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Ivan TSMOTS

Doctor of Technical Sciences, Professor,
Professor

Institutional affiliation: Department of
Automated Control Systems, Institute of
Computer Science and Information
Technologies, Lviv Polytechnic National
University

<https://orcid.org/0000-0002-4033-8618>

e-mail: Ivan.H.Tsmots@lpnu.ua

Volodymyr PETRYNA

Postgraduate Student

Institutional affiliation: Department of
Automated Control Systems, Institute of
Computer Science and Information
Technologies, Lviv Polytechnic National
University

<https://orcid.org/0009-0009-1330-199X>

E-mail: volodymyr.v.petryna@lpnu.ua

Oksana TSMOTS

Doctor of Philosophy (PhD), Assistant
Professor at the Department of Information
Systems and Networks

Institutional affiliation: Institute of Computer
Science and Information Technologies, Lviv
Polytechnic National University, Lviv,
Ukraine

<https://orcid.org/0009-0004-2208-090X>

e-mail: oksana.i.tsmots@lpnu.ua

Nataliia OLIINYK

Doctor of Philosophy, Associate Professor,
Associate Professor of the Department of
Restaurant, Hotel and Tourism Business
V. N. Karazin Kharkiv National University,
Kharkiv, Ukraine

<https://orcid.org/0000-0003-0378-0359>

e-mail: n.oliinyk@karazin.ua

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SENSOR COMPLEX AND HIERARCHICAL DATA PROCESSING ARCHITECTURE FOR SMART RETAIL ENTERPRISES

The paper addresses the applied scientific problem of designing a sensor complex and a hierarchical data processing system for a smart retail enterprise as the basic component of an adaptive management information technology. It is shown that conventional centralised data acquisition and processing architectures fail to provide the required management responsiveness when a retail enterprise simultaneously generates data streams from radio-frequency identification devices, smart shelves, POS terminals, video analytics systems, microclimate and energy consumption sensors, as well as from corporate ERP, CRM and WMS information systems and digital sales channels. Twelve principles for constructing the sensor complex of a smart retail enterprise are formulated. They cover modularity, peripheral intelligent data processing, interface compatibility and standardisation, multi-source data integration, continuous monitoring, scalability, distributed processing, reliability and fault tolerance, energy efficiency, security and privacy, self-diagnostics and adaptability. Based on these principles, a structure of the sensor complex is developed that combines nine functional groups of data acquisition means together with edge computing nodes and IoT gateways. For the first time, an architecture of a five-level hierarchical data processing system is developed. It comprises the level of sensors and primary data sources, the level of local processing, the level of data integration and consolidation, the level of intelligent analysis and decision making, and the level of decision implementation, communication and monitoring. For each level the functions are defined and the corresponding data transformation operators are formalised, and their composition is presented as a generalised model describing a closed adaptive management loop in which the results of implementing managerial decisions form updated data for the next processing cycle. A mathematical model for evaluating the efficiency of the architecture is developed. It is based on a set of temporal, resource, informational and functional indicators: data processing time and managerial decision formation time, network traffic volume, utilisation of the computing resources of the central platform, the scalability indicator, availability and fault tolerance, the composite quality indicator of integrated data, and the adaptive management efficiency indicator. An integral efficiency criterion and a system of conditions are proposed, under the simultaneous fulfilment of which the developed hierarchical architecture outperforms the traditional centralised one. It is demonstrated that the proposed solutions reduce the time of data processing and managerial decision making, decrease the network load and the load on the central information and computing platform, and increase scalability, integrated data quality, system availability and the efficiency of adaptive management of a smart retail enterprise in real time.

Keywords: sensor complex, smart retail enterprise, hierarchical data processing system, edge computing, Internet of Things, data integration, adaptive management, architecture efficiency evaluation.

1. Introduction

The current stage of economic development is characterized by a profound digital transformation of the retail sector, which is accompanied by a transition from the local automation of individual business processes to the construction of integrated digital platforms for enterprise management. The deployment of radio-frequency identification means, intelligent retail equipment, video analytics systems, mobile applications and digital sales channels causes an avalanche-like growth in the volumes of heterogeneous data on the state of inventories, consumer behavior, equipment operation and logistics processes [1, 2].

The conceptual basis of such a transformation is provided by the Smart Enterprise and Smart Retail concepts, which envisage the integration of cyber-physical systems, the industrial Internet of Things, cloud computing and artificial

intelligence methods within a single information environment of the enterprise [3]. Industry 4.0 reference architectures define a multi-level organization of such an environment, in which the functions of data acquisition, processing and use are distributed among devices, edge nodes and central computing platforms [4]. In the retail sector, these approaches are implemented through intelligent shelves, automated inventory control, personalization of offers and dynamic pricing [5, 6].

A key role in the construction of a smart retail enterprise is played by the combination of Internet of Things technologies, edge computing (Edge Computing), big data processing technologies (Big Data) and machine learning methods. Edge Computing technologies make it possible to perform primary data processing directly at the place where the data are generated, which substantially reduces delays and the volume of network traffic [7, 8], whereas the architectures of the “edge — fog — cloud” continuum ensure a coordinated distribution of analytical workloads among the levels of the computing infrastructure [9]. The development of edge intelligence (Edge Intelligence) makes it possible to transfer to the edge not only filtering and aggregation but also the execution of machine learning models [10].

At the same time, traditional centralized data processing architectures, in which the entire volume of primary information is transmitted to a central platform, have substantial limitations. These include: high latency in the formation of managerial decisions, a considerable load on the data transmission channels and on the computing resources of the central platform, reduced scalability when new retail facilities and sensors are connected, and a critical dependence of the operability of the whole system on the state of the central node [11]. For a retail enterprise, in which the cost of a delay in a managerial decision is directly determined by lost sales and product spoilage, these limitations are of fundamental importance.

