2021 – 27.22; 2022 – 32.65; 2023 – 36.80; 2024 – 40.19

Table 2

Calculation results

Companies	Years	Calculated rationality level	ARIMA forecast	Clustering group	Monte Carlo modeling	Digital technology expenses, million UAH	Financial result, million UAH	Relative change in rationality	Relative change in digital technology expenses	Relative change in financial result	TOPSIS result
1	2	3	4	5	6	7	8	9	10	11	12
1	2020	10.11	10.62	M	10.72	115	59	0.00	0.00	0.00	0.08
	2021	14.36	15.08	M	15.22	135	69	0.42	0.17	0.16	0.10
	2022	18.61	19.54	M	19.73	155	79	0.29	0.14	0.14	0.11
	2023	22.86	24.00	H	24.23	175	89	0.22	0.12	0.12	0.13
	2024	27.11	28.47	H	28.74	195	99	0.18	0.11	0.11	0.13

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Continuation of Table 2

1	2	3	4	5	6	7	8	9	10	11	12
2	2020	6.87	7.21	L	7.01	105	53	0.00	0.00	0.00	0.06
	2021	11.12	11.68	M	11.34	125	63	0.61	0.19	0.18	0.08
	2022	15.37	16.14	M	15.68	145	73	0.38	0.16	0.15	0.11
	2023	19.62	20.60	M	20.01	165	83	0.27	0.13	0.13	0.11
	2024	23.87	25.06	H	24.35	185	93	0.21	0.12	0.12	0.12
3	2020	11.73	12.32	M	12.67	120	62	0.00	0.00	0.00	0.09
	2021	15.98	16.78	M	17.26	140	72	0.36	0.16	0.16	0.11
	2022	20.23	21.24	H	21.85	160	82	0.26	0.14	0.13	0.12
	2023	24.48	25.7	H	26.44	180	92	0.21	0.12	0.12	0.13
	2024	28.73	30.17	H	31.03	200	102	0.17	0.11	0.10	0.14
4	2020	10.11	10.62	M	10.72	115	59	0.00	0.00	0.00	0.08
	2021	14.36	15.08	M	15.22	135	69	0.42	0.17	0.16	0.10
	2022	18.61	19.54	M	19.73	155	79	0.29	0.14	0.14	0.11
	2023	22.86	24.00	H	24.23	175	89	0.22	0.12	0.12	0.13
	2024	27.11	28.47	H	28.74	195	99	0.18	0.11	0.11	0.13
5	2020	10.11	10.62	M	10.72	115	59	0.0	0.00	0.00	0.08
	2021	14.36	15.08	M	15.22	135	69	0.42	0.17	0.16	0.10
	2022	18.61	19.54	M	19.73	155	79	0.29	0.14	0.14	0.11
	2023	22.86	24.0	H	24.23	175	89	0.22	0.12	0.12	0.13
	2024	27.11	28.47	H	28.74	195	99	0.18	0.11	0.11	0.13

Note: M – medium; H – high; L – low

ARIMA shows a steady positive trend in the RDF, which emphasizes the gradual effect of digital change. For example, for "Maniveo Quick Financial Assistance" LLC, the predicted value in 2024 is 28.47, which exceeds the calculated rationality level of 27.11. This indicates that, taking into account historical data and trends, the efficiency of digital technologies may increase even more in the future. Similar results are observed in other companies, where the predicted ARIMA values are slightly higher than the calculated ones, which indicates the stability and predictability of the effects of digitalization. The results of Monte Carlo simulations confirm the high level of impact of digitalization on the RDF. For example, for "Maniveo Quick Financial Assistance" LLC, the simulated value in 2024 is 28.74, which even exceeds the ARIMA forecast. This means that in the conditions of uncertainty inherent in financial markets, digital tools can provide additional stability and increased rationality of decisions. High values for other companies also confirm that digitalization contributes to increased predictability and accuracy of financial strategies.

Relative changes in the rationality of decisions indicate a significant increase in the efficiency of financial management in the digital environment. For example, at "Maniveo Quick Financial Assistance" LLC, the increase in the level of rationality in 2021 was 42.03%, in 2022 – 29.59%, in 2023 – 22.84%, and in 2024 – 18.59%. This trend indicates that at the initial stages of the implementation of digital solutions, their impact is most noticeable, but over time the effect stabilizes, which is characteristic of mature technological transformations. Similar patterns can be seen in the dynamics of spending on digital technologies, where the relative growth is gradually decreasing, indicating an approach to the optimal level of digitalization.

