

<https://doi.org/10.31891/csit-2026-2-13>

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Received: 02/04/2026

Accepted: 18/05/2026

Published: 31/05/2026

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UDC 004.8:005.5:658.8

## ADAPTIVE BIG-DATA MANAGEMENT OF SMART RETAIL ENTERPRISES

*The paper develops and substantiates an information technology for the adaptive management of a smart retail enterprise based on Big Data. The proposed solution is aimed at creating an integrated closed-loop management environment in which heterogeneous internal and external data streams are transformed into knowledge, forecasts, managerial decisions, and corrective actions in near real time. The study formulates a formalized system of functional, architectural, and operational requirements for such technology. These requirements include adaptability, data integration, scalability, support for batch and streaming processing, low decision latency, data security, fault tolerance, service orientation, and the capability of continuous self-learning. The methodological foundation combines the systems approach, the cybernetic approach, and data-driven management principles with methods of data mining, machine learning, forecasting, optimization, and multicriteria decision making. A formal structure of the technology is proposed as a set of interconnected subsystems for data collection, integration, storage, analytics, forecasting, decision making, implementation, and monitoring. Their interaction is described as a closed transformation cycle that links data acquisition with feedback-based managerial correction. The paper further develops the structural representation of the technology by distinguishing three completed functional stages: data formation, analytical processing with knowledge generation, and managerial decision implementation. A particular contribution of the study is the formal consideration of the relationship between the data-flow intensity and the throughput of the computing infrastructure. This makes it possible to define a real-time operation condition and to explain how overloads, queues, and excessive delays can be prevented when processing high-volume and high-velocity data streams. To assess the performance of the proposed information technology, a system of partial and integral criteria is introduced. The integral multiplicative efficiency criterion jointly takes into account qualitative, temporal, and resource parameters of all stages of the management cycle. In addition, an adaptability criterion is proposed to evaluate the quality of system response, reaction speed, and resource expenditure under changing operating conditions. The obtained results provide a formal basis for designing scalable intelligent management platforms for smart retail enterprises, improving the consistency of information processes, increasing the quality of forecasts and managerial decisions, and supporting proactive enterprise behavior in a dynamic digital economy.*

*Keywords: adaptive management, smart retail enterprise, Big Data analytics, intelligent decision support systems, machine learning, real-time data processing, data-driven management.*

### Introduction

The current stage of economic development is characterized by deep digital transformation affecting all sectors of economic activity, including the retail sector. The active implementation of information and communication technologies, the development of e-commerce, and the spread of artificial intelligence systems and big data analytics are creating new conditions for enterprise operation and placing increasing demands on management efficiency. Under such conditions, traditional approaches based on retrospective analysis and static models prove insufficient for ensuring competitiveness.

One of the promising directions for the development of modern enterprises is the concept of the smart enterprise, which involves the integration of digital technologies, business process automation, and the use of intelligent decision-support systems. Within this concept, data act as a key strategic resource that determines the quality of managerial decisions, the level of adaptability, and the enterprise's ability to respond quickly to changes in the external environment.

Of particular importance is the use of technologies for processing large data sets (Big Data), which enable work with large, high-velocity, and heterogeneous information flows. The data generated in the course of a retail enterprise's operation—transactions, consumer behavior, logistics processes, marketing interactions, and external market factors—create the basis for in-depth analytical processing, identification of hidden patterns, and the development of forecasting models.

At the same time, the effective use of Big Data requires the development of specialized information technologies that ensure the integration of heterogeneous data sources, their real-time processing, the generation of knowledge, and support for managerial decision making. Particularly relevant is the combination of Big Data technologies with the principles of adaptive management, which involves continuous monitoring of the enterprise state, forecasting of its development, and adjustment of managerial actions depending on changes in the internal and external environment.

Despite the substantial body of scientific research in the fields of the digital economy, data mining, and management automation, the development of integrated information technologies for the adaptive management of smart retail enterprises remains insufficiently elaborated. In particular, further development is needed in approaches to coordinating data flows with the capabilities of computing systems, integrating analytics, forecasting, and optimization processes, and ensuring system operation in real time.

In this regard, the task of developing an information technology for the adaptive management of a smart retail enterprise based on modern methods for processing large data sets is highly relevant. Such a technology should ensure the integration of data collection, storage, processing, and analysis processes with forecasting mechanisms and managerial decision making.

### **Literature Review and Problem Statement**

Recent studies in the field of enterprise management information technologies demonstrate the rapid growth of the role of the Big Data concept as a foundation for the formation of intelligent decision-making systems. Large volumes of data generated as a result of business process digitalization create new opportunities for improving management efficiency, but at the same time give rise to complex problems of data processing, integration, and interpretation.

Scientific publications emphasize that Big Data acts as a key factor in the transformation of management approaches by enabling a transition to data-driven management. In particular, study [1] presents a multidisciplinary analysis of the application of big data in management, highlighting its importance for optimizing operational activity, marketing, and strategic planning. Study [2] also confirms that the integration of big data analytics into business processes contributes to increased enterprise productivity and improved quality of managerial decisions.

At the same time, the literature emphasizes the lack of a unified systemic approach to enterprise management based on Big Data. As noted in [3], existing studies often focus on individual aspects (technological, organizational, or analytical), without ensuring the holistic integration of these components into a single adaptive management system. Similarly, study [4] stresses the need to develop dynamic capabilities in enterprises for the effective use of big data in a changing environment.

Researchers pay particular attention to issues of resource management and real-time decision making. In particular, [5] shows that the use of big data analytics makes it possible to form adaptive management mechanisms that take into account the dynamics of the external environment. However, the practical implementation of such approaches in retail enterprises remains insufficiently studied.

It should also be noted that contemporary research focuses on problems of data quality, system scalability, integration of heterogeneous information sources, and ensuring the timeliness of data processing. Studies [6–8, 10] emphasize the need to combine technological, organizational, and analytical components in order to build effective Big Data-based management systems.