The above determines the relevance of creating a hierarchical architecture of the sensor complex and of the data processing system of a smart retail enterprise, in which the functions of acquisition, preprocessing, integration, intelligent analysis and implementation of managerial decisions are rationally distributed among the levels of the system and ensure a closed loop of adaptive management in real time.

2. Analysis of Recent Research and Publications and Problem Statement

Current studies of Internet of Things and smart retail architectures demonstrate a steady transition from the three-layer “devices — network — applications” model to multi-level reference architectures with a dedicated edge computing level. Works [3, 4] generalize Industry 4.0 reference architectures and show that their key property is the separation of functions by levels of abstraction and the provision of component interoperability. Studies [5, 6] are devoted to the application of RFID means and intelligent shelves in retail trade; they demonstrate the effectiveness of these means for improving the accuracy of inventory accounting, however they consider mainly individual classes of devices outside the context of an integral enterprise architecture.

A considerable body of publications is devoted to approaches to the integration of heterogeneous data. Work [12] substantiates the role of data lakes (Data Lake) as the central element of enterprise data management, whereas [13] proposes semantic technologies for unified access to heterogeneous sources. These results create an instrumental basis for data consolidation; however, they do not take into account the specific features of the streaming arrival of sensor data of a retail enterprise or the requirements for the latency of their processing.

The problems of Edge/Fog/Cloud Computing are investigated in the review works [7, 8], which systematize resource management methods and computation orchestration models in the “device — edge — cloud” continuum. In [9], an architecture of streaming analytics based on the edge–fog–cloud continuum is proposed, whereas [11] considers the trade-off between latency and energy consumption during streaming data processing at the edge. Work [10] generalizes edge intelligence approaches. The above studies form the theoretical foundation of distributed processing; however, they are oriented mainly towards the tasks of smart cities, industry and telecommunications.

The analytical aspects of retail enterprise management on the basis of big data are considered in [14], which systematizes demand forecasting methods in supply chains, and in work [15], in which an information technology for adaptive management of a smart retail enterprise based on Big Data is developed and an integral criterion for evaluating its efficiency is proposed. The issues of data quality, which determine the reliability of analysis results, are investigated in [16, 17], whereas the issues of dependability, trust and availability of distributed systems are addressed in [18, 19]. The problems of interoperability and harmonization of data exchange protocols in real-time systems are considered in [20].

Despite the considerable body of scientific results, the following unresolved parts of the general problem have remained outside the attention of researchers:

- the absence of an integral architecture of the sensor complex of a smart retail enterprise that would harmonize the physical means of data acquisition with corporate information systems and digital sales channels within a unified information space;
- insufficient formalization of the functional distribution of data processing operations among the levels of the hierarchical system and the absence of a generalized model of data transformation in a closed loop of adaptive management;

– the absence of a consistent system of quantitative indicators and of an integral criterion that would make it possible to compare hierarchical and centralized architectures in terms of time, resource, information and functional characteristics.

Therefore, the research problem consists in the development of an architecture of the sensor complex and of a hierarchical data processing system of a smart retail enterprise, as well as of a mathematical model for evaluating its efficiency.

3. Aim and Objectives of the Research

The aim of the work is to increase the efficiency of adaptive management of a smart retail enterprise through the development of an architecture of the sensor complex and of a five-level hierarchical data processing system that ensures a reduction in the time of managerial decision formation, a decrease in the network load and an increase in the integrated data quality.

The object of the research is the processes of acquisition, processing, integration and intelligent analysis of heterogeneous data of a smart retail enterprise.

The subject of the research is the architecture of the sensor complex, and the models and means of hierarchical data processing of a smart retail enterprise.

In order to achieve the stated aim, the following objectives have been formulated:

- to formulate the principles of constructing the sensor complex of a smart retail enterprise;
- to develop the structure of the sensor complex that ensures the acquisition and preprocessing of heterogeneous data;
- to develop the architecture of a five-level hierarchical data processing system and to formalize the functions of its levels;
- to develop a generalized model of data processing and transformation in a closed loop of adaptive management;
- to develop a mathematical model and a system of indicators for evaluating the efficiency of the proposed architecture and to determine the conditions of its advantage over a centralized architecture.

4. Methodology and Research Results

4.1. Principles of Constructing the Sensor Complex of a Smart Retail Enterprise

The sensor complex of a smart retail enterprise should be considered as a set of physical sensors, intelligent devices, software means of data acquisition and information systems that generate heterogeneous data flows on the operation of the enterprise. The complex comprises RFID and NFC means of product identification, barcode scanners, intelligent shelves, weight sensors, video cameras, visitor counters, POS terminals, e-commerce systems, mobile applications, temperature, humidity and energy sensors, GPS/GNSS means of transport monitoring, as well as ERP, CRM, WMS and logistics information systems.

The construction of the sensor complex of a smart retail enterprise should be based on the following principles.

1. The principle of modularity, which envisages the construction of the sensor complex from functionally independent modules, each of which is responsible for a separate class of data: product identification, inventory control, sales registration, monitoring of consumer behavior, control of the microclimate, energy consumption, and warehouse and logistics processes. The modular organization simplifies the modernization, replacement and extension of the functional components of the complex.

2. The principle of edge intelligent data processing, which envisages the execution of primary processing directly in intelligent sensors, retail equipment and edge computing nodes with the use of Edge Computing technologies. At this level, filtering, verification of correctness, aggregation, event detection and the formation of informative features are performed, which makes it possible to reduce the volume of transmitted data and to reduce the latency of system operation.