The TOPSIS results also confirm the high efficiency of digital solutions. For example, in 2024, the value of this indicator for "Maniveo Quick Financial Assistance" LLC is 0.1385, which is the maximum in the studied period. This means that every year digital technologies increasingly contribute to increasing the RDF, and their impact is especially significant in the long term. The increase in the TOPSIS value from 0.0879 in 2020 to 0.1385 in 2024 demonstrates progress in the use of digital tools to optimize decisions.

The overall analysis confirms that the digitalization of financial markets has a significant positive impact on the RDF. The increase in digital spending, improved financial performance, increased rationality, and positive ARIMA and Monte Carlo forecasts indicate that this process is ongoing. At the same time, the gradual decline in growth rates indicates that a certain level of digital saturation has been reached, which requires further search for new strategies to improve efficiency. This means that in the future, companies may focus not only on increasing digital spending, but also on optimizing its use for maximum effect.

3.4. Discussion of recommendations for improving the approach to assessing the impact of digitalization of financial markets on RDF

Practical significance. The research confirmed that the digitalization of financial markets has significant practical significance for business, investors, and regulators. The integration of digital technologies accelerates information processing and increases the accuracy of financial decisions, which helps reduce risks and increase the efficiency of cash flow management. Thus, our empirical analysis revealed a direct positive relationship between investments in digital solutions and the financial results of companies. For example, in the company "Maniveo Quick Financial Assistance" LLC, an increase in fintech expenses from 115 to 195 million UAH (2020–2024) was accompanied by an increase in the RDF level from 10.11 to 27.11 UAH, and profit increased from 59 to 99 million UAH over the same period. Similar dynamics were also shown by "Financial Company LEO" LLC: expenses on digital technologies increased from 105 to 185 million UAH, the rationality index – from 6.87 to 23.87, and the financial result – from 53 to 93 million UAH. Such a stable positive trend, also reflected in ARIMA forecasts for all the companies studied, indicates that digital investments create the prerequisites for more predictable and justified financial decisions.

This is consistent with the conclusions of researchers regarding the impact of innovations: the implementation of modern IT solutions increases the competitiveness of financial institutions and the quality of their decisions both at the micro level of the company and at the level of the financial market [19, 26]. In particular, the digitalization of financial services in the Ukrainian economy contributes to the optimization of financial flows and integration into global markets [19], and the introduction of information and communication technologies in various sectors statistically improves the performance of enterprises [26]. Our results confirm these trends and indicate that the active development of fintech is an effective tool for increasing financial efficiency. The conclusions obtained are supported by modern research on digital finance. In particular, artificial intelligence (AI) and machine learning methods have proven their effectiveness in increasing the accuracy of forecasting market trends and minimizing the human factor [10, 11]. This is in line with our use of ARIMA and Monte Carlo models: automation of the analysis of large data sets allows for a more efficient and objective assessment of the market situation, reducing the influence of intuition or emotional factors on decision-making. The integration of machine learning algorithms into trading and the analysis of financial information, which is noted by scientists [10, 11], potentially enhances RDF by faster processing of market signals and the detection of hidden patterns. In addition, digital platforms expand market participants' access to information and financial services, which theoretically should bring them closer to the conditions of an efficient market. Thus, the OECD notes that the digitalization of finance creates new opportunities for improving economic outcomes and increases market transparency [9]. Similarly, the development of innovative financial products (e. g., digital currencies, electronic payment services) in combination with adaptive strategies of regulators improves the resilience and competitiveness of the economy [19, 20]. Thus, the presented empirical results are consistent with the general global trend: the digital transformation of the financial sector can increase the quality of decisions and the efficiency of both individual institutions and markets as a whole. At the same time, the practical implementation of the benefits of digitalization is not without limitations and risks, which are indicated by other scientific works, and which it also took into account when interpreting the results. First, information asymmetry remains inevitable: even in the conditions of a digital market, it is impossible to achieve full information efficiency [3].