Despite the considerable number of scientific works, the issue of creating an information technology for the adaptive management of a smart retail enterprise remains open. In particular, the following aspects are insufficiently investigated:

- models for integrating data flows in retail systems;
- methods of adaptive management under conditions of uncertainty;
- mechanisms for using Big Data for operational managerial decision making;
- smart-enterprise architectures with due regard to real-time operation.

Thus, the scientific problem lies in the development of an information technology for the adaptive management of a smart retail enterprise that ensures the effective use of Big Data to improve management quality, business process flexibility, and enterprise competitiveness.

### **Purpose and Research Tasks**

The purpose of the study is to develop and scientifically substantiate an information technology for the adaptive management of a smart retail enterprise based on modern methods for processing large data sets (Big Data), which ensures the integration of data collection, storage, processing, and analysis processes with forecasting

mechanisms and managerial decision making in real time, as well as improves the efficiency of enterprise operation in the digital economy.

To achieve the stated purpose, the following tasks must be solved:

- to formulate requirements and select approaches and principles for implementing the information technology;
- to develop the structure of the information technology for the adaptive management of a smart retail enterprise based on Big Data;
- to evaluate the efficiency of the information technology for the adaptive management of a smart retail enterprise.

### **Materials and Methods**

The object of the study is the adaptive management process of a smart retail enterprise under conditions of large-scale and heterogeneous data generation. The subject of the study is the methods and models of integration, processing, analysis, forecasting, and feedback-based use of Big Data in an adaptive management system.

The materials of the study include modern scientific publications devoted to Big Data analytics, intelligent information systems, enterprise management, cloud and distributed computing, as well as generalized classes of retail data generated during enterprise operation. These data include transactions, consumer behavior traces, logistics information, warehouse events, web and mobile interactions, and external market signals.

The methodological basis of the study combines the systems approach, which considers the enterprise as a complex multilevel dynamic system; the cybernetic approach, which emphasizes closed-loop control and feedback; and the data-driven approach, which treats data as the main basis for management decisions. Such integration makes it possible to consider the smart retail enterprise not as a set of isolated information subsystems but as a coherent management environment in which data and decisions are structurally connected.

For formalization of the proposed technology, methods of systems decomposition and mathematical modeling were used. The analytical component relies on data-mining and machine-learning methods capable of identifying patterns, forming knowledge, and producing forecasts. To justify managerial actions, optimization procedures and multicriteria choice methods were used. The assessment of efficiency is based on partial and integral criteria that combine quality, time, and resource parameters of the main functional stages.

### **Results of Developing the Information Technology**

#### **Formulation of Requirements and Selection of Approaches and Principles for Implementing the Information Technology**

The information technology for adaptive management of a smart retail enterprise based on Big Data must satisfy a set of functional, architectural, and operational requirements that determine its effectiveness in the context of adaptive management. The main requirements imposed on such technology are as follows:

- **adaptability** — the ability of the system to automatically modify data processing parameters, analytical models, and management strategies in accordance with changes in the market environment and the internal state of the enterprise;
- **integration** — the creation of a unified information space by combining data from heterogeneous sources (ERP, CRM, POS, IoT, web platforms) with support for standardized data exchange mechanisms;
- **scalability** — the ability to efficiently increase the volume of processed data and the number of users without significant loss of system performance;
- **support for Big Data processing** — the ability to work with large, high-velocity, and heterogeneous data streams using the 5V concept (Volume, Velocity, Variety, Veracity, Value);
- **support for streaming and batch processing** — the implementation of a hybrid data processing model to ensure both real-time operational analytics and in-depth historical analysis;
- **intelligence** — the use of Data Science, machine learning, and artificial intelligence methods for forecasting, clustering, optimization, and decision support;
- **closed-loop control** — the presence of a feedback mechanism that ensures continuous adjustment of managerial decisions based on actual results;
- **fault tolerance and reliability** — the ability of the system to remain operational in the event of failures of individual components and to ensure continuity of business processes;
- **data security** — the implementation of multilevel information protection, including access control, encryption, audit, and monitoring of data operations;
- **low decision-making latency** — minimization of the time between data arrival, analysis, and the generation of managerial actions;
- **cloud and service orientation** — support for distributed architectures and cloud platforms to ensure flexibility, availability, and efficient use of computing resources;
- **support for self-learning** — the ability of machine learning models to continuously update and improve forecast accuracy during system operation.

The combination of the above functional, architectural, and operational requirements defines the conceptual basis for constructing the information technology for adaptive management of a smart retail enterprise based on Big Data and ensures its ability to function effectively under conditions of high market dynamics. The implementation of these requirements makes it possible to provide integrated processing of large-scale data, support for intelligent analysis, forecasting, and optimization of managerial decisions, as well as coordination of information flows with the capabilities of the computing system in real time. As a result, an adaptive intelligent management system of a new generation is formed, ensuring improved enterprise performance, resilience to external influences, and the ability to respond proactively to changes in the market environment.

The implementation of the information technology for adaptive management of a smart retail enterprise based on Big Data is grounded in modern concepts of Data Science, artificial intelligence, and distributed information systems. Conditions of high market dynamics and growing data volumes require the application of integrated approaches to information processing and analysis, which is confirmed by contemporary studies in the field of Big Data analytics [1, 2, 11].

The following approaches are proposed as the basis for constructing the information technology for adaptive management of a smart retail enterprise:

- **systems approach** — which considers a retail enterprise as a complex multilevel system of interconnected elements, ensuring holistic modeling of business processes and information flows [4, 5] and making it possible to decompose the information technology into interrelated subsystems of data collection, processing, storage, and analysis while ensuring their coordinated interaction within a unified information management contour;
- **cybernetic approach** — which is based on the principle of closed-loop control with feedback between the system state and managerial decisions, forming the basis of adaptive management systems capable of responding promptly to environmental changes in real time [11, 12];
- **data-driven approach** — which implies that managerial decisions are made exclusively on the basis of data obtained from internal and external sources, and whose effectiveness is confirmed by modern studies in business analytics and Big Data [2, 11];
- **Big Data approach** — which is based on the processing of large volumes of data characterized by the 5V concept (Volume, Velocity, Variety, Veracity, Value), and whose architectural and analytical foundations are considered in studies [1, 2, 9];
- **machine learning and artificial intelligence approach** — which ensures the implementation of demand forecasting, customer segmentation, and optimization of business processes, the theoretical foundations of which are presented in studies [6, 7, 13];
- **service-oriented and cloud approach** — which involves the construction of modern Big Data systems based on distributed architectures such as MapReduce and Apache Spark, ensuring scalable data processing and the formation of a cloud infrastructure with high performance and fault tolerance [8, 9].