3. The principle of compatibility and standardization of interfaces, which envisages the use of unified protocols and application programming interfaces, in particular Ethernet, Wi-Fi, Bluetooth Low Energy, Zigbee, MQTT, HTTP/HTTPS, REST API, OPC UA and other data exchange standards. This ensures the integration of heterogeneous devices and information systems into a unified information space.

4. The principle of multi-source data integration, which consists in combining data from physical sensors, POS systems, ERP, CRM, WMS, e-commerce systems, mobile applications and external information services in order to form a consistent representation of the current state of the smart retail enterprise.

5. The principle of continuous monitoring, according to which data acquisition and transmission are performed continuously or with a specified periodicity that is sufficient for the timely detection of critical changes in inventories, sales, customer behavior, equipment operation and product storage conditions.

6. The principle of scalability, which ensures the possibility of increasing the number of retail facilities, sensors, data acquisition channels and users without a significant decrease in system performance. Scalability is achieved through the use of a distributed architecture, cloud computing and mechanisms for the dynamic allocation of computing resources.

7. The principle of distributed data processing, which envisages the distribution of the functions of acquisition, preprocessing, integration, analytical processing and managerial decision support among sensor nodes, edge gateways, local servers and the cloud Big Data platform.

8. The principle of dependability and fault tolerance, which envisages the redundancy of communication channels, data buffering, message retransmission, monitoring of the operability of sensor devices and automatic restoration of system operation after failures.

9. The principle of energy efficiency, which envisages the minimization of the energy consumption of sensor devices and edge nodes through the use of an adaptive polling rate and energy-saving operating modes.

10. The principle of security and confidentiality, which envisages device authentication, differentiation of access rights, encryption of data transmission channels, control of information integrity and the protection of personal and commercial data.

11. The principle of self-diagnostics, which ensures the automatic detection of failures, incorrect readings, loss of communication, anomalous device behavior and degradation of data quality.

12. The principle of adaptivity, which envisages the automatic adjustment of the data acquisition rate, the routing rules, the processing priorities and the distribution of computing resources in accordance with the intensity of the information flows and the current state of the smart retail enterprise.

Thus, the formulated principles of constructing the sensor complex define the methodological foundations for creating a scalable, fault-tolerant and adaptive system of acquisition and preprocessing of heterogeneous data, which provides the information basis for the intelligent analysis and adaptive management of a smart retail enterprise.

4.2. Structure of the Sensor Complex of a Smart Retail Enterprise

On the basis of the formulated principles of construction, the structure of the sensor complex of a smart retail enterprise has been developed, which is presented in Fig. 1.

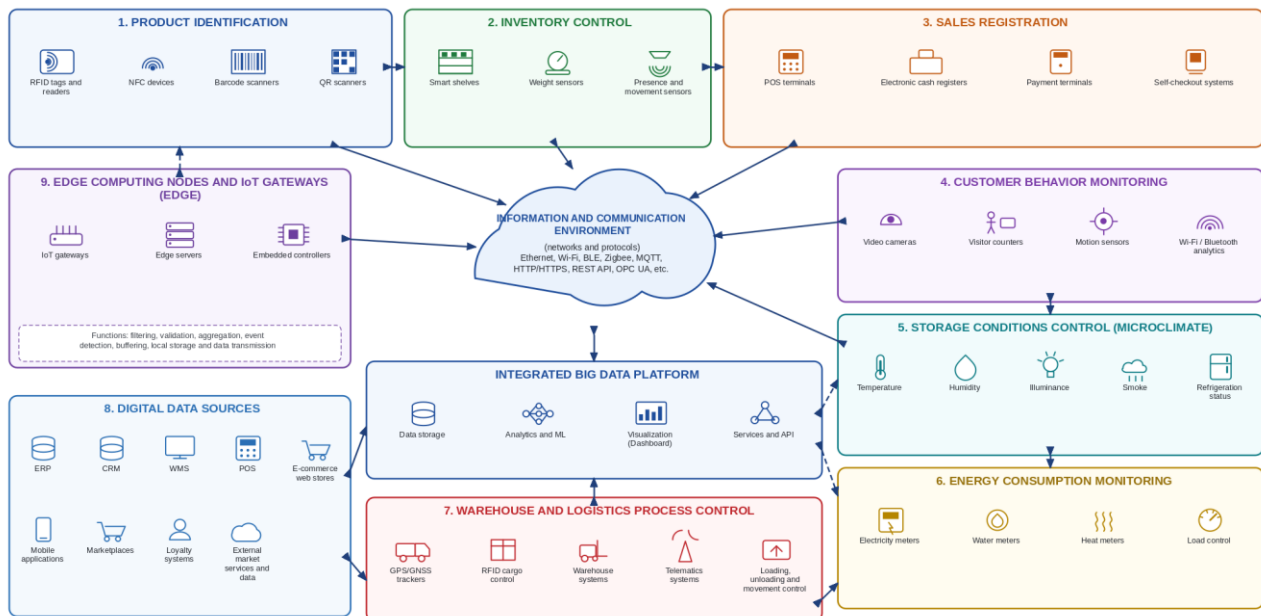


Fig. 1. Structure of the sensor complex of a smart retail enterprise

The developed structure of the sensor complex includes the following functional groups of means:

- means of product identification: RFID tags and readers, NFC means, barcode and QR scanners;
- means of inventory control: intelligent shelves, weight sensors, sensors of product presence and movement;
- means of sales registration: POS terminals, electronic cash registers, payment terminals and self-service systems;
- means of monitoring customer behavior: video cameras, visitor counters, motion sensors, Wi-Fi and Bluetooth analytics;
- means of storage condition control: sensors of temperature, humidity, illumination and smoke, and sensors of the state of refrigeration equipment;
- means of energy consumption monitoring: intelligent meters of electricity, water and heat, and means of load control;
- means of logistics process control: GPS/GNSS trackers of vehicles, RFID cargo control, telematics and warehouse systems;

- digital data sources: ERP, CRM, WMS, POS, web stores, mobile applications, marketplaces and external market services;
- edge computing nodes and IoT gateways, which ensure the acquisition, primary processing, buffering and transmission of data to the integrated information platform.