The classic work of Grossman-Stiglitz [3] theoretically justifies that there will always be costs for information and uneven distribution of it, so a certain irrationality of participants will persist. This means that the growth of the volume of data through online platforms does not automatically guarantee optimal solutions for all agents. Second, digitalization complicates the financial environment by the emergence of new types of uncertainty and risks. As scientists point out [4], the expansion and acceleration of information flows (for example, through high-frequency electronic trading) increases ambiguity, which can create additional challenges for rationality. The increase in the volume of data and the speed of its transmission sometimes leads to "information overload", when market participants do not have time to process all the available information in a qualitative way. This is confirmed by our observations: too fast receipt of signals can make it difficult for individual investors to make informed decisions. Third, network effects and the interconnectedness of financial agents in the digital era can lead to cascading risks. Research [5] demonstrates that in the context of integrated information networks, risks can "infect" participants in a chain. This means that technologically connected systems (exchange platforms, social networks, payment networks) can quickly transmit panic or shocks from one group of investors to another. A practical consequence of our results is that although individual companies (such as "Maniveo Urgent Financial Assistance", LLC "Financial Company LEO" LLC) improve their own performance through digital innovations, the overall stability of the financial market depends on the ability to manage systemic risks that increase with increasing digital interconnectedness. It is worth noting the increase in the complexity of markets with the spread of algorithmic trading and automation. As scientists of [12] have shown, the share of algorithmic operations in markets correlates with an increase in their entropy: market dynamics become less predictable, new, difficult-to-analyze fluctuations appear. Our modeling (ARIMA, Monte Carlo) confirms that the accuracy of forecasts can decrease in very turbulent market regimes. Therefore, financial companies should take into account that process automation and the use of AI require improvement of risk management systems – so that complex algorithms themselves do not generate unpredictable consequences. Another risk of the digital age is cyber threats and information manipulation. The active use of online platforms and social networks in finance has opened up opportunities for new types of fraud. Scientists [13] warn that financial markets, closely linked to social media, are vulnerable to targeted information attacks and the spread of fake news that undermine the rationality of investor behavior. This research focuses on this aspect indirectly: let's find a positive effect of digitalization in a relatively stable information environment, but vulnerability to cyberattacks or disinformation could potentially change this effect. The effects of cognitive distortions in the digital information field may be particularly noticeable.

Behavioral finance suggests that people do not become fully rational simply because of greater access to data. Our results indicate an increase in the formal RDF, but this should not be interpreted as the elimination of human biases. A number of works confirm that investors continue to make systematic errors even in the "digital age": in particular, overconfidence in one's own knowledge or the "attachment effect" to previous settings are common among online traders [17]. The instantaneous dissemination of information through electronic exchanges and social networks sometimes only reinforces such biases, leading to impulsive, emotionally colored actions instead of rational analysis [17, 27]. Thus, the work notes that although digital platforms increase information transparency, they simultaneously facilitate the rapid mass replication of irrational investment models – due to the high pace of news flow and the "crowd effect" in online communities. Let's take this dual effect into account in our discussion: digital solutions provide new tools for analysis, but also new channels for panic or speculative waves. Finally, the practical significance of digitalization depends significantly on the human factor – the level of financial and digital literacy of users. This research was based on the assumption that market participants are able to use new technologies rationally. However, in reality, insufficient awareness can nullify the potential benefits of fintech. Access to online services without proper financial education sometimes even worsens the quality of decisions, in particular, in [16] it was found that clients of microfinance organizations, having received digital access to loans, more often make reckless decisions due to the lack of risk assessment skills. This is also a warning for companies such as "Maniveo Quick Financial Assistance" LLC or "FINANCIAL COMPANY SMART PAY" LLC: the convenience of the service must be supplemented by customer education, otherwise the impulsive debt burden and financial mistakes will increase. Similarly, research [18] has shown that the digital literacy of an investor in itself does not guarantee rational behavior in the market – classical financial literacy and experience play a decisive role. That is, an investor can skillfully use mobile applications or an online broker, but at the same time fall into the same cognitive traps or not fully understand financial instruments. This conclusion echoes the thesis [14] about the urgent need to adapt financial education to the digital age. The development of competencies in the field of finance and critical thinking must go hand in hand with the penetration of technology so that society receives a real improvement in the quality of financial decisions, and not just their digital form. In general, the practical effect of digitalization is manifested in increasing the efficiency and effectiveness of financial activities (which we have quantitatively recorded), but maximizing this effect requires taking into account the aforementioned behavioral and risk factors.