The combination of the above approaches forms the methodological basis for developing the information technology for adaptive management of a smart retail enterprise based on Big Data and determines the principles of its construction and functioning as an integrated intelligent system. Their comprehensive application ensures systematic coverage of the processes of data collection, processing, analysis, and use, implementation of a closed-loop control system with feedback, and transition to data-driven decision making based on modern methods of artificial intelligence and machine learning. As a result, the prerequisites are created for the formation of a scalable, flexible, and high-performance information technology capable of functioning effectively under conditions of uncertainty, processing large-scale data in real time, and supporting proactive adaptive management of a smart retail enterprise.

To implement the information technology for adaptive management of a smart retail enterprise based on Big Data in the form of an adaptive intelligent management system of a new generation, it is proposed to use the following principles:

- **adaptability** — the system must ensure automatic adaptation to changes in the market environment, which is a key property of modern intelligent management systems [11, 12];
- **continuous data processing** — the combination of streaming and batch data processing makes it possible to ensure information relevance and prompt managerial decision making [8, 9];
- **intellectualization** — based on the use of artificial intelligence and machine learning methods to automate analytical and managerial processes [6, 7];
- **data integration** — the combination of data from various sources (ERP, CRM, POS, IoT) is the basis of modern business analytics systems and ensures the formation of a unified enterprise information space [2, 11];
- **scalability** — the use of distributed architectures such as Hadoop and Apache Spark ensures horizontal scaling of Big Data processing systems [8, 9];
- **self-learning** — machine learning models allow the system to adapt automatically to new data and improve the accuracy of forecasting models during operation [6, 7];

- **reliability and security** — ensuring data protection is a critically important requirement for Big Data systems, as confirmed by contemporary studies in distributed and cloud systems [9, 14];
- **the principle of modularity and service architecture** — the system should be built as a set of functionally independent but interconnected modules and services that ensure flexibility, scalability, simplified modernization, and integration with other information systems;
- **the principle of knowledge orientation** — the system should ensure the transformation of large-scale data into structured knowledge that is used to improve the validity, effectiveness, and explainability of managerial decisions.

The combined implementation of these principles, in particular adaptability, intellectualization, data integration, scalability, self-learning, modularity and service architecture, as well as knowledge orientation, ensures the formation of an adaptive intelligent management system of a smart retail enterprise of a new generation, capable of operating effectively under conditions of high environmental dynamics, processing large-scale data in real time, and generating well-grounded managerial decisions on the basis of knowledge.

#### **Development of the Structure of the Information Technology for Adaptive Management of a Smart Retail Enterprise Based on Big Data**

The information technology for adaptive management of a smart retail enterprise is a multilevel integrated human-machine system that provides the full data workflow: from data collection, transmission, integration, and storage to analytical processing, forecasting, generation of optimized managerial decisions, and implementation of a closed feedback loop in real time. Its architecture is oriented toward processing the large, high-velocity, and heterogeneous data streams characteristic of a smart retail enterprise. Formally, the information technology for adaptive management of a smart retail enterprise based on Big Data can be represented as follows:

$$IT_{BD} = \{D, I, S, A, F, R, E\}, \quad (1)$$

where D is the data collection subsystem, I is the data integration subsystem, S is the data storage subsystem, A is the analytical subsystem, F is the forecasting subsystem, R is the decision-making subsystem, and E is the subsystem for implementation and monitoring of managerial decisions.

The functioning of the information technology is determined by the sequence of transformations of information flows in accordance with the following expression:

$$D \rightarrow I \rightarrow S \rightarrow A \rightarrow F \rightarrow R \rightarrow E \rightarrow D, \quad (2)$$

This sequence reflects the closed-loop nature of adaptive management. New and updated data continuously enter the system, are transformed into knowledge and forecasts, generate managerial actions, and then return to the data layer through monitoring and feedback.

The first stage of the information technology covers data collection and data integration. Its role is to transform scattered, heterogeneous, and high-velocity streams into a coordinated information space suitable for subsequent storage, analytics, forecasting, and management support. The data-collection subsystem continuously acquires information from ERP, CRM, POS, e-commerce systems, mobile applications, web platforms, sensors, IoT devices, and external services. The subsystem should support both streaming and batch modes, primary validation, filtering, time synchronization, and normalization of data.