Thus, the developed structure of the sensor complex ensures the comprehensive acquisition, preprocessing and integration of heterogeneous data, creating an information basis for the intelligent analysis and adaptive management of a smart retail enterprise in real time.

4.3. Architecture of the Hierarchical Data Processing System

An architecture of the sensor complex has been developed that is based on the hierarchical organization of the processes of acquisition, preprocessing, integration, intelligent analysis and use of data. The architecture is implemented in the form of five interrelated functional levels, which ensure the successive transformation of primary sensor and transactional data into a unified information space of the enterprise, knowledge, managerial decisions and control actions.

The hierarchical organization envisages the functional distribution of processes among sensor devices, edge computing nodes, data integration means, analytical services and subsystems for the implementation of managerial decisions. Such an approach ensures a reduction in the volume of data transmitted to the central information and computing platform, a decrease in the delays of their processing, an increase in the scalability and fault tolerance of the system, as well as support for the adaptive management of a smart retail enterprise in real time.

The structure of the five-level hierarchical system of data processing and management of a smart retail enterprise is presented in Fig. 2.

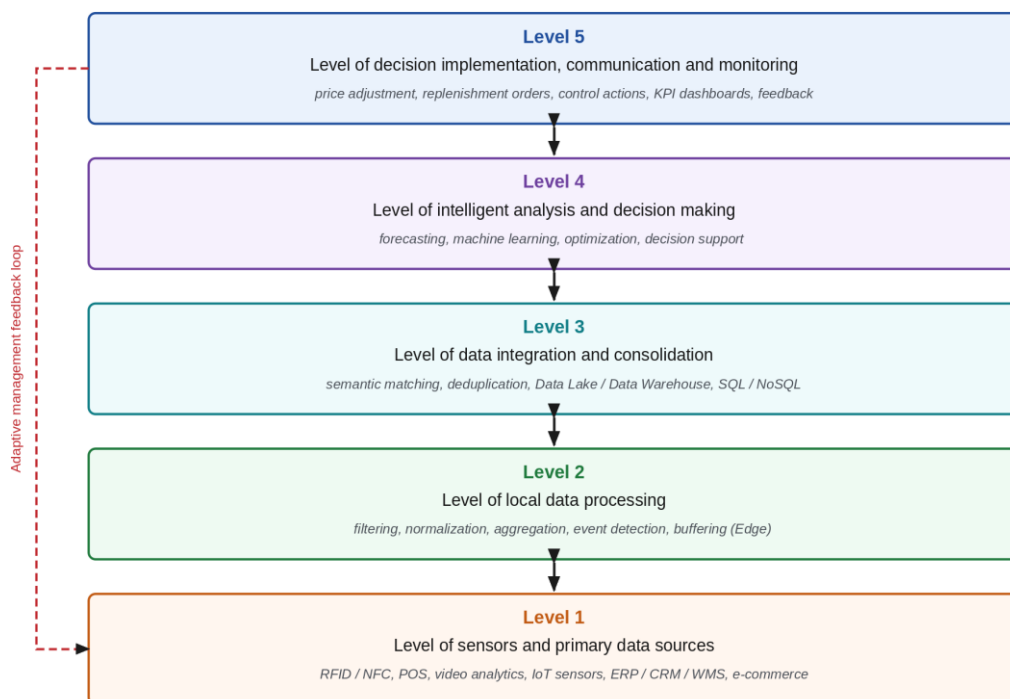


Fig. 2. Structure of the five-level hierarchical system of data processing and management of a smart retail enterprise

The proposed hierarchical system comprises five functional levels, each of which performs defined functions with respect to the formation, processing, integration, analysis and use of data.

4.3.1. Level of Sensors and Sources of Primary Data

At the first level, the primary data on the state of the smart retail enterprise are formed. The data sources are physical sensors, intelligent devices, retail equipment and corporate information systems.

At this level, the following are formed:

- data on the availability, quantity, location and movement of products;
- information on sales, return and payment operations;
- data on the number of visitors, their movement routes and their interaction with products;
- parameters of temperature, humidity, illumination and equipment condition;
- data on warehouse and transport operations;
- information on the operation of the web store, the mobile application and the loyalty programs;
- external data on prices, competitors, weather conditions, seasonality and the state of the market.

The set of primary data can be represented in the following form:

$$D = \{D_{RFID}, D_{POS}, D_{video}, D_{IoT}, D_{ERP}, D_{CRM}, D_{WMS}, D_{web}, D_{ext}\}, \quad (1)$$

where D_{RFID} denotes the data of the product identification means; D_{POS} denotes transactional data; D_{video} denotes video surveillance data; D_{IoT} denotes data from IoT sensors; D_{ERP} denotes the data of the corporate enterprise resource planning system; D_{CRM} denotes the data of the customer relationship management system; D_{WMS} denotes the data of the warehouse management system; D_{web} denotes the data of the digital sales channels; D_{ext} denotes the data of external information sources.

4.3.2. Level of Local Data Processing

At the second level, the preprocessing of data is performed directly in intelligent sensors, retail equipment, IoT gateways and edge computing nodes.