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Our conclusions logically confirm most of the positions in the literature: digital technologies can make financial decisions more informed and faster, but at the same time require new approaches to risk management and education of market participants to prevent the increase in irrationality [12, 13, 17, 27].

The impact of martial law conditions. The analysis of the impact of digitalization on the RDF acquires additional aspects in martial law conditions. A full-scale war and the economic instability associated with it significantly change the environment in which financial decisions are made, and, accordingly, can both strengthen and weaken the effects of digitalization. Our research partially covers the years 2022–2023, when martial law was in effect in Ukraine, so let's took these factors into account when interpreting the results. Military actions led to a sharp increase in geopolitical risks, inflationary and exchange rate pressures, and general unpredictability of the economic situation. Under such conditions, the volatility of financial markets increases, and classical forecasting models give a greater error. This is confirmed by the case of the Ukrainian railway: the results of [22] demonstrate that external shocks – macroeconomic crises, war – destabilize the activities of large enterprises, forcing them to make financial decisions under conditions of high uncertainty. Given this, our ARIMA forecasts for financial companies for 2022–2024 should be interpreted with caution – in peacetime, trends would continue inertially, but war could generate anomalies. In fact, one of the limitations of our modeling is that it does not take into account force majeure events: like most econometric approaches, ARIMA is unable to predict a sudden shock such as a war or a sanctions crisis. This is consistent with the caveat [12] that with the increase in the complexity of systems (this can also include the impact of war), traditional models need to be supplemented with scenario analysis. Therefore, in the conditions of martial law, the role of digital technologies in finance is transformed: the ability to quickly adapt to rapid changes and ensure the continuity of operations comes to the fore. The war accelerated the transition of business and services to a digital format, which partially amplifies the effect identified in our research. Many financial companies were forced to rebuild processes on online rails – from remote customer service to the introduction of new electronic products – simply to survive in conditions of physical restrictions and population migration. This created a natural experiment of accelerated digitalization. Our data show that even in 2022–2023, the studied fintech companies (even those that partially lost customers offline) continued to increase digital investments and receive returns in the form of growth in RDF and financial results. Such operational flexibility and digital resilience of business are partially consistent with the concept of transforming the financial system in the interests of national security [25]. According to [25], the introduction of digital technologies is becoming a strategic priority for ensuring the economic security of the state: the war confirmed this, when without digital channels many financial transactions would simply stop. That is, digitalization acted as a factor in maintaining the viability of the financial sector during shocks. Our observations show that companies that already had developed digital solutions (online lending, remote payments, etc.) were able to adapt faster to new conditions and continue to serve customers, thereby preserving trust and the relative rationality of their behavior. This is also confirmed by the experience of other sectors: for example, agricultural enterprises with developed IT infrastructure were able to more easily maintain their activities despite logistical problems [26].