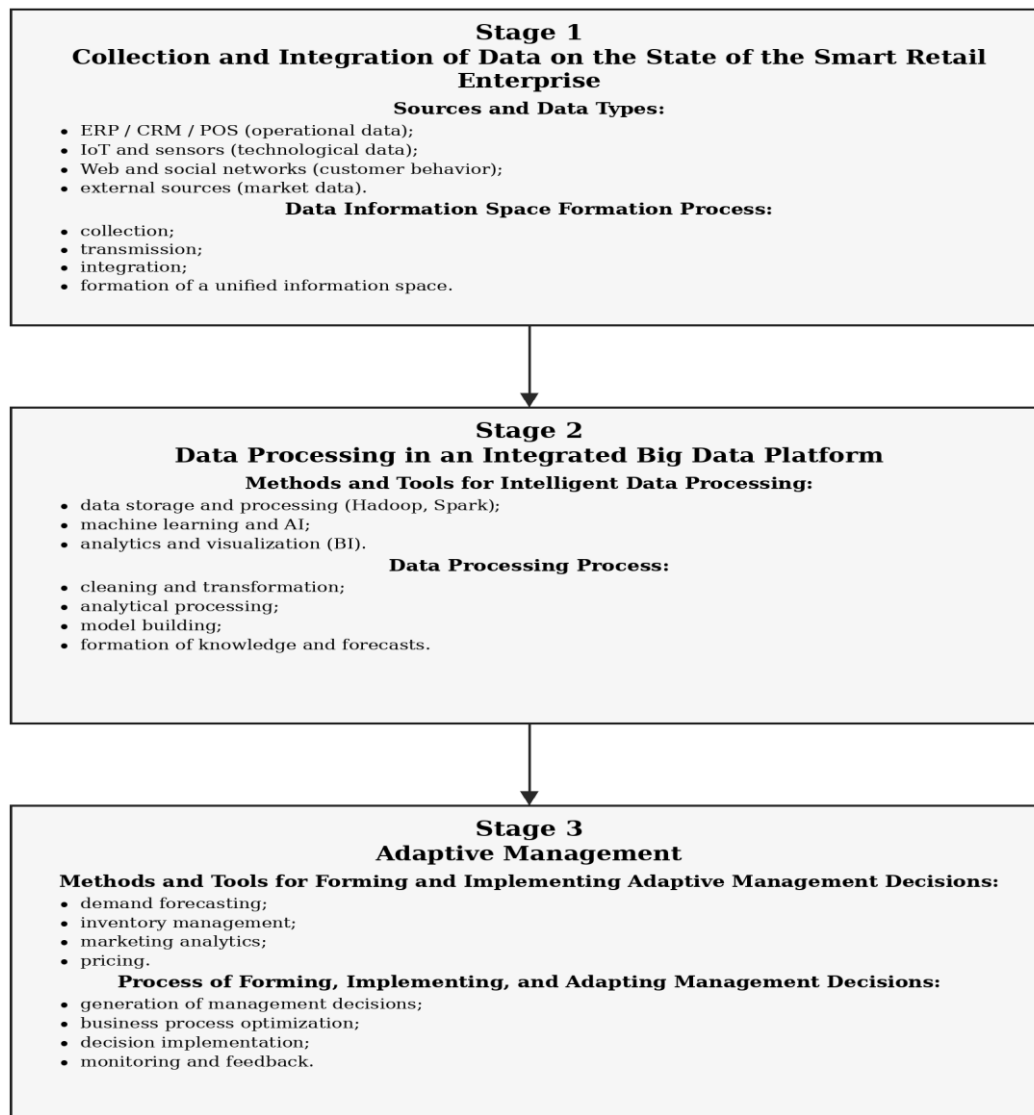
The data-integration subsystem consolidates and aligns the acquired data. It performs cleaning, deduplication, format unification, semantic matching, aggregation, and transformation into a unified enterprise information model. The coordinated functioning of the collection and integration subsystems is critical because analytical quality depends not only on the amount of data but also on its consistency, relevance, and semantic correctness. The first stage therefore establishes the informational basis for all subsequent stages of adaptive management.

The efficiency of implementing the first stage of the adaptive management information technology is evaluated using the following expression:

$$E_1 = \frac{Q_D \times Q_I}{(T_D + T_I) \times (W_D + W_I)}, \quad (3)$$

where  $Q_D$  is the quality of data collection (completeness, reliability, timeliness, synchronization);  $Q_I$  is the quality of data integration (consistency, integrity, absence of duplication, semantic correctness);  $T_D$  is the data collection time;  $T_I$  is the data integration time;  $W_D$  denotes the resource costs of data collection (computational, network, and hardware resources);  $W_I$  denotes the resource costs of data integration.

Thus, the first stage of the information technology ensures the transformation of fragmented data streams into a coherent information model that adequately reflects the state of the smart retail enterprise. The efficiency of its implementation determines the quality of subsequent analytical processing, the accuracy of forecasting, and the validity of managerial decisions within the closed-loop adaptive management system.



**Fig. 1. Structure of the information technology for adaptive management of a smart retail enterprise based on Big Data**

The second stage of the adaptive management information technology for a smart retail enterprise involves data storage, comprehensive analytical processing, and forecasting within an integrated Big Data platform. This stage is formalized as a sequence of mappings (operators) that implement the transition from integrated data to knowledge and forecast estimates:

$$I \xrightarrow{S} X \xrightarrow{A} K \xrightarrow{F} \hat{Y}, \quad (4)$$

where  $I$  is the set of integrated data obtained at the first stage;  $S$  - is the data storage operator;  $X$  - is the space of organized (structured/prepared) data;  $A$  - is the analytical processing operator;  $K$  - is the knowledge space (patterns, models, analytical dependencies);  $F$  - is the forecasting operator;  $\hat{Y}$  - is the set of forecasted system states.

Within this stage, coordinated interaction of the data storage (**S**), analytical processing (**A**), and forecasting (**F**) subsystems is implemented, ensuring the transformation of data into knowledge.

The data storage subsystem provides reliable, scalable, and efficient accumulation of data obtained at the previous stage. The main functions of this subsystem include:

- organization of long-term data storage;
- support for different data types (structured, semi-structured, and unstructured);
- ensuring fast access to data;
- management of historical and streaming data;
- data backup and fault tolerance.

The analytical subsystem performs intelligent data processing aimed at identifying patterns, dependencies, and hidden relationships in the data. Within this subsystem, descriptive, diagnostic, and partially predictive analytics are carried out, including customer behavior analysis, demand analysis, evaluation of business process efficiency, as

well as detection of anomalies and trends. Statistical analysis, data mining, and machine learning methods are used to increase the informativeness and value of the data.

The forecasting subsystem ensures the construction of models and evaluation of future states of the smart retail enterprise. It implements demand forecasting, sales forecasting, customer behavior prediction, as well as risk assessment and scenario analysis. The use of modern forecasting methods enables proactive management and timely adaptation to changes in both external and internal environments.

Coordinated operation of the storage, analytics, and forecasting subsystems ensures synchronization of data processing processes with the intensity of information flows, minimization of delays, and support for data processing in near real time. This creates an information and analytical foundation for the next stage—adaptive management.