The main tasks of this level are:

- verification of the correctness and completeness of the primary data;
- filtering of noise, erroneous and duplicated records;
- normalization of formats, time stamps and units of measurement;
- local aggregation of information;
- detection of events and critical deviations;
- formation of informative features;
- compression and reduction of the volume of data;
- temporary buffering in the event of a loss of communication;
- anonymization of personal data;
- formation of messages on malfunctions of sensors and retail equipment.

Local data processing can be formalized as

$$D^{(1)} = L(D), \quad (2)$$

where D is the set of primary data; L is the operator of local processing; $D^{(1)}$ denotes the cleaned, normalized and aggregated data prepared for further integration.

4.3.3. Level of Data Integration and Consolidation

At the third level, the integration of the heterogeneous flows arriving from sensors, edge nodes and corporate information systems is performed. The purpose of this level is to form a unified consistent information space of the smart retail enterprise.

The main operations are:

- semantic harmonization of data;
- identification of identical products, customers, transactions and business objects;
- elimination of duplication;
- synchronization of the flows in time;
- matching of schemas and formats;
- consolidation of data from physical and digital channels;
- loading into Data Lake, Data Warehouse, SQL and NoSQL storages;
- routing of the flows to analytical services.

The integration process can be represented in the following form:

$$X = I(D_1^{(1)}, \dots, D_i^{(1)}, \dots, D_m^{(1)}), \quad (3)$$

where $D_i^{(1)}$ are the preprocessed data from the i -th source; m is the number of sources; I is the integration operator; X is the unified consistent information space of the enterprise.

For this level to operate without overload, the following condition must be satisfied

$$P_d \leq P_c, \quad (4)$$

where P_d is the total intensity of the data flows; P_c is the throughput capacity of the integration means and of the computing infrastructure.

4.3.4. Level of Intelligent Analysis and Decision Making

At the fourth level, the integrated data are transformed into knowledge, forecast estimates and managerial decisions. For this purpose, methods of statistical analysis, machine learning, data mining, optimization, fuzzy logic and artificial intelligence are used.

The main tasks of this level are:

- forecasting of demand and sales volumes;
- determination of the optimal level of inventories;
- detection of a shortage or a surplus of products;
- segmentation of customers;
- formation of personalized offers;
- dynamic pricing;
- analysis of the effectiveness of marketing campaigns;
- forecasting of customer churn;
- detection of fraudulent and anomalous operations;

- optimization of warehouse and logistics processes;
- forecasting of equipment failures;
- formation of recommendations for managerial personnel.

The process of intelligent processing can be represented as a composition of operators:

$$U = R(A(X), F(A(X)), C), \quad (5)$$

where A is the operator of analytical processing; F is the operator of forecasting; R is the operator of decision making; C is the set of goals, criteria and constraints; U is the set of managerial decisions and control actions.

4.3.5. Level of Decision Implementation, Communications and Monitoring

At the fifth level of the hierarchy, the implementation of the formed managerial decisions, the transmission of control actions to the executive systems, the monitoring of the results of their execution and the formation of feedback for the next cycle of adaptive management are performed.

The main functions of this level are:

- automatic adjustment of prices;
- formation of orders to suppliers;
- redistribution of products among warehouses and retail outlets;
- management of product display;
- formation of personalized offers for customers;
- management of advertising and marketing campaigns;
- regulation of the parameters of lighting, ventilation, refrigeration and other technological equipment;
- formation of messages for personnel and management;
- visualization of key performance indicators (KPI);
- control of the execution of the adopted decisions;
- evaluation of the actual results of their implementation;
- formation of updated data for the next cycle of system operation.

The implementation of managerial decisions can be represented in the form

$$D^I = E(U, S), \quad (6)$$

where E is the operator of implementation and monitoring of managerial decisions; U is the set of control actions; S is the current state of the smart retail enterprise; D^I denotes the updated data on the results of the implementation of the managerial decisions.

Thus, the developed architecture of the sensor complex and the hierarchical model of data processing and transformation ensure the integration of heterogeneous information flows, the intelligent analysis of data and support for the adaptive management of a smart retail enterprise in real time.

4.4. Generalized Model of Data Processing and Transformation

A generalized model of data processing and transformation has been developed that is based on the successive processing and transformation of data within the five-level hierarchical system. At each level, defined functions with respect to the formation, preprocessing, integration, intelligent analysis and implementation of managerial decisions are performed, which ensures a closed loop of adaptive management of a smart retail enterprise.

The generalized sequence of the hierarchical processing and transformation of the data of a smart retail enterprise can be represented in the form

$$D \xrightarrow{L} D^{(1)} \xrightarrow{I} X \xrightarrow{A} K \xrightarrow{F} \hat{S} \xrightarrow{R} U \xrightarrow{E} D^I, \quad (7)$$

where D is the set of primary data; $D^{(1)}$ is the set of preprocessed data; X is the integrated information space of the enterprise; K is the set of generated knowledge; $\hat{S}$ is the set of predicted enterprise states; U is the set of managerial decisions; D^I is the set of data obtained after the implementation of managerial decisions; L is the local processing operator; I is the integration operator; A is the analytical processing operator; F is the forecasting operator; R is the operator of managerial decision formation; E is the operator of their implementation and monitoring.

In the general case, the process of data processing and transformation can be represented as a sequence of information transformations

$$\begin{aligned} & data \rightarrow information \rightarrow knowledge \rightarrow forecast \rightarrow \\ & management decision \rightarrow guiding influence \rightarrow updated data, \end{aligned} \quad (8)$$

which reflects the closed loop of adaptive management of a smart retail enterprise. In this loop, the results of the implementation of the managerial decisions form updated data on the state of the enterprise, which arrive at the first level of the hierarchical system and are used as input data for the next cycle of their processing, analysis and managerial decision making.