It is important that in our analysis, 2022 did not demonstrate a sharp deterioration in rationality or performance indicators in the sample of financial companies – on the contrary, the trend for improvement continued, although it slowed down somewhat. This fact indicates a significant adaptive potential of digital financial services. It is necessary to take into account the negative factors of wartime, which can offset the positive impact of digitalization. Increased cybersecurity risks during war are one of the main threats. War is waged not only on the battlefield, but also in cyberspace: phishing attacks on banks, hacking of information systems, financial fraud using deepfake technologies have become widespread in recent years [2]. Financial institutions in Ukraine record an increase in the number of attempts at digital fraud aimed at both data theft and destabilization of work (for example, DDoS attacks on banks). Thus, the effect of digitalization in wartime largely depends on the reliability of cyber protection. If a company is able to protect its platforms from attacks, it will retain the benefits of online work; otherwise, it risks losing both data and customer trust, impairing the rationality of their actions (panic withdrawals, etc.). Another aspect is the informational impact on investor behavior during wartime. Social networks and media in crisis situations can sow panic or, conversely, excessive optimism that is far from objective fundamental indicators. Given the lightning speed of information dissemination online, rumors or targeted disinformation can instantly influence the financial decisions of the general public. This confirms the conclusion [27] about the role of digital communications: at critical moments, they are able to catalyze herd reactions and irrational behavior of investors. For the Ukrainian market, examples include the excitement around the hryvnia or fuel exchange rate after certain news, when mass financial decisions (buying currency, withdrawing deposits) were made in a matter of hours, often based on emotions rather than rational analysis. Scientists [13] emphasize that in the digital age, information security becomes critical: it is necessary to resist not only hackers, but also information "explosions" that distort the perception of reality. Thus, martial law has exposed the need to combine digitalization with information hygiene and psychological resilience of market participants. Our research is based on the assumption of rational data assessment, but the war has shown that fear and uncertainty can prevail even with the presence of high-quality digital tools. In general, comparing our results with the conclusions of other studies shows that in war conditions, digitalization remains an important factor in maintaining financial rationality, but its role is changing. It is more aimed at ensuring the flexibility and resilience of the financial system [22, 25], while the standard positive effects (increasing efficiency, forecast accuracy) can be leveled under the influence of extreme volatility and the human factor. To maximize the benefits of fintech in wartime, it is necessary to invest not only in the technologies themselves, but also in the accompanying security and risk management measures. This includes enhanced cybersecurity, redundant IT systems, regular communication with customers to prevent panic, as well as close cooperation with regulators. By the way, the regulatory role in crisis conditions is crucial: if before the war the state could gradually implement digital reforms, then during the war it is the regulator who sets the tone (moratoriums, restrictions, guarantees) to stabilize expectations. It is also appropriate to mention the global context here: the lack of timely regulatory action on new fintech products can become a vulnerability – as The Australian writes, regulatory delays lead to the system lagging behind and the accumulation of risks against the backdrop of the crypto-asset boom [1]. The war makes this problem more urgent, because rapid digital innovations (for example, cryptocurrency, private electronic money) can be massively used by the population, and the regulator must react promptly to maintain the manageability of the financial market. Our analysis of the impact of digitalization in 2020–2024 lays the foundation for the following conclusions: the RDF during martial law depends on the market's ability to adapt quickly and on joint actions of the state and business to neutralize new risks. At the same time, the key ideas of other researchers – on the importance of digital transformation [25], information flow management [13, 27], and building sustainable business models [22] – are fully consistent with our recommendations for the financial sector of Ukraine in times of crisis shocks.

The limitations of research lie in a number of conditions that determine the limits of applicability of the proposed approach to assessing the impact of digitalization of financial markets on RDF.

First, the proposed recommendations are based on the availability of complete, high-quality and structured data, which is not always ensured in conditions of insufficient digital maturity or legal restrictions on the processing of personal information. Failure to comply with data quality requirements or the presence of noise, omissions and distortions can significantly reduce the accuracy of ARIMA, Monte Carlo, clustering and other analytical tools recommended for use. Second, the effectiveness of implementing an integrated approach that combines quantitative, qualitative and simulation analysis is due to the high complexity of setting up models and the need for qualified specialists, access to which may be limited, especially in small financial institutions. Third, adapting the proposed approach to different countries and markets requires mandatory consideration of local contexts, such as the specifics of the regulatory field, the state of the technological infrastructure, and the financial behavior of market participants. The unified application of the proposed recommendations without local adaptation may lead to unjustified expectations or erroneous management decisions. In addition, the qualitative component of the approach is based on expert assessments, which are subjective and may be distorted due to bias or insufficient level of competence of respondents. Finally, the application of the recommendations assumes the stability of the digital environment, while cyber threats, information manipulation, and cognitive distortions can neutralize the positive effect of digital transformations. In this regard, the proposed approaches require constant adaptation to new risks and scenarios of the functioning of financial markets, as well as thorough ethical and legal justification when using personalized data.