The technological basis of the data storage and processing subsystem within the integrated Big Data platform is a set of infrastructural, software, and algorithmic tools that provide scalable storage, efficient access, and high-performance processing of large, heterogeneous, and high-velocity data streams in near real time. The implementation of this subsystem relies on modern Big Data infrastructure solutions, including:

- **Data Lake**, intended for storing raw, unstructured, and semi-structured data in their original form, enabling accumulation of large volumes of heterogeneous information with flexible subsequent processing and analysis;
- **Data Warehouse**, focused on storing structured, cleansed, and aggregated data optimized for analytical queries, reporting, and managerial decision support;
- **distributed file systems**, providing scalable, fault-tolerant, and high-performance storage of large data volumes in a distributed environment;
- **NoSQL and SQL databases**, used for efficient storage and processing of different data types: SQL systems for structured data with rigid schemas, and NoSQL systems for flexible processing of large volumes of unstructured and semi-structured data.

The efficiency of implementing the second stage of the information technology depends both on the operators **S, A, F** and on the parameters of the data flow and computing system, in accordance with the following expression:

$$E_2 = f(S, A, F, P_d, P_c), \quad (5)$$

where  $P_d$  is the data flow intensity (amount of data per unit time);  $P_c$  is the throughput of the computing structure (amount of processed data per unit time).

To ensure real-time implementation of the second stage of the information technology, it is necessary to coordinate the data flow intensity with the throughput of the computing structure. The data flow intensity is determined by the following formula:

$$P_d = m_d n_d f_d, \quad (6)$$

where  $m_d$  – is the number of data input channels,  $n_d$  is the bit width of data input channels,  $f_d$  – is the data arrival frequency. The throughput of the computing structure is determined by the following formula:

$$P_c = m_c n_c f_c, \quad (7)$$

where  $m_c$  is the number of data processing paths,  $n_c$  is the bit width of processing paths,  $f_c$  is the pipeline clock frequency.

Real-time implementation of the second stage is ensured by coordinating the data flow intensity with the throughput of the computing structure, which is formalized by the following condition:

$$k = \frac{P_c}{P_d} \geq 1, \quad (8)$$

where  $k$  is the coordination coefficient between data flow intensity and computing structure throughput. If condition (8) is not satisfied ( $k < 1$ ), system overload occurs, leading to queue accumulation and processing delays.

To evaluate the efficiency of the second stage of the information technology, a generalized efficiency criterion is proposed, calculated as follows:

$$E_2 = \frac{Q_K \times Q_{\hat{Y}}}{T+W}, \quad (9)$$

where  $Q_K$  - is the quality of generated knowledge (reliability, completeness, relevance of identified patterns);  $Q_{\hat{Y}}$  is the quality of forecast estimates (accuracy, stability, consistency);  $T$  is the data processing time (result formation delay);  $W$  denotes computational and hardware costs (resource intensity of implementing operators **S, A, F**).

Maximization of the efficiency criterion  $E_2$  is achieved when condition (8) is satisfied, as well as through coordination of the parameters of operators **S, A, F**, minimization of processing delays, and optimal utilization of computational resources while ensuring high-quality knowledge and forecasts. This is a necessary condition for effective adaptive management in real time.

Thus, the second stage of the adaptive management information technology for a smart retail enterprise ensures the transformation of integrated data into knowledge and forecast estimates, which form the basis for generating well-grounded, timely, and adaptive managerial decisions. The efficiency of this stage determines the level of intellectualization of the management system and its ability to function under uncertainty and dynamic environmental changes.

The third stage of the adaptive management information technology for a smart retail enterprise is the final stage in the closed-loop management system and is responsible for decision making, implementation, and monitoring of managerial actions formed based on knowledge and forecasts obtained at the previous stage. This stage is aimed at

transforming analytical results and forecast estimates into specific control actions focused on achieving target enterprise performance indicators under uncertainty and high environmental dynamics.

The third stage of the information technology can be represented as follows:

$$\hat{Y} \rightarrow R \rightarrow E \rightarrow D, \quad (10)$$

where  $\hat{Y}$  is the set of forecasted system states;

$R$  is the decision-making subsystem;  $E$  is the subsystem for implementation and monitoring of managerial actions;  $D$  represents updated data on the system state generated through the feedback mechanism.

Within the decision-making subsystem (**R**), forecast estimates are interpreted, management alternatives are formed, and optimal or rational control actions are selected, taking into account defined efficiency criteria, resource constraints, and current operating conditions of the enterprise. Multicriteria optimization methods, data mining techniques, machine learning, and fuzzy logic are applied for this purpose.

The implementation and monitoring subsystem (**E**) ensures the execution of formulated managerial decisions within the relevant business processes of the enterprise and provides continuous monitoring of their execution. Within this subsystem, actual results are evaluated, deviations from forecasted values are identified, and feedback is formed and transmitted to the data collection subsystem (**D**) for the next adaptive management cycle.

Coordinated operation of the **R** and **E** subsystems minimizes delays between forecast generation and implementation of managerial actions, enables adaptation of decisions to environmental changes, and supports continuous management in near real time.

To evaluate the efficiency of the third stage of the adaptive management information technology, a generalized efficiency criterion is proposed, which accounts for the quality of managerial decisions, implementation speed, and resource costs:

$$E_3 = \frac{Q_R \times Q_E}{(T_R + T_E) \times (W_R + W_E)}, \quad (11)$$

where  $Q_R$  is the quality of managerial decisions (justification, optimality, consistency with objectives);

$Q_E$  is the quality of implementation of managerial actions (execution accuracy, stability, achievement of key performance indicators (KPI));  $T_R$  is the decision-making time;

$T_E$  is the implementation and monitoring time;  $W_R$  is the computational and informational cost of the decision-making subsystem;  $W_E$  is the resource cost of implementing and controlling managerial actions.

Maximization of the  $E_3$  criterion is achieved by improving the quality of managerial decisions and the effectiveness of their implementation while simultaneously minimizing time delays and resource expenditures. A key condition is coordination of the performance of subsystems **R** and **E** with the dynamics of enterprise state changes, ensuring adaptive management in real time.