The hierarchical organization of the process of data processing and transformation ensures a rational distribution of functions and computing resources among sensor devices, edge computing nodes, local servers and the cloud Big Data platform. Owing to this, the primary processing, filtering, normalization and aggregation of data are performed directly at the network edge, whereas the resource-intensive tasks of data integration, intelligent analysis, forecasting, optimization and managerial decision support are implemented at the upper levels of the hierarchical system. Such a distribution of functions ensures a reduction in the volume of transmitted data, a decrease in the latency

of their processing, a more efficient use of computing resources, an increase in the scalability and fault tolerance of the system, as well as support for operation in real time.

The developed model ensures the stage-by-stage transformation of primary sensor, transactional and behavioral data into control actions aimed at the adaptive management of a smart retail enterprise. Its use makes it possible to reduce the load on the central information and computing platform, to reduce the latency of data processing and of managerial decision making, and also to increase the reliability of the information used for monitoring the state of the enterprise and for supporting the management processes.

The use of the developed five-level hierarchical system ensures:

- continuous monitoring of the state of the smart retail enterprise;
- integration of physical and digital data sources into a unified information space;
- prompt detection of critical events and anomalous deviations;
- forecasting of demand and consumer behavior;
- optimization of inventories, pricing processes, logistics and resource use;
- automation of the processes of making and implementing managerial decisions;
- scaling of the information system by connecting new sensors, corporate information systems and external

services;

- implementation of a closed loop of adaptive management in real time.

Thus, the developed hierarchical model of data processing and transformation forms the methodological basis for constructing an information technology for the adaptive management of a smart retail enterprise. It ensures the integration of physical sensors, corporate information systems, Edge Computing means and the Big Data platform within a single information environment, supports the intelligent processing and forecasting of data, and also creates the conditions for the timely formation and implementation of managerial decisions aimed at increasing the efficiency of enterprise operation under the conditions of a dynamic market environment.

4.5. Analysis of the Advantages of the Proposed Architecture

The developed architecture of the sensor complex and of the hierarchical data processing system differs from traditional centralized approaches by combining the modular organization of the sensor infrastructure, edge intelligent data processing, multi-level integration of information flows and intelligent analysis within a single information environment. This ensures an increase in the operating efficiency of the information technology for the adaptive management of a smart retail enterprise.

The main advantages of the proposed architecture are as follows:

- reduction of the load on the central information and computing platform through the execution of filtering, normalization, aggregation and primary analysis of data at edge computing nodes;
- reduction of the latency of data processing and of managerial decision making owing to the use of Edge Computing technologies and the hierarchical distribution of functions among the levels of the system;
- increase in scalability through the modular organization of the sensor complex, which makes it possible to connect new sensors, retail facilities and digital services without a substantial restructuring of the architecture;
- integration of heterogeneous data sources into a unified information space, which ensures a comprehensive representation of the current state of the smart retail enterprise;
- increase in the reliability of information owing to the multi-level verification, cleaning, harmonization and integration of data;
- increase in the dependability and fault tolerance of the system owing to distributed processing, data buffering, redundancy of communication channels and self-diagnostic means;
- support for operation in real time, which ensures a prompt response to changes in the state of inventories, consumer behavior, logistics processes and the operation of technological equipment;
- increase in the efficiency of adaptive management through the integration of sensor data, corporate information systems, and means of intelligent analysis, forecasting and managerial decision support.

The efficiency of the developed architecture of the sensor complex and of the hierarchical data processing system should be evaluated by a set of time, resource, information and functional indicators, which can be represented in the following form:

$$P = \{T_{opr}, T_{dec}, V_{net}, R_c, S_c, A_s, D_q, E_a\}, \quad (9)$$

where T_{opr} is the data processing time; T_{dec} is the time of managerial decision formation; V_{net} is the volume of network traffic; R_c is the utilization of the computing resources of the central platform; S_c is the scalability of the system; A_s is the availability and fault tolerance; D_q is the integrated data quality; E_a is the efficiency of adaptive management.

One of the most important criteria of the efficiency of the developed architecture is the reduction of the data processing time. The total time of the passage of the information flow through the hierarchical system is determined by the sum of the durations of the main processing stages:

$$T_{opr} = T_{edge} + T_{tr} + T_{ana_{int}}, \quad (10)$$

where T_{edge} is the time of edge processing; T_{tr} is the time of transmission; T_{int} is the time of integration; T_{ana} is the time of intelligent analysis.

For a centralized architecture, the time of information passage is determined as follows:

$$T_{opr}^c = T_{tr}^c + T_{proc}^c, \quad (11)$$

where T_{tr}^c is the transmission time of primary data to the central platform, and T_{proc}^c is the time of their centralized processing.

The developed hierarchical architecture is more efficient under the condition

$$T_{opr} < T_{opr}^c. \quad (12)$$

that is, when the total time of information passage through the hierarchical system is shorter than in a traditional centralized architecture. The achievement of this condition is ensured by performing the preliminary intelligent processing of data directly at edge computing nodes, by reducing the volume of data transmitted over the network, and also by a rational distribution of the processing functions among the edge, integration and central levels of the system.

One of the advantages of the developed hierarchical architecture is the reduction of the volume of data transmitted to the central information and computing platform. This is achieved owing to the execution of preprocessing, filtering, aggregation and normalization of information directly at edge computing nodes. As a result, only a part of the primary data is transmitted to the central level, which is described by the relation

$$V_{net} = \varphi V_0, \quad (13)$$

where $0 < \varphi < 1$; V_0 is the initial volume of primary data; V_{net} is the volume of data transmitted over the network after edge processing; φ is the information flow reduction factor.