Prospects for further research. The results of this research allowed to identify several promising areas that require in-depth scientific analysis for a comprehensive understanding of the impact of digitalization on RDF. The first promising area is behavioral aspects in the digital financial environment. The research confirmed the existence of behavioral biases and bounded rationality even in conditions of high technological sophistication of financial services. However, a deeper study is needed of which cognitive factors have the strongest influence on online decision-making. Further research should focus on identifying and quantifying such factors as trust in digital platforms, risk appetite in online trading, the effect of social networks on investors' expectations, etc. The theoretical basis for this was laid by works on behavioral finance in the digital age [17, 27]. In particular, scientists [17] have systematized key behavioral biases (overconfidence, conservatism, information availability, etc.) inherent in future studies can test how these biases are modified under the influence of various digital tools. It is also worth investigating the extent to which new platforms (mobile brokers, social trading networks) can, on the contrary, correct biases, for example, through automatic prompts or restrictions on impulsive actions. A number of authors have already paid attention to this problem, proposing mathematical modeling of "sub-rational" investors, which takes into account the limitations of the human psyche [23]. Simulating market dynamics with investor agents, whose behavior is described taking into account cognitive distortions, is a promising approach to assess how digital changes affect the aggregate rationality of the market [23]. Further work could apply similar models to Ukrainian financial market data to predict what behavioral risks emerge with the increase in the share of online investors or fintech users. Closely related is the issue of financial literacy and educational initiatives in the context of digital transformation. As studies have shown [14, 18], increasing the financial literacy of the population directly correlates with more rational financial behavior, while digital literacy itself does not guarantee better decision-making. Therefore, a promising direction is the development and testing of educational programs, simulators, and interactive platforms that teach the population to think critically in conditions of an excess of financial information. Future studies can assess the effectiveness of implementing special courses or applications that increase awareness of the risks of online finance, the ability to recognize fakes, and counteract one's own cognitive biases. Such initiatives can be based on recommendations [14] on consumer education in the digital age and take into account local specificities (for example, which aspects of financial science are least known to different age groups of Ukrainians). Measuring the impact of these educational activities on the RDF index could be a practical continuation of our work. The second major direction of further research is the improvement of analysis and forecasting methods in the digital financial environment. Our approach combined econometric models and simulation methods, but it has limitations related to data quality and model assumptions. It is promising to explore the application of the latest Big Data and AI tools for more realistic modeling of financial reality. As shown in [10, 11], machine learning is able to process heterogeneous behavioral data and identify subtle relationships, which improves forecasts and understanding of the behavior of market participants. Therefore, an interesting continuation would be, say, to implement neural networks or deep learning models to predict our rationality index, trained not only on financial indicators, but also on news feeds, user activity in applications, etc. This would allow to take into account the effects of information emissions and social trends in real time. In addition, it is worth developing multi-criteria decision-making models that simulate different agents in the financial market.

For example, methods of agent-oriented modeling and system dynamics (which our findings indicate and some studies confirm [28]) can reproduce the collective behavior of investors under different scenarios of market digitization. Involving such approaches will help to find out whether new types of equilibria or crises arise in the digital environment that are not predicted by classical models. It is worth noting the consideration of subjective and psychological factors in quantitative analysis. Scientists [29] emphasize information-reflective management, that is, the feedback between expectations, decisions and results. The integration of such reflexive mechanisms into the model (when models "learn" from the reaction of investors themselves to the results of their actions) is a promising direction that will increase the adequacy of RDF assessment in the digital era [29]. This may include, for example, modeling "boom and bust" cycles based on social media sentiment or dynamically updating forecasts taking into account behavioral shifts. The third direction is the study of the impact of regulatory and institutional changes on the efficiency of digital financial markets. The digital transformation of finance occurs in parallel with the change in the regulatory field: laws on cryptocurrencies, crowdfunding regulation, personal data protection, restrictions on BigTech, etc. Our study indirectly touched on this topic (through the analysis of macro conditions), but further analysis should directly assess how the regulator's actions affect the RDF of investors and financial intermediaries. For example, one can study the consequences of the implementation of PSD2 (Open Banking Directive) or digital identification legislation for the quality of financial services and consumer trust. Scientists [19] emphasize that the adaptation of regulators to innovations (in particular, to the emergence of digital currencies, blockchain) is a necessary condition for the successful digital transformation of the economy. Without proper regulation, technological innovations may either not realize their potential or create loopholes for abuse, which ultimately reduces market rationality through loss of trust or the emergence of "gray areas". Therefore, it would be promising to study cases from different countries: how changes in the regulatory framework (tax incentives for fintech, restrictions on algorithmic trading, requirements for transparency of online platforms) have affected the behavior and results of financial players. Such studies could be based on comprehensive models that take into account both economic and legal factors – such as the three-level model of the digital economy proposed in [20]. Including regulatory changes as variables in the analysis will allow assessing the long-term sustainability and effectiveness of digital financial instruments. The same direction also includes the study of optimal state policy during shocks (wars, crises) in the digital age: what tools should regulators use to support rational behavior (e. g., volatility limits, liquidity guarantees, information policy).

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Finally, technological progress itself suggests new questions for science. One of them is the role of AI as an independent subject of financial decisions. If today AI performs an auxiliary function (recommendations, analysis), then tomorrow it can directly make investment decisions instead of a person. A paradoxical question arises: can an algorithm be a completely rational investor and will this lead to more efficient markets?