Thus, the third stage of the adaptive management information technology ensures practical implementation of analytical and forecasting results, formation of control actions, and closure of the feedback loop. The efficiency of this stage determines the level of adaptability of the management system, the speed of response to changes in the external and internal environment, and the degree of achievement of target performance indicators of the smart retail enterprise under uncertainty and dynamic change.

#### Evaluation of the Efficiency and Adaptability of the Information Technology

By combining the three stages, a formalized representation of the information technology for adaptive management of a smart retail enterprise is obtained in the form of the following sequence of mappings:

$$D \xrightarrow{I} X \xrightarrow{S} X_s \xrightarrow{A} K \xrightarrow{F} \hat{Y} \xrightarrow{R} U \xrightarrow{E} D, \quad (12)$$

where  $D$  is the set of primary data;  $I$  is the data integration operator;  $X$  is the space of integrated data;  $S$  is the data storage operator;  $X_s$  is the space of organized (structured) data;  $A$  is the analytical processing operator;  $K$  is the knowledge space;  $F$  is the forecasting operator;  $\hat{Y}$  is the set of forecasted system states;  $R$  is the operator (subsystem) for managerial decision making;  $U$  is the set of control actions;  $E$  is the operator for implementation and monitoring;  $D$  represents updated data generated through the feedback mechanism.

Thus, the generalized model (12) formalizes the adaptive management information technology as a single integrated process of transforming data into control actions with a closed feedback loop, implementing a continuous cycle

«data – information – knowledge – decision – action – data.».

To determine the degree of achievement of target performance indicators of the adaptive management information technology for a smart retail enterprise, as well as its adaptability, productivity, and economic feasibility, it is proposed to use a system of efficiency criteria. Taking into account the multilevel structure of the information technology and its implementation in the form of a closed-loop management system, efficiency assessment should be carried out both at the level of individual functional stages and at the integral level of the entire information technology.

This approach makes it possible to identify bottlenecks at individual stages of the information technology operation, assess the consistency of subsystem interactions, formalize the contribution of each stage to the final result, and justify directions for optimizing the parameters and structure of the information technology.

Accordingly, the efficiency of each stage of the information technology is characterized by the corresponding partial criteria  $E_1$ ,  $E_2$ ,  $E_3$ , which take into account qualitative, temporal, and resource parameters of subsystem

operation. The generalized assessment of the efficiency of the entire information technology is determined by an integral criterion that reflects the systemic nature of interaction among its components and the dependence of the final result on the efficiency of each stage.

For this purpose, an integral efficiency criterion of the information technology is introduced, defined as follows:

$$E_{IT} = E_1 \times E_2 \times E_3. \quad (13)$$

The efficiency criterion  $E_{IT}$  has a multiplicative form and reflects the systemic principle of coordinated functioning of all stages of the information technology, according to which a decrease in the efficiency of any stage leads to a proportional decrease in the overall system efficiency.

Taking into account the previously introduced partial efficiency criteria  $E_1$  (formula (3)),  $E_2$  (formula (9)), and  $E_3$  (formula (11)), the integral efficiency criterion of the information technology can be expressed in expanded form as:

$$E_{IT} = \frac{Q_D \times Q_I}{T_D + T_I + W_D + W_I} \times \frac{Q_K \times Q_F}{T + W} \times \frac{Q_R \times Q_E}{T_R + T_E + W_R + W_E}, \quad (14)$$

where  $Q_D, Q_I$  - denote the quality of data collection and integration;  $Q_K$  is the quality of generated knowledge;  $Q_F$  is the quality of forecast estimates;  $Q_R$  is the quality of managerial decisions;  $Q_E$  is the quality of implementation of managerial actions;  $T_D, T_I, T, T_R, T_E$  represent the time costs of the corresponding stages;  $W_D, W_I, W, W_R, W_E$  represent computational and hardware resource costs.

In the denominators of the criteria, time and resource costs are considered as additive sums, which corresponds to their independent influence on the efficiency of the information technology operation.

The proposed  $E_{IT}$  criterion provides comprehensive consideration of the key characteristics of the information technology functioning and allows formalization of conditions for achieving maximum efficiency. Maximization of the integral efficiency criterion  $E_{IT}$  is achieved by:

- improving the quality of data, knowledge, and forecasts;
- enhancing managerial decision-making methods;
- minimizing time delays at all stages;
- optimizing the use of computational resources;
- coordinating the parameters of data flows and the computing system.

An important condition for effective functioning of the information technology is coordination of data flow intensity with the throughput of the computing infrastructure, which is determined by satisfaction of condition (8). Compliance with this condition ensures real-time system operation, minimization of delays, and prevention of overload.

The efficiency of the information technology is determined not only by performance and resource efficiency indicators, but also by its ability to dynamically adapt under changing external and internal conditions. In particular, such a system should ensure:

- timely response to changes in the external and internal environment;
- capability for self-learning based on new data;
- formation of proactive managerial decisions;
- maintenance of stable and reliable operation.

To evaluate adaptability, an adaptability criterion is proposed, defined as follows:

$$E_A = \frac{Q_{adapt}}{T_{response} + W}, \quad (15)$$

where  $Q_{adapt}$  is the quality of adaptation, reflecting the system's ability to generate adequate, timely, and effective managerial decisions in response to changes in operating conditions;  $T_{response}$  is the response time interval, including data processing, analysis, forecasting, decision making, and implementation in response to changes in system state or external environment;  $W$  denotes resource costs.

The proposed adaptability criterion  $E_A$  makes it possible to evaluate the effectiveness of adaptive management by taking into account both the quality of system response to changes and the time and resource costs required for its implementation. Maximization of  $E_A$  is achieved by improving adaptation quality while simultaneously reducing response time and resource expenditures.