The degree of reduction of the network load is determined by the coefficient

$$K_V = \frac{V_0}{V_{net}} = \frac{1}{\varphi}, \quad (14)$$

which shows how many times the volume of data transmitted over the network is reduced. The larger the value of K_V , the more efficiently the network resources are used and the lower the load on the data transmission channels.

The proposed hierarchical architecture ensures a more efficient use of network resources under the condition

$$V_{net} < V_{net}^c, \quad (15)$$

where V_{net}^c is the volume of data transmitted in the traditional centralized architecture.

One of the important advantages of the proposed architecture is the possibility of its stage-by-stage extension by connecting new sensors, functional modules, retail facilities and information services without the need for a substantial restructuring of the system. This property is characterized by the scalability indicator.

Let N_s be the number of connected sensors, N_m the number of functional modules, and N_0 the number of elements of the basic configuration of the system. Then the scalability indicator can be defined as

$$S_c = \frac{N_s + N_m}{N_0}, \quad (16)$$

where N_0 corresponds to the basic configuration of the architecture.

The value $S_c=1$ corresponds to the basic configuration of the system, whereas for $S_c>1$ the system operates in an extended configuration. The larger the value of S_c , the higher the capability of the architecture for scaling without a significant decrease in performance and functional efficiency. The efficiency of the proposed architecture according to the scalability criterion is ensured under the condition

$$S_c > S_c^c, \quad (17)$$

where S_c^c is the scalability indicator of the traditional centralized architecture.

The integrated data quality is one of the key indicators of the efficiency of the proposed architecture, since it is precisely this quality that determines the reliability of the results of intelligent analysis and the validity of managerial decisions. The composite indicator of the quality of data integration should be defined as a weighted sum of the main characteristics:

$$D_q = w_1 C + w_2 A + w_3 I + w_4 T, \quad (18)$$

where C is the completeness of data (Completeness); A is accuracy (Accuracy); I is consistency (Integrity or Consistency); T is timeliness (Timeliness); w_i is the weighting coefficient of the corresponding characteristic.

The weighting coefficients are determined by an expert or a statistical method and satisfy the normalization condition

$$\sum_{i=1}^4 w_i = 1, \quad (19)$$

where $w_i \geq 0$.

The larger the value of the indicator D_q , the higher the integrated data quality and, accordingly, the operating efficiency of the information technology for the adaptive management of a smart retail enterprise. The efficiency of the proposed architecture according to the data quality criterion is ensured under the condition

$$D_q > D_q^c, \quad (20)$$

where D_q^c is the composite quality indicator of integrated data in the traditional centralized architecture.

An important characteristic of the efficiency of the proposed hierarchical architecture is its availability and fault tolerance, which are ensured by distributed data processing, redundancy of information channels, buffering of data flows and self-diagnostic means. The availability of the system is determined by the classical relation

$$A_s = \frac{MTBF}{MTBF + MTTR}, \quad (21)$$

where MTBF (Mean Time Between Failures) is the mean time between failures of the system; MTTR (Mean Time To Repair) is the mean time to restore operability after a failure.

It follows from formula (21) that an increase in the value of MTBF or a decrease in the recovery time MTTR leads to an increase in the availability of the system. The maximum value of the indicator A_s approaches unity, which corresponds to a practically uninterrupted operation of the information system.

The efficiency of the proposed architecture according to the availability criterion is ensured under the condition

$$A_s > A_s^c, \quad (22)$$

where A_s^c is the availability indicator of the traditional centralized architecture.

An increase in availability is achieved owing to the distributed execution of computations, the local autonomy of edge nodes, the redundancy of communication channels and the possibility of the continued operation of individual subsystems even in the event of a failure of individual components of the central information and computing platform.

The integral efficiency of the developed hierarchical architecture should be evaluated by a composite indicator that takes into account the time, resource, information and functional characteristics of the system. After the normalization of the partial indicators, the integral criterion can be defined in the form

$$E_a = \frac{\widehat{D}_q \widehat{S}_c \widehat{A}_s}{\widehat{T}_{dec} \widehat{R}_c \widehat{V}_{net}}, \quad (23)$$

where $\widehat{D}_q$, $\widehat{S}_c$, $\widehat{A}_s$, $\widehat{T}_{dec}$, $\widehat{R}_c$ and $\widehat{V}_{net}$ are the normalized values of the corresponding indicators reduced to the dimensionless interval [0; 1].

The integral indicator E_a increases with the growth of the integrated data quality, the scalability and the availability of the system, and decreases with an increase in the time of managerial decision formation, in the utilization of the computing resources of the central information and computing platform and in the volume of network traffic. Thus, a larger value of E_a corresponds to a higher operating efficiency of the information technology for the adaptive management of a smart retail enterprise.

The efficiency of the proposed architecture is ensured under the condition

$$E_a > E_a^c, \quad (24)$$

where E_a^c is the integral efficiency indicator of the traditional centralized architecture.

Thus, the developed architecture of the sensor complex and of the hierarchical data processing system is efficient if the following conditions are satisfied simultaneously:

$$\begin{cases} T_{opr} < T_{opr}^c \\ T_{dec} < T_{dec}^c \\ V_{net} < V_{net}^c \\ R_c < R_c^c \\ S_c > S_c^c \\ D_q > D_q^c \\ A_s > A_s^c \\ E_a > E_a^c \end{cases}, \quad (25)$$

where the superscript c corresponds to the values of the indicators of a traditional centralized architecture.