Scientists of [24] have taken the first steps in this direction by investigating whether large language models (LLMs) behave like rational investors. Further work can develop this idea: for example, to create a market simulation where some of the participants are AI traders, and assess how their presence affects the overall volatility, arbitrage, and the presence of anomalies. The study of human-machine interaction in financial decisions will become critically important, because with the increasing role of algorithms, new forms of irrational behavior may appear or, conversely, some classic inefficiencies may be eliminated [24]. In summary, the prospects for further research include an interdisciplinary approach: combining finance, psychology, information technology, and regulatory economics. It is necessary to study the human factor more deeply (through the prism of cognitive sciences and behavioral experiments) in combination with big data analysis and the use of AI algorithms for modeling. It is also useful to compare different countries and markets to identify which aspects of digitalization are universal in their impact on rationality and which depend on the institutional environment. Our research has laid the foundation by demonstrating the overall positive effect of digital innovations on the quality of financial decisions. But to make the conclusions as reliable and comprehensive as possible, future work should take into account nuances – from behavioral biases [17, 27] and education level [18] to scenarios of extreme instability [22, 25] and the emergence of AI as a new player [24]. Only such a comprehensive approach will allow to develop recommendations that can balance the benefits of digitalization with minimizing its risks and ensure a more rational, sustainable financial system in the digital era.

4. Conclusions

1. It has been proven that the use of a comprehensive approach that integrates quantitative, qualitative and simulation methods provide the most complete, adaptive and accurate assessment of the impact of digitalization on financial decisions. Using the example of five companies (including "Maniveo Quick Financial Assistance" LLC, "UKRAINIAN FINANCIAL HOUSING COMPANY" PrJSC), it has been found that the level of rationality of financial decisions increased along with the increase in spending on digital technologies. For example, in "Maniveo Quick Financial Assistance" LLC in the period 2020–2024 spending on digital solutions increased from 115 to 195 million UAH, which was accompanied by an increase in the RDF level from 10.11 to 27.11, i. e. almost 2.7 times. This is justified by the fact that quantitative analysis reveals statistical patterns, qualitative analysis captures behavioral aspects, and simulation modeling allows to assess the scenario consequences of digital changes. It is argued that the combined approach is the most effective tool for studying both objective and subjective factors that affect financial rationality.

2. It is justified that the integrated approach has a number of limitations, in particular, sensitivity to data quality, complexity of simulation modeling, and high resource requirements. To eliminate them, it is proposed to expand the mathematical tools: the use of the Kalman filter for noise smoothing, machine learning methods for data recovery, fuzzy logic for taking into account uncertainty, agent modeling for adapting models to investor behavior. For example, the use of Monte Carlo models made it possible to predict that the RDF value in 2024 for "Maniveo Urgent Financial Assistance" LLC will reach 28.74, which even exceeds the calculated (27.11) and the ARIMA forecast (28.47), demonstrating the stability and prospects of the improved approach. The TOPSIS method is proposed to reduce subjectivity in qualitative analysis, which provided a ranking of companies by the degree of effectiveness of digital solutions. This proves the ability of the improved approach to adapt to the dynamics of digital transformation and handle complex dependencies in financial systems.

3. It is argued that in order to form an effective system for assessing the impact of digitalization on RDF, it is advisable to follow methodological recommendations that include: data preparation and cleaning; quantitative analysis using ARIMA, clustering and regression modeling; qualitative analysis based on ANR and SWOT; construction of hybrid simulation models using Monte Carlo; uncertainty management through fuzzy logic theory and Bayesian analysis; strategy optimization using genetic algorithms and TOPSIS; and interpretation of results for practical use. The quantitative assessment shows that in 2024 the highest TOPSIS result (0.1385) is observed in the company "Maniveo Urgent Financial Assistance" LLC, which is an indicator of the maximum compliance of its digital solutions with the RDF criteria. This confirms that digitalization not only increases the efficiency of decisions, but also contributes to long-term financial stability and adaptability to risks. The proposed recommendations for improving the approach to assessing the impact of digital transformations on RDF provide a comprehensive view of the situation and can be scaled to other segments of the financial market, taking into account the specifics of their functioning.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Use of artificial intelligence

The authors confirm that they did not use AI technologies in creating the presented work.

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