To improve the correctness of comparing indicators of different nature (qualitative, temporal, and resource-related), normalization and weighting are proposed. For this purpose, the integral efficiency criterion may be expressed in normalized form as:

$$E_{IT} = \frac{Q_D^* \times Q_I^*}{\lambda_1 T_D^* + \lambda_2 T_I^* + \beta_1 W_D^* + \beta_2 W_I^*} \times \frac{Q_K^* \times Q_F^*}{\lambda_3 T^* + \beta_3 W^*} \times \frac{Q_R^* \times Q_E^*}{\lambda_4 T_R^* + \lambda_5 T_E^* + \beta_4 W_R^* + \beta_5 W_E^*} \quad (16)$$

where  $QD^*, QI^*, QK^*, QF^*, QR^*, QE^*$  are normalized quality indicators;  $TD^*, TI^*, T^*, TR^*, TE^*$  are normalized time parameters;  $WD^*, WI^*, W^*, WR^*, WE^*$  are normalized resource cost parameters, determined using the normalization formula  $X^* = X / X_{max}$ , or (for minimized parameters such as time and costs)  $X^* = X_{min} / X$ ;  $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$  are weighting coefficients reflecting the relative importance of temporal parameters at the corresponding stages;  $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$  are weighting coefficients reflecting the relative importance of resource parameters.

The weighting coefficients must satisfy the normalization condition:

$$\sum_{i=1}^m \lambda_i + \sum_{i=1}^m \beta_i = 1, \quad (17)$$

where  $m$  is the number of indicators.

Normalization allows all indicators to be converted into dimensionless form and ensures their comparability, while the use of weighting coefficients makes it possible to account for the specific operating conditions, priorities, and constraints of a particular smart retail enterprise.

Similarly, the adaptability criterion can be expressed in normalized form as:

$$E_A = \frac{Q_{adapt}^*}{\varphi_1 T_{response}^* + \varphi_2 W^*}, \quad (18)$$

where  $\varphi_1, \varphi_2$  the weighting coefficients reflect the relative importance of response speed and resource efficiency of adaptation processes.

The application of normalized criteria with weighting coefficients provides more flexible and adequate evaluation of information technology efficiency, improves the accuracy of analysis, and allows the evaluation model to be adapted to specific operating conditions.

Thus, the proposed approach to evaluating the efficiency of the adaptive management information technology for a smart retail enterprise is based on the use of an integral multiplicative criterion that incorporates normalization, weighting coefficients, and adaptive system properties, providing a comprehensive and formalized assessment of system performance in a dynamic environment.

### Discussion

The obtained results are a logical consequence of applying an integrated systems, cybernetic, and data-driven approach to the development of the adaptive management information technology for a smart retail enterprise based on Big Data.

In particular, the formalized structure of the information technology (formula (1)) and the sequence of transformations of information flows (formula (2)) ensure the implementation of a closed-loop management system, which explains the increased adaptability of the system. The presence of feedback allows the system to adjust managerial actions based on actual results (Fig. 1), which determines its ability to operate under conditions of uncertainty.

The results of evaluating the efficiency of the first stage (formula (3)) are explained by the fact that the quality of data collection and integration ( $Q_D, Q_I$ ) directly affects the reliability of subsequent analysis. High values of these indicators ensure the formation of a consistent information space, which reduces the informational entropy of the system.

The efficiency of the second stage (formulas (5)–(9)) is determined by the coordination between data flow intensity and the throughput of the computing system (condition (8)). Compliance with this condition explains the possibility of real-time data processing and the absence of overloads. In addition, the use of operators **S**, **A**, and **F** (formula (4)) ensures the transformation of data into knowledge, thereby improving the quality of forecasts.

The results of the third stage (formulas (10)–(11)) are explained by the application of multicriteria decision-making methods and monitoring mechanisms, which makes it possible to minimize time delays ( $T_R, T_E$ ) and improve the quality of managerial actions ( $Q_R, Q_E$ ).

The integral efficiency criterion (formulas (13)–(14)) has a multiplicative nature, which explains the systemic dependence of the final result on each stage: a decrease in the efficiency of any component leads to a proportional decrease in overall system efficiency.

In contrast to studies [1–3], where Big Data analysis is performed in a fragmented manner (analytics and management considered separately), the proposed information technology (formula (12)) ensures integration of all processes within a single closed loop. This enables a transition from reactive to proactive management.

Unlike the approaches considered in [4; 5], where adaptability is implemented mainly at the level of strategic planning, the present study realizes adaptability at all system levels, including the operational level (Fig. 1), which leads to a reduction in response time (formula (15)).

Compared to traditional Business Intelligence systems focused on batch data processing, the proposed solution supports a hybrid model (streaming and batch processing), which enables low decision-making latency.

The key advantages of the study include:

- integration of all management stages into a single system;
- implementation of a closed-loop management system in real time;
- coordination of data flows with computational resources (formula (8));
- application of a multiplicative efficiency criterion (formula (13)).

The problem identified in Section 2 consisted in the lack of an integrated approach to managing retail enterprises based on Big Data.

The obtained results ensure:

- resolution of the data integration problem through subsystems **D** and **I** (formula (1));
- adaptive management enabled by the closed loop (formula (2));
- real-time processing through compliance with condition (8);
- improved quality of managerial decisions through the use of analytics and forecasting (formula (4)).

Thus, the proposed technology largely eliminates the limitations identified in Section 2 by providing a comprehensive solution to the problem.

Further development of the research may proceed in the following directions:

- development of applied implementations and software platforms;
- experimental validation using real data;
- integration with artificial intelligence technologies (deep learning, reinforcement learning);
- improvement of forecasting and adaptation models;
- expansion of efficiency criteria to include economic indicators;
- investigation of cybersecurity and data protection issues.

The relevance of these directions is explained by the need to transition from a theoretical model to practical implementation and to improve the accuracy and reliability of the system.

Thus, the research results are well-grounded, have a systemic nature, and provide a basis for further development of adaptive management information technologies for smart retail enterprises.

### Conclusions

1. A formalized system of requirements for an information technology of adaptive management of a smart retail enterprise based on Big Data has been developed. These requirements cover functional, architectural, and operational aspects of implementation and are characterized by comprehensive consideration of adaptability, integration, scalability, intelligence, and real-time data processing support, which ensures increased system efficiency in a dynamic environment.