Therefore, the developed architecture ensures a reduction in the time of data processing and of managerial decision formation, a decrease in the network load and in the utilization of the computing resources of the central platform, as well as an increase in the scalability, the integrated data quality, the availability of the system and the integral efficiency of adaptive management.

5. Conclusions

1. The paper solves a relevant scientific and applied problem of developing the architecture of the sensor complex and of the hierarchical data processing system of an information technology for the adaptive management of a smart retail enterprise.

2. The principles of constructing the sensor complex of a smart retail enterprise have been formulated, which encompass modularity, edge intelligent data processing, multi-source integration, distributed processing, scalability, fault tolerance, adaptivity, information security and energy efficiency.

3. For the first time, an architecture of the sensor complex and of a five-level hierarchical data processing system of a smart retail enterprise has been developed that is based on the combination of the modular organization of the sensor infrastructure, edge intelligent data processing, multi-level integration of information flows and a closed loop of adaptive management, which ensures a reduction in the latency of data processing, in the network load and in the utilization of the computing resources of the central information and computing platform, as well as an increase in the scalability, availability and fault tolerance of the system.

4. For the first time, a mathematical model for evaluating the efficiency of the architecture has been developed that is based on a set of time, resource, information and functional indicators and on an integral criterion of efficiency, which makes it possible to perform a quantitative comparison of different architectural solutions.

5. A system of quantitative indicators for evaluating the efficiency of the architecture has been proposed, which encompasses time, resource, information and functional characteristics, as well as an integral criterion of the efficiency of adaptive management.

6. It has been shown that the use of the proposed architecture ensures a reduction in the time of data processing and of managerial decision making, a decrease in the network load and in the utilization of the computing resources of the central platform, as well as an increase in the scalability, the integrated data quality, the availability of the system and the efficiency of adaptive management.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

Conceptualization, I.T.; methodology, O.T.; validation, O.T.; formal analysis, I.T.; investigation, V.P.; data curation, V.P.; writing-original draft preparation, V.P.; writing-review and editing, I.T.; visualization, V.P.; supervision, I.T.; project administration, O.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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Іван ЦМОЦЬ, Володимир ПЕТРИНА, Оксана ЦМОЦЬ

Національний університет «Львівська політехніка»

Наталія ОЛІЙНИК

Харківський національний університет імені В. Н. Каразіна

АРХІТЕКТУРА СЕНСОРНОГО КОМПЛЕКСУ ТА ІЄРАРХІЧНОЇ СИСТЕМИ ОПРАЦЮВАННЯ ДАНИХ ТОРГОВОГО СМАРТ-ПІДПРИЄМСТВА

У статті розв'язано актуальну науково-прикладну задачу розроблення архітектури сенсорного комплексу та ієрархічної системи опрацювання даних торгового смарт-підприємства, які є базовою складовою інформаційної технології адаптивного управління. Показано, що традиційні централізовані архітектури збору й опрацювання даних не забезпечують потрібної оперативності управління в умовах, коли торговельне підприємство одночасно генерує потоки даних від засобів радіочастотної ідентифікації, інтелектуальних полиць, POS-терміналів, систем відеоаналітики, давачів мікроклімату та енергоспоживання, а також від корпоративних інформаційних систем ERP, CRM і WMS та цифрових каналів продажу. Сформульовано дванадцять принципів побудови сенсорного комплексу торгового смарт-підприємства, які охоплюють модульність, периферійне інтелектуальне опрацювання даних, сумісність і стандартизацію інтерфейсів, мультиджерельну інтеграцію, безперервний моніторинг, масштабованість, розподілене опрацювання, надійність і відмовостійкість, енергоефективність, безпеку та конфіденційність, самодіагностику й адаптивність. На основі цих принципів розроблено структуру сенсорного комплексу, що об'єднує дев'ять функціональних груп засобів збору даних та периферійні обчислювальні вузли й IoT-шлюзи. Вперше розроблено архітектуру п'ятирівневої ієрархічної системи опрацювання даних, яка охоплює рівень сенсорів і джерел первинних даних, рівень локального опрацювання, рівень інтеграції та консолідації, рівень інтелектуального аналізу і прийняття рішень та рівень реалізації рішень, комунікацій і моніторингу. Для кожного рівня визначено функції та формалізовано відповідні оператори перетворення даних, а їх композицію подано у вигляді узагальненої моделі, що описує замкнений цикл адаптивного управління, у якому результати реалізації управлінських рішень формують оновлені дані для наступного циклу опрацювання. Розроблено математичну модель оцінювання ефективності архітектури, яка ґрунтується на сукупності часових, ресурсних, інформаційних і функціональних показників: часу опрацювання даних і формування управлінського рішення, обсягу мережевого трафіку, використання обчислювальних ресурсів центральної платформи, показника масштабованості, доступності та відмовостійкості, комплексного показника якості інтегрованих даних і показника ефективності адаптивного управління. Запропоновано інтегральний критерій ефективності та систему умов, за одночасного виконання яких розроблена ієрархічна архітектура є ефективнішою за традиційну централізовану. Показано, що використання запропонованих рішень забезпечує скорочення часу опрацювання даних і прийняття управлінських рішень, зменшення мережевого навантаження та навантаження на центральну інформаційно-обчислювальну платформу, а також підвищення масштабованості, якості інтегрованих даних, доступності системи й ефективності адаптивного управління торговим смарт-підприємством у режимі реального часу.

Ключові слова: сенсорний комплекс, торгове смарт-підприємство, ієрархічна система опрацювання даних, периферійні обчислення, інтернет речей, інтеграція даних, адаптивне управління, оцінювання ефективності архітектури.