2. The methodological basis for constructing the adaptive management information technology has been substantiated. It is based on the integration of systems, cybernetic, and data-driven approaches using machine learning methods and Big Data technologies. This integration is characterized by their comprehensive application to formalize data processing and managerial decision-making processes in the form of a closed-loop control system, which enhances system adaptability and operational efficiency.

3. The principles for constructing the adaptive management information technology for a smart retail enterprise based on Big Data have been defined. These principles form the conceptual foundation of the technology and are distinguished by comprehensive integration of key properties, including adaptability, intellectualization, data integration and scalability, self-learning, reliability, and modularity. This ensures the functioning of the system as a flexible, scalable, and intelligent platform capable of efficient real-time processing of large-scale data, knowledge generation, and well-grounded managerial decision making in a dynamic environment.

4. For the first time, a formalized structure of the adaptive management information technology for a smart retail enterprise based on Big Data has been developed in the form of a set of interconnected subsystems and a corresponding sequence of information transformations. Unlike existing approaches, this structure integrates data collection, processing, analysis, forecasting, and decision making within a single closed-loop management system with real-time operation, which improves the coherence of information flows, reduces data processing delays, and increases the validity of managerial decisions.

5. The functioning model of the adaptive management information technology has been improved by representing it as a formalized sequence of information flow transformations. This model is distinguished by explicit consideration of the relationship between data flow intensity and the throughput of the computing structure, which ensures stable system operation and prevents overload during near-real-time processing of large data volumes.

6. The structuralization of the adaptive management information technology has been further developed by distinguishing three functionally complete stages—data collection and integration; analytical processing and forecasting; and decision making and implementation. This structure is characterized by systematic integration of the Big Data platform with adaptive management mechanisms, which enables proactive managerial actions and improves the efficiency of smart retail enterprise operation under uncertainty and dynamic environmental changes.

7. For the first time, an integral efficiency criterion for the adaptive management information technology of a smart retail enterprise based on Big Data has been developed. This criterion has a multiplicative nature and is distinguished by comprehensive consideration of qualitative, temporal, and resource parameters and their interrelationships, which provides a formalized assessment of subsystem coordination and overall system efficiency.

8. The method for evaluating the efficiency of the information technology has been improved by introducing a system of partial and integral criteria that take into account parameters of data flows and computing infrastructure. This method is distinguished by consideration of conditions for coordinating data flow intensity and system throughput, which ensures increased operational stability and real-time data processing without overload.

9. The method for evaluating the adaptability of management information technologies has been further developed by introducing an adaptability criterion that considers adaptation quality, response time, and resource costs. This criterion enables assessment of the system's ability to respond to environmental changes in a timely and effective manner.

10. The multicriteria efficiency evaluation method has been improved through normalization of indicators and introduction of weighting coefficients. This approach ensures comparability of heterogeneous parameters and

allows adaptation of the evaluation model to enterprise-specific conditions, thereby increasing the accuracy of managerial decision making.

#### ADDITIONAL INFORMATION

#### AUTHOR CONTRIBUTIONS

Conceptualization, I.T.; methodology, V.P.; validation, D.R.; formal analysis, V.P.; investigation, V.P.; data curation, I.T.; writing-original draft preparation, V.P.; writing-review and editing, D.R.; visualization, V.P.; supervision, D.R.; project administration, I.T. All authors have read and agreed to the published version of the manuscript.

#### DECLARATION ON THE USE OF GENERATIVE ARTIFICIAL INTELLIGENCE TOOLS

In preparing this work, the author used DeepL Translate and Grammarly for: grammar and spelling checks, paraphrasing, and rephrasing. After using these tools/services, the author reviewed and edited the content and takes full responsibility for the content of this publication.

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### ІНФОРМАЦІЙНА ТЕХНОЛОГІЯ АДАПТИВНОГО УПРАВЛІННЯ ТОРГОВИМ СМАРТ-ПІДПРИЄМСТВОМ НА ОСНОВІ BIG DATA

*У роботі розроблено та науково обґрунтовано інформаційну технологію адаптивного управління торговим смарт-підприємством на основі Big Data. Сформовано формалізовану систему вимог до технології, що охоплює функціональні, архітектурні та експлуатаційні аспекти й базується на принципах адаптивності, інтегрованості, масштабованості, інтелектуальності та обробки даних у реальному часі. Обґрунтовано методологічну основу, яка поєднує системний, кібернетичний і data-driven підходи із застосуванням методів машинного навчання. Визначено принципи побудови інформаційної технології, що забезпечують її функціонування як інтелектуальної, гнучкої та масштабованої платформи. Вперше розроблено формалізовану структуру технології у вигляді взаємопов'язаних підсистем, інтегрованих у єдиний замкнений контур управління, що охоплює процеси збору, обробки, аналізу, прогнозування та прийняття рішень у режимі реального часу. Удосконалено модель функціонування системи шляхом урахування взаємозв'язку між інтенсивністю потоків даних і пропускну здатністю обчислювальної інфраструктури. Подальшого розвитку набула структуризація інформаційної технології через виділення трьох етапів: формування даних, аналітичне опрацювання та реалізація управлінських рішень. Запропоновано інтегральний мультиплікативний критерій оцінювання ефективності, що враховує якісні, часові та ресурсні параметри, а також удосконалено методи оцінювання за рахунок введення системи часткових показників і умов узгодження потоків даних. Розвинуто метод оцінювання адаптивності шляхом введення відповідного критерію, що враховує якість*

*адаптації, швидкість реакції та ресурсні витрати. Удосконалено багатокритеріальний підхід до оцінювання ефективності з використанням нормування показників і вагових коефіцієнтів. Отримані результати забезпечують підвищення ефективності управління, узгодженість інформаційних процесів і підтримку прийняття рішень у динамічному середовищі.*

*Ключові слова: адаптивне управління, торгове смарт-підприємство, аналітика великих даних, інтелектуальні системи підтримки рішень, машинне навчання, обробка даних у реальному часі, data-driven управління.*